HISTORY OF
THE SECOND WORLD WAR

UNITED KINGDOM CIVIL SERIES

Edited by Sir Keith Hancock

WAR PRODUCTION SERIES

Directed by M. M. Postan

The authors of the Civil Histories have been given free access to official documents. They and the editor are alone responsible for the statements made and the views expressed.

DESIGN AND DEVELOPMENT OF WEAPONS

STUDIES IN GOVERNMENT AND INDUSTRIAL ORGANISATION

BY

M. M. POSTAN

D. HAY

J. D. SCOTT

LONDON: 1964

HER MAJESTY'S STATIONERY OFFICE

AND

LONGMANS, GREEN AND CO.

First Published 1964

HER MAJESTY'S STATIONERY OFFICE

London: York House, Kingsway, W.C.2 & 423 Oxford Street, W.1
Edinburgh: 13a Castle Street   Cardiff: 109 St. Mary Street
Manchester: 39 King Street   Bristol: 50 Fairfax Street
Birmingham: 35 Smallbrook, Ringway   Belfast: 80 Chichester Street

LONGMANS, GREEN AND CO LTD
48 Grosvenor Street, W.1
Thibault House, Thibault Square, Cape Town
605–611 Lonsdale Street, Melbourne, C.I.

LONGMANS, GREEN AND CO INC
55 Fifth Avenue, New York, 3

LONGMANS, GREEN AND CO
20 Cranfield Road, Toronto, 16

ORIENT LONGMANS PRIVATE LTD
Calcutta, Bombay, Madras
Delhi, Hyderabad, Dacca

Price £3 3s. od. net

Printed in England by H.M. Stationery Office Press, Manchester

CONTENTS

PART II: ARMY WEAPONS

PREFACE

THE present volume does not appear at its appointed time or in its planned shape. The original intention of the planners and editors of the series of civil histories was to produce a volume on design and development of weapons at the same time as the other main studies on war production or soon after them. Unfortunately, this plan was to remain stillborn. At the time when the early drafts for this volume were being completed international complications raised awkward problems of security, while at home the future of certain branches of the munitions industry threatened to be involved in political debate—a debate to which official histories were not meant to contribute. The volume has thus been delayed far longer than the most pessimistic of editors would have foretold at the time it was first conceived. Delays were further aggravated by the need to rely on spare time services from both the contributors and the editor. Such work as they were able to do had to be dovetailed into busy academic and literary timetables.

The changes in the planned shape of the volume have also been considerable. It was the original intention of the editors to produce an integrated discussion of the problems of design and development of weapons thrown up in the course of rearmament and war. This intention came to nought mainly because it proved impossible to include in this volume the history of naval weapons. The decision not to include naval weapons was one which both the authorities in the Admiralty and the editors took with great regret, but which was nevertheless inevitable. Owing to a variety of circumstances—mostly the late hour at which the composition of this volume could begin—it proved impossible to assemble and digest material relating to naval architecture and the design of naval weapons without very great, and in the circumstances unjustifiable, expenditure of money and labour. But once it was decided not to include the story of naval material the whole project of the comparative historical study of design and development became much less attractive and less feasible than it once appeared. The editor and the authorities therefore reluctantly decided to give up the idea of a single unified story and to publish instead a collection of essays on the separate branches of design and development without attempting to aggregate them round the common problems. And it is in this form that the present volume is now presented to the reader.

The separate studies, being separate, are not uniform either in their approach to the subject or in the method of presentation. The editor's own study—that on the design and development of aircraft—is arranged round the main topics of design and development. The other contributions are nearer in form and substance to the original narratives into which the contributors cast the material they assembled.

To say that most of the studies in this volume do not greatly depart from the historical narrative of events, is not to suggest that the material in them is presented, so to speak, in the raw. As the editor explained in the introductions to some of the earlier volumes in this series, the procedure in the compilation of the official histories of munitions has been as follows. Official files in the government departments in their thousands were consulted and digested. The officials concerned with the administration of design and development were interviewed, and sometimes composed written statements and memoranda of their own. In addition, the contributors to this volume visited a large number of firms engaged in war production, saw their directors and designers, and were sometimes allowed to consult correspondence, charts and memoranda in the firms' own offices. The mass of material thus assembled was then predigested into 'narratives' dealing with individual subjects or events. Thus the history of the design and development of each individual aircraft designed since 1934 was written up as a short historical biography, and these individual biographies were available to the editor in the composition of his own essay. In general the contributors to this volume based their work on such preliminary 'narratives' in a manner little different from that in which writers of other historical books base themselves on various 'secondary' authorities.

The body of contributors to this volume is thus more numerous than the three names on the title page. Of the three authors named, Professor D. Hay is responsible for Part II (Chapters X–XIV) dealing with army weapons, Mr. J. D. Scott for Parts III and IV (Chapters XV–XIX) dealing with radar and scientific establishments respectively, while the editor is responsible for Part I (Chapters I–IX) concerned with aircraft. A number of other persons, however, contributed to the story in different ways. In addition to the men and women who assisted in the study of documents or in the composition of smaller narratives, several other writers produced independent studies of considerable length and substance. Mr. D. A. Parry compiled an industrial and administrative history of aircraft engines and Mr. J. L. Thorne wrote a similar history of aero-engine design. From these two studies the editor drew most of his material on this subject. Mr. K. E. B. Jay conducted the researches and composed the narrative relating to the history of radar and some of the narratives on the scientific establishments on which Mr. Scott based the corresponding sections of his chapters. Miss Cynthia Keppel, in addition to composing most of the aircraft biographies, wrote full-length studies of the timetable of design and development and of the history of the jet engine, of which the abridgments have been incorporated into the editor's section.

The editor received generous and continuous assistance from officials in ministries and scientific establishments who, to repeat, supplied information and advice in the early stages of research and composition and criticism in its later stages. Their names must unfortunately remain anonymous, but anonymity rules do not prevent the editor and the contributors from mentioning by name the temporary civil servants who have now reverted to their civilian posts. Of these, nobody was in a better position to help with information and criticism than the late Sir Henry Tizard, Sir William Farren, Sir Arnold Hall, Sir Harold Roxbee Cox, Sir Robert Renwick, Major-General Sir Edward Clarke, Major-General A. P. Lambooy and Mr. A. A. M. Durrant. Above all, the editor owes a debt of gratitude to the heads and employees of private firms who opened their archives and their minds to him and his colleagues; in the first place, Lord Hives and Dr. A. A. Griffith of Rolls-Royce; Sir Reginald Verdon Smith and Mr. L. G. Frise of Bristol Aircraft Co.; the late Sir Frederick Handley Page; the late Mr. R. K. Pierson and Dr. B. N. Wallis of Vickers-Armstrongs (Aircraft); Mr. L. F. Little of Vickers-Armstrongs, Chertsey; Mr. J. C. Heseltine and Mr. R. T. Jenkins of Vickers-Armstrongs, Elswick Works; Sir Sydney Camm of Hawker Aircraft; Mr. W. E. W. Petter of Westland Aircraft; Sir Roy Dobson of A. V. Roe; Mr. J. Lloyd of Armstrong-Whitworth; Mr. J. D. North of Boulton Paul; Sir Geoffrey de Havilland and Mr. R. E. Bishop of de Havilland's; the late Lord Nelson of Stafford of English Electric; Mr. A. I. Baker of Baker Perkins and many others who could not be mentioned by name without converting this list into an inventory of war-time leaders of munitions industry. They will surely forgive the editor for not invoking their names here. In conclusion, I must mention Miss Hilda Merrifield who looked after the multifarious business of preparing this and other volumes in this series and without whose devoted and scholarly attention these pages might never have seen the light of day.

M. M. POSTAN

June 1963

ABBREVIATIONS

A.A.	Anti-aircraft
A.D.G.B.	Air Defence of Great Britain
A.E.C.	The Associated Equipment Co. Ltd.
A.F.V.	Armoured fighting vehicle
A.I.	Air Interception
A.P.	Armour piercing
A.P.C.	Armour piercing (projectile) capped
A.P.C.B.C.	Armour piercing (projectile) capped with ballistic cap
A.R.C.	Aeronautical Research Committee (later Council)
A.S.V.	Air-to-Surface Vessels
A.T.	Anti-tank
B.B.C.	British Broadcasting Corporation
B.E.F.	British Expeditionary Force
B.O.A.C.	British Overseas Airways Corporation
B.S.A.	Birmingham Small Arms Co. Ltd.
C.H.	Chain Home
C.H.L.	Chain Home Low
D.A.	Delayed action
E.M.I.	Electric and Musical Industries Ltd.
F.A.	Field artillery
G.C.I.	Ground Control Interception
G.H.	Blind bombing system using range measurements from pairs of ground stations
G.H.Q.	General Headquarters
G.L.	Anti-aircraft Gun Laying
G.S. Specification	General Staff Specification
H.A.A.	Heavy anti-aircraft artillery
H.E.	High explosive
How.	Howitzer
H2S	Home Sweet Home: centimetric navigational aid for bombers
I.C.I.	Imperial Chemical Industries Ltd.
I.F.F.	Identification of Friend or Foe

L.M.S.Railway	London Midland and Scottish Railway Co. Ltd.
L. & R.	Left and right
M.A.P.	Ministry of Aircraft Production
M.G.	*Machine gun*
M.G.O.	Master General of the Ordnance
M.T.	Motor transport
M.V.	Muzzle velocity
P.P.I.	Plan Position Indicator
R.A.E.	Royal Aircraft Establishment
R.A.F.	Royal Air Force
R.C.M.	Radio countermeasures
R.D.F.	Radio Direction Finding (later Radar)
R.O.F.	Royal Ordnance Factory
S.A.P.	Semi-armour piercing
S.C.	Solventless cordite
S.L.C.	Searchlight Control
S.P.	Self-propelled
S.T.	Sticky type
T.	Tank
U.P.	Unrotated projectile (later rocket)
V.1	Pilotless aircraft
V.2	Long range rocket
V.H.F.	Very high frequency

PART I

Aircraft

CHAPTER I

THE DOCTRINE OF QUALITY[1]

(i)
Introduction

THE provision of aeroplanes for the R.A.F. could not be and was not measured by their quantities alone; their operational quality was at least as important. The combatant strength of the R.A.F. could only be expressed in terms of aircraft capable of meeting and out-fighting the enemy force in the air. In theory at least it was always possible to achieve immense aircraft production and to maintain a vast front-line establishment made up of inferior aircraft. Fortunately this was never attempted. Ever since the early stages of the expansion and throughout the war it was the primary object of the supply branches of the Air Ministry and of the Ministry of Aircraft Production to maintain the quality of aircraft at the highest possible pitch even though this was bound to reduce the output. Much of the Ministry of Aircraft Production's activities were, therefore, devoted to the design and development of new aircraft or to improvements in current types. The story of this process, of its management by government machinery, of its failures and successes and of its eventual effect on the quality of the British aircraft output as a whole, will form the subject of this study.

(ii)
The Official Doctrine

The doctrine of quality, i.e. the view that the power of the R.A.F. depends largely, if not wholly, on the perfection of its equipment, was one which the Air Ministry handed down to the Ministry of Aircraft Production and which the Air Staff consistently pressed. It was

[1] In this volume 'quality' means essentially what are nowadays technically termed 'qualitative requirements', i.e. quality of technical performance as against quality of manufacture. *Readers not interested in the evolution of the official doctrine on this subject will be advised to proceed directly to Chapter II.*

equally accepted that sacrifice in the numbers of output and establishment was necessary in order to maintain quality; and it was well understood, both on the Air Staff and in the Supply branches, that perfection of aircraft had to be paid for in terms of output.

Had aircraft design and development been frozen or even retarded at the beginning of the expansion or even at the beginning of the war, and no modifications or replacements allowed to interfere with the flow of production, the output would have well outstripped the actual figures. Whenever obsolete types were 'faded out' and new ones were brought in, the flow of production was inevitably interrupted at the very time when all the 'teething' troubles had been overcome and the smooth flow of production could develop. But, apart from new types, continuous modifications of the existing types to fit them to the ever-changing conditions of war in the air continually disrupted the work at the factories. The curves of output of all the well-established and, consequently, much modified types, like the Spitfire, the Wellington, the Mosquito, are bent and broken by repeated depressions, each caused by some new modification or improvement.

The dilemma was well understood and, as a rule, taken for granted. For obvious reasons it found its clearest expression in the highest Service circles, i.e. on the Air Staff and among the Commanders-in-Chief. But the point of view was also fully accepted in the supply branches of the Air Ministry and in the Ministry of Aircraft Production. It was apparently accepted by Lord Swinton and his collaborators during the crucial years of pre-war expansion. In the hectic and heroic months of the Battle of Britain Lord Beaverbrook adopted a somewhat different policy.[1] But his successor, Colonel Moore-Brabazon as he then was, repeatedly gave expression to the established views on quality. Writing to the Prime Minister in November 1941, on the memorable occasion of the Bomber Programme, he had to lay down that technical development to achieve superiority in performance was essential to the prosecution of the war; therefore the inevitable effect on production must be accepted. But nobody expressed the view more clearly than Sir Stafford Cripps in his speech to the aircraft workers in September 1943. 'We have throughout', he said, 'applied one cardinal principle—that quality is more important than quantity. Nothing but the best and most up-to-date is good enough for our magnificent airmen. Whatever the complications or drawbacks arising from the rapid introduction of improvements and changes, we must introduce these at the earliest practicable moment.'

---

[1] See pp. 6–8.

(iii)
Pre-war Relaxations

So much for the doctrine. Its main principles and its implications were throughout the period accepted without demur. This does not, however, mean that in actual practice, i.e. in the framing and in the carrying out of aircraft programmes, it was always fully and consistently applied. The dilemma between quantity and quality was much easier to resolve in principle than in application, and occasions were bound to arise, both before and during the war, when in numbers alone the R.A.F. was so deficient that the sacrifice of quantity could not be faced. On these occasions the doctrine of quality had to be much diluted, if not dispensed with altogether.

One such occasion occurred at the very beginning of the expansion in 1934. There was no other way of inaugurating the process of rearmament in the air except by a temporary contravention of the quality doctrine. It will be remembered that the first measure of expansion leading to the programme of 1935 had to be taken at a time which, from the point of view of aircraft design, was most unpropitious.[1] Aircraft development was on the eve of a major revolution. The era of the fabric-covered biplane, with a fixed undercarriage and low landing speed, was definitely over. With improvement in fuels came the high-power engines and vast progress had also been made in aerodynamics. From this twin evolution came the type with which, in the early 'thirties, the Americans had equipped their civil air lines and with which the Germans were known to be equipping the rising *Luftwaffe*, i.e. the fast monoplane with fully cantilevered wings, retractable undercarriage, variable pitch airscrew, all-metal construction and stressed skin.

The forward ideas in the Air Ministry were accordingly centred on an image of an Air Force entirely equipped with aircraft of the new types. Yet the aeroplanes available for quantity production in 1934 and 1935, the Gloster Gladiator and the Hawker Fury fighters, the Hawker Hart and Hind bombers and even the Wellesley and Harrow bombers, still belonged to the old and outdated race. They were all either biplane or much be-strutted monoplanes with fixed undercarriages and relatively feeble engines. It is, therefore, no wonder that the Air Staff viewed the project of immediate full-scale expansion with misgivings bordering on fear. What they were afraid of was that if pressed too hard the Government might embark on a premature expansion which would saddle the Air Force for many years to come

[1] See M. M. Postan, *British War Production* (H.M.S.O. 1952), Ch. I, Section (iii), and Ch. II, Section (ii).

with obsolete or obsolescent aircraft. It is, therefore, no wonder that political pressure for immediate expansion was resisted by the Air Staff, partly for fear that suitable personnel would not be available in time, but chiefly for fear of cluttering up the Air Force establishment with low quality aircraft.

In the end, however, a partial concession to the policy of immediate expansion had to be made. The full-scale rearmament was successfully delayed for nearly two years, until the newer and better types—Spitfire, Hurricane, Whitley, Blenheim, Battle, Hampden and Wellington—matured for quantity production. Nevertheless, in the interval public demands and political pressure for a larger Air Force had to be satisfied by large orders for admittedly inferior types. In placing the orders the Air Ministry could to some extent justify them by the deterrent effects of an expanded front-line and by the facilities which the additional aircraft could provide for training and additional ground equipment. Furthermore, the expansion was to be confined almost entirely to the front-line, and there was no danger of reserves of obsolescent aircraft being built up. Yet there is no doubt that from the point of view of the Air Staff the situation, though in the nature of a compromise, was highly unsatisfactory. And it was with every sign of relief that by 1936 the Air Ministry were able to propose a programme of expansion much more to their liking.[1] By that time the design of the new aircraft of the Spitfire and the Wellington class had sufficiently advanced to make it possible to frame a programme in terms of the newer types. In the words of an Air Ministry memorandum, they at last felt that 'without taking unjustifiable risks' they could concentrate further orders 'on new types of greatly improved performance'.

The next occasion when the need for mere numbers threatened to take precedence over the improvements in quality was the crisis in the spring of 1938 which followed Hitler's march into Vienna and which led to the emergency aircraft programme L of 12,000 aircraft by the 1st April 1940. Under the pressure of events abroad and of the almost irresistible demands from Parliament and public opinion, the Government at last swept away all the financial impediments to the expansion of the Air Force, and decided to place as many orders as the industry could possibly undertake to fulfil by the spring of 1940. The emphasis was thus definitely on numbers, and the determination to achieve them was so great that it would not have been surprising if real sacrifices of quality had been made. It says much for the Air Ministry and for the advanced condition of aircraft development of the time, that the programme contained very few types which the

---

[1] Scheme F.

Air Staff could consider as operationally unsatisfactory.[1] A certain amount of improvisation was called for, and a larger number of Wellingtons, Hampdens, Blenheims were ordered for the Bomber Force than might have been ordered in more leisurely circumstances. But the sacrifice was certainly not great, for the Blenheim, measured by standards of 1938, was a fast and versatile aircraft, and the Wellington and Hampden were by no means outclassed in their original role of heavy-medium bomber.[2] The entire Fighter Force was conceived in terms of the Hurricane, the Spitfire and the Defiant; and the chief effect of the expansion under the scheme was to increase the orders for the Spitfire and Defiant.[3]

The demands for quantity persisted throughout the eighteen months which separated the inauguration of the 1938 scheme and the outbreak of the war. When, after the Munich crisis, it was decided to extend production under the scheme beyond April 1940, and to increase the total on order to 17,500, the new orders had to be confined to types available for rapid production—although in the view of the Air Staff the step involved 'equipping many squadrons with aircraft of which the operational value is limited'. Similar steps became even more inevitable after the outbreak of the war. Under the various plans for mobilising the 'war potential' the existing capacity was to be deployed for the production of current types. And there is in any case no doubt that the immediate additions to the Air Force, which were made necessary by the beginning of hostilities, could not possibly have been achieved in any other way.

Yet even now little was done to interfere with the projects of the newer types scheduled to come in during 1940 and after. New and important specifications were being pushed forward in the hope of introducing them into the Air Force in the second year of the war—those for cannon fighters included the Whirlwind and those for the new heavy bombers included a super-heavy bomber of 1939 vintage, the B.1/39. In fact, the first additional batch of orders asked for by the Air Ministry for 1941 was to a large measure to be made up of these newer types. It was not until the spring and

---

[1] The principal orders placed for obsolescent aircraft were for Battles at Austin's and 300 Gladiators at Gloster's. The 12,000 aircraft to be ordered under Scheme L, and delivered before March 1940, were all of types either already in production or to be in production before the end of 1938. The extra aircraft however were not to be produced at the expense of the new heavy bombers. None of them was strictly speaking included in Schemes F or L, although initial orders at the parent firms had already been given, but the Air Council was determined that their introduction should not be prejudiced at the cost of extra aircraft of earlier types.

[2] No extra Whitleys were ordered as two months previously 140 machines, cancelled the year before because of the unfavourable comparison between the Whitley and the P.13/36, were restored to Armstrong Whitworth's order book. See p. 12 for continuation orders for the Whitley.

[3] No Hurricanes were required as only recently an extra 300 had been ordered from Hawker's to compensate for an expected delay in Spitfire production.

the summer of 1940 that emphasis on quantity was so placed as seriously to interfere with the progressive improvement of aircraft and to postpone the development of new types.

(iv)
The Emergency Measures of 1940

The interference is usually, and on the whole rightly, associated with the emergency measures which had to be taken by Lord Beaverbrook in June 1940. It would, however, be hardly fair to the men responsible for it not to mention the steps in the same direction which had to be taken some time before Lord Beaverbrook was appointed as the first Minister of Aircraft Production. For as the first winter of the war was drawing to its end, Germany's power in the air came to be more clearly realised. In February 1940 an assessment of German aircraft production made for the Chief of the Air Staff, brought home Germany's superiority in most classes of aircraft, and especially in long-range bombers. This, coupled with the general feeling of an impending crisis which spread abroad early in the spring, caused the Air Ministry to revise their demands for quality. The Secretary of State for Air (Sir Samuel Hoare) proposed an immediate increase in aircraft production, and the only way in which the Air Member for Design and Production could meet the Minister's request was by offering to provide an additional monthly production of 150 Hampdens, Blenheims and Whitleys at the expense of heavy bombers.[1] But within a few days of this proposal the Government was reconstructed, the Ministry of Aircraft Production was formed and Lord Beaverbrook took charge of aircraft production in preparation for the Battle of Britain.

The concentration of production on the five types (Wellington, Whitley, Blenheim, Hurricane and Spitfire), as agreed on the 15th May between Lord Beaverbrook and the Air Staff, is now a well-known landmark in the history of the war. Its corollary in matters of quality was the pause in development or, to be more exact, a pause in all development which could not be directly related to the immediate needs of the Battle of Britain. This meant that a great deal of development work continued, but it was subject to the overriding test of urgency. Apart from theoretical research into basic aeronautical problems which was not to be stopped, all other research, design and development were to be devoted to the modification and improvement of the five preferred types. The

[1] Increased production of medium bombers was to be at the expense of Stirlings, Halifaxes and Manchesters.

Minister's instructions were that such additional effort as could not be absorbed in the aircraft of first priority could be diverted to the aircraft of second priority and to such other work as 'could be made effective within a year'.

This order of priority still allowed work to continue on the heavy bombers of the 1936 specifications (the Stirling, the Halifax and the Manchester) which were expected to come into operational use during 1941. It may also have stimulated improvements in existing types, some of which were doubtless of very great importance. The one for which Lord Beaverbrook would probably take personal credit was the speeding up of the installation of the 20 mm. gun in the wings of the Hurricane and Spitfire in time for the later stages of the Battle of Britain.[1] But the period also saw some immensely important developments of radar and of certain other aids to air defence. Only slightly less important was the installation of the new engines, such as Merlin XX in the Hurricane and Merlin 45 in the Spitfire,[2] or the adaptation of the Blenheim, the Beaufighter, the Defiant and, above all, the Hurricane to new functions in land battles and in sea convoys.[3] Moreover by the autumn of the same year the first priority was widened sufficiently to include the principal Fleet Air Arm types as well as a certain amount of advanced work on high-altitude aircraft. From the latter came not only variants of the Spitfire and Mosquito but also such novel aircraft as the F.4/40 (the Westland Welkin) and the F.9/40 (the Gloster jet-propelled fighter).

Generally speaking, however, the work on most of the advanced types was suspended for about nine months and possibly for more, and among the projects first to be jettisoned or postponed were the prototypes for some of the aircraft with which it was planned to re-equip the Air Force in 1942, e.g. the new bomber designed to the

---

[1] Four cannon wings were introduced in the Hurricane production line at Hawker's (Mark IIC) in February 1940. Thirty Spitfire I's with wings fitted with two cannon only were delivered to the Service in August 1940. Thirty sets of damaged Hurricane wings were converted by semi-tooled and bench methods to carry four cannon. Owing to technical difficulties they were not delivered to the Service until about January 1941.

[2] The Hurricane II with Merlin XX engines had been projected since the early months of 1940. It was not at first expected to come in until December 1940, but delivery was now brought forward several months to August 1940. The installation of Merlin 45 engines into Spitfires was first suggested in December 1940. It became an urgent Air Staff requirement and was introduced into the production line at Supermarine's (Marks VA and VB) in March 1941. Twenty-three Spitfire I's were converted to Spitfire V by Rolls-Royce at Hucknall and were in service by February 1941.

[3] The Hurricane Mark IIB with 12 Browning guns was introduced in March 1941. Other variations included the important Sea Hurricane Marks IA and IB with catapult and arrester gear for the merchant ship fighter scheme which was rushed through in the early spring of 1941; the tropical version of the Hurricane Mark II was also completed in spring 1941. The Beaufighter was modified for long-range fighter duties with Coastal Command. The Beaufighter Mark II with Merlin XX engines, to be used for night fighting in conjunction with the newly developed A.I. interception equipment, was introduced into the production line in March 1941. The Defiant Mark I was modified for night fighting and later, owing to Service requests, the Defiant II with Merlin XX engines was introduced.

1939 specification (B.1/39) which was under development at the Bristol Aircraft Co. and at Handley Page's and the cannon turret under development at Boulton Paul's. The progress of bomber-borne armament was similarly arrested. But even more important than the suspension of current projects and the jettisoning of prototypes were the more general effects on experimental work and thought. The concentration on immediate operational requirements affected the practical facilities of research and development. Thus aircraft and pilots were withdrawn from experimental establishments for service in operational squadrons, with the result that the Director General of Research and Development was moved to complain 'the establishments were no longer capable of the tremendous effort required . . . on projects of great urgency'.

This particular difficulty could be, and in fact was, easily remedied. What could not be remedied were the delayed effects of the pause. For they were felt not only in the day-by-day activity of men engaged on design and development but also in the ideas of men responsible for the future shape of the Air Force. If, as we shall see later, the planning of operational requirements and of types to meet them suffered a partial eclipse in the years 1941 and 1942, and experimental development became somewhat haphazard and unsystematic, the cause was, in part at least, to be found in the disruption of forward thought in the pause of 1940–41.

The pause itself came to an end in the spring of 1941. By that time some of the suspended projects, such as the Typhoon, were resumed. In this period the prototype Mosquito was completed; the night fighter was developed; the Whittle jet engine was pushed forward and was given priority for further development and production; prototypes were ordered for a new medium bomber, the Buckingham, and came very near to being ordered for the Hawker high-speed bomber.

Some re-equipment of the Air Force at some future date was again contemplated, and in the new programmes of July and October 1940 (the so-called Hennessy programmes) new bombers and fighters were to be introduced wholesale in the later stages. When, a few months later, the ambitious plans of aircraft production under the recently adopted Hennessy programmes were scaled down and more realistic versions were formulated, the same assumptions continued to be made about the renovation of the Air Force. So, broadly speaking, one can say that during the first half of 1941 the Air Staff and the M.A.P. were able to restore something like the pre-Battle of Britain relations between quality and quantity. Once restored, this relation prevailed until the end of the war, and was never wholly destroyed by recurrent deviations from the general line. These deviations were sufficiently important to be worth discussing in greater detail, but we must nevertheless guard ourselves against attaching to them a greater importance than they actually had. Though continually disturbed and diluted, the policy of quality remained on the whole effective throughout the period following its restoration in 1941.

(v)
The Bomber Programmes

The occasion for the first deviation came with the so-called Bomber Programme of December 1941. The genesis and the consequences of the Bomber Programme have already been told elsewhere.[1] It will be remembered that on the 7th September 1941 the Prime Minister issued a request for the production by the end of 1942 of an additional number of medium and heavy bombers, about 3,500 in all, over and above the number laid down in the current programme. It will also be recalled that, while doubtful about the possibilities of large additions to bomber production, the M.A.P. proceeded to adjust their previous plans with a view to an immediate increase in output. In the words of a somewhat earlier summary, the policy meant 'sacrificing total bomb-carrying capacity in 1943 to secure a larger first-line strength of aircraft capable of action against the Ruhr in 1942'. In terms of a production programme this meant placing additional orders for existing types at the expense of future replacements and in the first place continuing the production of the Wellington in the two Vickers factories (Weybridge and Chester) where an early 'fade out' of the type was planned. This also meant that the introduction of at least one new aircraft, the Warwick, was put off; and as the subsequent history of the aircraft showed, its postponement was equivalent to scrapping it altogether as a bomber replacement. Other new aircraft were probably not directly affected. But there is little doubt that the new emphasis on numbers made the authorities very reluctant to face any replacement of existing types which might, to begin with, reduce the flow of bombers into operational squadrons. It is largely for these reasons that continuation orders were given for Blenheims to continue right into 1943 and Wellingtons into 1945, and so little was done to reduce the numbers of competing types in production and service.

[1] See M. M. Postan, *British War Production* (H.M.S.O. 1952), Ch. IV, Section (iii).

(vi)
Stop-gap Orders

This naturally leads to another point, or rather a series of points, at which deviations from the doctrine of quality had to be made. In addition to moments of acute crisis like the beginning of expansion in 1935, Scheme L in 1938, the Battle of Britain and the Bomber Programme, when the sense of numerical insufficiency led to a policy of plenty, there were also, throughout the history of aircraft production, certain more chronic causes at work which now and again forced the Air Ministry and the M.A.P. to deviate from ideal standards of quality. The principal of these were for the so-called 'stop-gap' orders, and the maintenance in production of several types serving the same operational purpose.

The stop-gap orders had been an established practice in the Air Ministry and M.A.P. from the beginning of the expansion in 1934 and 1935. The immediate cause was as a rule to be found in the timetables of the newer types scheduled for replacement. When the hazards of design or the delays in development resulted in a postponement of the date at which the squadrons should be equipped with the new types, the temptation to order a larger quantity of the older types was difficult to resist. The decisions were sometimes based on service grounds, i.e. the argument that squadrons which were being formed in anticipation of the new aircraft had somehow to be equipped in the meantime. They would sometimes be based on grounds which were largely political, i.e. the need to maintain before Parliament or the Cabinet the reassuring picture of mounting supplies. But more often the stop-gap orders were prompted by industrial reasons. It was an accepted doctrine in the Air Ministry and the M.A.P. that industrial organisations, and above all the labour force, stood in danger of being dissipated every time a factory was forced to reduce its operations. Stop-gap orders were thought necessary in order to prevent the firms from losing their labour, and especially their skilled labour, during the interval between the lapse of the old type and the full flow of the new one.

As we shall see later this policy was sometimes inescapable. But whatever its justification, its effect undoubtedly was to swell the relative proportion of 'second-class' aircraft, and possibly even to delay the supply of the first-class ones. The extent to which, as a result of 'stop-gap' orders, obsolescent types continued in production beyond their planned span of life is best shown by the examples of aircraft like the Battle, the Whitley or the Blenheim. The Battle was from the very outset an aircraft nobody much wanted.[1] The very conception of a single-engined bomber on which it was based (Specification P.27/32) was originally little more than a tentative project drawn up in 1932 for experimental comparison with the twin-engined specification (B.9/32) out of which the Wellington and the Hampden were later to grow. Certainly by 1933 the Air Staff, as represented by its Deputy Chief, formed the view that the specification was not likely to produce a light day bomber of high performance. But as the pressure for immediate expansion of the first-line had become insistent, and as no other aircraft was available, large provision for the Battle aircraft was made in the air programme. An order for 655 was placed with Fairey's, the parent firm, and 400, with materials for another 100, with Austin's new shadow factory. Even then the Air Council showed itself very anxious not to have more Battles than was absolutely necessary, and in fact the 189 aircraft which were not expected to be delivered from Fairey's by the 31st March 1939 (which was the final date of the Scheme F) were cancelled. In the early spring of 1938, the Air Ministry was faced with the prospect of production at Fairey's and Austin's tapering off as the orders were being completed. But the arrival of the Scheme L in 1938, with its emphasis on maximum output and its figures of 12,000 aircraft, meant further orders for the Battle, and another 363 aircraft making 863 in all were ordered from Austin's. A few months later in autumn 1938, to compensate for failures in production at Austin's, an order for 200 Battles was given to Fairey's.

So far, the additional Battles, though definitely against the spirit of the quality doctrine, were part and parcel of the expansion of 1936 and 1938, and could not yet be strictly speaking regarded as stop-gap orders. But from the end of 1938 till the outbreak of war a series of 'stop-gap' orders, pure and simple, were given even though the official view was that the Battle was 'redundant for operational use'.

This view was reinforced by operational experience at the beginning of the war. The Battles saw active service in France in the spring offensive of 1940, but their losses, owing to their slow speed and light defensive armament, were very heavy indeed. In fact, like other obsolete aircraft, they were soon turned over to Training Command and to various other auxiliary functions. At the outbreak of the war 400 were ordered as target towers. But even if the last orders were not counted, production of the aircraft, which by the Air Staff standards was obsolescent in 1938 and definitely obsolete by 1939, and which was originally scheduled for disappearance by the

[1] Details of the maintenance of the Battle as an operational type and of the successive contracts that were placed from 1936 until 1939 are given in Appendix I, Note 1.

1st April of that year, continued at Fairey's and Austin's until November and December 1940 respectively. Altogether over 3,100 were produced by December 1940, or over $2\frac{1}{2}$ times as many as were originally intended in Scheme F of 1936.

The stories of the Whitley and the Bristol Blenheim look better only in so far as that both aircraft at the beginning of their careers were regarded with favour and were not altogether treated as unwanted children. The Whitley[1] was designed, or rather adapted from a somewhat earlier design for foreign use, in response to the Air Ministry 1934 specification for what was then regarded as a heavy bomber (B.3/34). When the first expansion programme, i.e. Scheme C of 1935, was launched some 80 Whitleys were ordered 'off the drawing-board'. Under Scheme F of 1936 the order was increased by 240. But in the same year the specifications for bombers (P.13/36 and B.12/36) of greatly increased range and weight-carrying capacity were formulated. Out of these specifications the Stirling, the Halifax and the Manchester were to grow and this immediately made the Whitley obsolete as a heavy bomber and all but obsolescent as a medium bomber.

Yet, before long additional orders were given. They continued to be given with every programme and between programmes, partly because of sudden emphasis on numbers at times of crisis, partly because Armstrong-Whitworth were at that time not considered capable of efficiently organising the quantity production of a new type, but chiefly because the production of replacement bombers was repeatedly postponed. Altogether 1,812 Whitleys were produced or nearly six times the number originally planned.[2] Production continued for seventy-seven months and did not stop until three years after the date originally set for its completion. Needless to say the Whitley had in the meantime been much improved by the installation of Merlin engines. Its bomb-load was more than doubled and even its speed was slightly raised. But a half-hearted attempt to extend its life and its usefulness by the installation of four engines came to nothing. At the time when it was rolling out in highest numbers it was no longer usable as a bomber, and was employed chiefly for glider towing, paratroop dropping and Coastal Command work. But many, perhaps most, of the Whitleys produced during the war scarcely left the Aircraft Storage Units.

The story of the continuation orders for the Bristol Blenheim is less lurid, but equally instructive.[3] The Blenheim began its life as a

---

[1] Details of the maintenance of the Whitley as an operational type and of the successive contracts that were placed from 1935 until 1942 are given in Appendix I, Note 2.

[2] See Appendix I, p. 494.

[3] Details of the maintenance of the Blenheim as an operational type and of the successive contracts that were placed from 1935 until 1942 are given in Appendix I, Note 3.

useful light-medium bomber and as very nearly the first of the new race of all-metal, cantilever monoplanes. It was adapted in the course of late 1935 and 1936 in response to urgent requirements of the Air Force from the civil aeroplane 'Britain First' ordered privately by Lord Rothermere. Under the Scheme F of 1936 a large production was planned and altogether over 1,500 aircraft were ordered. With the coming of Scheme L in April 1938 the number of Blenheims on order at the three firms was increased to over 1,700. The additional orders as yet contained very few that could be legitimately described as 'stop-gap'. But by degrees they crept in, when Bristol's received an extra order for 70 aircraft in November 1938 to compensate for an unexpected failure of a general reconnaissance aircraft designed and produced by Blackburn's (the Botha) and, early in 1939, when the Air Council recommended ordering a further 62 from Bristol's 'to fill the gap . . . before the Beaufort comes into production'. Additional orders were also given to Rootes and A. V. Roe's which entailed continuation of the type well into 1940. In April 1939 stop-gap orders for 800 aircraft were authorised by the Air Council and of these 250 were to be Blenheims from Rootes. 250 were also ordered from A. V. Roe's in June 1939.

A yet further stimulus to continuation orders for Blenheims was given by the war. By that time Bristol's themselves were apparently on the point of winding-up the Blenheim production, for they were already involved in the production of the Beaufort, and, in addition, the Beaufighter was expected to mature for production within a few months. Nevertheless, Blenheims lingered on at Bristol's until March 1940, chiefly because of the delays in the introduction of the other two types. Moreover Rootes were to carry on the production of the Blenheim for at least another eighteen months: they had 850 on order and an order for 400 more was placed immediately on the outbreak of the war, and during the winter another 800 were added, making, with 220 transferred from A.V. Roe's, a total of 2,270 in all. Then under the so-called Harrogate Programme of January 1940, production was to be carried forward to September 1942 for which about 1,900 more Blenheims would be needed. As the Blenheim figured among Lord Beaverbrook's five preferred types, it received a further injection of orders in the opening stages of M.A.P's career. And this had the effect of extending A. V. Roe's commitments in the production of Blenheims at the expense of the Manchester. Further additional orders followed each other in quick succession. 800 were ordered in June and nearly 400 in August, so that the total on order at A. V. Roe's grew by the end of August to 1,575 and was designed to prolong production until March 1942. Similarly, additional orders for 600 and 780 were given to Rootes, and their total on order by August 1940 reached well over 3,400 and was sufficient to carry the firm on to February 1942.

The numbers were, from the Air Council's point of view, too much of a good thing. Writing on the 16th January 1941, the Air Member for Supply and Organisation gave the Air Staff's opinion that 'the Blenheim is an obsolescent type whose purpose and armament are inadequate for operational conditions to-day'. Because of this and because American medium bombers could be obtained in increasing numbers, the Air Ministry asked for Blenheim production to be reduced so that capacity could be turned over to Lancasters and Halifaxes. Rootes suffered a small reduction in total orders, and A. V. Roe had the larger part of the remaining Blenheims still outstanding cancelled. But before the cancellations could take effect the operational qualities of the Blenheim had been somewhat improved, and the Air Staff reversed their decision owing to the heavy overseas commitments of the Air Force in late 1941 and early 1942. Consequently production continued at Rootes during 1942 at an average monthly rate of nearly 60, right up to June 1943, or over eighteen months later than the date of extinction originally fixed, and the cancelled order at Rootes had to be restored in August 1941 with another 250 or so more added. The Air Ministry were even forced to protest at the deficiencies of Rootes' production which were holding up vital overseas shipments in the early spring of 1942. Finally, however, with the introduction of the Halifax into the Rootes' organisation 250 Blenheims were cancelled. Altogether Blenheims were in production at Rootes for nearly five years and the firm produced nearly 3,500 out of the total of 5,421 produced by all three firms.

The Battle, the Whitley and the Blenheim have been chosen for illustration but they stand by no means alone. The Wellington, the Hurricane, the Albemarle, the Warwick and several of the naval types could provide examples of aircraft maintained in production for industrial reasons long after they could be fully employed in their original operational roles. Needless to say, in this, as in many other similar instances, the aircraft which thus continued to be ordered were not always wholly superfluous. With or without later improvements and modifications most aircraft produced in those lean years (and in time of war all years are lean) could be put to some use somewhere. As the following list shows, for every one of the stop-gap types, some new use was found.

Type	*Designated function*	*Converted function*
Albemarle	Medium Bomber	Transport for Russia; Medium Bomber Operational Training Unit; Air/Sea Rescue; Meteorological Flights; Glider Tug.
Battle	Medium Bomber	Trainer; Target Tower.
Defiant	Turreted Day Fighter	Target Tower.

Type	*Designated function*	*Converted function*
Hampden	Medium Bomber	Torpedo Carrier; Minelayer.
Wellington	Medium Bomber	Coastal Command (Reconnaissance, Torpedo-Bomber, Anti-Submarine); Freighter.
Whitley	Medium Bomber	Coastal Command; Paratroop Dropping; Glider Tug; Freighter; B.O.A.C. Transport.
Warwick	Heavy Bomber	B.O.A.C. Transport; R.A.F. Transport; Air/Sea Rescue; General Reconnaissance.

For this and other reasons it would be wrong to classify all the continuation orders merely as stop-gap ones. Thus, many of the later orders for the Hurricane were prompted by Russian needs and by the new use for the aircraft which was opened up by its adaptation to seaborne air convoy.[1] It may thus be difficult to disentangle stop-gap orders in the narrow sense from those continuation orders which had to be given for strategic and political reasons in moments of crisis or in response to the new operational need. Yet, all these qualifications notwithstanding, it remains broadly true that stop-gap orders were both continuous and abundant, and that, but for these orders, the average quality of aircraft turned out by the industry between 1935 and 1944 would have been considerably higher and much nearer the Air Force ideals of quality. It is not merely that all but obsolescent aircraft formed a greater proportion of current output than the planners originally intended, but that the introduction of new types was in some cases impeded. In general, the industry, or at any rate important sections of the industry, preferred producing the well-established types. It is therefore no wonder that the behaviour of individual firms gave grounds for suspicion that the introduction of new types was delayed in the hope of 'wangling' a continuation order. Fortunately, the firms against whom this accusation was levelled were few, but there is little doubt that even the most public-spirited of the firms might not exert themselves in changing over to new types when orders for the old ones were to be had.

(vii)
Multiplicity of Types

The other chronic deviation from the policy of quality will be found in the multiplicity of types in production and service. In principle

[1] Nevertheless in April 1942 the Minister of Aircraft Production, Colonel Llewellin, wrote to Sir Charles Bruce-Gardner pointing out that Hurricanes were being built to compensate for the laggard Typhoons so as to 'splice' the programme.

this multiplicity ran counter not only to the Air Staff striving after quality, but also against their well-established preference for an unspecialised Air Force. Ideally, aircraft production should be so distributed among the different types as to supply one, and no more than one, type of aircraft for each tactical function. In theory at least there should have been one heavy bomber, one medium or light bomber, one day fighter, perhaps one night fighter, and so on. In actual fact the theory could never be applied in a form quite so simple, for strategy and tactics dictated a differentiation of functions which was much more subtle and complicated. Specialised subdivisions were bound to be introduced into the general classifications of bombers and fighters. Thus, in 1940 and early 1941, the Air Staff began to press for high-altitude fighters, and for a long time, because technical problems made it difficult to produce an aircraft capable of flying equally well at all altitudes, specialised high-altitude aircraft, like the modified Spitfire or the Welkin, had to be designed and produced. About the same time requirements for high-altitude bombers brought forth a number of projects of special pressurised bombers. It will also be shown that the Mosquito was originally designed as the first of a new tactical class of bombers: the fast unarmed raider.[1] There were also other innumerable minor functions for which specialised aircraft were demanded: functions ranging from photographic reconnaissance to air/sea rescue.

This process of continuous differentiation of functions could not be, and was not in fact, met by production of rigidly specialised types. New functions budding off the old ones were, as a rule, fulfilled by adapting the well-tried basic designs. It would take a whole book to describe all the uses by which, as a result of this continuous adaptation, the Hurricane became an entire Air Force in itself. The functions it eventually fulfilled were those of day fighter, night fighter, fighter-bomber, tank and ship buster, catapult fighter for convoy protection and fleet fighter. The Wellington proved almost equally versatile. Except for the first raids of 1940 and early 1941, it was not employed as a day bomber over Germany, but almost every other function came within its scope including that of minesweeper. The Spitfire, for all its specialised features, was also used in more than one role. As for the Mosquito it was almost from the very beginning cast for the role of maid-of-all-work. It was originally pressed on the Air Ministry and M.A.P. as a light unarmed bomber; it was eventually accepted, largely with the intention of using it for photographic reconnaissance, but long before it got to the quantity production stage it had to branch off into a fighter variant for night work. Other variants followed including a medium bomber,

---

[1] See Ch. IV, Section (vii).

a fighter-bomber, a six-pounder tank buster and a civil transport. By the end of 1943 there were about 15 marks of the Mosquito in operation including seven fighter versions alone. In fact, the lesson which M.A.P. and the Air Ministry appear to have learned from the history of the Hurricane, Spitfire, Wellington and Mosquito was that, given a good basic design, the aircraft could be made to do an infinite variety of jobs in addition to that for which it was originally designed.

So, what with the continuous evolution of tactical functions and the adaptability of the better types, it is easy to understand why the Air Ministry found it both impossible and unnecessary to adhere to a rigidly functional demarcation and to demand as many types as there were possible differences in tactical use. Little was thereby sacrificed in the general quality of the Air Force. If anything the Air Force gained in ease of service. By the second year of the war, i.e. by the time the experience of changing requirements had been accumulated and digested, the preference for a non-specialised or an under-specialised Air Force came to be clearly expressed in a statement of official policy.

This point of view was for the first time expressed with all the necessary clarity and pungency in the letter which the Chief of the Air Staff wrote to Colonel Moore-Brabazon soon after the latter's appointment as Minister of Aircraft Production; a letter which, on this and other matters, constituted the first broad statement of aircraft policy in matters of design and development since the great disturbance of midsummer 1940. The official formula now was 'a flexible force well supplied with general purpose weapons'. As a matter of general policy specialisation in classes of aircraft was not to be encouraged:

> We have not, and probably we never shall have, an Air Force adequate to the needs of the Empire. Time and time again we are forced to use aircraft intended primarily for one theatre in some other theatre, or for some duty for which they were not originally intended. Specialisation is therefore undesirable, and unless we keep this firmly in mind we lose flexibility and find ourselves saddled with types of very limited usefulness. I agree that some specialisation is unavoidable, e.g. the flying boat, the pressurised bomber, the pressurised fighter and a few others, but it is only for some inescapable physical reason that we should accept specialisation.

In view of the clear preference for a small number of types it is at first sight difficult to understand the other deviation from the principle of one aircraft for one function, a deviation which is wholly contrary to that which we have so far discussed. In spite of their opposition to the multiplicity of types the Air Ministry and M.A.P.

were forced to reconcile themselves to, and for a long time to condone, the multiplicity of types performing the same tactical function. At almost any point in the history of aircraft production more than one, usually more than two, aircraft were turned out for the same operational class.

In the early days of rearmament there were two fast day fighters, the Hurricane and the Spitfire, intended for largely the same role and originally designed for much the same requirement. The Wellington and the Hampden were similarly related to each other among the early medium-heavy bombers of the new dispensation. By 1944 the Tempest largely duplicated the later series of the Spitfire in the role of fast fighters. Regarded from the point of view of their bomb-carrying capacities, the Buckingham duplicated the Mosquito in the light-medium bomber class.[1] The Welkin duplicated the pressurised Mosquito in the high-altitude fighter and photographic reconnaissance class. But the most conspicuous duplication between 1940 and 1944 was in the class of heavy bombers. By the end of 1943 the following aircraft were designed and were produced as heavy bombers: Stirling I, Halifax II, Lancaster II and III and the Warwick,[2] and yet another, a fifth type, the Windsor, was due to make an appearance, as well as the improved Lancaster, known as the Lincoln.

Some such redundancy was inevitable. It followed from the Air Staff policy of development and, more especially, from the principles of development in force before the war, and could on those grounds be justified. In fact it was thus justified by the Prime Minister (Mr. Chamberlain) in a famous debate in the House of Commons on 25th May 1938:

> I agree that it is desirable to reduce the number of types and to standardise them as far as possible as a general principle, because the nearer you can get to standardisation the easier it is to engage in economical quantity production. But I would suggest to Hon. Members that in a transition period, and that is what we have been passing through, a transition period from old designs to new designs of an entirely different character, you can easily carry that principle too far. It would not be right to put too severe a brake upon the inventive genius of our people in manufacturing and design, if we want to get the best results . . . Therefore, while it is undoubtedly the policy of the Air Ministry always to be reducing the number of types it has in use, and to standardise their construction as far as possible, yet I say that during this transition period it was inevitable that the

---

[1] They were not duplicates in the more technical classification of aircraft functions: the Buckingham was armed and the Mosquito unarmed.

[2] Fifty-seven Warwick I's were produced as bombers before production could be changed, when the Air Ministry decided not to use the type as a bomber. See pp. 129–130.

> number of types should be considerably in excess of the number to which you would hope to get down when you had had further opportunities of experience.[1]

As a rule, when a new improved specification was issued, designs from more than one firm were invited in order to secure the best possible design and in order to make competitive tendering possible. Very often more than one promising design emerged from the competition, and when this happened more than one design was allowed to proceed to the prototype stage or even to that of development orders. The underlying policy was expressed by the Director General of Research and Development who said 'We should limit our fighter types to two with a possible maximum of three in any one class with the object of providing a minimum safeguard against the temporary collapse of any one type putting the whole fighter force out of action'.

This policy offered many advantages. It carried a valuable insurance against the hazards of development and of early operational experience. For it was very difficult to predict in the design, or even in the prototype, the eventual success of a given aircraft in operation, and thereby to avoid the danger of a premature concentration on one type. Thus, if at an early stage in the development of the heavy bomber it had been decided to concentrate on the one type only, that type would have been not a member of the Manchester/Lancaster family—which in the end provided the Royal Air Force with its best heavy bomber—but the Halifax. For in 1939 when the future policy for the heavy bombers was discussed it was taken for granted in the Air Staff and in the M.A.P. that eventually the Halifax would be the only heavy bomber in quantity production. A decision was not taken at that time and the bomber force was thus saved from the incubus of a second-best aircraft. Later again in early 1941 the same controversy arose over the request of A. V. Roe's to be allowed to proceed with the conversion of the Manchester into the Lancaster. Had then the view (much urged by some people) that the Halifax was sufficient for the heavy bomber role prevailed, the Lancaster would never have seen the light of day. It was very largely on the same grounds that the historian would justify the maintenance in production of the Hurricane and the Spitfire, the Wellington and the Hampden, to mention the two most obvious instances of duplication.

This, however, is only half the story. Insurance against hazards of development and early operational experience does not account for all the redundant types. Most of the duplication occurred as a result of historical and technical accidents and could not be justified

[1] H. of C. Deb., Vol. 136, Col. 1257, 25th May 1938.

on any grounds consistent with the doctrine of quality. Thus in the case of the late bombers, the original plans as conceived in 1936 provided for only one four-engined super-heavy aircraft, that of Specification B.12/36 out of which the Stirling was to emerge. The next class was to be made up of somewhat similar bombers of the P.13/36 specification equipped with only two engines, weighing about 45,000 lbs. all-up against the Stirling's 55,000 lbs. These plans were, however, completely upset by the troubles of the Rolls-Royce Vulture engine on which the Halifax/Manchester designs were based. When in the summer of 1937 the doubtful prospects of the Vulture became apparent, the Air Ministry induced Handley Page to change the design of the Halifax, much against their wishes, into a four Merlin-engined aircraft of a somewhat greater weight. The Manchester was still allowed to struggle with an insoluble problem of an overweight aircraft equipped with two under-powered engines, until finally A. V. Roe's on their own initiative and against some opposition in the M.A.P., redesigned their aircraft to take four Merlins, like the Halifax, and likewise to expand in weight and dimensions.

In this way the class of super-heavy bombers was swollen by two new unpremeditated additions. Two more additions were to follow as a result of somewhat different accidents. Even before the heavy bombers of the 1936 class were ordered, the Air Ministry put out to open tender a specification, B.1/35, to replace the Whitley, and Vickers-Armstrongs obtained the order with a much enlarged version of the Wellington. But as the P.13/36 group (Halifax/Manchester) surpassed the B.1/35, the Air Ministry did not appear to be certain whether the aircraft were really needed except in so far as this carried the Wellington's 'geodetic' construction a stage further. The firm, on their part, were so busy with the design and development of the Wellington with its many variations, and with other projects, that it allowed the B.1/35 to go slow. So what with vacillations in the government departments, the delays at Vickers, and a fundamental redesign to bring it up to the P.13/36 requirements, the aircraft did not finally emerge from the prototype stage until late 1942. By that time it was superior in range and load, but not in speed or reliability, to the Wellington X, and inferior in every respect to the other heavy types.

A somewhat similar career awaited Vickers' next design, the Windsor. The Windsor was conceived very largely on the initiative of the Vickers firm. It was sponsored for a specialised function of a heavy, high-altitude bomber, but was apparently adopted in order to make it possible for Vickers to produce a four-engined machine of geodetic construction. But the early stages of this type were beset with uncertainty and vacillations almost as marked as in the case of the Warwick. In the end, i.e. by the time it reached the prototype stage, it came to be no more than yet another heavy bomber, somewhat superior in range to the new Lancaster. Its real justification in the later stages of its development was to be found in its superior speed and armament, enabling it to fill a new position of a 'fast' heavy bomber. But even so, there was every chance that by the time the Windsor was in operational use, the new super-Lancaster, the Lincoln, might compete with it in efficiency of armament.

Thus, as a result of accidents, of delays in development, and of uncertainties in policy, the M.A.P. found themselves by the beginning of 1943 having to provide for the continued production of at least three four-engined bombers, and of at least four aircraft of heavy bomber weight, with the prospects of a fifth in the offing. On the strength of the figure of performance accepted by the Directorate of Technical Development at M.A.P. most of these aircraft, however different in quality, were near enough to the Lancaster and to each other in specification to be more or less redundant. This is clearly shown in the following table:[1]

	Weight lbs.	*Max. speed at height*	*Max. range with bomb load*	*Max. bomb load with range*
Warwick I (2 Wasp)	46,000	250 m.p.h. 15,500 ft.	1,550 miles 5,400 lbs.	8,000 lbs. 870 miles
Halifax (4 Merlin X)	59,000	262 at 18,000	1,740 miles 8,500 lbs.	13,000 lbs. 1,000 miles
Stirling (4 Hercules XI)	70,000	260 at 10,500	1,930 miles 5,000 lbs.	14,000 lbs. 690 miles
Lancaster III (Merlin 22)	63,000	270 at 19,000	2,450 miles 5,500 lbs.	14,000 lbs. 1,020 miles
Windsor (B.3/42) (Merlin 100)	82,000	290 at 26,000 (cruising)	3,150 miles 3,200 lbs.	14,000 lbs. 1,800 miles
Lincoln (Merlin 85)	75,000	319 at 18,500	2,930 miles 4,150 lbs.	14,000 lbs. 1,470 miles

When the multiplicity of types was due not to insurance but to a mere string of accidents, and when, moreover, it was allowed to continue beyond the stage of initial production and long after the relative operational qualities of each type came to be known, the reluctance to concentrate on the best type could not be regarded as anything else except a sacrifice of quality.

Needless to say the sacrifice was not wholly indefensible and was in fact defended. Arguments against concentration were various and strongly pressed. There were strong production reasons against a

[1] The figures for all the bombers are based on the rather conservative tables of actual performance kept by the Assistant Director of Research and Development (Technical Investigation) 1.

changeover from an established line of production to another aircraft however superior in quality. That the Lancaster was the best of the heavy bombers came to be realised quite early in 1942. From the very moment this was realised proposals for transferring the capacity from the Stirling, and possibly from the Halifax, were made. Throughout 1942 and 1943 most of these proposals were turned down at the highest level for fear of losing numbers and falling behind the heavy bomber programme. In October 1942 a Committee under the chairmanship of the Minister of Production considered the future types of bombers and, among other things, recommended that the 'changeover of Short's (except Short-Harland) and Austin's factories from Stirling to Lancaster should be carried out as soon as possible'. This decision was in the end accepted by the Cabinet, but it obviously did not embrace a wholesale changeover to a single type. The production of the Halifax was not to be curtailed at all, while the replacement of the Stirling, agreed upon, was not to be completed till July of 1944, and in the end was never carried out as planned. More far-reaching plans for doing away with both the Stirling and the Halifax were adumbrated by the Chief Executive at the end of December, but again little was done to follow them up.[1]

It was obviously difficult to cut out types at this late hour when their redundancy became apparent, for it involved large sacrifices of all-too-precious bombers at a time when the bombing offensive was at its height. The difficulty, however, was largely one of timing. It might never have arisen had, at the beginning of the process, the nature or the dimension of the sacrifice been properly understood. In this, as in many other problems of policy concerning quality of aircraft, the Air Staff, the M.A.P., and, in fact the Cabinet as a whole, were for a long time handicapped by the absence of a clear measure of operational quality and by the difficulty of evolving one. How were mere preferences for one type or another to be substantiated, and concentration on better types decreed, if a clear

---

[1] Much involved with all these proposals were the problems created by the several Vickers' bombers, the Warwick, the Windsor and the Wellington. The latter was long overdue for replacement, while the other two were bombers of the heavy class more or less competing with the Lancaster. The Minister of Production's Committee, already referred to, proposed to replace the Wellington, at least at one factory, with the Windsor, on the ground that the latter promised much better performance and that it would come in sooner than the improved variant of the Lancaster. The argument as yet found little favour with the Prime Minister and the problem of the Windsor was to come up several times again. By March 1943 the prospect of introducing the Windsor before the improved Lancaster had proved to be illusory, but the Windsor still appeared to be the best heavy bomber in prospect, and a compromise proposal to change over to the Lancaster in one of the Vickers' factories (Chester) and to persevere with the Windsor in the Vickers' parent factory was adopted. The position was reviewed in a joint paper put up to the Defence Committee (Supply) by the Minister of Aircraft Production and the Secretary of State for Air entitled 'The Replacement of the Wellington and the Warwick' and at the meeting of the Defence Committee (Supply) on 30th March 1943.

notion of what constituted a better type was not to be had? The problem was difficult enough in all conscience in deciding between rival types of fighter. For it is not speed alone, and not even speed and manoeuvrability, that marks off one good fighter from a better one. Things like rate of climb, operational ceiling, range, sturdiness, armament, all enter into the controversy and prevent the taking of clear-cut decisions. When in March 1944 Lord Beaverbrook was moved to declare in debate in the House of Lords that the Merlin-engined Mustang was the best fighter in existence, no expert could either support or refute him.[1] For from some points of view, that of range, sturdiness and manoeuvrability, it was at the time the best fighter in existence, but it was rivalled by the current types of Spitfire in speed and excelled by them in rate of climb.

The quality of bombers is even more difficult to measure with exactitude, for there, in addition to range, weight-carrying capacity, stowage space, speed, climb and height, it is also very important to consider the aircraft's survival rate, i.e. its ability to defend itself, to withstand punishment and to fly damaged to its home base. In the absence of a formula comprising all these variables the superiority of the Lancaster was difficult to establish, and, once established, was difficult to set off against losses in numbers. It was not until early in 1944 that a special branch of Operational Requirements, Air Ministry, set out to devise a comprehensive scientific measurement of bomber efficiency in which all its determinants were given their proper weight.[2] Until then the Air Staff, the M.A.P. and the Cabinet had to base their decisions on much more imperfect measurements.

The evolution of these measurements will be described later.[3] But in discussing the redundance of heavy bomber types it is important to bear in mind that a wholly satisfactory measurement was not evolved until December 1943, and that by then the plans of heavy bomber production for war with Germany were past mending.

This concludes our story of the quality doctrine. Now and again—usually in moments of crisis—it was contravened to permit large and sudden increases in numbers; over the period as a whole it was somewhat diluted by stop-gap orders and by the continued production of types which were little better than second best, and were otherwise redundant. Yet, as we have already said, these departures from the doctrine of quality are apt to loom larger in this narrative than they appeared to be at the time. Above all, most of them were, in the special circumstances of war, never allowed to become anything more than temporary and unfortunate departures from the ideal and

---

[1] H. of C. Deb., Vol. 131, Col. 265, 23rd March 1944.

[2] The section was established under Group Capt. Boothman in May 1942 and later taken over by Group Capt. Combe.

[3] See Ch. IV, Section (v).

were always regarded in the Air Ministry and the M.A.P. as merely an inevitable evil. Apart from the special conditions of the summer of 1940, the government departments in charge of requirements and production never advocated 'output at all costs' and at no time was quality neglected or allowed to be wholly submerged by mere numbers. In spite of all the deviations the general line was clear enough.

CHAPTER II

ORGANISATION OF DESIGN AND DEVELOPMENT IN AIRCRAFT FIRMS

(i)
The Designing Firms

THE next problem to consider is how the quality of British aircraft was safeguarded and advanced, i.e. by what methods new technical requirements were conceived, newer and better types brought forward, and older types improved. The answer to this question naturally falls into two parts. It cannot be repeated too often that the progress of British aircraft was the work of both the industry and the Government. And as long as both the Government and the industry contributed to the quality of the British aircraft each had to possess for that purpose a machinery of its own.

Nearly all the firms before the war, and most of them during the war, were capable of designing engines and aircraft and as a rule produced aircraft to their own designs.[1] Since the beginning of the expansion a number of large industrial units, such as the airframe factories of English Electric Co. Ltd. and Metropolitan-Vickers Electrical Co. Ltd., the Nuffield, Austin and Rootes 'shadow' factories, or the Ford and Standard aero-engine factories grew to become large and important producers. None of the new entrants however undertook the work of design and development, and this remained until the closing stages of the war mainly in the same hands as before, i.e. in those of the sixteen 'family' firms, of which fourteen, Vickers (Aviation) Ltd., Supermarine Aviation Works (Vickers) Ltd., Hawker Aircraft Co. Ltd., A. V. Roe & Co. Ltd., Gloster Aircraft Co. Ltd., Handley Page Ltd., de Havilland Aircraft Co. Ltd., Fairey Aviation Co. Ltd., Short Brothers (Rochester & Bedford) Ltd., Westland Aircraft Ltd., Boulton Paul Aircraft Ltd., Bristol Aeroplane Co. Ltd., Sir W. G. Armstrong-Whitworth (Aircraft) Ltd., and Blackburn Aircraft Ltd., were responsible for most of the new designs.

---

[1] See M. M. Postan, *British War Production* (H.M.S.O. 1952), p. 5.

On the engine side, their counterparts appeared to be the four engine firms, i.e. Rolls-Royce Ltd., Bristol Aeroplane Co. Ltd., D. Napier & Son Ltd. and Armstrong Siddeley Motors Ltd. and, to some extent, the de Havilland Aircraft Co. Ltd. But the design organisations of Armstrong Siddeley, de Havilland and Napier were, for the greater part of the time, relatively unimportant compared with those of Bristol's and Rolls-Royce. So small and relatively inactive was the design department of Armstrong Siddeley that from 1936 to 1944 the Cheetah and the Tiger were the only Armstrong Siddeley engines of any importance to the R.A.F. Similarly, de Havilland's engines were of relatively little importance until the coming of the jet propulsion engine in 1941. The firm had entered the expansion period with a small family of Gipsy engines and did little during the war beyond adding one or two more variants.[1] This they were able to achieve with a small development section and with the part-time services of a distinguished designer (Major Halford) whom they shared with Napier's. The scale of activities at Napier's was somewhat, but only somewhat, greater. Between 1934 and 1939 their design department was so small and devoid of drive that nothing comparable in quality and importance to their famous Lion of 1920 appeared on the stage till the emergence of the Sabre in 1939 and 1940.[2] The situation was not transformed even after the arrival of the Sabre. It was very largely the repeated failures and delays in the first three years of the Sabre and the inadequacy of Napier's development organisation that led the M.A.P. in 1943 to enforce the transfer of the Napier organisation to the English Electric Company.

The main burden of engine design thus fell on the remaining two firms: Rolls-Royce and Bristol's. Both firms, and especially Rolls-Royce, possessed large and active organisations for the design and development of engines. But two features of organisation must be noted for comparison with what we shall have presently to say about the design of airframes. One was in marked contrast to aircraft firms; the other was common to both. The contrasting feature was the independence of engine projects. The two engine firms, and especially Rolls-Royce, initiated and developed most of their engines

---

[1] In 1939 the de Havilland Gipsy family consisted of the following types:
Gipsy Minor; Gipsy Major Series I and II; Gipsy Six Series I and II; Gipsy Twelve (see Society of British Aircraft Constructors Ltd. publication *The British Aircraft Industry*, 1939).
During the war (up to 1943) the following Gipsy types were produced:
Gipsy Major I and Ic; Gipsy Queen II and III; Gipsy Six.

[2] Major F. B. Halford designed two engines for Napier's. One was the Rapier, type tested in 1934, and the other the Dagger. Both were air-cooled in-line engines designed to obtain economy in frontal area. The first developed 300 h.p. and the second 1,000 h.p. The Rapier was installed in the Fairey Seafox, a small seaplane carried on some naval vessels; the Dagger VIII was installed in 100 Handley Page Hampdens manufactured at Short & Harland's and renamed Herefords. See Ch. V, Section (ii).

without much stimulus or guidance from the Air Ministry or the M.A.P. Their decision to undertake or to abandon new designs and their entire policy of engine development remained throughout the war the one independent and, from the point of view of the Government, largely uncontrolled factor in the progress of British aircraft. The other feature was the part which, in the most critical period of the firms' history, was played by their chief technical directors. The position of Sir Roy Fedden at Bristol's until the end of 1942 was in every respect similar to that of the chief designer of aircraft firms, about which more will be said later. He concentrated in his hands the main direction of design policy and personally directed the entire work of design and development. Somewhat less concentrated was the régime at Rolls-Royce where separate projects appeared to be more independently conducted. But there too the work was unified and centralised under their chief technical director, Mr. E. W. Hives, as he then was.[1]

In comparison with the design of engines, that of aircraft was more closely dependent on the government departments. The detailed administration of design and development varied from firm to firm. But by the end of 1943, i.e. at the point of time at which such new designs as could be used against Germany were completed, the design departments in most aircraft firms came to possess many common characteristics and to raise a number of identical problems.

The typical layout was a concentrated one. For, on the whole, British aircraft firms did not adopt the American system of independent 'project teams' under which each project and aircraft, from the moment of its preliminary design to its final modification, was put in the charge of an *ad hoc* group comprising designers, experts in aerodynamics, and engineers in charge of stresses and structures. The only major British aircraft firm in which an organisation resembling the American team system came to be introduced was Fairey's. The system was adopted for a number of causes peculiar to that firm: the protracted absence in the United States of Sir Richard Fairey and, to some extent also, the disappointing record of their design work between 1940 and 1942. After the re-organisation of their design department at the end of 1942, new projects were entrusted to separate groups co-ordinated and administered at the top by their new chief engineer, Mr. Hollis Williams. In most other aircraft firms, a much more centralised and integrated system prevailed. All projects of design and modification were made to pass through the same channels and, in the upper levels, through the same persons.

---

[1] See Ch. V.

In the airframe firms new designs as a rule started with the chief designer.[1] He would be expected to conceive the main principles of a new design or an important modification, and to discuss it with the technical officers of the M.A.P. For these discussions preliminary rough drawings of the aircraft as a whole, and often a small model indicating its shape in the round, would be submitted. These preliminary drawings and the rough calculations accompanying them would as a rule be prepared by various specialists working under the chief designer. But the real function of the specialists was to work out the details of the new type after the preliminary, or, as they were usually called, the 'tender' designs, had been accepted by the M.A.P. and the prototype or production order had been issued. This working-out took the form of detailed drawings and detailed calculations of the aerodynamic features of the aircraft, of its stresses, structures and so forth. The prototype itself would as a rule be constructed in the experimental workshop, but even where the prototype was merely the 'first off' the quantity order, the experimental workshop might be called upon to construct sections and parts of the aircraft for preliminary trials. Occasionally, as in the early stages of the Stirling, a half-scale flying model of the aircraft would be constructed for preliminary experiments and tests. On its completion the prototype would be passed to the test pilot's department for contractor's test flights. The design cycle would be then completed by the official tests which were as a rule carried out at the Aircraft and Armament Experimental Establishment, Boscombe Down, by Service pilots. Parallel to this main stream of work on current designs, the design departments also conducted a certain amount of advanced work preparatory to designs which had not yet matured. In addition, they would be expected to design and test that continuous flow of modifications which were, as a rule, introduced into types in current production.

Each of these functions was, as a rule, entrusted to separate sections of the design organisation. Most design departments contained an aerodynamic section, a stressing section, a structure section and a test pilot's section. In addition most firms possessed experimental workshops and also certain specialist facilities for aerodynamic and structural tests of an advanced character, including in some places, e.g. Fairey's, Westland's, Vickers-Armstrongs and Bristol's, wind tunnels. The whole design organisation was served by a drawing office which in some cases was responsible only for prototype drawings and in others for production drawings as well. In later years, the drawing office was also entrusted with the various

---

[1] The special part played in generating the main ideas of design by Mr. Wallis of Vickers and Mr. Russell of Bristol's will be mentioned below, p. 30.

substitutes for drawings, i.e. the photographing of designs, their 'lofting', and direct transference on metal etc.[1] Exact lines of demarcation within the various sections and their hierarchy were of course bound to differ from firm to firm.

(ii)
The Higher Technical Personnel

The unifying and the centralising authority in this organisation, in fact its lynch-pin, was the chief designer. In some firms the Chief Designer came to be designated by other titles, i.e. Chief Engineer, Technical Director, etc. But whatever his title, his chief function was leadership in design. In most firms he had, long before the war, ceased to be the sole author of new aircraft or even of important modifications, but in all firms, with the possible exception of one or two, he initiated most of the new projects and determined the programmes to which the specialist sections worked. So, although all designs which appeared since 1934 were co-operative products, the part played in them by the chief designers was sufficiently marked to justify the attribution of personal authorship. Hence 'Mitchell's' Spitfire, 'Camm's' Hurricane, Typhoon and Tempest, 'de Havilland's' Mosquito, 'Miles'' Master, 'Chadwick's' Lancaster.

The authority of the Chief Designer did not, however, wholly derive from the part he played in the creation of new aircraft. It largely reflected his general position in the firm. He was almost invariably one of its leading lights, often its head and sometimes its founder, as at de Havilland's, Fairey's and, to some extent, Handley Page's. Elsewhere he was as a rule a prominent member of the firm, closely associated with the direction of its affairs.[2] Mr. Sydney Camm of Hawker's, Mr. Roy Chadwick of A. V. Roe's, Mr. Gouge of Short's, Mr. W. E. W. Petter of Westland's, Mr. L. G. Frise of Bristol's, Mr. R. K. Pierson of Vickers, perhaps Mr. Bishop of de Havilland's, and certainly Sir Roy Fedden (until his resignation in 1942) of Bristol Aero Engines and Mr. Hives of Rolls-Royce, were all leaders of their firms, often members of their board of directors, and always exercised or at least claimed considerable influence on general policy.

The next most important office in the design organisation is more difficult to determine. In an organisation like Vickers Aviation,

---

[1] See p. 39.

[2] The principal exceptions were Armstrong-Whitworth, Gloster's, Vickers (Supermarine), and Boulton Paul. In all but the last case the position was complicated by the fact that the firms formed part of larger combines.

where the Chief Designer (Mr. Pierson) was primarily the administrative head of their large design organisation, a special position was occupied by the Assistant Chief Designer (Mr. B. N. Wallis), who was in fact the fountain head of most of their forward ideas. It was he who brought into existence the 'geodetic' construction, which was a characteristic feature of the Vickers' bombers, and from him came also the guiding principles determining future design.[1] A similar, though somewhat less influential, position was occupied in the Bristol organisation by Mr. Russell, their Deputy Chief Designer between 1940 and 1943, and Chief Designer under Mr. Frise from 1943. The respective functions of the head of the design organisation and his second-in-command were somewhat inverted at Westland's, where most of the functions of the chief designer were in the hands of their Technical Director (Mr. W. E. W. Petter), and the direct executive charge of new projects was in the hands of their Chief Development Designer (Mr. Davenport). This relationship was to some extent paralleled in the de Havilland organisation where the officer designated as Chief Designer (Mr. Bishop) was in fact second-in-command to Sir Geoffrey de Havilland himself from whom for a long time many of the ideas originated. Less definable still was the position at Handley Page's where at one time the Chief Designer (Mr. Volkert) had to accommodate himself to the views of the Managing Director and the founder of the firm, Sir Frederick Handley Page. In short the position and the functions of the second-in-command reflected the interests and the qualities of the head of the design department and were therefore bound to differ from firm to firm.

It will be unnecessary and probably impossible to define the exact position in the organisation of the other senior members of the designing staff.[2] One characteristic of the 'other ranks' must, however, be described, for it represents an important peculiarity of the British organisation before and during the war. This was the predominance of people who had risen to their position from humble beginnings in the drawing office or in the workshop. The problem of the training and education of the technical personnel of the aircraft industry cannot be dealt with in this study, but in describing the design departments of British firms it is important to record the relatively small part played in them by the highly trained university-educated aeronautical experts. Their numbers were quite small. 'Half-a-dozen at the utmost' appeared to be the usual prescription, and even that half-a-dozen were as a rule confined to the aerodynamic and stress sections or, as at Bristol's and Westland's, to the

---

[1] See pp. 78–79.

[2] It may perhaps be worth pointing out such obvious local deviations as the important place occupied in the Westland design department by the test pilot, Mr. Penrose.

staff of the experimental engineer in charge of the wind tunnel or of the long-term experimental studies.

One of the reasons why university-trained men were few in the firms is that there were, as yet, very few of them in the country. As long as the industry was new, its future uncertain and employment restricted, it could not figure prominently in the expectations of young men training for careers in universities, or of their parents and advisers. Not only were the aeronautical departments in universities as yet few and small, but men whom the universities trained for other branches of engineering were not going into the aircraft industry in large numbers.

The shortage of supply does not however explain everything. There was also a deficiency in demand. The recruiting policy of the chief designers was to some extent shaped by their own life experiences. Most of the chief designers, like many of the other heads of the firms, were self-made men who had grown up in the industry. Mr. Frise of Bristol's, Mr. Volkert of Handley Page's and Mr. Petter of Westland's were probably the only university-trained heads of design departments. The others started as junior technicians, draughtsmen or just 'hands'. Mr. Sydney Camm began his career with Hawker's as an apprentice in the carpenters' shop from which he later passed to the drawing office. Mr. Gouge of Short's started in much the same way. Mr. Chadwick of A. V. Roe's began in the drawing office; Mr. Lloyd of Armstrong-Whitworth's was in his youth engaged as a junior technician in civil engineering from where he passed in a junior capacity to the Royal Aircraft Establishment at Farnborough. Mr. Mitchell of Spitfire fame had a similar career.

In short, like most new industries and like all British industries in the Industrial Revolution, airframe construction was developed by pioneers who had been drawn into it at a time when the only way of learning the job was by doing it. It is not therefore surprising to find most of the heads of the design departments laying down for their staffs the same routes for entry and advancement which they had themselves so successfully trodden in the past, i.e. from junior apprenticeship in the shop or in the office *via* evening classes and part-time technical courses to more responsible posts in the design organisation.

(iii)
The 'Practical Bias'

It would nevertheless be wrong to ascribe the emphasis on practical training entirely to the personal likes and dislikes of the chief designers. It is doubtful whether they would have been able, or even willing, to indulge in their practical predilections, had they felt acutely the need for more theoretical work within the firms. The need was not there. The bulk of the advanced research in aeronautical, and more especially aerodynamic, problems was largely done for the industry by other bodies and, to some extent, by other industries. Some of it was conducted in the universities and especially in the aeronautical department at Cambridge, from whence issued some of the new ideas about aerodynamics which prepared the revolution in aircraft design in the early 'thirties. A certain amount was done in the National Physical Laboratory and more important still was the work of the R.A.E. and of the other research establishments administered by the Air Ministry or M.A.P.[1]

The organisation and work of the official research bodies will be described in greater detail elsewhere in this volume. One point, however, will have to be anticipated here. The R.A.E. largely devoted itself to theoretical problems allied to production and, in addition, performed experiments, tests and calculations of problems passed to it for solution by the firms. In addition, persons and groups at the R.A.E. from time to time developed or perfected, on their own initiative, individual items of equipment or individual components of aircraft which later came to be embodied in their aircraft by the firms. In this way the R.A.E., and to a much less extent the Aircraft and Armament Experimental Establishment, performed for the industry much of that theoretical and semi-theoretical work which in other industries is often performed by their own research organisations.

For a long time this division of functions between the design departments and the technicians outside the industry was taken for granted. It was not until the end of 1943 that doubts came to be expressed in M.A.P. whether the delegation of long-term research to the R.A.E. and universities had not in fact gone too far, and whether it would not have been better for the future of British design if some of the long-term problems were investigated, as they were in the United States, by the design departments of the firm and in close conjunction with the ordinary work of design. Commenting on the review of research programmes of Government Departments for the War Cabinet undertaken by Sir Edward Appleton in 1943,[2] the Controller of Research and Development was able to say that it was M.A.P's policy to encourage each firm to build up its own research organisation in order to handle research projects. As an example of this he quoted the pressure which M.A.P. put on Bristol's 'to get them to expand their research work upon cooling problems'. But

---

[1] See p. 71.

[2] See pp. 48–49. Sir Edward Appleton (Secretary of the Department of Scientific and Industrial Research) was directed by the Lord President to undertake a central survey of research projects as agreed at a meeting of the War Cabinet on 18th February 1943.

by the middle of 1943 this policy had, as yet, borne little fruit, and the bulk of basic research was still conducted outside the firms.[1]

In dealing with the practical bias of the design departments it is also important to bear in mind the extent to which, in the crucial years of aircraft development from 1934–43, the British aircraft industry, and even the British engine industry, were able to borrow from abroad. It is now generally realised that the quality of British aircraft in that decade outstripped that of comparable foreign types. This should not, however, blind us to the fact that the great progress of practical design in those years owed much to the lessons learned from the American, and to a much smaller extent, from the German aircraft industries. The great revolution of ideas which marked the British designs of 1934–35 was based on the new engines using the new high octane fuels, on the cantilever method of wing construction, on all-metal monocoque bodies, stressed skins, retractable undercarriages, improved lift devices and variable pitch airscrews. Some of these ideas had originated in this country or were influenced by British-based research. In the sphere of engines much independent progress was made by Bristol's and Rolls-Royce. Yet on the whole, many, perhaps most, of the new technical ideas, in the form in which they were to be embodied in the new race of airframes, had been tried out and embodied in American aircraft some time before they came to be adopted in this country. The novelties of American aircraft design and production greatly impressed the Director of Technical Development (Air Commodore Verney as he was then) during his visit to the United States in 1934. He came back from that journey a convinced advocate of the new types. Needless to say Air Commodore Verney was not the only interested traveller in the United States. He was both preceded and followed by the leaders of most engine and aircraft firms: Mr. Pierson of Vickers Aviation,[2] Mr. Fairey, Mr. Frise of Bristol's and probably others as well. All of them brought back new ideas, and some of them travelled home with complete designs of aircraft and engines. The British industry did not of course adopt the American ideas blindly, but had much of its own to add, especially in the field of engines. The protracted and costly development work at Rolls-Royce in the 'thirties soon outstripped the contribution which the American engine development had made to the Merlin's progenitors.[3] Even more independent and

[1] Mr. B. Lockspeiser (Director of Scientific Research), in a paper on 'The Future of Research in Aeronautical Science' written in May 1943, said of research in airframe firms—'the amount is small . . . in aerodynamics the government and the university scientists lead'.

[2] Mr. Pierson visited America in 1934 with his General Manager and chief test pilot. Sir Richard Fairey together with one of his co-directors, his chief engineer and chief designer visited the United States in August 1934.

[3] Rolls-Royce produced the R.1/31 for the Schneider Trophy winning aeroplane. The R.1/31 was based on their Buzzard engine. The Goshawk and Kestrel engines also preceded the Merlin.

equally costly appears to have been the experimental work on the sleeve valve at Bristol's.[1] On the aircraft side it may be necessary to add to the 'independent' credit of the British industry, Mr. Wallis's geodetic structure which sprang more or less directly from the design of the R.100 airship. There may also be some reason for adding to this account the principles of small high-speed monoplane construction which Mr. Mitchell had learned from the Schneider Trophy designs and was later to incorporate in his Spitfire. Yet, in general, it remains true to say that without expending vast funds and much time on fundamental research, British industry would not have been able to start in the 'thirties on the magnificent series of the Battle of Britain types had it not been for the earlier achievements of the American aircraft industry.[2]

Of these earlier achievements—and to some extent of the advanced theoretical work in the universities and the R.A.E.—the British aircraft of the mid-thirties were merely a brilliant practical development. For seven or eight years after 1934 the British fruits of the development went far to outclass the American seeds from which they had sprung. Indeed, Britain in the throes of rearmament and war became a forcing house of new ideas and the leader in the field of military aeroplanes. But, great as the British progress was, it was achieved without invoking any new principles of aerodynamics or of construction and without altering what had by that time become the established principles of design. It was not until 1943 or 1944 that new principles associated with the prospects of supersonic speed and with gas turbines brought aircraft design to the verge of a new revolution and made it again necessary to turn the attention of industry to those long-term problems which could, with relative impunity, be neglected by the industry between 1934 and 1943.

Thus, broadly speaking, the theoretical frontiers of new design between 1934 and 1943 were set by people outside the British aircraft firms. Within these frontiers the work of the designer was, and could afford to be, very practical. What made it still more practical was the pressure of operational requirements. From the point of view of general suitability for service theoretical performance was not the only hallmark of a good aircraft. Other, and more practical qualities, varying from the type and the fire power of guns to the accessibility of cockpit controls, counted for a great deal and often had to be satisfied at the expense of performance.

---

[1] The new sleeve valve was used in the Aquila, Perseus, Taurus and Hercules engine designs. See pp. 105–106.

[2] The borrowings from Germany were much smaller and less successful. The best known example is the unorthodox shape and layout of the Hampden fuselage, which, together with some other features of the Hampden design, were introduced by the German designer at Handley Page's, Dr. Lachmann, in imitation of the contemporary Messerschmitt practice.

It is, therefore, no wonder that few of the types which proved successful in service in any sense broke new ground. They were mostly orthodox designs, which were well within the limit of existing aeronautical principles, but which happened to surpass other aircraft in a number of practical features. That eminently successful and long-lived fighter, the Hurricane, was a good example of this. So unexceptional was it in conception that the original design from which it grew was at one time turned down by the Air Ministry as being too 'pedestrian'. In its final form it was still a very orthodox article. But it had a very sturdy construction which made it possible to fit guns up to 40 mm. calibre into, or under, its wings, to hang on it bombs up to 1,000 lbs. in weight and external fuel tanks, to adapt it to a multiplicity of roles, and to employ it in the rough-and-tumble conditions of Russian airfields. The Wellington was very long-lived for similar reasons even though its 'geodetic' structure was novel in conception; it had a large and roomy fuselage which permitted a seemingly endless process of 'stretching'.[1] On the other hand the design of the Hampden bomber, though made to the same specification as the Wellington, subordinated the entire layout to the aerodynamic doctrine of the time in a manner which made future adaptations and further development very difficult. Similarly one of the reasons why the Westland Whirlwind never developed into what the Mosquito was to become later (though at one time it had every prospect of doing so) was that it was too small and for this and other reasons could not be developed by the installation of larger engines.

A good practical designer therefore had to devote much—often most—of his attention to the elements of design which might strike an uninformed observer as secondary, but which from a practical point of view were fundamental. Writing in May 1941 Sir Henry Tizard drew attention to the fact that the design of fighters was largely determined by armament. 'In the past aircraft used to be built and guns put on afterwards. Now everybody realises the importance of building the fighter aircraft round the guns.' But in fact the starting point of many a successful design was even further removed from pure aeronautics than were the fighters' guns. Thus, according to Mr. Chadwick's own account of his work on the Manchester/Lancaster, he began his entire design by working out the main features of the bomb compartment, and in doing so he paid special attention to the bomb compartment doors in order to be able to accommodate the very large bomb, the advent of which he foresaw. The next step was to design a simple retractable undercarriage and thus to avoid the difficulties which the designers of the Stirling

---

[1] See pp. 75–76.

had with their undercarriage. The rest of the aircraft followed more or less 'as a matter of course'. By contrast, the aircraft which embodied more than the average dose of new inventions sometimes, for that very reason, failed to come off. The Whirlwind, which was the pioneer of twin engine fighters was a case in point.[1] The other Westland aircraft, the Welkin, which embodied a number of experimental features in its construction, and especially a very high proportion of magnesium castings, turned out to be a similar example.[2] In fact the Spitfire was probably the only highly successful aircraft to incorporate certain features, such as the thin wings, which at the time of its inception may have been considered well in advance of the existing practice.

So much for the practical bias of the design department. It reflected the personal inclination of the chief designers, but was also made possible by the theoretical work done elsewhere. But above all it was made necessary by the severely practical requirements of operational aircraft. The need for another and a more theoretical orientation, and for academically trained personnel was not greatly felt and did not constitute a major problem. Major problems in the organisation of design departments which appeared during the war, were nearly all of an administrative and perhaps economic character, and were mostly products of war-time expansion.

(iv)
Problems of Expansion

The expansion of aircraft production between 1934 and 1943 raised a number of difficulties all of which affected the development of the design organisation and some of which were still unsolved in 1945. The earliest, and throughout the most conspicuous, of these difficulties was that of mere size. Changes in the size, composition and influence of design departments were bound to take place in the years of rapid expansion. In peace-time, i.e. before the expansion of 1935 and 1936 raised for the industry the problems of quantity production, most of the aircraft factories were little more than

---

[1] Amongst the novel features claimed by the Whirlwind designer the following were the most important: magnesium monocoque fuselage, which enabled the skin to be thicker, yet lighter, than aluminium; radiator in the leading edge of the wing, which reduced engine drag; wing fuel tanks, integral with construction, but detachable for maintenance reasons; Fowler flaps—a high lift device to reduce wing area; large chord lifting slots. Of course the main cause of the Whirlwind's failure was its inability to accommodate a different and a larger engine.

[2] The main reason for the failure of the Welkin to establish itself in service was probably the highly specialised character of its specification as a defence against the high-flying bomber.

experimental aircraft shops built around their design establishments. If the design departments in the narrow sense of the term sometimes appeared to be small, this was merely because at that time it was not at all easy to draw a line between design and development on the one hand and production on the other. So small were the production orders before 1935 and so important was the work of design, that in almost every firm the whole factory and its entire staff were at the disposal of the designer, and the firm as a whole was a mere extension of the design organisation.

The expansion led to a great development of the manufacturing side of the aircraft firms and was therefore bound in the end to affect the work of the design departments and their place in the firms. The changes were not all sudden, and were by no means all to the detriment of the designers and to the unmixed benefit of production. In a number of firms the legacy of the days when they were little more than design establishments still lingered on, and production continued to suffer from handwork methods. In fact, many of the criticisms levelled, often justly, against the aircraft firms in the war, were based on the impression that the firms, having been selected on the strength of their achievement in design, proved incapable of handling the purely industrial problems of aircraft production on a large scale.

Yet in the end the work of design was also bound to suffer. The first effect of increasing pressure at the production end of the firms was to withdraw from the design departments some of the material facilities which they enjoyed in the pre-quantity days. As long as the entire floor space was available for the construction of the prototypes and experimental parts, the absence of specialised experimental workshops was not strongly felt. But when all the capacity came to be absorbed in production, the work of design and development in most firms, including such well provided firms as Vickers-Armstrongs, began to suffer from lack of facilities.

The problem came to the notice of the Air Ministry late in the summer of 1938 and from that time onwards the Air Ministry adopted the policy of fostering experimental workshops. In the subsequent years most firms equipped themselves with facilities of this nature; yet, as late as 1942, Sir Ernest Lemon's investigation into the timetable of design and development revealed that some firms were still unprovided with experimental workshops, and that in most firms the introduction of new types was slowed down by insufficient allocation of floor space and plant for the work of development.

The chief stringency, however, was not in material facilities but in technical personnel. This became more acute as time went on. One of the effects of expanding production was to set up a drain on the skilled personnel of the design departments. The skilled manual labour, which had formed the bulk of the labour engaged on experimental construction, was now needed to reinforce and to train the masses of the new unskilled and semi-skilled labour drafted into production. More important still, and certainly more conspicuous, were the growing difficulties of the drawing office. Draughtsmen were diverted, either permanently or at frequent intervals, to deal with production drawings and, above all, with the flow of modifications which were constantly being introduced into the production lines. In at least one important factory the management computed that

> although the number of draughtsmen employed on modification has been skinned to the bone we are not able to put even 50 per cent. of our total strength on the new four-engined heavy bomber.[1]

As early as the summer of 1938 the shortage became sufficiently noticeable to attract the attention of the Air Ministry and to affect its attitude to new projects. The policy of 'rationing' projects so as not to overtax the strength of the design departments and, above all, their drawing offices became the settled policy of the newly appointed Air Member for Development and Production (Sir Wilfrid Freeman).[2] At one point in September 1938 he went so far as to warn the Chairman of the Society of British Aircraft Constructors that drawing offices should not 'waste their time on new designs'. He went on to say that for himself he 'would refuse to look at such [new] designs'. In subsequent years the tendency of new projects to proliferate continued to be consistently curbed by the Air Ministry and the M.A.P., and by virtue of this policy more than one privately sponsored design had to be 'snuffed out' at its very inception.

Various methods of relieving the position in the drawing office were considered at different times. In 1938, when the problem became for the first time acute, people in both the Air Ministry and the industry sponsored schemes for the pooling and the exchange of draughtsmen. Mr., later Sir Ernest, Lemon after his first investigation of the industry in September 1938 suggested a wholesale transfer of draughtsmen.[3] The Air Member for Development and Production at about the same time pressed the Hawker-Siddeley firms to close down the design department at Gloster Aircraft Co. for a number of months in order to release draughtsmen for A. V. Roe's. Somewhat similar proposals at various times had been made

---

[1] The drawing office referred to was at Vickers-Armstrongs Ltd., Weybridge.

[2] 'The necessity for making the very best possible use of the limited resources in draughtsmen' was mentioned by the Secretary of State for Air at a meeting of the Panel of Industrial Advisers.

[3] On 14th September 1938, it was reported that the Air Ministry favoured 'a reduction in the number of design staffs'. 'It might not be practicable or desirable' for all existing firms to 'retain their individuality as designing units'.

by the chief designers themselves, e.g. by Mr. Smith of Supermarine in 1939,[1] and Mr. Lloyd of Armstrong-Whitworth in 1940. Now and again small transfers of this kind were made, e.g. from Airspeed to de Havillands in 1940,[2] but as most aircraft firms felt the pressure the scheme could not be generally applied.

In the end the problem had to be tackled in the same way as other shortages of skilled labour, i.e. by training and by changes in the methods of work. Some firms, such as Bristol's, organised the training of draughtsmen on a very generous scale and in the end came, by this means, to solve many of their difficulties. Equally important, were the various changes in methods adopted to economise in drawing office labour. Some of these methods, such as the 'lofting' of designs as in shipbuilding, or the photographic reproduction of drawings and their direct printing on metal, were noted with approval in the American factories by the Fedden Mission to the United States early in 1943. By that time they had begun to be introduced also in British factories and became general in 1944.

The shortage of draughtsmen made it difficult to expand the designing organisations, but it was by no means the only cause. Certain other types of technical personnel were also in short supply. Compared to the United States, the British aircraft industry was ill-provided with college trained engineers of junior status and of humbler rank than the few university trained British aeronautical engineers employed in the firms. The stage half-way between the rank-and-file of the drawing and testing offices and the mathematical engineers in charge of the aerodynamical calculations appeared to be largely unfilled; and it is difficult to see how it could have been filled in war-time without altering the whole system of British university training or at least improvising temporary university facilities of a novel kind—a clearly impossible task. So, what with the dearth of draughtsmen, the shortage of junior technicians, and now and again the unwillingness of firms to shoulder vast financial commitments in the experimental field, it is no wonder that the expansion of the design departments in most firms failed to keep pace with the progress of aircraft production. In the end the typical British firm which had entered the period of expansion very largely as an experimental, or very nearly experimental, organisation turned in the late years of the war into a vast industrial concern with a relatively modest establishment for design and development.

The disparity was well understood both in the government departments and in the industry, but its full significance was not

[1] Mr. Smith's suggestion was that there should be a scheme for pooling draughtsmen through the Society of British Aircraft Constructors. A number of draughtsmen from each existing office would be on call for urgent demands from other firms.

[2] Twelve draughtsmen were borrowed when de Havilland's took over Airspeed's and they never went back.

perhaps realised until the Fedden Mission of early 1943 made it possible to compare it with the American practice. The contrast with the United States was indeed striking. Most of the American aircraft firms maintained organisations for research, design and development which were much greater than the British, relative to the size and the output of the individual firms. Thus, Boeing's employed in 1942 2,700 technicians of various grades on their engineering, i.e. design staff. The figures for Glenn Martin and Consolidated were 2,000 each and for Douglas Aviation Company 1,600. As the Report of the Fedden Mission containing these figures states, they represent 'a much larger proportion of the firm than the corresponding design and drawing office staff in Britain'. The report goes on to say:

> Of the total personnel in a firm, the percentage in the Engineering Department may be anything between 3 per cent. (as in the case of Bell) to 8 per cent. (as in the case of Boeing); and of this percentage, which is on the average four or five times as large as for design and drawing office staffs in Britain, about one-third are college-trained engineers.

By virtue of their greater resources in equipment and personnel, the American firms were able to give more attention to the detailed design, and generally speaking treated their new projects with a greater thoroughness than was possible in Britain. What struck the Fedden Mission and other witnesses most was the remarkable development of practical tests and measurements. Aided by much greater facilities, both human and material, the American firms were able to gratify the experimental bias of their training and outlook by organising a system of practical tests and trials for materials, for stresses, and for other problems of aerodynamics and structure, which in this country would normally be worked out on paper. In the opinion of some observers the immediate fruits of this prodigality were perhaps out of proportion to the effort expended, but no observer could tell how great the benefits of the system were going to be in the long-run. As we shall see further, by the end of 1943 the quality of the American aircraft began to bear unmistakable signs of the wealth of the design departments.[1]

[1] The advantages of the larger staffs in forward development of a bold and advanced kind were noted by Air Marshal Sir Ralph Sorley, then Assistant Chief of the Air Staff (Operational Requirements and Tactics), during his tour of American aircraft factories in November 1942.

(v)

Co-ordination of Design and Production

The other effects of the war on the mere size and relative position of the design departments in aircraft firms belong to the purely industrial history of aircraft construction. But size was by no means the only administrative problem of design raised by the expansion. Equally important was the problem of relations between design and production. In the pre-expansion days when aircraft were largely hand-made ease of quantity production could be disregarded. With expansion came also the need for economical design, i.e. design calculated to facilitate production by machine tools and jigs, and by a sparing use of 'difficult' components and of skilled labour. This necessitated a much closer co-ordination between the drawing office and the shop floor, and a closer contact between designers and production engineers in every stage of design.

In the hurly-burly of the expansion few aircraft factories were able to take stock of the new situation and to sort out the relations between their designers and producers. Their contacts remained as a rule as informal as ever, and were often not only informal but also very close. The best example of this is probably that of A. V. Roe in the late 'thirties and early 'forties. At the very top, the relations of the three leading Directors, the Managing Director (Mr. Dobson), the Chief Designer (Mr. Chadwick) and the Production Manager (Mr. Fielding), were so close that it was difficult to distinguish any phase in the evolution of the Lancaster to which the three gentlemen did not jointly contribute. Similar contacts were also fostered in the lower ranks, and nothing illustrates them better than the housing arrangements at their main factory at Chadderton, near Manchester, where no partitions or corridors were allowed to separate the drawing office from the rest of the firm's offices, and where all the necessary 'liaison' could be had by exchange of views across a desk. It was partly as the result of an organisation such as this that the Lancaster turned out to be not only a good aircraft but also a very economical article to produce.

The relations of design and production were almost equally intimate, though possibly more formalised, in a firm like Westland's, where new designs were, as a rule, subjected to preliminary discussion at conferences between the design staff, the Works Manager and the jig and tool designer. But in another firm, as late as the summer of 1943, it was still possible for Sir Geoffrey de Havilland and the Chief Designer, Mr. Bishop, to express their opinion that the contact between production and design could be much closer than it was, and that, as designers, they felt the lack of sufficient advice and criticism from the production side. It therefore says a great deal for the excellence of the Mosquito design that that remarkable aircraft did not turn out to be more costly in man-hours than it actually was. The problem was, to a great extent, one of personalities.

(vi)

Co-operation between Firms

The problem of contacts within the industry brings us to the question of co-operation between the design departments of individual firms. The intercourse between firms in matters of design did not figure among 'headache' problems of the war, and was not actually felt by the designers themselves. Yet a number of pertinent questions are bound to emerge from any attempt to survey the war-time organisation of design by individual firms. To what extent could individual design departments count upon each others assistance, and to what extent were they able to draw on anything in the nature of a common stock of ideas and experience? The general impression is that common action was relatively rare. Closest of all were probably the relations between some engine firms, and especially Rolls-Royce, on the one hand and some aircraft firms on the other. The progress of aircraft design was so dependent upon the development of the power unit that both the chief aircraft designers and the engine makers were anxious to keep each other fully informed of their future developments. The most interesting example of this co-operation was the relation between Rolls-Royce and Vickers (Supermarine), the designers of the Spitfire. The various stages in the development of the Spitfire were closely linked with what Rolls-Royce could tell Supermarine about the future timetable of the Merlin and the Griffon engines.[1] Many a design in other firms was similarly planned in anticipation of future engines, and on the strength of information obtained from the engine firms. The advent of jet propulsion witnessed a similar liaison between the makers of the power unit, such as Power Jets Ltd., de Havilland's, Rolls-Royce and Metropolitan-Vickers, on the one hand, and the firms designing jet-propelled airframes, such as Gloster's and the airframe division of de Havilland's, on the other.

Less noticeable was the traffic of ideas and information among the airframe firms themselves. Where several firms formed part of the same industrial group, such as Vickers or Hawker-Siddeley, one might expect contacts closer than elsewhere. This in fact appeared

[1] See Ch. IV, Section (viii).

to be the case in the Vickers group, where the relations of Mr. Pierson of Vickers (Weybridge) and Mr. Smith of Vickers (Supermarine) were not exactly those of one chief designer to another. It is also possible that between firms belonging to the same industrial group some division of labour could be enforced. Thus within the Vickers group, Vickers (Weybridge) concentrated on bombers, and Supermarine on fighters; while within the Hawker-Siddeley group, A. V. Roe's specialised in bombers while the Hawker and Gloster designers devoted themselves to fighters.[1] But even this was not wholly due to agreed arrangements between firms, for some specialisation would in any case have resulted from the war conditions and from the policy of His Majesty's Government. Both the Air Ministry and the M.A.P. consistently tried to cultivate 'special lines' of design and to entrust new projects to firms which had in the past shown special aptitude for certain types. Thus Vickers, Handley Page's, Short's, and in later years A. V. Roe's, came to be regarded as firms best qualified to design large multi-engine types; Hawker's, Supermarine, Westland's and Gloster's were treated as fighter firms *par excellence*; while Fairey's and Blackburn's were given over to the design of naval types.

Apart from this rough specialisation, the aircraft firms not connected by common ownership, as a rule, worked more or less in isolation. Now and again M.A.P. tried to arrange for exchange of plans and information between firms engaged on development projects of the same character. Thus in 1939, when the project of the heavy bomber B.1/39 was under design, the Air Ministry stipulated that the two designing firms, Handley Page's and Bristol's, should work in collaboration and specify the same components. In 1940 when the design of the F.9/40 jet-propelled fighter was put out to Gloster's, a special request was addressed to Westland's to put at Gloster's disposal the experience which they would have gathered on the design of the pressure cabin for the high-altitude Welkin. Generally speaking the development of the jet-propelled aircraft and engines was marked by the continuous endeavour of M.A.P. to persuade firms to pool their knowledge and resources. M.A.P. also tried and succeeded in organising a division of labour between several firms in the development of Radar equipment[2] and of the electrically-operated remote control of guns.[3]

On the whole, however, rugged individualism marked the mutual relations of design departments. Friendly visits there doubtless were, and a certain amount of mutual borrowing was inevitable. Thus

---

[1] The abortive project of the Hawker high-speed bomber to Specification B.11/41 was probably the only exception.

[2] See Ch. XV.

[3] See p. 117.

according to one version of the facts some of the Bristol methods of construction were adopted by other designers. The Bristol designers themselves admitted to have learned a little from Mr. Petter's experience with magnesium castings. Mr. Petter has claimed to have demonstrated to other designers the virtues of radiator installation in the leading edges of wings. It is also possible that many lessons, positive and negative, were learnt by designers from other aircraft in operation. Yet, as a general rule, it can be said that little endeavour was made to investigate and mutually to solve common problems of design. The problems of structure, which in theory presented all the designers with identical problems, were tackled independently in each firm, and successful solutions were seldom adopted by the industry as a whole. Thus A. V. Roe's highly practicable bomb-carrier was not incorporated in other bombers in spite of some pressure from M.A.P. Similarly in engine design some research and development was duplicated by Rolls-Royce and Bristol's. Thus the progress of the Centaurus engine and of the Buckingham aircraft was very much impeded by certain stubborn problems in the development of the supercharger. In these problems Rolls-Royce had apparently made greater headway, but not until much valuable time had already been lost were their experts called in to solve the difficulties at the Bristol works.

This lack of contact may have been partly due to the lingering effects of pre-war competition, and may have reflected the healthy rivalry between designers. It does however appear probable that some 'common denominator' problems were not shared for the simple reason that they happened to belong to that range of theoretical and semi-theoretical topics which the firms were satisfied to leave in the hands of universities, the Royal Aircraft Establishment and the learned Societies. In 1942 the Society of British Aircraft Constructors took steps towards organising common investigations and a pool of ideas on such common matters as structures, use of materials, etc. Special committees were then established and a promising programme was drawn up, but not enough had resulted from this organisation by 1943 to modify our general verdict. When light was needed on general problems or when information was sought about the general theory of aeronautics and the movement of ideas abroad, the designer fell back on informal contacts with other experts, on the meetings and publications of the Royal Aeronautical Society, or on the assistance of the Royal Aircraft Establishment. But the work of design proper was predominantly the activity of the individual firms.

CHAPTER III

THE ORGANISATION OF DESIGN AND DEVELOPMENT IN THE AIR MINISTRY AND M.A.P.

(i)
Introduction

THIS concludes our summary of the methods and organisation of design and development in firms, and brings us to the organisation and methods of design and development in the government departments. As has already been said, the technical progress of British aircraft was the joint product of private initiative and government stimulus and supervision. In producing new types, the aircraft firms could only act in response to the needs of the Air Force and in relation to the general industrial and strategic plans of the Government. This correlation of design to Service needs and to the government plans in general could only be done by the government departments and, more especially, by the Air Ministry and M.A.P.

In the discharge of their functions, i.e. in formulating demands for aircraft, the Air Ministry and M.A.P. had to perform at least two separate services. In the first place the tactical and strategic ideas of the Services had to be focussed on problems of aircraft or aircraft equipment. This meant considering and defining to what extent the quality of the existing types met, or failed to meet, the requirements of the men who flew them and what further improvements in quality, i.e. speed, range, load, etc., would be necessary. In the terminology of the R.A.F. administration this function was described as 'O.R.' (Operational Requirements) and expressed the 'user' point of view in the narrower sense of the term.

The second function was to direct the progress of successive aircraft through the various stages of technical evolution. Whereas operational requirements were expressed in tactical terms, i.e. speed, ceiling, bomb-load, range, etc., the demands of the industry had to be formulated in terms of aeronautical and engineering design and also fitted in the general framework and timetable of aircraft programmes. This meant deciding what technical features were required to meet the new operational demands, what modifications, if any, were needed in the existing types and whether types should be ordered from the industry. If a new type was to be ordered, its broad technical characteristics, or what would be usually termed its specification, had to be formulated. This also involved inviting designs from firms; judging the quality of the firms' projects (whether produced in response to Government specifications or as private ventures); ordering prototypes; watching over the successes or failures of the prototype tests and development, and finally recommending the new aircraft or the modification of the established aircraft for quantity production. This second function is commonly described, and is subsequently referred to, as 'design and development'.

(ii)
Operational Requirements

The method in which the first of those functions, i.e. formulation of operational requirements, was fulfilled need not delay us long. The very fact that it followed directly from the strategic notions of the Air Staff or from the tactical experience of the Royal Air Force made it an integral part of the Air Staff duties. All that need be noted here is that between 1934 and 1943 the volume of work falling upon the branch of the Air Staff in charge of operational requirements grew both in volume and in complexity. The tendency, therefore, was for this branch to grow and to assume somewhat greater autonomy than it had at the beginning. From being originally a small section responsible to the Deputy Chief of the Air Staff through the Director of Operations and Intelligence, the Operational Requirements Branch developed in 1936 into a Deputy Directorate.[1] In 1938 it was detached from the Deputy Chief of the Air Staff and put in the charge of the newly created office of the Assistant Chief of the Air Staff.[2] In the following year the Deputy Director of Operational Requirements was upgraded to full Director and shortly after the outbreak of the war the increasing importance of both Operational Requirements and Operations necessitated a further division of labour. Responsibility for 'operations' was removed to a second Assistant Chief of the Air Staff thus leaving Operational Requirements as the sole responsibility of an Assistant Chief of the Air Staff (Operational Requirements and Tactics) (A.C.A.S.(T)). By that time the organisation of the Director of

[1] The first Deputy Director of Operational Requirements was Group Captain Oxland.
[2] The office of Assistant Chief of the Air Staff was created in February 1938.

Operational Requirements had grown to many times its 1936 size, and worked as one of the principal departments of the Air Ministry. Thus organised, it continued to function throughout the war.

(iii)
The Controller of Research and Development

More must be said of the organisation of the second Government function, that of design and development, if only because it stood much nearer to aircraft production, and was in fact part of M.A.P., or of those branches of the Air Ministry which were transferred to M.A.P. in May 1940. The detailed layout of this work need not concern us here,[1] but some idea of its organisation must be given if its problems are to be understood. Before the expansion, i.e. during the years 1921–34, it formed part of the field administered at the Air Ministry by the Air Member for Supply and Research. As the title of the office shows, the duties of the Air Member for Supply and Research comprised everything dealing with the provision of aircraft, i.e. both design and production, but the former was separately administered by two subordinate directorates—Directorates of Scientific Research and of Technical Development. In 1934, on the eve of the expansion, research and development were separated from supply and placed in the charge of a specially designated member of the Air Council, i.e. the Air Member for Research and Development (A.M.R.D.). This situation continued until 1938, when all the functions dealing with provision of aircraft, including development work, were brought together again under the Air Member for Development and Production (A.M.D.P.), whose department concentrated the entire industrial activities of the Air Ministry, and in the summer of 1940 branched off into the Ministry of Aircraft Production. Within that department, the work of research and development was, from June 1938, organised as a Directorate General (D.G.R.D.). But at the end of the first year of its career in M.A.P., the post of A.M.D.P. having lapsed, this Directorate General was raised into a more exalted office of a Controller of Research and Development (C.R.D.). The structure of the Controller's department reflected the many duties which it was expected to perform. Its responsibilities for the design and development of engines, armament and equipment, as well as airframes, were each discharged through specialised directorates. There were separate

---

[1] See Appendix II.

Directorates of Armament Development and of Engine Development.[1] To these were later added Directorates of Marine Craft Development and of Special Projects.[2] But from the point of view of this study the significant administrative division was that which corresponded to the main functional division of the work, i.e. of scientific research and of technical development.

(iv)

The Directorate of Scientific Research

The administration of research by the Directorate of Scientific Research in M.A.P. was primarily concerned with the general progress of scientific and engineering knowledge relating to aircraft and its components, but it was also responsible for linking up current development work with the general scientific progress, and for administering the various scientific agencies attached to M.A.P. Its work was, therefore, done through various scientific and research organisations, and through similar bodies managed or assisted by His Majesty's Government, such as the Royal Aircraft Establishment at Farnborough, the National Physical Laboratory at Teddington, the Aeroplane and Armament Experimental Establishment at Boscombe Down, etc., and it also farmed out and directed a great deal of research in aeronautical and kindred subjects in the Universities.

Generally speaking the Directorate promoted and organised the overall progress of scientific research in aeronautics. It would however be wrong to assume that most of the work directed by the Director of Scientific Research was devoted to the general and distant problems of aeronautics. The bulk of the investigation conducted in the Royal Aircraft Establishment, and even some of the work done in Universities and in the National Physical Laboratory, related to immediate problems of design and development. At the R.A.E. especially, much was done to test parts and components on behalf of the industry, to solve conundrums referred to them by the firms, and to think out improvements in airframes and equipment capable of immediate application. In fact when in the spring of 1943 Sir Edward Appleton, the Secretary of the Department of Scientific and Industrial Research, carried out, on the Prime Minister's direction,

---

[1] The Directorate of Armament Development, M.A.P., (short title D.Arm.D.) was formed in January 1940. The Directorate of Engine Development, M.A.P., (short title D.E.D.) was formed in December 1940.

[2] The Directorate of Marine Craft Development was formed in September 1941. The Directorate of Special Projects was formed in August 1943.

an investigation into resources devoted to research in various government departments, he discovered that in the research work conducted by M.A.P. immediate problems greatly predominated over basic research. If the term research were so defined as to include all subsidised work in Universities and to cover 15 per cent. of development contracts and 10 per cent. of contracts on modifications, 'basic' research would still form a relatively small proportion of scientific work directed by M.A.P. In the R.A.E. the proportion of investigation which could be regarded as 'long-term' or 'basic' to investigation of immediate applicability was as one to four.

(v)
The Directorate of Technical Development

Yet in spite of his pre-occupation with short-term problems the Director of Scientific Research did not directly control the work of design and development. He and his department were not concerned with specifications for new aircraft or with the issue of development orders. These decisions were prepared and formulated by the Directorate of Technical Development. In the words of an official survey, the Directorate of Technical Development was 'responsible for the design of aircraft as a whole, i.e. for its success in fulfilling given operational functions'. Its object was to bridge the gap between the operational requirements and the production orders in quantity. This it did by a number of successive stages, each of which will be discussed in greater detail later.[1] It kept the industry informed of the trend of the user needs; it issued specifications for the design of new aircraft; it watched over the production of prototypes and their tests; and, generally speaking, it piloted the aircraft throughout their development to a point at which they were capable of being ordered and produced in quantity. Nor did its responsibility cease then. So long as an aircraft was in production the Directorate retained control over further development and technical standards.

Within the Director of Technical Development's department the functions were divided among four Deputy Directors, of which two, Deputy Director Research and Development (Instruments) and Deputy Director Research and Development (Equipment Installation)[2], supervised the development of instruments and the installation of operational equipment respectively, and two were more directly concerned with the design of aircraft. One of these was the Deputy Director of Research and Development (Aircraft),[3] whose main

[1] See Ch. IV, Section (iv). See also Appendix II.
[2] Short titles D.D./R.D.Inst. and D.D./R.D.Q.
[3] Short title D.D./R.D.A.

function was to look after the engineering problems of aircraft both during the prototype stage and subsequently. The other was the Deputy Director of Research and Development (Technical Investigation)[1] in charge of forward developments of a technical nature. To this last fell the main task of watching over the main trends of aircraft design. His work entailed the analysis of all projects and hypothetical designs submitted by firms or by the Operational Requirements Directorate of the Air Ministry, the calculation of weights and performances of projected aircraft of all types, the collation and analysis of foreign aircraft and the formulation of the official views of all trends of aeronautical progress. Finally, it was his duty to prepare for transmission to the industry the specifications for new aircraft, and to lay down instructions about general design requirements.[2] In other words, D.D./R.D.T.'s department represented the part of the administrative machinery which was most intimately concerned with purely technical aspects of design, and functioned as the main administrative source of official specifications. It was also the repository of all the official knowledge and opinion on the technical problems of quality. Its actual importance in the history of British design was further enhanced by the remarkable continuity in its structure and personnel.

(vi)

Problems of Co-ordination: General

Generally speaking, the official organisation from the Controller of Research and Development downwards showed remarkable continuity in administration and policy. Not only were the main subdivisions in 1945 largely the same as in the early stage of expansion between 1936 and 1938, and even before, but much of the procedure and a considerable part of the personnel were identical. Yet this stability was not a mark of complacency. Important and difficult problems of organisation were repeatedly thrown up during the decade of expansion and war, and were very frequently discussed, even though some of them had to remain unsolved, while others could only be solved by personal and informal means. Most of these problems were created by the official machinery itself, and followed from the separation of the essential functions between the Air Force,

---

1 Short title D.D./R.D.T.

2 Throughout most of the expansion period and the first year of the war, its functions were in charge of a single section of the branch of the Deputy Director of Research and Development (Technical Investigation) (A.D./R.D.T.), but in June 1940 the actual preparation of aircraft specifications and certain other miscellaneous duties were separated and put in charge of a new Assistant Director, A.D./R.D.T.2.

the Air Ministry and M.A.P. and the industry. Gaps at different points of contact were inevitable and various methods of bridging them were, from time to time, tried. The first and the most obvious was at the point of contact between the flying branches of the Service on the one hand and the branches of the Air Staff in charge of operational requirements on the other; the second was at the point at which the operational requirements, as formulated by the Air Staff, were taken over by the Controller of Research and Development in M.A.P.; the third was the contact between the latter and production.

(vii)

Problems of Co-ordination: Operational Requirements

The first of these contacts lies largely outside our field and beyond our competence. If it is mentioned at all it is because the method by which operational requirements were formulated and transmitted played an important, and a somewhat disturbing, part in the general progress of aircraft development. Generally speaking the M.A.P. and the aircraft industry were fortunate in having to cater for a Service so technically minded and so forward-looking as the R.A.F. In formulating their demands for weapons the R.A.F. had advantages which were denied to the other Services and especially to the Army. In the first place the very act of flying and navigating, even when it happened to be non-combatant, provided them with a fund of operational evidence. This alone enabled the R.A.F. even before the war to accumulate more and better experience than was, in the field of land weapons, available to the Army. The disparity became still more pronounced in the early stages of the war when the R.A.F. found themselves more heavily and more continually engaged than any of the other Services. In the second place, the personnel of the R.A.F., like that of the Navy, but unlike that of the Army, was better capable of giving technical expression to its operational experience. There are many Air Ministry files abounding with inquests on flying accidents, which, reported by technically qualified pilots, were bound to be of great technical value. With the outbreak of war a new class of operational evidence was opened by reports on operations collected by the Intelligence Officers attached to Stations. These, when assembled in departments of the Director of Operational Requirements, came to form the main fund of the collective operational experience of the Royal Air Force.

These advantages went far to explain the greater precision and up-to-dateness of the technical demands of the Royal Air Force as compared with the demands for weapons of the other Services. Broadly speaking the Royal Air Force 'knew what they wanted' and seldom made the mistake of preparing themselves for the last war. From this point of view and thus far the supply departments at the Air Ministry and later the M.A.P. were faced with an easier task than the Ministry of Supply, and this must be borne in mind when the quality of British aircraft is compared with that of the tanks or the infantry weapons. Nevertheless, it would be wrong to conclude that the formulation of operational requirements of the Royal Air Force was always as perfect as the production department might have wished it to be. From the point of view of the men who looked after the aircraft programmes and designed the actual aircraft the requirements appeared sometimes unstable, sometimes inconsistent, and sometimes impracticable. Some such faults were inevitable under war conditions. But some may well have been due to certain imperfections in the methods by which the requirements were formulated and transmitted.

The methods which prevailed at the bottom of the ladder, i.e. in operational units, cannot be dealt with here. There is no doubt that the efficiency with which the flying experience of aircrews was assembled and analysed went far to determine operational requirements. But most of this work was done in squadrons and in other operational Commands and its story therefore belongs to the domestic history of the Royal Air Force. At a somewhat higher level a link might have been provided by the so-called Operational Research Groups. Their use in the field of battle dates back to late 1940 and early 1941 when a team of scientists was set up at a certain Dominion Command. Their precursor in this country was, perhaps, the group of scientists who on the outbreak of war were sent from the Bawdsey Research Station to Fighter Command to study the operational use of R.D.F. for controlling fighters. By the late autumn of 1941 they were well established in both the R.A.F. and A.A. Command. Although their personnel was administered by the Director of Scientific Research at M.A.P., the Groups were controlled by the Operational Research Committee, a standing interdepartmental body on which both Air Ministry and M.A.P. were represented. The full record of operational research thus lies outside the scope of this narrative and has little bearing on our problem. Not only were the Groups from the very inception conceived as attachments to the operational Commands, but in actual fact had little to do with the performance and design of aircraft.

From the point of view of aircraft design, much more relevant to the business of this study, and more directly felt in the M.A.P., was the system which governed the handling of requirements at the very top, i.e. at the links of the chain nearest to the Director of Operational

Requirements and the Assistant Chief of the Air Staff (Operational Requirements and Tactics). A characteristic feature of the system was the absence of anything that might be described as a strictly concerted progression of ideas. The official route from squadrons to the Directorate of Operational Requirements by which technical notions were supposed to travel in the direction of M.A.P., was by no means their only channel. The policy of operational requirements was an Air Staff matter, and the views of individual members of the Air Staff, especially of the Chief of the Air Staff himself and of the Commanders-in-Chief, swayed the decisions of the Director of Operational Requirements and the Assistant Chief of the Air Staff (Operational Requirements and Tactics) and sometimes even superseded them. Thus Air Marshal Sir Hugh Dowding, when at the head of Fighter Command, held and expressed strong, if sometimes homespun, views on a number of subjects of vital importance in the design of fighters, such as the range of fighter aircraft, their ability to fly over water, their powers of interception, the lethal effects of multiple machine guns and cannon. Needless to say, these views did not come to the knowledge of the technical department of the Air Ministry through the routine channels. Similarly the views of Air Marshal Sir Arthur Harris, Commander-in-Chief, Bomber Command, since 1942 about aircraft and about the armament of bombers were bound to influence the official policy in these matters between 1942 and 1944. An even more striking example was that of Air Marshal Sir Arthur Tedder, as he then was, a former Director of Operational Requirements and Controller of Research and Development, who, when in command in the Middle East, carried out on his own initiative some very important modifications, and was largely responsible for the adaptation of the fighter to a bomber role. Even more important was the scope which the personalities of the Director of Operational Requirements and the Assistant Chief of the Air Staff (Operational Requirements and Tactics) found in the formulation and interpretation of requirements. No observer will fail to notice how these personal factors gave vigour and consistency to the operational requirements of the Air Ministry between 1936 and 1938 and to a somewhat smaller extent between 1939 and the spring of 1940. For all these reasons it is impossible to blame the exigencies of war for all the uncertainties and vacillations which occasionally marked the Air Staff policy in the matter of requirements. Some of them must also have been due to multiplicity of channels through which the views of the Air Force could be made known and to the complicated play of personalities, a play which only the history of the Royal Air Force can hope to disentangle.

These facts, elusive and inconclusive as they are, are all that can here be said about the first point of contact, i.e. that between the collection of operational experience and the formulation of technical requirements. Somewhat easier to describe, and much nearer to the main subject of this paper, was the second point of contact, that between operational requirements on the one hand and design and development on the other. In so far as the latter, i.e. design and development, was administered by the M.A.P., the general problem became one of its relations with the user, i.e. the Air Ministry and the Royal Air Force.

Before the end of 1938, i.e. before the rapid expansion under Scheme L got under way, operational requirements and technical development were each controlled by a not over-large directorate of the Air Ministry, and the problem of their contacts did not raise many difficulties. In theory it was the duty of the Director of Operational Requirements to formulate the operational requirements of the Air Staff, and it was the duty of the Director of Technical Development to translate them into technical specifications. This theory was, on the whole, well observed in practice and such problems as may have arisen were continually settled in the daily contacts of the two directorates.

Changes in relations began to appear in the summer of 1938, when the whole organisation of the departments of the Air Ministry in charge of aircraft supply was recast. As has already been mentioned elsewhere, and will be mentioned again later,[1] the department of the Air Member for Development and Production was then created under Sir Wilfrid Freeman to co-ordinate the various functions of aircraft supply, and in the new department the control of design was taken over by the then Air Vice-Marshal Tedder, as Director General of Research and Development.

The main pre-occupation of the times however was with production, and under the new regime production and development were brought closer together. Measures to improve the contacts with the operational requirements branches of the Air Staff were not considered till the following year. By that time the branches of the Air Staff concerned with operational requirements had grown in size and importance, and by the beginning of 1939 the opinion gained ground that the time was ripe for tightening up the relations of the operational and of the technical branches of the Air Ministry. In the words of a contemporary memorandum 'the liaison between the Director of Armament Development's Directorate and that of the Directorate of Operational Requirements was . . . excellent', but 'the same could not be said with regard to certain other Directorates'. It was largely in order to correct this state of affairs that meetings

---

[1] See pp. 47 and 60. See J. D. Scott and Richard Hughes, *Administration of War Production* (H.M.S.O. 1955), Chs. III and XIV.

between the Assistant Chief of the Air Staff (Operational Requirements and Tactics), who had the chief responsibility for operational requirements, and the Director General of Research and Development, who had the same position in matters of research and development, were inaugurated in January 1939. The scope of the Committee was defined to comprise such subjects as:

(a) Proposals for new types of aircraft or equipment or modifications thereto.

(b) Progress of Air Staff projects and proposals already referred to the Director General of Research and Development's department.

(c) The regulation of what projects were or were not ripe for discussion with the industry and through what channels.

These meetings were usually attended by the Director General of Research and Development, the Director of Technical Development, the Director of Armament Development, the Director of Engine Development and Production and the Director of Communications Development, all of them representing design and development, and the Assistant Chief of the Air Staff (Operational Requirements and Tactics), the Director of Operational Requirements and the Director of Signals, all of them representing the operational side. They were usually held monthly, but sometimes more frequently, and continued until the autumn of 1940, by which time, as will be shown later,[1] the Director General of Research and Development's department had been removed from the Air Ministry. Although the Committee had no executive powers and its conclusions were not binding, it played an important part in formation of policy. It discussed and very frequently settled all the 'long-term' projects of an experimental character, such as the high-speed aircraft and jet propulsion aircraft. In the autumn of 1939 it defined the entire experimental programme, which included completely new development types including an unarmed bomber. In the December of the same year it also laid down lines of general policy about gun development in advance of Air Staff requirements. In addition numerous *ad hoc* problems were discussed, such as the .5 in. machine gun versus the .303 in.; the 20 mm. turrets for heavy bombers; belt feed and cooling for 20 mm. guns. A number of important requirements at that time introduced into operational aircraft were thrashed

---

[1] See pp. 60–61.

out at those meetings, e.g. the self-sealing tanks, armour plating, the improvement of surface finish for aerodynamic purposes. Now and again fundamental decisions were taken about the prospects of individual types. It was thus at one of these meetings that Coastal Command's objections sealed the doom of the ill-fated Botha.

The meetings continued after June 1940, i.e. after the formation of M.A.P. and the separation of the Air Member for Development and Production's department from the rest of the Air Ministry. But their influence began to wane. The procedure which was previously confined within the same Ministry now became a matter for inter-departmental relations, and it soon became necessary to emphasise the fact that the discussions were only 'exploratory' and that the liaison was 'tentative'. The authority of the meetings was not enhanced by the new atmosphere in M.A.P. Lord Beaverbrook's dislike of committees was intense, and the wonder is that he allowed this particular series to continue for a whole five months. In September the Minister directed that the Director General of Research and Development should take 'special steps . . . to ensure that the findings of these meetings are not read by anyone as authoritative in the sense that modifications or extra work are introduced without full consultation with, and approval of, the production authority concerned'.

In fact by that time a number of important technical issues, such as the fitting of the 20 mm. gun into single-seater fighters, were discussed and decided through entirely different channels. In the meantime also the personnel of the Director General of Research and Development's department had been expanded and altered, especially at the top, and the close relations between the departments that undoubtedly existed before were severed. In the autumn Sir Wilfrid Freeman (A.M.D.P.) left the M.A.P. to return to the Air Ministry as Vice-Chief of the Air Staff, and his Director General of Research and Development (Sir Arthur Tedder) was appointed to the Middle East. Thus the two persons most immediately connected with the building up and maintenance of the whole fabric of relations with the Air Staff were removed, and the foundations of the old order destroyed.

For a time nothing took its place. Under Lord Beaverbrook the tendency was for the M.A.P. to claim and to obtain a somewhat greater independence from the Air Staff wishes and policy than hitherto prevailed. The men who succeeded the A.M.D.P. and the D.G.R.D. were not in a position either to impress themselves on the Air Staff or to represent the Air Staff views at M.A.P. Sir Henry Tizard, who was appointed to fill the position previously occupied by Sir Wilfrid Freeman, was not a member of the Air Council and, what was worse, was not in the inner Councils of the Minister. Nor did the function devolve upon the new D.G.R.D. (Air Vice-Marshal Hill). Such contacts came to be concentrated in the hands of Mr., later Sir, Patrick Hennessy, Lord Beaverbrook's chief adviser, who as a rule communicated the M.A.P. development policy to the Air Ministry. He maintained touch with the Assistant Chief of the Air Staff (Operational Requirements and Tactics) and the Commanders-in-Chief by personal and informal meetings and sometimes through a member of the Secretariat. Yet it was during these crucial months, and especially in November and December, that a number of most important development projects were discussed, including the high-altitude bomber, night fighters, the Mosquito variants, the Beau-bomber, and the twin-engined Gloster jet fighter. A somewhat more formal contact between the two Ministries came to be restored at the turn of the year. But the demand for it came very largely from the production directorates, and its chief object was not so much integration of requirement and design, as that of design and production.

By the end of 1940 the lack of concerted action between the two Ministries came to be openly discussed at M.A.P., and was even mentioned to the Minister. On 6th January 1941, the Deputy Director General in charge of engine production reported to his superiors his conviction that development policy of future engines and aircraft was in 'a mess'. Whereas under the Air Ministry the whole question of development and production of aircraft used to be focussed in the Air Member for Development and Production, under existing arrangements there did not seem to be any 'adequate co-operation and cohesion between the Air Ministry and ourselves'. The document proposed to restore a unified control through a small co-ordinating committee. Its proposals were accepted, and the Joint Production and Development Committee was thus established early in 1941. The Committee was not destined to function for more than five months, but while it functioned it to some extent fulfilled the various co-ordinating functions of some of the lapsed committees of old. In the words of its own minutes the Committee performed a useful function for 'it provided a valuable means of co-ordinating development and production and ensuring that both proceeded in accordance with Air Staff requirements'. Yet it very nearly fell victim to an anti-committee campaign which swept over the Ministry in April 1941, and it was finally suspended in June.

By that time, however, Lord Beaverbrook had been translated to the Ministry of Supply, and a more intimate personal connection was re-established between the Air Staff and the upper ranks of the Ministry of Aircraft Production. Above all, a close connection was now set up by the appointment of Air Vice-Marshal Linnell as Controller of Research and Development. The new Controller had held in the Air Ministry the post of Assistant Chief of the Air Staff (Technical Requirements) and on joining the M.A.P. was made an additional member of the Air Council. This procedure of appointing a former Assistant Chief of the Air Staff in charge of operational requirements to the post of Controller of Research and Development in M.A.P. was to be followed in April 1943 when Air Vice-Marshal Sorley, as he was then, succeeded Air Vice-Marshal Linnell. Like his predecessor, he was given a place on the Air Council. But even more than his predecessor he was able, in his own person, to bridge the gap between the two functions. For, as a junior officer, he had played an important part in the framing of Air Staff requirements, and was considered as one of the pioneers of the policy which led between 1934 and 1936 to the re-equipment of the Air Force with the multi-machine gun types of the Spitfire/Hurricane class and 20 mm. Hispano fighter types, of which the Whirlwind was the original conception.

It was on personal ties and personal qualities such as these that the relations between the Air Staff and the M.A.P. were to depend in the subsequent two or three years. Attempts at organised contacts were not of course altogether given up. In December 1941 a series of fortnightly meetings between the Air Ministry and the M.A.P. was inaugurated. Their discussions covered the entire field of subjects common to M.A.P. and the Air Ministry, and Air Staff requirements were continually defined and re-defined. Nothing testifies more to the importance which the series of meetings promised to assume than the attendance, at their own request, of the Permanent Under-Secretary of the Air Ministry, and of the Permanent Secretary of the M.A.P.

But by then the highest point of its influence and usefulness was reached, and perhaps passed. The very appearance of the Civil Service heads showed that the meetings were becoming institutionalised to a greater extent than most of its other participants originally intended. Apparently the more personal and informal links on the Air Marshal level were to be preferred. The argument and the facilities for personal contacts of this kind were both reinforced in November 1942 when Sir Wilfrid Freeman retired from his post of Vice-Chief of the Air Staff, and returned to the M.A.P. with the new title of Chief Executive but with his old functions of co-ordinating development and production. From that time onwards the exchange of demands and ideas came to be largely canalised through the frequent personal contacts between the Chief Executive and the Chief of the Air Staff and, immediately below them, by the regular meetings and exchange of views between the Controller of Research and Development and the Assistant Chief of the Air Staff (Technical Requirements) and, lower again, between the Director of Operational Requirements and the Director of Technical Development.

(viii)

Problems of Co-ordination: Design and Production

It now remains to consider the third, and, from our point of view, the most important relation, that between design on the one hand and production on the other. The need for proper co-ordination of design and production arose quite early. From the very beginning of the expansion the dangers of independent design and of production unrelated to development were well understood in the Air Ministry as well as in the industry. In at least one field, that of retrospective modifications, they were felt so constantly, and yet so acutely, that permanent co-ordinating machinery was soon devised.[1] In other fields the demand for co-ordination and the efforts to supply it were somewhat more sporadic.

Co-ordination of design and production depends on relations within the government machinery as well as on relations between the Government and the industry. On the whole the former were apt to be less clearly defined than the latter, largely on the theory that within government departments things could well be left to personal links and contacts. Least defined and least permanent was the tie at the highest official level, i.e. between the heads of the various departments in charge of design and production. In so far as the problem was that of relations between M.A.P. and the Air Staff it has already been accounted for above.[2] The problem, however, was not only one of relations between the two Ministries but one of design and production within M.A.P. It had in fact been raised in the Air Ministry before the M.A.P. was formed, and it was for the first time seriously tackled in 1938. By that time the impression got abroad that expansion was hampered not only by insufficient planning of production, but also by independent action of technicians, who were impeding production by excessive changes in design. The complaint was voiced in Parliament[3] and in newspapers and was strongly impressed upon the Air Ministry by the Chairman of the Society of British Aircraft Constructors.

In fact, the latter made during the discussion a number of proposals not much different from the principles on which the administrative reforms were eventually to be based. As we have already mentioned,

---

[1] See Appendix III.
[2] See Section (vii) above.
[3] H. of C. Deb., Vol. 336, Cols. 1233–1350, 25th May 1938.

these reforms created the combined office of Air Member for Development and Production under Air Vice-Marshal Sir Wilfrid Freeman.[1] Within this new department the functions of production and of design were entrusted to two newly created Directorates General: that of production under Sir, then Mr., Ernest Lemon, and that of research and development under, as he was then, Air Vice-Marshal Tedder. The new grouping was bound to make for closer integration, but equally important were the informal ties which grew up between the Air Member for Development and Production and the Director General of Research and Development at the top, and between the various sections of the Directorate General of Research and Development and the Directorate General of Production lower down. In the instance of engines, the control of both production and development directorates was vested in one and the same man.[2] Elsewhere mutual understanding rested on a purely personal foundation. Positions of importance on both sides were held by members of the Service or by technical officers with previous experience of the Air Ministry or the R.A.E. To put it in the cruder language of everyday comment in the Ministry itself, 'everybody knew everybody else' and 'things were very much mixed up'.

Arrangements so personal and so informal could not survive the events of 1940. We have seen that the Air Member for Development and Production's organisation, as formed in 1938, and as established in Harrogate in September 1939, grew into an all-but independent department, and was in the end to form the nucleus of the new Ministry of Aircraft Production.[3] But the continuity was more of records, machinery and lower personnel, than one of policy and administrative principle. Although the office of the Air Member for Development and Production was not at once abolished, it could not retain under Lord Beaverbrook the same overriding authority which it had enjoyed at Berkeley Square and in Harrogate. As has already been pointed out,[4] in the autumn of 1940 Sir Wilfrid Freeman relinquished his post of Air Member for Development and Production to return to the Air Ministry, and Sir Arthur Tedder left his post of Director General of Research and Development to go to the Middle East. Thereby, not only was the liaison with the Air Staff weakened, but the personal ties which had bound the direction of research to that of production were also snapped. No real successor to Sir Wilfrid Freeman was appointed. Sir Henry Tizard was officially entrusted with control of design, development and production at the highest level, but in fact production was to control itself

[1] See p. 47.

[2] Major G. P. Bulman was Director of Engine Production (D.E.P.) and Deputy Director of Engine Development (D.D./R.D.E.).

[3] See p. 47.

[4] See p. 56.

and for a short time to overshadow all the other activities of M.A.P.

In the conditions of the summer of 1940 this was perhaps inevitable. It has already been shown that for the time being quantity and output were the main pre-occupation of the new Ministry.[1] For this and other reasons production directorates grew thick and fast and had to be staffed with new men 'who knew not Joseph'. The survival of the older practice, whereby the Director General of Research and Development himself and some of his principal assistants were serving R.A.F. officers on the establishment of the Air Ministry, may have helped to maintain the links between the Air Staff and the technical departments in M.A.P., but it did nothing to reinforce the Director General of Research and Development's position with the Ministry at a time when 'the Air Marshals' were in the Minister's black books. Lord Beaverbrook's own decisions, and the authority which he conferred on his principal assistants in charge of production, did much to co-ordinate production with such design and development as there was. But the co-ordination was a matter of *ad hoc* decisions and was largely the work of the men whose main pre-occupation was with production.

We have seen that at that time the liaison with the Air Staff was carried out through the Minister's principal adviser (Mr., later Sir Patrick Hennessy) and his assistants.[2] On them fell also the duty of guiding design and production. Thus it was through them that the fitting of the 20 mm. cannons into single-seater fighters was pursued in the second half of 1940, and it was they who took charge of the development programme for night and high-altitude fighters and for the Mosquito. To advise him Mr. Hennessy occasionally held meetings in his room attended by Sir Henry Tizard, the Director General of Research and Development (Air Vice-Marshal R. Hill), the Director of Technical Development (Mr. W. S. Farren) and a Deputy Director General of Production (Major Buchanan) at which problems of production and development were discussed. But the discussions could not produce a combined policy even though the need for such policy was felt within the Ministry.

We have already shown how eventually, from within the production departments, a proposal emerged for a unified control of research, development and production, and how, in consequence, the Joint Production and Development Committee was born in mid-January of 1941.[3] One of its purposes was to co-ordinate requirements and design, but the co-ordination of production was its main object. With its disappearance in June 1941 nothing else to take its

---

[1] See M. M. Postan, *British War Production* (H.M.S.O. 1952), Ch. IV.
[2] See pp. 56–57.
[3] See p. 57.

place was found.[1] For the general co-ordination of development with production the Ministry had to wait for the 'Cripps era', for the re-appearance of Sir Wilfrid Freeman in M.A.P. as Chief Executive in the autumn of 1942, and for the appointment of Air Marshal Sir Ralph Sorley as Controller of Research and Development in April 1943. This, when it happened, was as much a revival as an innovation. The office of Chief Executive was apparently designed as something of a replica of the Air Member for Development and Production's office of old. The part it was to play in re-establishing a personal link with the Air Staff has already been mentioned. Within the M.A.P. it was able to secure the relation between Production Directorates and the Controller of Research and Development which, in the old days, marked Sir Wilfrid Freeman's collaboration with Air Vice-Marshal Tedder.

(ix)

Problems of Co-ordination: Government and Industry

On this personal basis the harmonisation of design and production in M.A.P. was sustained until the end of the war. But official relations are only one half of the story. Proper co-ordination between design and production also implies close and intimate contacts between the technical branches of the Ministry and the design offices and the workshops of the aircraft firms.

As we have already noted here, and shall have to note again, design and development was a co-operative effort in which both industry and Government shared to an approximately equal degree. The formal procedure which regulated the relations between the technical departments of the Ministry and the private designers, i.e. the procedure of notifying the Air Force requirements to the industry, of issuing specifications and calling Advisory Design Conferences and of ordering prototypes, was well established by 1934, and will be described in greater detail elsewhere.[2] But in addition to the formal procedure of specifications, and, so to speak, behind it, there were other and less formal contacts between the Air Ministry, the M.A.P., and the principal designers. Most of the new ideas born in the designing offices of the firms were discussed with the authorities in M.A.P. long before they were crystallised in preliminary designs. In fact the

---

[1] The 'joint meetings' of the Air Ministry and M.A.P. were little concerned with production, and the only occasions for joint consideration of problems were provided by *ad hoc* conferences between officials to consider the programmes and prospects of individual aircraft. There were also occasional special conferences with representatives of the firms to discuss the prospects and development programmes of individual types.

[2] See Ch. IV, Section (iv). Also Appendix II.

preliminary stages in the history of almost every aircraft were marked by constant and informal collaboration between the designers and officials paving the way for the issue of the official specification and for the submission of the preliminary designs. Both sides stood to benefit from the consultation. The designers kept the Ministry abreast of the technical developments in the industry. On their part, the technical directorates at the Air Ministry and the M.A.P. from time to time issued to the industry informal notifications of the future trend of requirements in order to enable the designers to frame their future policies and expectations.[1]

The informal contacts were even closer and more regular in the later stages of design and development. All through the period when a prototype was constructed and an aircraft was developed the coming and going between the firm and the Ministry was continuous. Not only was the Ministry anxiously watching the timetable and the general progress of the prototype and of the early production aircraft, but it very often discussed with the firm (as it was bound to do) the modifications which were found necessary in the course of prototype construction. In short, as far as the design and production of individual aircraft went, the collaboration between the technical branches of the Ministry and the designing staffs of the industry was very close indeed: much closer than the relations between customer and supplier usually are.[2]

However the daily contacts were not confined to the high-ranking technicians on both sides and were not altogether left to informal and unorganised interviews, telephone calls and correspondence. A more constant and intimate connection was provided by a special liaison service. The technical branches of the Air Ministry, and later the M.A.P., maintained in individual firms resident officials who acted as a regular channel of communication and were always available on the spot to interpret to the industry the point of view of the Ministry.

In a sense the most important of these representatives were the so-called 'Overseers', the first of whom was appointed in June 1939, and who, by the end of 1942, were attached to almost every major aircraft factory. The Overseer's functions by that time can best be defined in the words of a report of an M.A.P. committee which, in November 1943, reported on the work of the M.A.P. representatives at contractors' works:

> The Overseer is the principal representative of the Ministry to whom the firms are entitled to refer all questions requiring immediate decision and to look for advice and assistance in every way possible. . . . As the Department's principal representative

[1] See Ch. IV, Section (v).
[2] See pp. 77–78.

> the Overseer is responsible for securing the fullest co-operation between the M.A.P. representatives at the firms, and in this capacity he also presides over the Local Technical or Modifications Committee. By virtue of the close contact which he is required to maintain, through the Commands, with the Service Units using the products of the firm, the Overseer serves as a direct link between the firm and the resident representatives of the Ministry on the one hand and the user on the other, is in a position to interpret the user's experience to the firm and these representatives and to ensure that the equipment supplied by the firm to the Unit is kept operationally serviceable.

On the whole, the very variety of the functions which the Overseer had to perform made him less important from the point of view of design and development than the other local M.A.P. official, i.e. the Resident Technical Officer. These officers represented in the designing firms the Director of Technical Development and were charged on his behalf with all the technical problems which arose locally in connection with design, experiment, development and modification of aircraft. As their primary function was to link up firms with the Directorate of Technical Development they were, as a rule, attached only to the so-called designing firms. Most of these firms housed Resident Technical Officers as early as the mid-twenties, and by the summer of 1943 some twenty-seven of the Directorate of Technical Development's Resident Technical Officers were in action. In addition, by the autumn of 1943, some twenty-eight similar officers came to be attached to firms engaged in the design and development of aero-engines and armament to represent the Director of Engine Development and the Director of Armament Development. Their duties were defined very widely. In the terms of the report already cited, they included

> the supervision of designs to ensure that the technical and operational requirements of contracts are met; the granting of design concessions to facilitate production; the technical approval of designs, modifications and amendments; and the issue of design clearance of aircraft before flight tests are undertaken by Service personnel.

Their more general function, however, was the guardianship of technical standards on behalf of the Ministry. They were expected

> to give general guidance to the firm in the application of technical policy arising out of current research and development work, to take an active interest in maintaining the standard and improving the quality of the firm's business and to see that the daughter firms, sub-contractors and repair firms receive the technical assistance they need from the parent firm.

The Resident Technical Officers were also able to keep abreast of current developments in the experimental establishments and the Service units, to all of which they were given direct access. Needless to say, the day-to-day performances of the technical officers, even the best of them, were somewhat more modest than the field of action charted out for them in official documents. But apart from the staff of the Aeronautical Inspection Directorate, the Resident Technical Officers were the oldest resident officials and were able to take root in the firms to which they were attached.

This account of the relations between the technical branches of M.A.P. and the designers should not be taken to mean that the industry or the M.A.P. were always satisfied with them. Although the industry was closely bound up with the evolution of individual types of aircraft, they were not, as a rule, consulted about the general policy of design and development. It is therefore no wonder that from time to time the firms expressed the desire to be associated with the Air Ministry and M.A.P. in those stages of requirements and design which the government departments regarded as their own. Throughout the war years the desires of the firms, when voiced, were all in favour of what they called 'closer contacts' between themselves and the user. In this connection the term 'user' commonly designated not the M.A.P. but the Air Force and the Fleet Air Arm. The firms were obviously harking back to the pre-expansion days when there was a great deal of coming and going between the serving officers of the Air Staff and individual firms, and when designers learnt much about Service requirements from daily contact with the men who flew the planes. In at least one case before the war, the representatives of the industry were actually encouraged to go about the R.A.F. stations in search of first-hand operational information. When, in 1934, the specification for the Army Co-operation plane (A.39/34) was put out to tender the representatives of Westland's (the Technical Director, Mr. Petter, the test pilot, Mr. Penrose, and the Chief Designer, Mr. Davenport) obtained permission to visit the Army Co-operation squadrons in order to collect ideas about the kind of aircraft which was required from the operational point of view. As a result, they were able to produce six different designs, from which the design of the Lysander was eventually evolved. This was perhaps an extreme case, but there is no doubt that many of the ideas which went into the making of the aeroplanes of the 1935, 1936 and 1937 vintage embodied notions derived from R.A.F. crews.

Some of these contacts survived the outbreak of the war. To quote one instance, Capt. Frazer Nash, the turret designer, succeeded in maintaining, as late as 1942, the personal links with flying personnel which stood him in such good stead in the early years of the turret.[1] But generally speaking during the war, and more especially with the establishment of the M.A.P., the industry lost its earlier access to the Royal Air Force. From that time also the representatives of the industry began to voice their demands for closer consultation on matters of design and development. It was very largely in response to these demands that the Select Committee on National Expenditure[2] expressed its opinion that the main contractors were 'not sufficiently consulted on programmes and designs which are under consideration', and that

> while it is necessary that the authorities responsible for production should be fully informed of what the Service authorities require, it is equally important that the latter should fully appreciate the realities of the production side of the problem.[3]

These demands came to a head in the late spring of 1942, in an exchange of letters between the Chairman of the Society of British Aircraft Constructors and the Minister of Aircraft Production. The exchange was opened by Sir Charles Bruce Gardner's letter on the 15th April 1942 requesting a closer liaison between the manufacturers, the M.A.P., the Royal Air Force and the Fleet Air Arm. What, in his view, was needed was the 'closest co-operation . . . between those who operate in the field and those who have to embody that experience in the engineering product'. But as this correspondence revealed, the real complaint and the practical demands were not so much about consultation on technical topics as of the whole technique of formulating the policy of design and development. The firms appeared to resent their exclusion from the consideration of design and development programmes at the highest level. In Sir Charles Bruce Gardner's words, the industry's view was 'that the Air Staff having decided strategical and tactical requirements, the industry should supply the engineering interpretation of these requirements in the form of operational aircraft'. The demand was that the industry should be associated with the M.A.P. and the Air Ministry as an equivalent partner at the stage of discussion at which the programmes of design and production were decided.

This request was to remain unsatisfied. Various attempts to meet it halfway or part of the way were occasionally made, and on at least one occasion the general views of the industry on problems of development were invited. The earliest organised attempt to bring the industry in at the highest and earliest levels of discussion was made in 1935 when the Deputy Director of Scientific Research (Dr. Pye)

---

[1] See Ch. V, Section (iv).
[2] Eighth Report from the Select Committee on National Expenditure, Session 1941–42.
[3] Ibid, p. 9.

proposed that annual conferences between the Air Staff, the technical departments of the Air Ministry and the industry should be held 'with the dual purpose of indicating in advance the probable evolution of R.A.F. tactics and of forecasting and co-ordinating design of airframe and power plant'. But the proposal did not find favour with the Air Member for Research and Development (Air Vice-Marshal Dowding) or with the Deputy Chief of the Air Staff (Air Vice-Marshal Courtney), and came to nothing.

The only occasion traceable in the records on which the chief designers were collectively consulted about general problems of policy occurred at the end of August 1940 when the Air Member for Development and Production (Sir Wilfrid Freeman) asked the Director of Technical Development to invite Mr. Frise of Bristol Aeroplane and Mr. Pierson of Vickers Aviation to meet him, Mr. Hennessy and other high technical officers to give them personal advice on the development of bombers, and also Mr. Camm of Hawker's and Mr. Petter of Westland's to advise him similarly on fighters. The question which the designers were, on that occasion, asked was 'what ought we to do to make the best use of our resources'. But this was probably the only instance when a question as general as this was asked. At all other times such consultations with the chief designers as there were had to be confined to the concrete problems relating to the development of individual types. On matters of policy, i.e. the balance of programmes and general control of quality, the cobbler was politely told to 'stick to his last'.

The importance of this restriction must not be exaggerated for the official policy itself was 'cobbler made'. By comparison with government departments, the industry suffered little from being excluded from discussions of general principles for the simple reason that the general principles were seldom discussed. Between 1940 and 1943 the balance of aircraft programmes from the point of view of quality was not 'made' but 'just happened', so that an historian in search of general principles must distil them from the welter of individual decisions taken with reference to individual aircraft. Yet even had general policy been more evident than it was, the exclusion of the industry from its consideration could not possibly have affected the technical progress in the individual aircraft. In the latter, the co-operation between the firms and the Ministry was as complete as co-operation between industry and State could possibly be.

CHAPTER IV

CO-OPERATION OF GOVERNMENT AND INDUSTRY: AIRFRAMES

(i)
Introductory

THE history of the methods which Government and industry employed in promoting the progress of aircraft design is incomplete without some appraisal of the two contributions. It is impossible, and probably undesirable, to try to allocate credit with any degree of exactitude. The respective shares of the Government and the industry are difficult to measure, and most attempts to do so have in the past been somewhat mixed up with political discussion. Yet, much as an historian would wish to steer clear of a subject at once so elusive and controversial, he cannot avoid it altogether. In the field of design the relations of Government and industry have provoked a number of questions which are essential for the full history of 'quality' and about which ascertainable historical evidence is available. Was the technical progress of British aircraft at all points solely determined by the activities of the industry, or was it ever dependent on official initiative and guidance? Did the private designer function as a mere instrument of the technical departments of the Air Ministry and the M.A.P. or was he, on the contrary, a 'prime mover' unto himself? Were the government departments at any point capable of stimulating a forward movement of design, or were they, on the contrary, mere agents of bureaucratic control, or, at best, the industry's passive customers?

A broad answer to these questions is implicit in the history of the machinery as expounded above.[1] The industry and the State were partners in the business of design and development, and the quality of British aircraft must therefore be credited to the joint account of the firms and the ministries. This, however, is not the answer which has sometimes been given. No interested observer would fail to notice the existence of two largely opposite points of view on this subject. In certain circles, especially in the higher ranks of the R.A.F. and the

[1] See Chs II and III.

M.A.P., it has frequently been assumed that the main contribution to the progress of design was made by the government departments. This point of view was seldom put into words, but it often underlay the criticisms which were addressed from other official bodies or from Parliament to the M.A.P.

The best known instance of this occurred in the debate on the Fleet Air Arm in the House of Lords on 27th January 1943, when most of the speakers showed an inclination to blame M.A.P., not only for the insufficient numbers, but also for the technical shortcomings of naval aircraft.[1] Other and less public occasions on which similar assumptions were made were perhaps too numerous to be recorded here *seriatim*. But a good example was provided by a note of the Air Ministry submitted to the M.A.P. in the course of the discussion of the aircraft programme of July 1942. The note surveyed the entire prospect of aircraft design and in doing so took it for granted that the inadequacies of design and development could in large part be put down to the policy of the M.A.P. The Ministry were taken to task for not having forced engine design to provide sufficient high power for new types; for not having created sufficient capacity for the changeover to new types; and for a general 'reluctance to press forward with new projects'. Generally speaking a student of the records will discover that in the circles outside the M.A.P. the tendency was to blame H.M. Government for lack of progress in design, just as it was the tendency within the Air Ministry to take much of the credit for the general advance in aircraft performance before 1940.

This assumption must be contrasted with the better publicised opinion that the aircraft industry, and the aircraft industry alone, were responsible for the progress of aircraft design. That this view should have been held by the official representatives of the industry is natural enough. When, in his discussions with the Minister of Aircraft Production in June 1942, the Chairman of the Society of British Aircraft Constructors tried to define the functions of the industry, he took it for granted that the source of ideas was 'the designer with his vision and creative skill and ingenuity'. But the same view was often held by persons who at one time or another directed the activities of M.A.P. or the Air Ministry. This was essentially the point of view which Lord Beaverbrook repeatedly announced in publications and speeches. In the debate in the House of Lords on the 27th January 1943, he based his entire exposition of the aircraft industry on the proposition that His Majesty's Government depended for quality of aircraft on the firms producing them. 'Beginning with the design of the aircraft, the responsibility of the

[1] H. of L. Deb., Vol. 125, Cols. 794–829, 27th January 1943.

firm prevails there.' 'In fact', he continued, 'the aeroplane depends on the work of the firm. If there is a good firm there is a good effort, if there is a bad firm almost certainly it will be the reverse.'[1] A few months later Air Chief Marshal Sir Hugh Dowding in a newspaper article[2] reinforced this view with all his customary vigour and simplicity:

> . . . when it comes to State intervention in the design and development of aircraft and engines, I do know what I am talking about, because I was for six years at the head of that department of the Air Ministry which was concerned with research and the design and development of aviation material.[3]

Looking back over that period the Air Chief Marshal felt that it was not an unfair claim to make that

> the derisory sums voted for the technical equipment of the R.A.F. produced types of aircraft and engines which compare favourably with those of other nations . . . One of the basic causes of this comparative efficiency was, in my opinion, the fact that Government departments took no positive part in the design or production of aircraft and engines.

The same view was now and again expressed by other prominent persons both in and out of the M.A.P. and by journalists reflecting their opinions.[4]

Viewed in the light of historical evidence neither doctrine is wholly tenable. That the main responsibility for new designs did not rest with the government departments is obvious. The Ministry did not engage in the direct design of entire aircraft or engines, for no design organisation, in the narrower sense of the term, was maintained by the Government, and no person officially employed by His Majesty's Government was ever entrusted with the complete design of an aircraft. The Government withdrew from the field in 1918 when the Royal Aircraft Factory in Farnborough was wound up and a decision was taken not to design or build complete aircraft in any government institutions. As a result of this policy the Air Ministry, unlike the Admiralty or the War Office, never possessed industrial establishments of its own and was entirely dependent on the aircraft firms for final design and production. Thus far Lord Beaverbrook was perfectly right. 'If there is a good firm there is a good effort, if there is a bad firm almost certainly it will be the reverse.' No amount of help,

---

[1] H. of L. Deb., Vol. 125, Col. 804, 27th January 1943.
[2] *Evening Standard*, 8th April 1943, p. 6.
[3] Sir Hugh Dowding was Air Member for Supply and Research from 1931 to 1934 and Air Member for Research and Development from 1934 to 1936.
[4] D. Farrer, *The Sky's the Limit: Lord Beaverbrook at the M.A.P.* (London, 1943), p. 52.

guidance and sponsoring from the government departments could coax a good design from a bad designing team, and as we shall see later good designers sometimes succeeded in evolving excellent aircraft with little official encouragement, and sometimes even against official opposition.

(ii)
State-assisted Research

Thus, in a sense it would be true to say that the design of new aircraft was the responsibility of the firm. But the truth of this proposition depends on its not being cited to point a contrast to Government action. For the design of aircraft could be the function of the industry and, at the same time, be assisted and sponsored by the State. The forms and the degree of State assistance were very many. To begin with, as we have seen, the private designers depended for much of their theoretical work and for most of their experimental tests on the research work financed and directed by the M.A.P. and on the facilities at the Royal Aircraft Establishment at Farnborough, the Aeroplane and Armament Experimental Establishment at Boscombe Down and at the National Physical Laboratory. To some extent the research work conducted within the firms was instigated and financed by the Directorate of Scientific Research at the M.A.P., and from 1943 onwards the relative importance of investigations 'farmed out' to the industry was to grow in importance.[1]

(iii)
The Nursing of Private Designers

The real assistance to private designers went further than research and experiment. It would not be an exaggeration to say that His Majesty's Government made itself responsible for the very existence of civil designers, and did so to an extent which makes it very difficult to consider private designers and their departments as independent emanations of individual enterprise. The self-denying ordinance, by which the Air Ministry refused to provide itself with Royal Aircraft Factories, did not mean that the business of designing aircraft was wholly abandoned to free and untrammelled competition of 'all-comers'. In order to maintain the existing industrial capacity for design the Ministry had to place a number of firms in a position so close to itself as to make the ordinary distinctions of state control

[1] See pp. 31–32, 36–37 and 48–49.

and private enterprise out of place. As we have repeatedly shown, the Ministry tried to the best of its ability to keep in being a group of established firms (sometimes described by the misleading term of 'family') consisting of about sixteen aircraft firms and four engine firms.[1] This, coupled with the nature of the aircraft industry, its large capital investment, its need for special experience and its exacting technical standards, made it very difficult for new firms to establish themselves, and kept the circle of established design firms unbroken.

In spite of the hazardous and unprofitable nature of aircraft business before the war, attempts to enter the circle were from time to time made. But they did not as a rule succeed. Some of the earliest and the most characteristic instances occurred not in the field of airframes but in that of engines, and will be discussed in a later section.[2] But occasionally new firms also tried to establish themselves in airframe construction. In the early stages of the expansion, pressure from 'outside' firms led to a certain amount of public agitation and formed the subject of a debate in the House of Lords in December 1936.[3] On that occasion, one firm, Airspeed (1934) Ltd., succeeded in establishing itself 'on the fringe' of the industry, and was seriously considered for a possible design of a Fleet Air Arm type. Other 'fringe' firms, such as General Aircraft, Folland Aircraft and Cunliffe-Owen's, also repeatedly tried to have their designs considered. But it was not until the concluding stages of the war with Germany, and not until the M.A.P. plans came to be influenced by post-war prospects, that the Ministry began to consider at a high level the necessity of enlisting other firms, such as English Electric. Even then the proposals were not to break the circle of design firms but merely to enlarge it by inducing certain firms of proved efficiency to enter it.

From the point of view of this study, the most important aspect of the policy is the protection it provided for the existing design teams. Indeed the main justification of the 'family' system was that it enabled the firms to maintain their design staff. In the article already quoted, Sir Hugh Dowding makes it clear that the orders for engines were so distributed as to keep the existing design organisations in being. 'Although it would have been theoretically desirable to have more than four aero-engine firms from the point of view of competitive efficiency, practical considerations did not permit of this.'[4] And the practical consideration which the Air Chief Marshal had in

---

[1] See Ch. II.
[2] See Ch. V.
[3] H. of L. Deb., Vol. 103, Cols. 974–1004, 17th December 1936.
[4] *Evening Standard*, 8th April 1943, p. 6.

view was the need to keep going the existing design organisations of private firms.

In the 'nursing' of private design bodies the Ministry went beyond the mere rationing of orders. More positive steps were from time to time taken to feed individual design departments with the type of project in which the Air Ministry wished them to specialise. It has already been indicated that the Air Ministry and the M.A.P. tried to maintain some specialisation in design as between firm and firm. We have already seen that some designing organisations, e.g. Vickers-Armstrongs, Handley Page, and to some extent, A. V. Roe and Bristol's, were normally entrusted with the design of bombers, Supermarine's, Hawker's, Gloster's and Westland's were considered as fighter firms, while Fairey's and Blackburn's were given over to naval types.[1] Within each of these groups the position of design departments was closely watched, and whenever a pause in their activities was threatened, projects were proposed to keep them fully employed in their own lines. Thus, when on the eve of the war it appeared probable that some firms would not have sufficient design work to occupy their staffs, the Air Ministry proposed to give firms a number of purely experimental projects in order to direct the attention of their design staffs to problems within their field of interest. Blackburn, Armstrong-Whitworth and A. V. Roe were to be asked to design an experimental high-speed bomber, Hawker's and Phillips & Powis were to be entrusted with aircraft for the highest possible speed, and Gloster's were to be encouraged to embark on jet-propelled aircraft. In the course of the subsequent three years the Air Ministry and M.A.P. sponsored or kept alive a number of projects, such as the Gloster day fighter, the Hawker high-speed bomber, the Buckingham, the Warwick and the abortive Vickers' high-altitude bomber,[2] for very largely the same reasons, i.e. in order to occupy the designing staff of firms with designs which, in the view of the Air Ministry, suited them best. In the midst of the war, i.e. 1942 and 1943, the 'nursing' of design organisations could occasionally take a more drastic and even a punitive form. Thus in the winter of 1942 the design department at Fairey's was completely re-organised with much encouragement from M.A.P.

---

[1] See Ch. II, Section (vi).

[2] Specifications F.9/37; B.11/41/H; B.2/41 and Buckingham I/P.I; B.1/35 and B.5/41 respectively.

(iv)
Guidance of Airframe Design by Specification

There is thus little doubt that the design of aircraft, 'private' as it may have been, was in more than one sense state-aided. But, as we have already suggested, private design was not only aided by the State but also often sponsored and guided by it.[1]

The routine vehicle of official sponsorship of new types was, of course, the 'specification'. In ordinary circumstances the Air Ministry, and later the M.A.P., inaugurated a new aircraft by issuing a 'specification', which summarised in broad terms the main features of the aircraft to be designed. Its Appendix B laid down the minimum requirements for such things as speed, ceiling, climb, bomb-load, range, fuel capacity, armament etc. In addition the main body of the document at one time adumbrated the main features of the design, such as the number of engines, the type of structure, i.e. monoplane construction or cantilever wings, and always gave general indications of the engineering characters such as the various strengths and load factors.[2]

The importance of the specification in guiding the designer was thus very considerable, but the part it played in technical progress must not be exaggerated. On the whole it was much greater in defining the operational purposes of the aircraft than in laying down its technical features. The latter were as a rule mentioned only in so far as they happened to affect the operational use of the aircraft. Airbrakes would be specified for an aircraft to be used as a dive-bomber; variable pitch four-blade propeller would be specified for an interceptor fighter; arrester gear for carrier-borne aircraft. None of these technical requirements could, or was meant to, initiate new trends in aircraft design and construction, and it would be unusual to find technical novelties in an official specification. More often than not, technical demands were made merely in order to indicate the Air Ministry's choice between the well-established technical possibilities or else to facilitate the installation of some fully developed items of equipment. Thus a specification might lay down the type of engine to be installed or might demand a provision for the installation of a certain mark of radio.

Moreover, even as a statement of broad operational features and as a catalogue of established technical principles, a specification

---

[1] See Ch. III, Section (ix).

[2] Specification procedure and the contents of specifications were greatly changed after 1940. This and other aspects of specifications are discussed in greater detail in Appendix II.

did not invariably lead the way. It was sometimes issued merely in order to formalise and to sanction the designs already submitted to the Ministry. Very frequently an official specification, though bearing every superficial sign of a wholly novel conception, in fact did nothing else than bring to a head discussions with industry of ideas which had been largely generated within the industry itself. Thus several designs which had been conceived more or less on the initiative of the firm, were followed by a *post-factum* specification.

Specifications of this kind were issued in 1939 and early 1940 to give official blessing to the Beaufighter and the Mosquito, and to certain other types.[1] In the second half of 1940 and in 1941 official specifications followed the design of the Lancaster, the pressurised Wellington, the Hawker high-speed bomber and the fighter variant of the Mosquito.[2] At the end of 1941 and during 1942 and 1943 *post-factum* specifications were written for at least one variant of the Tempest, for the abortive Vickers' high-altitude bomber, for the super-Stirling, for the Mosquito replacement, for the York transport version of the Lancaster, for the 'thin wing' Spitfire development with Griffon 6 engines and for the two-seater high-altitude fighter derived from the Welkin.[3] From 1940 onwards the whole procedure was modified to suit the changed circumstances of aircraft design, and specifications were issued either in order to sanction privately conceived designs or to authorise departures from standard engineering practice of M.A.P., as defined in its codified engineering instructions.[4]

Even on those occasions when the specification preceded the preliminary design and laid down its operational and engineering principles, it was sometimes disregarded by the designers. In the words of Lord Beaverbrook's speech, already quoted:[5]

> It is true the Ministry issues their specification, but that specification is sometimes rejected and frequently amended by the firm—usually improved. In the case both of the Spitfire and the Hurricane, those great aeroplanes, the design which was produced by the firm did not at all resemble the specification issued by the Air Ministry.

An even better example than the one Lord Beaverbrook quoted was provided by the 1934 generation of heavy-medium bombers, the Wellington and the Hampden. The Specification B.9/32 which called for this design was based on the tare weight limit of 6,000 lbs.

---

[1] Specification numbers F.17/39 and B.1/40/DH.

[2] Specification numbers Lancaster I/P.1, 17/40/V, B.11/41/H and F.21/40.

[3] Specification numbers F.10/41, B.5/41, B.8/41, B.4/42, O.1/42, F.1/43 and F.8/43 respectively.

[4] See Appendix II.

[5] See pp. 69–70.

laid down by the Geneva Disarmament Convention. But from the very beginning the two firms, Vickers and Handley Page, refused to be bound by this limitation, and in the end submitted designs which greatly exceeded the limit. The limits were further extended in the subsequent version of the Wellington, so that by 1942 an aircraft which was to have weighed 11,000 lbs. overall reached no less than 36,000 lbs.[1]

(v)
Guidance of Airframe Design before and after Specification

Thus, in so far as government departments took upon themselves to instigate new designs and new technical departures, they could not very well do so by specification, or at any rate by specification alone. But a variety of other methods were open to them, and were used for the purpose. In the later phases of the war the private designers were, to an ever-growing extent, guided by the standard engineering practice of M.A.P. In order to standardise the production of parts and components and to simplify the provision of raw materials and parts, the M.A.P. began in 1940 to lay down rules about engineering methods, and by 1944 these rules came to cover a very large proportion of the engineering detail of aircraft construction. These were not wholly, or even largely, addressed to the designers, but they inevitably circumscribed the scope of technical changes in new types. By the end of 1943, and possibly even earlier, specifications themselves had to be adjusted to these common denominators of M.A.P. engineering practice, and became little more than lists of features in which the new requirements differed from standard practice.[2]

In addition, both before and after the issue of the official specification the Air Ministry and M.A.P. found themselves able to influence design. In the first place the technical branches and the scientific establishments were in the habit of issuing advisory technical memoranda containing suggestions about the best ways of meeting the official requirements laid down in specifications. These were not however linked to any particular design, and not being mandatory, could be followed or disregarded at the discretion of the firms. But there were also other channels of influence more definitely

[1] See Appendix II. The Specification B.9/32, before the rescinding of the weight restriction, endeavoured unsuccessfully to limit the all-up weight to 11,000 lbs.; the prototype Wellington weighed 22,000 lbs. all-up; the Wellington X with 2 Hercules VI engines weighed no less than 36,000 lbs. all-up.

[2] These common denominators of engineering practice came to be embodied in a number of documents and memoranda issued to the manufacturers.

related to individual projects. Soon after a design had been chosen and prototypes ordered, the firm and the representatives of the technical branches of the Ministry met at the Advisory Design Conference. This was an occasion at which the firms could obtain a modification or a relaxation of the specification, but it could also be used to convey to a firm in greater detail the technical views of the department.

Later, in the prototype stage, the official technicians could influence design by controlling the installation of equipment and by supervising the construction of the prototype. Their responsibility for equipment came to be taken for granted from the early 'twenties. The instruments, including radio and the various aids to comfort and efficiency such as the general layout and method of working of the controls and of the crews' compartments, have always been considered as something external to the main design and as something which the user, and he only, could determine. As we have already suggested elsewhere,[1] the history of British types belies the notion that equipment did not affect the essential quality of aircraft. Nevertheless, the view that it was an operational matter and was for the Air Ministry and M.A.P. to determine prevailed throughout the years of rearmament to the war. The responsibility was in the hands of certain sections of the Directorate of Operational Requirements at the Air Ministry, and above all in those of D.D.R.D.Q. (Deputy Director of Research and Development/Equipment Installation) at the M.A.P., and their intervention into design as a rule culminated in the 'mock-up conferences'. At these conferences the interested parties foregathered to consider the layout of equipment, control and crew accommodation on wooden models of the fuselage and of the other relevant parts of the aircraft. Decisions then taken were supposed to be more or less binding on the makers. The latter may on occasion have chafed at the delays, the compromises and various other encumbrances to free design inherent in the system. But whatever the attitude of the designer there is no doubt that the mock-up conferences had a great effect upon the final shape of the design itself.

Equally important, were other and more piecemeal interventions by M.A.P. in the later stages of design and development. The technical branches of M.A.P. closely and sometimes anxiously watched the construction of the prototypes and of the early production models and now and again sanctioned or even suggested minor changes in the original design and specification. Modifications were also apt to be introduced in order to accommodate new or alternative types of equipment or to allow for sudden changes in operational ideas. For some of these alterations the firms themselves were

[1] See pp. 35–36.

responsible, but many of them, and possibly most, were due to, and blamed on, the Air Ministry and M.A.P. Whatever their source, their cumulative effect was to influence the quality of the aircraft.[1]

In some ways even more fundamental, though much more informal, was the part played by the technical branches of the Air Ministry and the M.A.P. in the stages of design preceding the issue of the specification. On several important occasions the Air Ministry and the M.A.P. endeavoured to forecast and to guide the principal trends in aircraft design, and in this way to co-operate with the industry in determining the technical characteristics of future aircraft. It was the business of the Director of Technical Development's department in the Air Ministry and later in M.A.P. to watch the general movements of technical progress in this country and abroad, and from time to time to revise their notion of what a good military aircraft should be. On their part, the firms, in shaping their long-term plans, also tried to anticipate future changes in military demand. It is, therefore, not surprising to find that as a general rule the evolution of technical ideas in the ministries broadly synchronised with similar movements in the firms.

In so far as there was anything resembling a consistent policy of design, it invariably sprang from some such merger of ideas. How old and how firm that merger was will be clear from a survey of the basic technical ideas. It has already been shown how in 1934 and 1935 the need for a new race of monoplanes came to be felt more or less simultaneously in the Air Ministry and in the firms, and how both sides were stimulated by contemporary advances in aeronautical science and by what they had learned from journeys to the United States.[2]

A similar convergence of ideas marks the next important stage, i.e. the genesis of the big bomber. Throughout the early years of expansion, the Air Staff showed every predilection in favour of the heavy long-distance bombers. This attitude became crystallised by 1938 when the bombing of the enemy war machine came to be regarded not only as the chief offensive weapon available in this country, but also as the only effective defence against enemy air attack. This notion took a definite technical shape in the discussions between 1936 and 1938. The first articulate contribution to the discussion was made by the Air Staff themselves. The operational and technical branches of the Air Ministry had been re-examining the inter-relation between range, carrying capacity, cost of production and vulnerability to attack. Discussions had been going on throughout 1937, and the views of designers, especially those of Mr.

---

1 See also Ch. VII, Section (iv).
2 See Ch. II, Section (iii).

Frise of Bristol's and Mr. Wallis of Vickers, were taken. As a result of these discussions opinion crystallised around the idea of a bomber of 50,000 lbs., to begin with, and the possibility of still greater increases in the future.[1] At least one of the conceptions put forward during the discussions—that of Mr. Wallis—was based on the argument that for maximum effect, i.e. for the highest load carried over the longest distance at the lowest cost in human power, bombers had to be much larger than those under construction in 1936, and provided a theoretical justification for further increases in maximum limits to about 80,000 lbs. on the eve of the war, and 90,000 lbs. by spring 1941. This discussion was interrupted in the middle years of the war by the somewhat 'hand-to-mouth' procedure forced upon the Air Staff by circumstances, but was resumed in 1943, and culminated in a further statement of ideal bomber requirements suited to the technical requirements of the war with Japan and based on the accumulated experience of four years of heavy bombing.[2]

The heavy bomber policy in many ways overshadowed all other long-term decisions on technical trends. The only other pre-war decision of this kind which may deserve a separate mention was the specification for the fast cannon fighter in replacement of the Hurricane and the Spitfire. In so far as these projects were linked with the evolution of the cannon their story belongs to the history of air armament and will be told later.[3] What interests us here is the effect of the change on the design of airframes. At the turn of 1935 and 1936 the Air Ministry issued a specification for a twin-engined cannon fighter out of which the Westland Whirlwind was to emerge.[4] Great hopes were centred on the Whirlwind throughout 1938 and 1939, chiefly on account of its cannon armament. It was very largely in order to fill the gap which its failure might cause, and in

---

[1] This was taken as the limit of landing weight and therefore compatible with an all-up weight on taking off of as high as 65,000 to 70,000 lbs.

[2] The different stages in the evolution of the heavy bombers reflecting this growth of ideas were roughly as follows. In 1936 came the two specifications for the heavy bombers, P.13/36 and B.12/36, of which the latter contained a requirement for four engines. This was to a large extent derived from what the Air Ministry had learned from the Russian and American experience of four-engined aircraft, and from the ideas at that time current in the Air Ministries of Germany and France. From the Specification B.12/36 the Stirling grew out directly, and from the P.13/36 the four-engine Halifax somewhat more indirectly. The Halifax was originally a twin-engined design to Specification P.13/36. The next stage was represented by the 1939 specification for the super-heavy bomber (B.1/39). But although in May 1940 the construction of the prototype at Handley Page and Bristol's was stopped, the Air Ministry and the M.A.P. encouraged the firms to enlarge the existing heavy bombers, and especially the Lancaster. The emergence of the super-Lancaster (Lancaster IV) and Windsor in 1943, with a wing span of 120 ft. and an all-up weight fully up to the maximum laid down in 1938, was thus a logical fulfilment of the projects conceived in 1939. The next and the final stage came with the consideration at the turn of 1943 and 1944 of the 75,000 to 100,000 lbs. bombers for the war with Japan.

[3] See Ch. V, Section (iii).

[4] Specification F.37/35.

fact did cause, that other cannon projects were launched on the eve of the war.

One such project was the Bristol Beaufighter;[1] the other came to be linked with Mr. Sydney Camm's Typhoon. Quite early in 1937 he conceived the notion of a fighter not only faster than the Hurricane but also larger and more heavily armed. A preliminary design of an aircraft with a Sabre engine, foreshadowing in some respects the later Camm fighters, but as yet armed with twelve Brownings, began to take shape on the drawing-board. The design was ready for discussion with the Director of Technical Development in the summer of the same year. But when in July Mr. Sydney Camm officially submitted the drawings and the scheme to the Air Ministry, he was told that the Air Staff were themselves proposing to issue a requirement for a new type of fighter on the same lines and that further action on his design had better be postponed until then. In fact we learn from the minutes of the Air Council and from other evidence that, while Mr. Sydney Camm was preparing his preliminary drawings, the members of the Air Staff had made up their minds in favour of a cannon-firing fighter, to begin with a two-engined one. When, in the new year, the specification was issued it, in fact, embodied most of the features of Mr. Sydney Camm's design, but was, at the same time, calculated to meet the Air Staff demands for a cannon fighter.[2] Out of this specification came the Tornado-Typhoon-Tempest family of fighters.

The story of the cannon fighter concludes the pre-war phase of forward planning of design in the Air Ministry. In view of what has already been said it will not be surprising to find that in the subsequent two or three years, i.e. from the eve of the war to the end of 1942, His Majesty's Government's share in determining the major technical trends were somewhat smaller than in the preceding three years. For one thing there were very few long-term decisions to be taken. The opening of the war brought with it an overwhelming sense of urgency and made it difficult to consider technical problems of aircraft as part of long-term plans. Under the pressure of events the technical requirements of the Air Ministry and the M.A.P. were both piecemeal and opportunist. It was not until the climax of the air war with Germany was passed, i.e. at the turn of 1943 and 1944, that the technicians in high places were able to 'sit back' and to relate the strategical and tactical needs of the war with Japan to the major trends of aircraft design. In the intervening period major departures in design were generally speaking few and far between. We shall see further that, in so far as the quality of British aircraft

---

[1] Specification F.17/39.
[2] Specification F.18/37. Appendix B issued to firms 15th January 1938.

continued to rise, the rise was largely due to progressive improvements in existing types, and more especially to the development of the one or two basic engine designs. The only novelties of design which reflected new tactical ideas or new aeronautical principles were the fast unarmed bomber and the high-altitude aeroplane. Both were instigated by the industry, and for that reason alone they deserve a somewhat more detailed description.

The part which, at the outbreak of the war, de Havilland's played in putting forward the project of a fast unarmed bomber will be told later as part of the story of the Mosquito.[1] The same firm also played a part in preparing the arrival in 1941 and 1942 of the high-altitude aircraft. Generally speaking, the high-altitude flight became practicable with the development of the special 'booster' by Rolls-Royce and the emergence in 1942 of the high-altitude Merlins (Marks 61 and 73). But, long before that time, the advantage of high-altitude bombers and fighters was driven home by the German success in developing the high-flying injection engine. At de Havilland's the need was understood quite early. In the initial stages of the Mosquito design, i.e. at the very beginning of the war, de Havilland's showed the desire to instal pressure cabins, and by the end of 1940 they succeeded in evolving the high-altitude type by extending the wing span by about nine feet. So, when the Germans started to come over very high, and the M.A.P. became anxious to obtain some high-flying machines, de Havilland's were able to reveal that such a machine was almost ready. In fact six pressurised Mosquitos were delivered within three months of the Air Ministry's requirements—a record time. And eventually a substantial number of pressure cabin aircraft were delivered by de Havilland's.[2]

Somewhat less successful were the high-altitude bombers from the Vickers' stable, but there too the initiative largely lay with the firm. Its designers were converted to high-altitude flight some time before the war. Sometime in 1939 Mr. Pierson, in a personal interview with the Air Member for Development and Production (Sir Wilfrid Freeman), persuaded him to give the high-altitude bomber a chance. Although the Air Ministry at the time did not see the necessity for day bombing at high altitudes, it was Sir Wilfrid Freeman's policy to encourage speculative designs, and eventually two marks of the Wellington (V and VI) were given over to high-altitude versions. If neither proved very useful in practice it was not because the underlying technical idea was at fault, but chiefly because suitable engines took a long time to perfect, and because the Wellington airframe itself had become relatively obsolescent.

---

[1] See pp. 84–86.

[2] Mosquito Mks. PR.XVI and B.XVI.

More abortive still, were the projects for two specially designed high-altitude heavy bombers for which Vickers were also responsible. The first, directly derived from the Wellington pressure cabin, was the design for a pressurised development of the Warwick in late 1940. It met with some support from M.A.P. and in January of 1941 Lord Beaverbrook instructed the firm to press on with their high-altitude bombers, especially with the Warwick. In July 1941 the firm received an order for two prototypes, each with 4 Merlin 60 engines, and a draft specification (B.5/41) was prepared around the Vickers' design. Design and model experiments continued until, as has already been shown, at the end of 1942 the needs of the bomber programmes compelled M.A.P. to concentrate on fewer types of heavy bombers.[1] Much of the design was 'lifted' into the new B.3/42 design (Windsor), but the pressure cabin work was abandoned. The second Vickers' project was for a fifty ton six-engined bomber, derived from their 1937 plans for a super-heavy civil aircraft operating at normal altitudes. The war-time version began to crystallise in Mr. Wallis's mind in July 1940, and the pressure cabin was to be very similar to the Warwick development. The bomber's real purpose, however, was to carry one huge bomb of 20,000 lbs., also to Mr. Wallis's design. It never received more than bare tolerance from M.A.P. chiefly because of the Air Staff's negative attitude towards 'single purpose' aircraft. It was finally abandoned in September 1941.

In the evolution of the high-altitude fighter the industry and the government departments co-operated, if anything, more closely than they had in the development of the pressurised bomber. In so far as the high-flying performance could be achieved by installing the high-altitude Merlin in the Spitfire, the story was one of gradual evolution in which Supermarine's and Rolls-Royce took a leading part. But the specialised high-altitude fighter was in many ways a characteristic example of combined initiative. Throughout the war and even earlier certain private designers tried to persuade the Air Ministry and the M.A.P. to adopt the principle. As a result of war-time experience, M.A.P., acting in agreement with the Air Staff, issued the specification for the design of an experimental pressure cabin fighter, chiefly in order to acquire the necessary experience in the design and operation of pressure cabins.[2] It was at this point that the official initiative crossed the path of similar projects which Mr. Petter of Westland's had been nursing for some time. The Welkin designed by Westland's to that specification was the result. The official part of this project did not, however, cease with the

---

1 See p. 22.

2 Specification F.4/40. Invitation to tender was issued on 20th July 1940; Minister's approval for prototype order 29th November 1940.

issue of the order to the firm for two prototypes, for the R.A.E. was to advise Westland's on the design and to co-operate in the development of the cabin, with its host of novel problems.

(vi)
Private Ventures: General

In view of these facts the historical relation between the 'specification type' and the 'private venture' would appear to be more complicated than the mere etymology of the terms would suggest. The superficial distinction between the two procedures is very simple and has been well summarised by Sir Hugh Dowding:

> The basis of the system was the Air Ministry's specification which said in effect 'this is what we want' but it was always open to a firm to say 'we know what you want better than you do yourselves. We are going to enter this competition with our own experts and when you see our product you will agree that we are right and you will have to give us a production order.' If they fail in their attempt they have lost their money.[1]

Thus defined, private ventures stood for something completely independent of the official inspiration and were a clear alternative to design to official order. Private ventures of this kind played an important, though a well circumscribed, part in the development of British aircraft. In Sir Hugh Dowding's opinion they gave the Air Staff an enlarged field of selection without any cost to the public and also 'kept the Air Staff on its toes' in the matter of requirements which they laid down for specification.[2] We shall also see that one or two of the most successful types ever produced by British industry were, in fact, private ventures in this sense of the term. But as long as the term is used in this simplest and clearest of all its possible senses, it does not apply to many of the designs thus described and does not justify the view that the majority of British aircraft, and all the successful ones, were private ventures. This is in fact the view which has been most clearly expressed by Lord Beaverbrook. In a speech quoted above he presented all the successes in aircraft design as private ventures:

> The work of the firm is almost invariably a private venture; the design is a private venture, put forward by private enterprise, by private capital. The individual responsibility for the design of the aircraft and for the development of it prevails completely, not

[1] *Evening Standard*, 8th April 1943, p. 6.
[2] Ibid.

> only in the Spitfire, which was designed by Mitchell and produced by Vickers-Supermarine, but in the Hurricane, designed by Camm and produced by Hawker. . . . The same argument applies to the Lancaster and the Mosquito.[1]

Claims that their designs were private ventures were also advanced by designers of a large number of aircraft and the general notion that most aircraft were private ventures was repeatedly voiced by the official spokesmen of the industry.

All these views had undoubtedly a grain of truth in them. We have seen how frequently the designers acted independently of specifications, i.e. forestalled them or deviated from their requirements.[2] If all the designs embodying independent contributions of industrial designers were to be considered as private ventures, then undoubtedly the bulk of British aircraft would be covered by the term. But used in this sense the term does not denote a true alternative to officially sponsored design. In this sense of the term it is possible for the aircraft to be a private venture and an official design at one and the same time.

(vii)
Private Ventures: Mosquito

To make the true relation between the two procedures clear, it will be necessary to survey the better-known cases of the so-called private ventures. The purest case of a 'private venture', coming nearest to Sir Hugh Dowding's definition, would be an aeroplane conceived independently of the Air Staff's requirements of the moment. The independence from the Air Staff does not of course signify complete departure from, or indifference to, Service opinion. What happened in the few cases of 'pure' private venture was that a firm in close consultation, very often informal, with individuals in the Service or in the M.A.P. produced a sketch design and worked out the performance of an aeroplane, which they believed to be a real requirement even if the Air Staff might be blind to the fact.

Since the beginning of the rearmament one aircraft, and perhaps one only, was conceived in this way. And this needless to say was the Mosquito. The reason why the makers of the Mosquito—de Havilland's—were ready to design an aircraft so completely free from official inspiration will be found in the peculiar position which they

---

1 H. of L. Deb., Vol. 125, Col. 804, 27th January 1943. See also D. Farrer op. cit.
2 See above Section (iv).

occupied in the aircraft industry. In spite of the fact that they were officially included in the list of 'family firms' and frequently received from the Air Ministry invitations to tender, they, in fact, took very little part in the design and production of military aircraft. They preferred to specialise in the manufacture of civil aeroplanes, and their great successes immediately before the war were in the design of the record-breaking Comet in 1936 and of the passenger and mail aircraft—the Albatross—in 1938 and 1939. But their aloofness from the Air Ministry was due not only to their preference for civil aircraft, but also to their distrust of design to government specification. In Sir Geoffrey de Havilland's view official requirements suffered from the pressures of various specialist interests represented in the Air Ministry and in the Air Force—the tacticians, the armament specialists and the equipment experts. For this and other reasons official specifications invariably represented a compromise inimical to the design of 'clean' advanced types.

When, therefore, the firm found itself at the beginning of the war short of orders and anxious to contribute to the war effort they proceeded to design an aeroplane without any official prompting from the Air Ministry. They had to think out for themselves the whole tactical and strategic purpose of the aircraft, and thus made a number of strategic and tactical assumptions which were not those of the Air Staff. While the Air Ministry was still wholly devoted to the doctrine of night bombing by heavy bombers, Sir Geoffrey de Havilland conceived the idea of day bombing by fast unarmed aircraft. He calculated that if design and production were allowed to proceed quickly he would be in a position to produce a bomber fast enough to outpace the then-known German fighters. This would enable it to fly unarmed and thus to keep its speed and performance unspoilt by turrets and by other excrescences.

In the circumstances of 1939–40 this was an entirely new and independent set of ideas. Even though it was conceived in consultation with persons in the Air Force and in the Air Ministry, the official attitude of the Ministry and of the Air Staff was bound to be one of opposition. The opposition was further reinforced by the scepticism of the Ministry's technical branches. The previous experience of the Director of Technical Development's department in evaluating the promises of private designers taught them to scale down promises of performance by 10, 15 or even 20 per cent.[1] If Sir Geoffrey de Havilland's estimates were thus to be scaled down, the whole case for a Mosquito as a fast day bomber was bound to

[1] When the firm first sent in the unarmed bomber scheme, the preliminary estimates of the Director of Technical Development's department differed considerably from those sent in by the firm. A.D./R.D.T. (Capt. Liptrot) said on this occasion—'we do not accept designer's usually optimistic claims without independent check'.

suffer.[1] It was, therefore, fortunate that almost from the very outset of the negotiations with the Air Ministry, the Air Member for Development and Production, Sir Wilfrid Freeman, was able to back the de Havilland proposal. He regarded it as a gamble, but thought that the risks were worth taking; and in December 1939 the first order for the Mosquito was placed. In this way a very remarkable aircraft was brought into existence.

Yet even then the de Havilland ideas were not for the time being accepted in full. The first order was agreed on the understanding that the aircraft would be used for photographic reconnaissance. In the early summer de Havilland's put forward a suggestion for a long-range fighter role—they had always envisaged such a fast aeroplane being useful for other purposes—and in July 1940 the Air Ministry accepted this alternative. Its use for the purpose for which it was originally designed, i.e. as a fast bomber, came last of all. It was not until the 28th July 1941, i.e. nineteen months after the first order, that the idea of the unarmed bomber was finally assimilated, and de Havilland's were instructed to go ahead with the unarmed bomber version. The actual proportion of bombers to other Mosquito types was not settled till the middle of August; and to the very last, the bulk of the Mosquito output continued to be devoted to purposes other than bombing.[2]

(viii)

Private Ventures: Spitfire and Hurricane

Most of the other ventures which went into production between 1935 and 1944 were private only in part. The amount of official guidance or assistance varied from design to design, and so did also the degree to which firms acted independently of government specifications. But in every instance some action unrelated to specification and a certain amount of government initiative was to be found. It should, in fact, be possible to place most of the so-called

---

[1] The two Mosquito designs, unarmed and with a tail turret, were discussed at a meeting at the Air Ministry attended by the Air Member for Development and Production and representatives of the firm on 22nd November 1939, and it was agreed that the turret and consequent loss of speed would defeat the firm's object. It was again discussed at a meeting on 12th December 1939 attended by the Assistant Chief of the Air Staff, the Air Member for Development and Production, the Director General of Research and Development and the Air Officer Commanding-in-Chief, Bomber Command. Bomber Command's requirements for a high-speed *defended* bomber were agreed to be a bad compromise, but the C.-in-C. maintained he had no operational use for an unarmed bomber except for photographic reconnaissance work.

[2] See p. 402.

'private' ventures on a scale ranging from aircraft almost as independent in conception as the Mosquito to aircraft designed very largely in response to specifications and in accordance with them.

The earliest and the most spectacular of the all-but-complete 'private' ventures were the Spitfire and the Hurricane. The history of the Spitfire has been publicised so often and so well that its main episodes are now known to every schoolboy. But it is doubtful whether the popular version pays sufficient attention to the less personal and less romantic stages of the story. As is now commonly accepted, the technical genesis of the Spitfire must be sought in the flying boats which were designed by Supermarine's in the 'twenties for the Schneider Trophy. The experience of these racing models not only enabled Rolls-Royce to develop the main principles of a compact liquid-cooled engine layout, but also taught Mr. Mitchell, of Supermarine, innumerable lessons of fast monoplane design.

Early in the 'thirties Mr. Mitchell began to apply the lessons thus learned to the design of fast military landplanes. To begin with, his experimental projects were far removed from the design which eventually became known as the Spitfire. For not only had his own ideas to grow still further, but it was also necessary for Rolls-Royce to evolve a suitable engine and for the Air Staff to graft on to the original Supermarine design their own tactical and technical requirements—above all, the installation of eight guns.

From Mr. Mitchell's point of view the trend of official requirements was most propitious. In 1930 the Air Ministry began to consider a replacement for the fighter squadrons equipped with the antique Bristol Bulldogs, and their Specification F.7/30 was accordingly issued. Supermarine's submitted a design and were, on the 2nd August 1932, given a contract for a prototype. By the beginning of 1934, Mr. Mitchell had completed an all-metal cantilever monoplane with a Rolls-Royce Goshawk II engine capable of a maximum speed of 238 miles per hour. But almost immediately he began to discuss with the Air Ministry a number of drastic changes in the design to increase its all-round performance, and thus to prepare the ground for what was to prove a brand new design.

Several things had happened since 1930 to make a new design necessary. In the first place his own ideas had greatly developed and now embraced a retractable undercarriage as well as a more adventurous wing-shape and improved cooling system. In the second place Rolls-Royce had at last evolved their P.V.12, which was the first version of the Merlin. Finally the appetites in the Air Ministry had grown far above the modest ambitions of the F.7/30. Its technical branches became greatly concerned with the superiority of the fighters which were being developed abroad and were anxious not to perpetuate this British inferiority in the process of rearmament. An exchange of minutes in the middle of July 1934 between the Director of Technical Development (Air Commodore Cave) and the Deputy Director of Technical Development (Major Buchanan) showed that opinion in the Air Ministry had rapidly moved towards a much more ambitious type of aircraft.[1]

It is, therefore, not surprising to find the Air Ministry falling in with Mr. Mitchell's proposals for redesigning his aircraft and with similar proposals of Mr. Camm's of Hawker's. A contract for what was at first to be regarded as an improved version of the F.7/30 was placed on the 1st December 1934, and after a month or two of discussions and modifications the new prototype was legalised by the issue of a special specification for an experimental aircraft (F.37/34) on the 15th January 1935.

The experimental aircraft which Mr. Mitchell had evolved was in most respects identical with the final design for the Spitfire. The only major development still to come was the improvement of the armament. The demand for eight guns was very strongly pressed by Squadron Leader Sorley of the Operational Requirements Branch of the Air Staff[2] and was accepted by Mr. Mitchell on 29th April 1935. With this final addition, the design was sufficiently near to the Air Ministry's ideal for the Director of Technical Development (Air Commodore Verney), his deputy (Major J. S. Buchanan) and Squadron Leader Sorley to force through the Air Staff the decision to accept Mr. Mitchell's experimental aircraft in satisfaction of the demand expressed in the latest specifications, i.e. F.5/34 and F.10/35. Squadron Leader Sorley went as far as to demand the placing of orders without waiting for prototypes or trials.

The Hurricane was conceived in similar circumstances. Its genesis, like that of the Spitfire, can be traced to the Bulldog replacement and the Specification F.7/30. Hawker's were asked to tender, and Mr. Camm submitted alternative designs of a biplane and a monoplane fighter. Neither was accepted. Even the monoplane was slower than the competing designs and was too orthodox even for the Air Ministry. But, undeterred by the rebuff, Mr. Camm proceeded to design a fighter as a private venture. His hopes of success largely hinged upon the prospects of replacing the Goshawk engine by the Rolls-Royce P.V.12. When in July 1934 the whole British fighter design and the relative superiority of foreign fighters came under review in the Air Ministry, the Deputy Director of Technical

---

[1] This opinion had already found some expression in the Specification F.5/34 for the Fury replacement, which was issued in the late summer of 1934 and another Specification F.10/35 which was never actually put out to tender although its requirements were well-known to the industry.

[2] See Appendix VI.

Development was able to report that the preliminary designs of the Hawker private venture had been completed and that Hawker's were on the point of embarking upon the construction of the prototypes. In the summer of 1935 Mr. Camm's aircraft was sufficiently advanced, and sufficiently promising, to be considered for the Specification F.10/35 as an up-to-date replacement of the Fury.

The Director of Operational Requirements (Squadron Leader Sorley) adopted towards it the same attitude as to the Spitfire. In his view the aircraft embodied most features of the new official specification and needed only a few major modifications, chiefly the installation of more guns, to meet the official requirements in full. Even though it was in a more advanced stage of construction than the Spitfire, the Director of Operational Requirements thought that it could still take modifications.[1] His advice was followed and on 7th February 1936 the Hurricane prototype was flown to Martlesham.

The subsequent history of both types reflects not only the same independence on the part of the firms but also the same eagerness to meet, and even to anticipate, the trend of technical opinion in the Air Ministry. The independence was perhaps more clearly marked in the later history of the Spitfire than it was in that of the Hurricane. The successive marks of the Spitfire: Marks II and V with the more powerful versions of the Merlin (XII and 45) and the latter with better armament; Marks VII and VIII with the much improved high-altitude engines (Merlin 63 and 70); Marks XII and F.21 with the Griffon engine, and the still later versions with much modified wings: each represented an important stage in the improvement on the basic design. As a result of these transformations the Spitfire was able to add between 1938 and 1944 nearly 100 miles to its top speed, to improve its armament and other fighting qualities, and thus to maintain its lead over all other fighters and to answer the Air Staff requirements for specialised high-altitude and low-altitude performance.

As the mere list of the 'marks' suggests, the main factor in the Spitfire's progress was the continuous improvement of the Rolls-Royce engine, for it was only with the changeover to the Merlin 45 and 61 families that spectacular increases in speed were made possible, and it was with the changes from the earlier middle-altitude Merlin to the Merlin 63 and 70 with ceilings of over 40,000 ft. that the Spitfire could be converted into a high-altitude fighter. Yet the mere appearance of suitable engines would not have produced the necessary results had not Mr. Mitchell's successors at Supermarine's (Mr. Smith and Mr. Clifton) redesigned the airframe to take the new engines. There were, broadly speaking, four such

[1] The prototype was too far advanced to modify the wings to take 8 guns, so an alternative pair were made and delivered in June 1936.

major redesigns. If the original Mitchell's airframe were to be numbered 1, there was an airframe number 2 designed in 1939 to take the Merlin XX, the airframe 3 to take the Merlin 61 family and the airframe 4 to take the Griffon. Each of these major redesigns was carried out in anticipation of the coming engines and well in advance of the official decision to instal them. The whole process was thus one of close co-operation between the airframe manufacturers and engine makers and of a development proceeding in response to purely technical necessity and almost independently of the trend of the official specifications.

Almost independently, but not wholly so. In the later history of the Spitfire, as in its earlier stages, there were episodes and whole phases in which Government intervention played an important part. In addition to modifications designated by 'Marks' there were other modifications, otherwise distinguished, which contributed to the progress of the Spitfire but which were due at least as much to official inspiration as to private initiative. Improvements in armaments were one of them, the adaptation for fighter-bomber use was another. Even in matters of speed, altitude, manoeuvrability, etc., important changes were at times introduced at the direct request of the R.A.F. and the M.A.P. One of the latest examples of this was in 1943 when the Rolls-Royce engine was modified at Middle East Command's request and the wings clipped at Fighter Command's request to produce a low-flying version. In many other cases where modifications were not made in response to direct requirements of this kind, a potential R.A.F. requirement was always implied. For however independently the modifications were developed, they were independent of official requirements formally presented, but not of the currents of informed opinion in the R.A.F. and M.A.P. They were more in the nature of intelligent anticipation of the official point of view than of radical departures from it.[1]

The later stages of development of the Hurricane conformed, if anything, more closely to the trend of official opinion. To begin with, from an aerodynamic and structural point of view the Hurricane was more conservative than the Spitfire in the sense of being less capable of progressive development as a fighter. In fact since 1938 or 1939 such hopes as Mr. Camm and Hawker's may have had of developing a high performance fighter centred on the Tornado/Typhoon, and the Hurricane was, so to speak, given over to other uses. In the autumn of 1940, its speed was raised and altitude lifted by the installation of the Merlin XX, and in 1943 a specialised low-flying version was evolved by the installation of the Merlin 27. But apart from these two modifications most of the changes were

[1] For a detailed study of the later Spitfire developments see below Ch. VIII.

concerned with the armament or with various specialised functions. The Hurricane was the first fighter to carry four 20 mm. cannon in the wings; the first to be turned into a 'tank buster' by the installation of 40 mm. cannon; the first to be fitted with Rocket Projectiles and the first aircraft to be adopted for catapult launching at sea; as well as the first British fighter to be used as a fighter-bomber. With the exception of the last, each of these modifications required major redesign, but in each instance the redesign was undertaken at the special request, and sometimes even under direct pressure, of the M.A.P.

(ix)

Private Ventures: Blenheim, Lancaster and others

So much for the Hurricane and Spitfire. Another instance of an early private venture, invariably described as such in documents both private and official, was the Bristol Blenheim bomber. Its origin, however, is markedly different from that of the two fighters. It was deeply rooted in private enterprise and yet owed more to official guidance than the two fighters. The Blenheim design was improvised at short notice in 1935 by adapting for bomber use an existing civil type. The civil type itself (the Bristol 142) was made available to H.M. Government by Lord Rothermere's generosity and competitive zeal. In friendly rivalry with Lord Beaverbrook, who was the proud owner of an American Douglas aircraft, Lord Rothermere ordered from the Bristol Aircraft Company a specially designed twin-engined monoplane of all-metal construction capable of more than 200 m.p.h. On its completion the aircraft, suitably christened 'Britain First', was presented to the R.A.F., and the present turned out to be very timely. At that particular moment the R.A.F. found themselves short of light, or as they then ranked, medium bombers of modern design to replace the obsolete Hart. The danger of war was becoming real, and there was little time for producing the necessary number of bombers out of a brand new design. The Air Ministry therefore eagerly adopted the Bristol proposal to convert the 'Britain First' into a light bomber, and in March 1937 placed an order for 250 of Bristol's private venture to be officially known as the Blenheim.

Thus far, viewed superficially, the history of the Blenheim was one of private venture pure and simple, but the venture loses some of its privacy if looked at more closely. In the first place, the civil aircraft from which the Blenheim was developed owed not a little to earlier official assistance. 'Britain First' was not in fact the first of its breed in

Bristol's stables. The first of the new race was the Bombay bomber transport of a relatively advanced design evolved to an Air Ministry specification in 1931. In developing that aircraft the Company had to draw on official assistance. Up to that time they had concentrated mostly on small types and were now in need of greater official guidance than usual in order to meet the requirements for a larger troop-carrying aircraft. On the structural side the design of the Bombay owed a great deal to the information which the firm obtained from an earlier experimental contract placed by the Air Ministry for the design, construction and test of a multi-spar wing. The Bombay gave the Bristol engineers further experience in the design of stressed skin structures and of monocoque bodies.

In the second place, the conversion of the 'Britain First' into a bomber also required and received a great deal of guidance from the Air Ministry. Writing on the 9th September 1937 the Resident Technical Officer put it on record that the Company had to be given considerable technical assistance in the design. They had very little to learn in the construction of purely civil aeroplanes such as the original type 142, but, he went on to say, 'to convert this aeroplane to a medium bomber was an entirely different proposition'. The Resident Technical Officer may have been an interested witness, but he could claim in support of his views 'the fact that the really complete Blenheim aeroplane has not yet been delivered to the Service, two years after the placing of the contract'.

It will be unnecessary to survey the later developments of the Blenheim for they do not present any new or novel features. Most of the later marks were designed to meet official requests. In fact so close was the co-operation that towards the end of 1943 the representatives of the Company were inclined to blame official influence for the shortcomings of the later marks, especially of the Mark V.

Equally prominent and equally justified are the claims advanced on behalf of A. V. Roe's Lancaster. The story of the Lancaster is something of a reversal of that of the Blenheim. If the Blenheim was an officially sponsored modification of a privately designed aircraft, the Lancaster was a privately sponsored modification of an officially instigated design. The latter was the Manchester which, together with the Halifax, was designed in 1937 to the official specification for the heavy bomber P.13/36. The original version, as summarised in the specification and embodied in A. V. Roe's and Handley Page's designs, differed from the other variant of the heavy bomber, the B.12/36, chiefly in that only two engines were specified, and the all-up weight was consequently made somewhat smaller, 45,000 lbs. instead of 55,000 lbs. Circumstances, however, combined against the 'small big bomber'. The two-engined Halifax never took the air. Even before the design was completed, its engine, the Rolls-Royce

Vulture, gave trouble in development, and the Air Ministry was compelled to revise its specification and to instruct Handley Page, very much against their wishes, to redesign it as a four-engined aircraft taking four Rolls-Royce Merlin units.[1]

The Avro Manchester however had a somewhat different career. It was allowed to proceed through the prototype trials to the early production stages. But long before quantity production commenced, its impending failure became clear to everybody in the Ministry and at A. V. Roe's. It was to be engined by the Vulture, and it was also overweighted for its engine power, even though the original conception included provision for assisted take-off. So when the Vulture was removed from the Rolls-Royce programme, the whole future of the Manchester also came into question. The apparent intention at the newly-formed M.A.P. was to cancel the project altogether. This, however, did not take into account the dynamic resourcefulness of A. V. Roe's Managing Director, Mr. Dobson, or the skill of their chief designer, Mr. Chadwick. They were determined to subject the Manchester to the same operation which had been performed on the Halifax and to redesign it as a four-engined aircraft.

It would be idle to pretend that the project met with any enthusiasm in M.A.P. The Manchester was thought to be incapable of further development, and Mr. Dobson's and Mr. Chadwick's optimistic promises were thought to be ill-founded. Above all, the redesigned Halifax showed such promise and was so ably advertised by its makers that another similar aircraft appeared unnecessary. In an official interview with Mr. Dobson, the official who, under Lord Beaverbrook, took charge of new projects, went so far as to refuse Avro's the raw materials necessary for the construction of the first prototype. According to Mr. Dobson's recollection, the official's reply to a request for materials was to 'go and dig for it'. And dig they did. Out of the crevices and interstices of the, as yet imperfect, distributive system for light alloys they scraped up enough material to build a prototype. At the same time the inside views of the Ministry were neither so final nor so unanimous as the official's attitude implied. In the exchange of minutes within the Ministry the official took up a more lenient and hopeful attitude. So, when in the beginning of 1941 the prototype of the modified Manchester (or Lancaster, as it came to be known) was beginning to show real promise, there was enough support in the Air Ministry to permit a sizeable order.[2]

---

[1] See p. 21.

[2] A direct order was given by the Director General of Production on 15th November 1940. The contract for 450 machines was formally placed on 6th June 1941.

In this way, almost by accident, the most successful British heavy bomber and the mainstay of the subsequent British aircraft programme was born. But for Mr. Dobson's and Mr. Chadwick's ingenuity, perseverance and initiative, it would never have seen the light of day. Yet remarkable as was their initiative, it was not altogether unrelated to what the government departments had themselves been trying to do. As we have already said, the plan of transforming the twin-engine version into a four-engine one was suggested by what the Air Ministry and the M.A.P. succeeded in carrying out in the case of the Halifax. Thus Mr. Dobson's and Mr. Chadwick's great service consisted not only in working out a highly practical and economical design, but in forcing upon an unwilling His Majesty's Department what originally was that Department's own idea.[1]

The Mosquito, the Battle of Britain fighters, the Blenheim and the Lancaster, all these have been treated here merely as examples demonstrating the relation between private initiative and public enterprise in questions of design. Many other examples could easily have been found. In the field of fighters the birth of the Tempest in 1943 took place in circumstances which the earlier examples of fighter development have made familiar, i.e. on the initiative of the designer acting within the framework of the changing views in the R.A.F. and the M.A.P. In the later history of the Bristol types it would be possible to find several instances of private ventures in the broader sense of the term. Thus the Beaufort was essentially a marriage of two specifications, one for a bomber reconnaissance and the other for a torpedo-carrying aircraft; and the evidence makes it obvious that the union was conceived by Mr. Frise some time in 1936 and 'sold' by him to the Air Ministry. The Beaufighter was an outgrowth of the Beaufort redesigned as a cannon fighter, and the adaptation was also a product of Mr. Frise's ingenuity acting in response to the Air Ministry's anxiety in 1938 to procure a cannon fighter. In the field of medium and heavy bombers, it would be possible to single out the case of the Albemarle which was conceived by Mr. Lloyd of Armstrong-Whitworth in 1938 to meet the Air Ministry's need for a bomber independent of the supplies of light alloys, or the transformation of the Lancaster into the York transport plane devised by Mr. Chadwick to fill an obvious gap in the British aircraft programme and to satisfy what was at that time a well-known demand of M.A.P. In short, the list of all the aircraft classifiable as private ventures, would add little to the story of co-operation between the technical branches of the Air Ministry and M.A.P. on the one side and private designers on the other.

---

[1] See pp. 166–167.

In fact the story of co-operation would have come out equally clearly if, instead of analysing the history of the so-called private ventures, we had concentrated upon the history of the so-called specification types. As we have already said there were a number of aircraft, some of them quite successful ones, which have never been claimed as private ventures and which, in the common view, represented orthodox designs to official specifications. Such were the Whitley bomber, the Halifax, the Manchester and the Stirling, possibly the Whirlwind and the Tornado/Typhoon fighters, most of the naval types, and most of the bomber designs considered for the war with Japan at the end of 1943 and in 1944. Yet 'official' as all these designs were, it would be difficult to find among them a single aircraft, especially a successful one, which did not contain an element of private venture. As we have already repeatedly suggested, it became an almost accepted part of an established routine for designers to overstep, to anticipate or to supplement, official specifications by ideas of their own. So, even had this story of the relation of private ventures to official specification been told from the angle of 'official ventures', its main outline would have remained substantially the same. It would have shown how private ventures and official initiative, broadly defined, combined to produce individual aircraft designs. It would have also shown that private ventures and official participation in design were very seldom true alternatives.

CHAPTER V

CO-OPERATION OF GOVERNMENT AND INDUSTRY: ENGINES AND GUNS

(i)

General

WHAT has so far been said about the co-operation of Government and industry applies not only to airframes but also to the infinite variety of decisions affecting major components and equipment. The evolution of the components, even of the principal ones, cannot be discussed here in full detail; all that we can do is to cite two items—engines and armament. They have been selected as examples not only because they were of crucial importance in aircraft design, but also on account of their value as illustration. The history of engines shows the action of private enterprise least inhibited and least assisted by government participation. On the other hand in the history of airborne weapons State action and private enterprise combined in a great variety of ways. Some armament was due largely to private enterprise, other largely to official initiative and guidance; and a little of both can be found in every case. In fact it is possible to discover in the evolution of air armament the entire gamut of relations between State and industry.

(ii)

Engines[1]

The four 'family' firms designing engines—Rolls-Royce, Bristol, Napier and Armstrong Siddeley—received in the period between the wars as much protection as the airframe contractors. In fact one of the most notable manifestations of the Air Ministry's guardianship in the period between the two wars was provoked by an engine project and was made in defence of engine firms. Mr. Fairey, who was a maker and designer of R.A.F. aircraft, attempted during 1925

[1] The section on engines is based on a study of the design and development of engines prepared by Mr. D. A. Parry.

and 1926 to obtain the Air Ministry's backing for his attempts to enter into aero-engine design. He proposed to buy an American engine (V.1400 Curtiss) and to bring it to this country for further development and manufacture. But from the very beginning he met a determined opposition from the Air Member for Supply and Research (Sir Geoffrey Salmond) and from the Secretary of State himself. In the Air Ministry's view they were already having the greatest difficulty in keeping alive the existing engine designers by farming out minute orders and could not expose the struggling engine firms to yet further competition.

On the other hand, the Air Ministry and M.A.P. did not exercise the same tutelage over the design departments of engine firms as they did over the design departments of airframe firms. For reasons which will be presently described the engine firms, and especially Rolls-Royce and Bristol's, tried (and on the whole were able) to run their own design departments without government assistance. It was only later in the war that the M.A.P. began to assert itself in the management of the less efficient engine makers. In 1942 M.A.P. forced through a drastic reform of Napier's engine firm, and helped to transfer its ownership to the English Electric, primarily in order to improve and enlarge the facilities for design and development of the Sabre. In the same period M.A.P. tried to sponsor some co-operation between the development branches of Rolls-Royce and Bristol's. We shall also see that the advent of jet-propulsion brought new and wide responsibilities to H.M. Government and compelled it to take the initiative in re-organising the existing development organisation.[1]

Apart from these instances, the management of design and the initiative in sponsoring design projects was, until the closing stages of the war, almost exclusively in the hands of the engine firms themselves. The best instances of private ventures totally independent of official inspiration were in fact to be found in the field of aircraft engines.

In the field of design the two principal engine firms, and especially Rolls-Royce, were completely autonomous. The reasons for this must be sought in the history of the industry. A brief summary of this history is therefore essential for the proper understanding of the position which the engine firms occupied between 1935 and the end of the war. In 1914, whereas both Germany and France had vigorously tackled the problem of designing aero-engines, British attempts had been sporadic and half-hearted. The country's organisation for design and development consisted of two main elements, commercial firms and the Royal Aircraft Factory. Neither of these

[1] See Ch. IX.

had any extensive experience of aero-engines, and Britain was almost entirely reliant on engines of foreign design. Steps were taken to remedy this situation in two ways: work in the Royal Aircraft Factory was intensified and the motor car industry was brought in. As the war drew to its end, the pioneer firms of the industry, Sunbeam, Austro-Daimler, Napier's, Rolls-Royce, Siddeley Deasy, Lanchester and Wolseley, as well as the Royal Aircraft Factory, could lay claims to considerable advance in this field.[1] The end of the war found Britain with a virile development organisation which had achieved a world-wide reputation.

Elsewhere in this volume the story is told of the way in which the prestige and importance of the Royal Aircraft Factory—called by this time the Royal Aircraft Establishment—declined in the years after the First World War.[2] It was not until 1926 that the headquarters organisation for guiding engine development rose to the dignity of an assistant directorate, and it was the settled policy of this organisation to rely wholly on the ability, initiative, and independence of the firms. The R.A.E. maintained its position of a specialist adviser and as an authority capable of checking the estimates of optimistic designers, but it was not encouraged to take any hand in shaping the policy of engine development. On their part the firms had learned to rely upon their own research facilities for most of their basic investigations. Although guided and almost completely subsidised by the Air Ministry, they continued to bear the ultimate responsibility for decisions, and thus gradually established their complete ascendancy in the design of engines.

Who were these firms, and how did they come to undertake aero-engine work? By the end of the First World War, as we have seen, the main part of the motor car industry had been brought into the field. After 1920, however, there followed the inevitable retrenchment, and with one or two exceptions the firms returned to their normal peace-time work. The exceptions were Napier's, Rolls-Royce and Armstrong Siddeley. Napier's alone deserted the motor car industry altogether in favour of aero-engine work; their decision doubtless being influenced by the fact that by 1920 their famous Lion engine had already established an enviable reputation in the forefront of the liquid-cooled designs.

As it turned out, the Lion marked the highest point of Napier's achievements. For a time indeed the firm rested on its laurels and allowed the development side of its organisation to lapse. Mr. Rowledge, the designer, left for Rolls-Royce, and only three engines of any note were designed up to 1945, all being the work of Major

---

[1] See H. A. Jones, *The War in the Air*, Vol. III (Oxford, 1931), Ch. IV, and Vol. VI (1937), Ch. II. Also *History of the Ministry of Munitions*, Vol. XII (H.M.S.O. 1920), Pt. I.

[2] See pp. 437–438 and 445–446.

Halford, Napier's technical director, whose part-time services they acquired in 1927. Of these three engines, the Rapier was too small for Service use, the Dagger was not highly successful,[1] while the last, and the most promising of all, the Sabre, provided one of the Second World War's most melancholy stories.

The case of Armstrong Siddeley was in many respects similar. Dividing their time between motor cars and aero-engines, they succeeded in producing in the early 1920's a number of very successful radial engines of which the best known was the Jaguar. But apart from this, the firm did very little in the way of design in subsequent years. During the expansion period, they had under development the air-cooled, 3 row 21 cylinder Deerhound and later a 4 row engine, the Wolfhound. The project was nearly abandoned in the critical days of 1940, and the firm's progress continued to be so slow that in October 1941 the M.A.P. asked them to part company with reciprocating engines and undertake work on jet projects.

Napier's and Armstrong Siddeley had thus become largely ineffective. Fortunately Rolls-Royce and Bristol's—the latter hitherto a firm new to aero-engine work—succeeded in pulling the chestnuts out of the fire. Rolls-Royce never made the mistake of pinning their faith on current types and neglecting their 'forward' design and development work. After the First World War they kept their aero-engine department very much alive and, during the interwar years, succeeded in designing a large number of engines of continually improved performance. It was owing to this assiduous nursing of design and development that they were able to meet so adequately the many demands on them during the course of rearmament and war.

The Bristol Aeroplane Company, with no previous experience of aero-engine design, took in 1920 the bold step of entering the field by the acquisition of the Cosmos Engineering Company. The two chief assets of the firm were the Jupiter engine and Mr. Fedden, its technical director. Both were to prove invaluable. The virility of the organisation set up by the Bristol Company and the multiplicity of radial types it evolved paralleled the achievement of Rolls-Royce in the liquid-cooled sphere. Although later arrivals on the scene, they far outran Armstrong Siddeley, and by the start of the expansion period they had won an unchallenged supremacy as designers of radial engines.

These, then, were the four firms which, during the lean years, struggled for their share of the meagre military and civil orders which kept them alive. The Air Ministry carefully nursed the chosen

---

[1] See M. J. B. Davy, *Handbook of the collection illustrating aeronautics, III*; *The Propulsion of Aircraft* (H.M.S.O. 1930).

few by apportioning orders between them—a policy which led to criticism from more than one quarter.

Nevertheless two new firms achieved partial success in breaking down the barricade. These were de Havilland's and Alvis. De Havilland's entered the industry in 1927 when they produced the Gipsy engine for the Moth. This was designed by Major Halford in collaboration with Captain de Havilland, and with Major Halford's assistance the firm succeeded in producing a series of Gipsy engines of varying sizes which were used extensively, and very successfully, in civil aircraft.[1] None of them however was sufficiently powerful to be of importance in military design other than for training purposes.

Alvis arrived on the scene later, in 1935, and their entry into the aeroplane industry appears to be something of a mystery. They were warned by the Air Ministry that orders were scarcely sufficient to keep in being the existing design firms, but they ignored the advice. Fortunately for them their entry coincided with the beginning of the rearmament, and since they had plant and organisation immediately available, the Air Ministry decided to bring them into the 'shadow' scheme[2] in preference to creating new capacity elsewhere. During the negotiations with Bristol's, Alvis agreed to desist from developing engines exceeding 12 litres capacity.

The war on the other hand did not bring any new entrants. The motor car industry, Rootes, Ford, Standard, and the rest of the great motor car firms were again mobilised, but only to assist in production. Design and development remained dependent on the few, which meant so far as engines of operational type were concerned, Rolls-Royce, Bristol's and, to a small extent, Napier's.

So much for the main firms comprising the aero-engine industry of the interwar period. Their place in the industry, indeed their very survival, was the achievement of a few individuals of outstanding ability. These were Mr. Fedden at Bristol's, Mr. Hives at Rolls-Royce and Major Halford at Napier's and de Havilland. Although these three technical directors were responsible for very many advances made in British aero-engines after the First World War, their respective positions within the firms differed fairly considerably. Mr. Fedden was considered by many authorities to be the most outstanding engineer of air-cooled engines in the world. He started in the drawing office of Cosmos Engineering, Brazil Straker as it was then called, and subsequently became works manager. During the First World War, when the firm was engaged on the

---

[1] These included the Gipsy Minor, Gipsy Major Series I and II, Gipsy Six Series I and II and Gipsy Twelve. See Society of British Aircraft Constructors' publication *The British Aircraft Industry* (1939).

[2] See further W. C. Hornby, *Factories and Plant* (H.M.S.O. 1958), Ch. VII.

manufacture of Rolls-Royce engines, he was Technical Director and had already designed one or two radials including the Jupiter when the firm was taken over by Bristol's in 1920. At Bristol's, holding the position of Chief Engineer, he was a leading executive member of the firm. He initiated, and exercised a close personal supervision over, all engine design and development work and also exerted a strong influence over matters of general policy. When for personal reasons he parted company with the firm at the end of 1942, he was invited to act in an advisory capacity by the Minister of Aircraft Production, leaving the engine side of Bristol's to be, in the words of Lord Brabazon, 'Hamlet Ltd., without the Prince of Denmark'.[1]

Mr. Hives joined Rolls-Royce at the age of 22 and remained with them until he became General Manager shortly after the start of the expansion period. Although he was in control of technical development he did not occupy himself with the detailed work on individual projects as Mr. Fedden apparently did. This was as a rule allocated to separate development teams. Mr. Rowledge in particular, who joined Rolls-Royce from Napier's, and Mr. A. G. Elliot occupied a prominent place in the organisation. But when it came to the co-ordination of this work and to matters of general policy Mr. Hives' position was paramount, and a lion's share of the credit for the striking advance made by Rolls-Royce engines during the war years must be given to his drive and executive ability.

Major Halford's position was different again. After a spell in 1918–19 with H. Ricardo, a consulting engineer who also made an important contribution to aero-engine development, he preferred to remain unattached. When in the end he came to throw in his lot with a firm, he divided his time between de Havilland's and Napier's. While therefore his importance as a designer may be judged from the fact that he was responsible for all the Napier H types, including the Sabre, and had a leading hand in all the de Havilland Gipsy series, he never occupied with either firm a position comparable to that of Mr. Fedden or Mr. Hives.

Thus in the development of aero-engines initiative and technical progress came from a very small nucleus of men, all of whom operated inside the industry. Their achievement in advancing the quality of engines as far as they did, independently of any non-industrial establishment and without much official prompting, was greatly facilitated by the technical situation in the interwar years. By 1919 the basic designs of the aero-engine were established. The problem now narrowed down to extracting the maximum power

---

[1] H. of L. Deb., Vol. 125, Cols. 70–79, 17th November 1942.

from basic layouts by meticulous and painstaking development of the V and radial types.[1]

The problem of increasing the output of basic design was approached in three main ways. In the first place supercharging, which was in its infancy in 1920,[2] was successfully developed into a fine art, due chiefly to great progress in fuel technology. Secondly, immense strides were made in the use of aluminium alloys which kept down weight. Thirdly, a considerable amount of progress was made in the detailed design of the actual engine.

As early as 1905–7 important research work into the combustible properties of fuel and air mixtures was undertaken by Professor Hopkinson at Cambridge, but this was of course very much of a preliminary character. It was left to H. Ricardo in 1916 to find that if the compression ratio of the spark ignition engine was increased certain fuels tended to detonate in the cylinders; this was found to vary with fuels of different origin. Petrol consisted of a mixture of hydro carbons of three series. Of the three main hydro carbons in petrol—aromatics, naphthenes and paraffins—aromatics and naphthenes, e.g. benzole and toluene, were the least prone to detonation. The increase of the proportion of aromatics in petrol therefore went a very long way to overcoming the anti-knock difficulty although it did not overcome pre-ignition. Working at the same time as Ricardo, Chavanne and Simon in France found that the addition of aniline to petrol improved its anti-knock qualities. At the end of the First World War a comprehensive programme of research was put in hand by the Shell Company, who engaged Ricardo to undertake the study of the theory, causes and effects of detonation.

During the period after the last war up to 1929–30 other companies both in England and abroad also did a considerable amount of research work. But while Great Britain played a leading part in this pioneer work, a large share of the credit for improved fuels must go to the United States. In 1921 Midgeley and Boyd, sponsored by Kettering of the General Motors Corporation, discovered that tatraethyl lead suppressed detonation even when administered in minute quantities. The widespread utilisation of this discovery had a far-reaching effect on the performance of the aero-engine. The further discovery in 1925 by Graham Edgar that the iso-octanes had about the highest anti-knock value of any pure hydro carbons at that time,

---

1 The most important exceptions were the H type Napier engines designed by Major Halford. An interesting example of the new trend was the Rolls-Royce engines. Every important aero-engine produced by the firm from 1920 onwards, culminating in the 2,000 h.p. Griffon 61, followed the same basic layout as that of the Eagle and Falcon.

2 In 1917 an engineer named Rateau came over from France to the R.A.E. and the subsequent pooling of ideas resulted in the successful flight of an engine with a turbo supercharger. In the United States in 1918 a Liberty engine with turbo supercharger was successfully tested on Pike's Peak. See S. A. Moss, *Superchargers for Aviation* (National Aeronautics Council, New York, 1942).

coupled with the knowledge that normal heptane was the worst hydro carbon known, resulted in the method at present generally accepted of measuring the anti-knock quality of fuels by the so-called octane number scale.

In 1933 the first leaded fuel was introduced into the Service with an octane value of 87. While Britain was concentrating chiefly on the addition of lead to straight run fuels, the Americans established the production of iso-octane and other blending agents on a commercial basis, which opened the way to large scale production of fuels with octane values in excess of 87. After 1934–35 great strides were made in the extension of the range of these blending agents and synthetic fuels, and 100 octane fuel came into full military use in 1939–40. By 1944 it was used in nearly every type of operational aircraft.

Meanwhile, it had been found that octane number alone was hardly a sufficient guide to the anti-knock quality of fuel. Two fuels, one containing a large proportion of aromatics and the other a very small proportion, might, for the same octane number rating and under take-off conditions in a full scale engine, give a completely different power output before the onset of detonation. Since the standard octane number method of rating measured the anti-knock quality of fuels under weak mixture conditions it became clear that fuel performance varied with the mixture strength. Accordingly, from about 1936, full scale single cylinder aero-engine units were used in Great Britain to determine the take-off performance of fuels, and in the early days of the war a certain minimum quality was called for in this respect although it was not inserted in the specification as a definite requirement.

These great strides in the development of fuel facilitated corresponding improvements in supercharger performance. Superchargers were of two main types: the turbo-supercharger with a blower driven by exhaust, and the type with a blower drive off the crankshaft by means of gears. The turbo-supercharger was first in the field. Almost from the earliest beginnings of aero-engines, designers had been worried about the tremendous energy running to waste in the exhaust in the form of hot gases under great pressure. Early superchargers were therefore designed to harness this power and put it to good use. The great point in favour of the turbo-blower was that the higher the altitude of the aircraft the greater the difference in pressure between the inside of the engine and the surrounding atmosphere, and the more powerful the action of the turbo. Shortly after the First World War the R.A.E. evolved a successful gear driven supercharger which was far more reliable than the turbo-blower and did not involve the risk of fire, which was the great drawback of the turbo-supercharger. By 1925 engines experimentally fitted with turbo-superchargers included the Lion, Condor, Jupiter VI and Orion, while mechanically driven superchargers were fitted in the Mercury and Jaguar. Service tests of both varieties were undertaken in the R.A.F. in 1925–26.

About 1927 the turbo-supercharger fell out of favour and the entry of considerable numbers of Jupiter VII into the R.A.F. at this time was symbolic of the ascendancy of the gear-driven type, which was soon to become world-wide. In Britain all intensive work on the turbo-driven variety ceased immediately; America was the only country where faith persisted in the possibilities of a successful design—a faith which was completely vindicated by its performance in the Second World War in the American high-altitude bombers.

The different interest and emphasis in Europe and America depended upon differences in geography and strategical thinking. In Europe the emphasis remained throughout on the high-altitude fighter. In America, however, the primary objective was the development of engines with high power for take-off for heavily loaded transports and bombers. The result was that the ratio of blower speed to engine speed tended to be higher in European engines than in American engines.

Before long, however, demand was felt for a more uniform increase in performance along the whole of the altitude scale: in Europe for better take-off and climb, in America for better high-altitude performance. The result was the emergence of the two-speed blower which, by giving two performance peaks at entirely different altitudes, did much to eliminate this drawback. Initial development of the two-speed blower was undertaken in France in the early 1930's—a remarkable achievement, since France had up to this time shown little interest in supercharging.[1] The outbreak of war took the process a stage further with the development of the two-stage supercharger. This consisted of two impellors arranged in tandem each of which compressed the mixture in turn so that there were two distinct stages of compression. Thus pressure could be maintained at still greater altitudes without recourse to correspondingly increased impellor speeds to which there was a safe limit. A special two-stage supercharger was fitted to the Bristol Pegasus for the high altitude record of 1937, but its first Service use was with the Rolls-Royce Merlin and Griffon.

Great advances in the power output of aero-engines after 1920 therefore were made possible by better fuels and a higher degree of supercharging. But to enable full use to be made of improvement in fuel octane value it became necessary to devise new materials and

---

[1] *Flight*, No. 1251, Vol. XXIV, No. 51, 15th December 1932, 'Engine Features from the Paris Show', by Major G. P. Bulman.

also to make detailed improvements of design. With regard to materials, considerable progress was made in the First World War in steel castings and in the heat treatment of alloy steels, but the science of alloys combining lightness with strength was in its infancy.[1] After 1920, however, there followed a most fruitful period of metallurgical development in which the metallurgist proved fully equal to the demands of the engine designer. In this field as elsewhere Rolls-Royce technicians played a particularly important part. The range of alloy steels was considerably extended, and alloying elements included nickel, chromium, vanadium, manganese, molybdenum, tungsten, silicon and various combinations of these metals.

Perhaps even greater advances were made in the field of aluminium alloy. Duralumin was found particularly suitable in cast and forged forms, being ten times lighter and nearly 100 per cent. stronger than the usual crank case of aluminium alloy. The well-known 'Y' alloy with elements of copper, nickel and magnesium was used in pistons in many engines and in the cylinder heads of air-cooled engines.[2] Pistons, crank cases, connecting rods, cylinder heads and so forth, were all made of light alloy forgings. First introduced in the Bristol Mercury, they were subsequently used very extensively in American radials.[3]

Besides these improvements a vast amount of effort was expended on the improvement of the exhaust valve, which constantly became overheated. The situation was entirely transformed in the early 1930's by the introduction of sodium-cooling and stellite valve seatings.

In addition to developments in materials many advances were made in detailed design. Among these were spur-reduction gearing and the variable pitch airscrew, sleeve valves and the power plant. Spur-reduction gearing for the airscrew, which enabled maximum speed and power to be developed by a crankshaft while keeping propeller speeds sufficiently low to give maximum performance, was first employed on an extensive scale in the Napier Lion and the Rolls-Royce Condor. It soon became a standard feature of all high performance aero-engines. Allied to the question of spur-reduction gearing was the variable-pitch propeller: without these two inventions many advantages derived from supercharging would have been lost.

But one of the greatest single advances in the improvement of engine design, or at least of design of radial engines, was the sleeve valve. About 1925 aero-engine designers believed that if they were to

---

[1] *The Journal of the Royal Aeronautical Society*, Vol. XLVIII, 1944, The Thirty-Second Wilbur Wright Memorial Lecture on 'Aircraft Power Plant—Past and Future', by Sir A. H. Roy Fedden, Section 3.

[2] V. W. Page, *Modern Aviation Engines*, Vol. I (New York, 1929), p. 778.

[3] *The Journal of the Royal Aeronautical Society*, Vol. XLVIII, 1944, op. cit., Section 4.

accept any substantial increase in the application of supercharging to low-level performance as opposed to power-altitude compensation, they must first abolish the exhaust valve. In the light of current knowledge the only practicable alternative seemed to be a single sleeve valve. This had first been fitted to an aero-engine in 1914, but it was not until 1926 that the Bristol Aeroplane Company, with the Air Ministry's support, decided to endeavour to perfect the single sleeve valve. Mr. Fedden and Mr. Ricardo played a conspicuous part in this development which lasted over a number of years. The first test unit was produced towards the end of 1927, but it was 1932 before the first successful engine passed its type test.[1] Since then all new Bristol engines were of sleeve valve design; the only other important engine to use this new system was the Napier Sabre. Many other advantages were claimed for the sleeve valve, but perhaps the greatest advantage lay in the small number and simplicity of its components which reduced maintenance routine to a minimum. A further improvement was that it operated with unvarying efficiency at all speeds.[2]

Finally there was the integrated assembly of the engine and its mounting. The advantages of a compact, self-contained and detachable power unit complete with all accessories appealed to aero-engine designers from a very early date. Boulton Paul, for example, exhibited a hinged power plant at the Paris Exhibition of 1919, and a further stage of development was reached in 1924 when a Bristol Jupiter was fitted to a Bristol transport aircraft in such a way that the complete unit could be swung sideways for inspection and maintenance.

Impressed by these developments Rolls-Royce set up a special department in 1929 to carry out development work on this contrivance, and in 1935 another special department to undertake the flight testing of motors and other installations. The combined result of these activities was the emergence of complete Rolls-Royce power plants. By 1939 Rolls-Royce and Bristol's were both well established as suppliers of complete power plants, and during the war further advances were made in the installation of these in bomber aircraft.

So much for the technical progress in the development of engines. Running through this story is the theme of the independence of

---

[1] Sir Roy Fedden said that the perfection of the sleeve valve took ten years. See *Flight*, No. 1616, Vol. XXXVI, 14th December 1939, 'War—and the development of the Aero-Engine', by A. H. R. Fedden.

[2] See *The Journal of the Royal Aeronautical Society*, Vol. XXXIV, 1930, No. 240, Eighteenth Wilbur Wright Memorial Lecture on 'The Development and Progress of the Aero-Engine', by H. R. Ricardo; *Flight*, No. 1718, Vol. XL, 27th November 1941, 'The Bristol Hercules', by G. Geoffrey Smith, and *The Institution of Automobile Engineers Proceedings*, Session 1938–39, Vol. XXXIII, 'The Development of the Mono-sleeve Valve for Aero Engines', by A. H. R. Fedden, February 1939.

technical efforts of private firms. We have seen that for this autonomy a number of factors were responsible. Engines were better suited to independent industrial design than were airframes. They were 'technical jobs' not directly related to immediate tactical and strategic needs of the Air Staff. As a result, the continuous progress of, for example, the Rolls-Royce engines from the Schneider Trophy type to the Merlin and the Griffon, and the progress of the Merlin from one mark to another, could proceed without the Air Ministry's prompting, and sometimes even without their knowledge. In the second place the engine firms drew much less than the airframe manufacturers on the long-term investigations in the National Physical Laboratory and the Royal Aircraft Establishment. For most of their basic investigations they relied upon their own research facilities.[1]

However the main foundation of the firms' independence was their reputation and achievements. Their prestige was so high and the successes of the engines, the Kestrel and the early Merlin, the Perseus, Taurus and Hercules, so convincing that nobody in the Air Ministry could question the wisdom of leaving the future of the engines in the firms' hands. It was taken for granted that their technicians would, if left alone, do all that could possibly be done, and as a result little interference with their activities was attempted or permitted. The firms determined their own programmes of development, and decided for themselves what engines should be pushed ahead at a given point of time and what projects should be given precedence. In this sense all their engines were private ventures.

(iii)
Armament: Guns

Much of the armament story, especially in its early phases, is concerned with the number and the calibre of airborne weapons. On this subject ideas advanced most rapidly in the mid-thirties. It was in those years that the multiple-gun fighter and the power-operated gun turret took shape, and both were fostered by Government and industry alike. The demand for the eight-gun installation came from the Air Staff, but the designers were sufficiently alive to the need to have designed aircraft capable of meeting the Air Staff requirements, so to speak, on the spot. The original versions of the two modern fighters which were being designed in 1934 to replace

[1] This was reflected in the very insufficient provisions for engine research in the R.A.E.

the biplane Fury, and which were in the end to develop into the Hurricane and the Spitfire, provided for only four guns each (the Supermarine design in addition continued to bunch its guns in the undercarriage). The Air Staff, however, had been engaged in recalculating the lethal effects of concentrated gunfire, and its Operational Requirements Branch had been considering the possibility of an eight-gun installation. The Browning gun itself was becoming so reliable that it was possible to remove it out of the pilot's reach and to instal it in the wing. As a result the Air Staff introduced the requirement for eight-gun wings into the final specifications for the new fighters.[1] The requirement was at once accepted by Mr. Camm for the alternative Hurricane wing and Mr. Mitchell was only too anxious to incorporate it into the final design of the Spitfire.

The next most important stage in armament installation came with the 20 mm. cannon fighter. An experimental, not to say a wild, proposal to instal heavier guns had been made long before 1935, in fact long before the rearmament. As an experiment, Westland's had actually installed a 37 mm. gun in a fighter as early as 1927, and Bristol's also claim to have been interested in the installation of large guns. But at that time neither the guns nor their installation were such as to justify a change in the Air Force tactics or in the Air Ministry specifications. It was only in 1935, when most countries began to instal armour in fighters and bombers, and the metal construction of aircraft was becoming strong enough to take heavy recoils, that the larger gun became a practical proposition.

The part which the Air Staff's pre-occupation with cannon played in initiating the Tornado/Typhoon has already been described.[2] But even before the specially designed single-engined cannon fighter took shape, technicians in the Air Ministry planned to fit the cannon in the two-engined fighters and in the later versions of the Hurricane and the Spitfire. The Whirlwind owed its adoption largely to the Air Ministry's interest in the cannon, and for a long time it was referred to in official papers as 'the cannon fighter'. Unfortunately the early promise of the Whirlwind was not realised, and at the beginning of the war the Air Staff began to cast about for another cannon-firing type. As a result the Beaufighter was, so to speak, conjured up by the same parallel effort in the Air Ministry and in the industry which, as we have seen, marked so many other departures in aircraft design.

Somewhat more complicated was the story of cannon installation in the Hurricane and the Spitfire. During 1939 it became clear to

---

[1] Specifications F.5/34 and F.10/35.

[2] See pp. 79–80.

some people in the Air Ministry that the cannon-firing Tornado/Typhoon was as yet too far ahead to be of much help against the German aircraft, and that cannon would have to be installed in the existing single-engined fighters. As the Hurricane had a wing sturdy enough to take a heavy gun, the Air Ministry naturally turned to Mr. Camm. On his part the latter was sufficiently alive to the need, and sufficiently well prepared for it, to produce a trial installation within a few months.[1] As it turned out, it was also possible to instal two cannon in the much thinner wings of the Spitfire,[2] and by the end of 1940 the cannon became a standard feature of all fighter specifications.

Nevertheless, in judging the part played by the Air Ministry it is important to note that while most designers were anxious to instal heavier guns and were ready for the installation when the demand came, a large body of opinion in the Air Ministry, and later in the M.A.P., continued to oppose the cannon wing, and as late as August 1940 the fitting of these wings to the single-seater fighters was still under discussion.[3] The opposition has in some accounts been magnified into a dramatic story of a struggle between the cannon-minded Lord Beaverbrook and the cannon-allergic Air Marshals. This story is apt to disregard the strong pro-cannon line taken by the Air Staff since 1935, the progress already achieved by 1940, the existence of the specialised cannon designs of the Whirlwind, the Beaufighter and the Tornado. But the story clearly reflected the doubts and the opposition which surrounded the installation of cannon guns into fighter wings. By overriding them, as completely as only he knew how, Lord Beaverbrook finally ensured the general turnover to the new design.

The subsequent stages in gun installation present few facts which have not already been told here. The fighting in Libya and the part which aircraft were then called on to play against tank and transport, led the Air Staff to the idea of the 'Tank-buster' carrying a 40 mm. gun.[4] As on earlier occasions, the Hurricane was the aeroplane chosen for the part, and as on earlier occasions Hawker's anticipated the demand early enough to be able to supply a 40 mm. installation

---

[1] Hurricane I fitted with 2 cannon was tested at Hawker's in May 1939. A Hurricane I fitted with 4 cannon was delivered to North Weald to join an operational squadron in August 1940.

[2] A Spitfire with 2 cannon fitted was cleared for technical trials in a Service squadron in December 1939. 30 Spitfires were modified to take 2 cannon and delivered to a Service squadron for trial in August 1940.

[3] In August 1940 the Secretary of State for Air officially requested the Minister of Aircraft Production to give first priority to the Hurricane and second to the Spitfire. Contracts for Hurricane and Spitfire wings fitted with cannon were eventually placed with the firms in September 1940.

[4] Vickers had attempted to build a turret fighter with 40 mm. guns in 1938. See p. 118.

within four months of the demand.[1] Later still in 1943 on M.A.P.'s initiative the Mosquito was modified to carry a six-pounder gun in the fuselage. Similarly it was entirely due to the R.A.F. and more especially to Air Marshal Tedder's initiative in Egypt that bombs began to be fitted to fighters, and a new race of fighter-bomber came into existence in the Western Desert at the end of 1940.

The final stage in the evolution of the airborne weapons is represented by the rocket. The exploits of the rocket-firing Typhoons and their successes against the tanks have been described in accounts of the fighting in France.[2] But the genesis of the airborne rocket antedates its use in France by three years. One of the earliest uses of airborne rockets was probably in the Swordfish operating against submarines. The Air Staff became interested in the wider use of the rocket in the late summer of 1941 as a result of a report by the British Military Mission in Moscow. In August of that year the Russians were using rocket-firing aircraft with good effect against German tanks and bomber formations. Early in September Air Vice-Marshal Sorley (Assistant Chief of the Air Staff, Operational Requirements and Tactics) asked the Controller of Research and Development (Air Vice-Marshal Linnell) to investigate the possibility of using rockets in aircraft, in the first place against ships and tanks. In response to this request M.A.P. began, in November 1941, experimenting with the necessary installations.

In these experiments two problems had to be faced. The first was to design a projector fitted to the aircraft from which the rocket could be fired. The second problem was to adapt an existing rocket projectile. The latter was done by the projectile technicians in the Ministry of Supply. The existing 3 in. high-altitude anti-aircraft rocket was chosen and modified to fit the rails of an aircraft projector. The projector itself was designed and developed at the Royal Aircraft Establishment between November 1941 and the spring of 1942. By August 1942 three Hurricanes were fitted with projector rails, and tests proved them to be effective. A special branch in the Directorate of Armament Development, M.A.P. was thereupon formed to deal with further development of the weapon.

The problem which the new branch concentrated on was the aerodynamic effects of the new weapon, for there had been many complaints of loss of performance resulting from the installation of the original R.A.E. projector. It is at this point that a private firm came into the picture. At first the R.A.E. were instructed to produce

---

1 Hawker's received an Air Staff request for the 40 mm. gun in May 1941; the trial installation was ready for delivery to the Aircraft and Armament Experimental Establishment on 19th September 1941.

2 See Major L. F. Ellis, *Victory in the West*, Vol. I (H.M.S.O., 1962), Chs. IX–XX and App. III and Denis Richards and Hilary St. G. Saunders, *Royal Air Force* 1939–1945, Vol. III, (H.M.S.O. 1954), Ch. VI.

streamlined rails offering less wind resistance than the equipment originally designed. By November 1943 it became quite clear in M.A.P. that R.A.E. would not get their design into production in time to be of use operationally. Hawker's were therefore asked to produce a design of their own. This they did in two weeks; and no sooner was their design cleared than the Controller of Research and Development placed an initial order for 500. But for these drastic steps the rocket-projectile-firing fighters would not have been available for fighting in Normandy.

Action did not end with the Hawker design. Subsequent to the Controller of Research and Development's order the Directorate of Armament Development itself designed an improved installation and put it out to a firm for manufacture. One of its advantages over both the R.A.E. and the Hawker equipment was that it clipped directly on to the bomb-carrier of fighter-bombers and thus made it possible for the aircraft to be changed over very rapidly from one function to another; another was that the rails themselves could be jettisoned by pulling the bomb switches. This was of obvious value, for, however streamlined, the best of rails produced drag and a slight resistance.

On their part the private designers continued the development of the rocket armament to meet the Air Staff requirements. Hawker's had followed up their rocket projectile design for the Typhoon by a very successful design of their own for the Tempest. It could not be jettisoned in flight, but it had very low resistance and interfered little with the performance. However in this, as in the Typhoon project, Hawker's appear to have acted with some reluctance, and on one occasion Mr. Sidney Camm had to be given a categorical instruction to pursue the necessary development. For this lack of enthusiasm several explanations can be given. But the most probable one will be found in the ancient, and otherwise healthy, rivalry between the Supermarine and the Hawker stables. It had always been the ambition of Mr. Sidney Camm to design a fighter second to none in performance, and he was naturally anxious not to incorporate into his fighter, whether Typhoon or Tempest, the type of equipment which would reduce its top speed and put it definitely out of the interceptor fighter class into the category of fighter-bomber.

(iv)

Armament: Turrets and Sights

The story of the weapons is paralleled by that of their ancillary equipment, and especially by the development of such important elements of aircraft armament as power-operated turrets, remote control links, and automatic sights. The first of these, the power-operated turret, was in its initial stages a product of private enterprise, although the conception itself cannot be claimed by either the designers or the Air Ministry. It was in France that the first successful airborne turrets were developed and it was from the French models and from the lessons of the French aircraft shows that the British designs directly, or indirectly, derived. Of the two chief British designs, one, Boulton Paul's, was a mere adaptation of the French Société Anonomyne Machines Motrices turret which Mr. North of Boulton Paul produced under licence in 1933 and installed in 1934 in the Sidestrand bomber. In the end an all-hydraulic turret of Société Anonomyne Machines Motrices basic design came to be installed in Boulton Paul's own Defiant and in the Halifax bomber.

Less direct was the French influence on the other, more widely-used, British turret, the Frazer Nash.[1] Its tactical and technical principles were doubtless influenced by what its designer, Captain Frazer Nash had seen in France. But its standard versions, the F.N.4, 5 and 20—which came to be installed in most of the bombers at the eve of the war and were to remain largely unchanged until 1944—emerged from a purely indigenous evolution and followed a series of Captain Frazer Nash's own inventions. As a result of close personal contacts with R.A.F. personnel, Captain Frazer Nash realised very early in the 'thirties the need for a much improved gun mounting. As the speed of the aeroplane was rising, the standard gun mounting of the early 'thirties—the Scarfe ring which balanced aerodynamic load against spring compression—was obviously insufficient to protect the gunner against the air flow and insufficient to enable him freely to manipulate his guns. Captain Frazer Nash's first solution was little more than a powered and shield-protected Scarfe ring which was designed in 1932 and installed in 1934 in the Demon fighter. Two intermediate improvements, F.N.2 and F.N.3 with collapsible shields and Lewis guns followed soon after. But it was not until, following the French example, Captain Frazer Nash designed a complete hydraulically-operated cupola turret and equipped it with continuously-fed Vickers guns that the standard Frazer Nash turret came into existence.

This initial development owed little to official initiative or even to official encouragement. In its early stages the turret received some enthusiastic backing from one or two persons in the Air Ministry, and notably from Squadron Leader, later Air Vice-Marshal, Davis. Otherwise the Ministry was for a long time content to leave the initiative in the hands of the firms. By the beginning of the war the

---

[1] See Appendix VI.

armament branches of the Ministry began to consider long-term plans for turret armament, but the plans were nipped in the bud by the freezing of forward developments in the summer of 1940. For a couple of years, therefore, development of turrets continued to depend entirely on private designers. More especially Frazer Nash continued to produce further and more advanced experimental models, and at one time in 1942 came very near to placing on the market a turret mounting 20 mm. cannon, the F.N.79, embodying the lessons of the famous Augsburg daylight raid of 17th April 1942. Later other firms had also come forward with advanced types of turrets and one of them, the B.17 designed by Bristol's, won a great deal of support in the M.A.P.

In the end, however, the main responsibility for future plans was bound to pass to the official technicians. The effects of the freezing order of 1940 wore off by the end of 1941 or the beginning of 1942, and improvements in power operation, calibre of guns and their control began to be sought. By that time also a great deal of technical experience had accumulated in the office of the Director of Armament Development. Thanks to its central position and its knowledge of what the individual designers had been doing, the office enjoyed advantages which were denied to the private firms. It is therefore not surprising to find the official technicians gradually asserting themselves. By the end of 1943 they began to lay down exact specifications and to issue detailed instructions on all matters of turret design such as fields of fire, materials, finishes, in fact on everything necessary for the design except the actual blue print. The F.N.82, a .5 in. tail turret, was produced by Frazer Nash to a specification of this kind. Moreover, the Department had begun to force the firms to pool their resources and to exchange technical information and even enforced a certain amount of specialisation between them.

The story of the turret shows how, in the later stages of the war, the official agencies and especially the Directorate of Armament Development gradually began to guide the design of what had originally been a privately conceived and a privately developed installation. They played the same role in the development of such a latter-day device as remote control. Indeed, in the history of the remote control the official and unofficial lines of development intertwined in a manner so characteristic that more space might well be given to it here than the intrinsic importance of the contrivance would by itself justify.

The idea of a remotely controlled gun is older than the aeroplane or even the automatic gun, for it has occupied the attention of the Admiralty since the 1880's. Its advantages from the point of view of aircraft design have always been understood. In the words of an official document of 1940 it should provide a 'means of improving bomber armament without increasing crew or adding weight in positions which are unacceptable for aerodynamic reasons'. Even where it could not add to the total armament of an aircraft it should make it possible to increase the security and the comfort of the gunners and to reduce the aerodynamic drag of the turrets.

It is, therefore, not surprising to find the Services, and especially the Admiralty, asking for and projecting remotely controlled gun turrets even before the original, or locally controlled, turret armament became general. It was discussed in connection with certain naval types and was included in the specification for a Fleet Air Arm aircraft S.9/36,[1] and during the discussion of the S.24/37 specification for the naval torpedo-bomber-reconnaissance aircraft (Barracuda) the Admiralty again asked for it. In 1940 the Air Ministry considered several projects for the installation of remotely controlled armament on several of the heavy bombers, and certain types of remotely controlled turrets were in fact experimentally installed in the Wellington and the Havoc. But firm Air Staff requirements did not come until late 1942, and in any case it was not until 1942 that the device progressed far enough to be practicable.

In the interval, especially between 1938 and 1940, different private firms had a 'shot' at the problem. In 1939 Boulton Paul had on their drawing-board a mechanical and hydraulic scheme which they had designed for inclusion in the Barracuda. In 1941 Frazer Nash designed an experimental installation for six guns remotely controlled, but without a turret, for the Havoc; at about the same time Bristol's experimented with a remotely controlled nose-mounting of their own design for the Buckingham bomber; and, as we shall see further, Vickers had in the same period evolved a mechanically operated installation. But little practicable came out of any of these projects. Such mountings as eventually passed for installation in 1944 descended not from the earlier experiments of the private firms but from two later lines of development: one wholly private, and the other officially directed but incorporating elements of private design.

The private line of development was closely linked with Vickers-Armstrongs. That firm's interest in remote control dates back to the pre-war rearmament and probably derives from their preoccupation with the problems of predicted gunfire for naval and anti-aircraft purposes. In the course of 1938–39 their chief armament designer, Captain Nannini, evolved a mechanically operated turret for the remote control of 40 mm. aircraft guns, and in 1939 the firm were able to submit to the Air Ministry a design of a heavily armed

[1] The project had to be given up for lack of suitable remote control equipment.

twin-engined fighter incorporating the turret (P.V.F.22/39). In the early stages of the war they tried out their turret on the Wellington and proposed to introduce it into the design of the Warwick, and at one time it was also considered for trial and installation in the Barracuda. But none of these mechanically operated designs met the needs of the Air Ministry and were not developed much further. Nevertheless the firm persevered in its experiments. Early in 1942 they were brought into a scheme for the adaptation for the Buckingham bomber of an electric-hydraulic equipment which, as we shall see later, had been developed by the Admiralty Research Laboratory[1], and by the middle of that year they were busy at work on an electric-hydraulic system of their own.

With this design, the story of Vickers' remotely controlled air armament was brought to a more or less satisfactory close. Although at one time it was considered for incorporation in the Warwick, the Vickers high-altitude bomber (B.5/41) and the Hawker high-speed bomber, its development eventually merged with that of the Windsor aircraft. The latter was conceived as a heavy bomber travelling at a speed so high as to force the enemy fighters to attack it from astern. Into this conception remotely controlled backward firing barbettes in the engine nacelles fitted very logically. Having received the official *fiat* the firm proceeded with their work in the full privacy of their own drawing office and experimental shops and free from all official intervention or guidance. In the conditions of 1942 they did not find it difficult to secure the autonomy they wanted. They had strong personal links with the M.A.P. and they also benefited from the special respect which the Ministry at that time paid to the independence of firms and the principle of private enterprise. As a result a wholly private design of a remotely controlled turret reached its final stages in the second half of 1944.

The story of the officially-sponsored equipment was much more complicated. In the official programme of research and development remote control figured very prominently from the early stages of the war. In April 1940 the Director General of Research and Development (then Air Vice-Marshal Tedder) brought to the notice of his subordinates the decisions of a meeting at the Air Ministry by which remotely controlled guns were placed on the short list of urgent developments, extravagantly but picturesquely described as the 'war winners'.[2] Exactly a year later Sir Henry Tizard drew the attention of the Director of Scientific Research to the vital importance of remotely controlled guns for bomber armament and asked for measures to be taken to speed up the development.

---

[1] See p. 116.

[2] The meeting was also attended by Sir Wilfrid Freeman (A.M.D.P.), Air Vice-Marshal Saundby (A.C.A.S.(T)) and Sir Henry Tizard.

Yet, in spite of the continued interest in high quarters, official action was for a time somewhat indecisive and not altogether successful. The first thing the Directorate of Armament Development did in response to Sir Arthur Tedder's instructions of April 1940, was to recommend that a special 'cell' should be established at R.A.E. to take charge of the automatic sight and the remote control. The coupling of the two projects was necessary, as the long-term plans of remotely controlled turrets appeared to depend on the perfection of the sighting. But, as a result of this coupling, the interests of the R.A.E. 'cell' moved away from the problem of remote control, and in the spring of 1941 the Directorate had to report to Sir Henry Tizard that very little had been done, and that the R.A.E. had so far worked only on the gyro-sight.

It was not until then, and as a result of Sir Henry Tizard's intervention, that further steps were taken. By then it had become clear that the mechanically operated controls hitherto considered had very limited possibilities, which, such as they were, had been fully exhausted in the private designs for the experimental turrets. Far greater possibilities were to be found in controls wholly or partly electric, and in order to explore them it was decided to bring into the project the Admiralty Research Laboratory, under Colonel Kerrison, who had had some previous experience in the design of distant control on an electric repeater system. At first it was proposed to combine the electric-hydraulic link of the Admiralty with turrets of Vickers-Armstrongs' design and to instal this equipment in the Bristol Buckingham. But, in the end, nothing came of the Buckingham project, and in August 1942 the Admiralty Research Laboratory system was installed in the Halifax for air tests. The results of the tests were not wholly satisfactory, and even to some extent discouraging. 'The electric-hydraulic link failed to give the required accuracy of follow between sight and gun.'

This was a considerable disappointment but it did not stop the official exploration. With the electric-hydraulic system in doubt the way was open for what was for some time considered an alternative, namely the all-electric system. It had been known for some time that electric 'links' were under development at different places, and the Admiralty Research Laboratory had recently surveyed the different systems with special reference to naval and anti-aircraft guns. All-electric operation had by 1942 proved its superiority over 'ordinary' turrets such as the turret for large-calibre guns which Bristol's had designed in the middle of 1942, and an all-electric system of remote control was also being developed in the United States, by the General Electric Company, where it had been seen by the visiting representatives of the Directorate of Armament Development and the R.A.E.

In this country, however, the main credit for designing the suitable electrical link belongs to the British Thomson-Houston Company. Early in 1942 the firm got into touch with the Air Ministry and received an order to develop an electric remote control on the so-called Amplidyne system of their own design. This they proved well able to do. The technicians of the British Thomson-Houston Co. had for a long time been interested in indirect control in general application to electrical engineering. In August 1942 their principal technician, Mr. Whiteley, visited the United States where he was able to co-ordinate their design with the work done in their associated firm in the States, the General Electric Co. In this country they received constant assistance from R.A.E. and more especially from Sir Arnold Hall, Mr. A. A. Hall as he was then. Thus assisted, the firm were able to evolve by 1944 a satisfactory electrical link not unlike the American. On their part the Directorate of Armament Development organised the division of labour and brought Boulton Paul's into the design of the turret itself. It was as a result of this combined effort of British Thomson-Houston Co., Boulton Paul and R.A.E., under Mr. A. A. Hall as technical adviser, that the most promising of the designs, and one of the two most advanced, finally emerged.

By comparison with the remote control, the other 'war winner'—the automatic sight—was largely a product of official initiative and of state-directed research. Its history was altogether simpler and more successful than that of the remote link. The need for a predictor sight was realised later than the need for a turret, but once realised it was soon followed up by official requirements and by suitable designs. Until about 1937 it was generally assumed that the speed and the armament of the fighters would result in air combats at very short, or point-blank, ranges and thus make 'kills' possible without special aiming equipment. But as speeds increased and the defence of bombers improved, the difficulties of shooting down enemy aircraft in flight became apparent, and by 1938 it came to be felt that the gunner, i.e. the pilot in the interceptor fighter and the gunner in the bomber turret, needed automatic aids to correct his aim for the relative speeds of the aircraft and the ballistic behaviour of the bullets. Some such aid was for a time provided by the tracer bullet, which made it possible for the gunner to watch the direction of his fire and to connect it with his target.[1] But this was on the whole an imperfect and a deceptive indicator, which could not fulfil the purposes of an automatic sight. These purposes had been served by a simple device—a 'deflection ring' fitted to the fixed sight, which

[1] The theory underlying tracer fire technique was worked out by Professor Sir B. Melvill Jones in 1938.

could be used by well-trained gunners to correct their aim by changes in the relative position of the target. The deflection ring could not however make any correction for ballistic errors.

By 1938 it was becoming clear that the right solution could only be found in the gyroscope.[1] The idea was strongly backed by Professor Melvill Jones, and in the summer of that year several firms—Nash and Thomson, Vickers and Pullen—were given special contracts for computor sights capable of allowing for the relative speed of the target. But none of these contracts resulted in an acceptable sight. Although Vickers included in their 1939 project for a fighter armed with a 40 mm. gun a predictor making allowances for 'own' and 'enemy' speeds,[2] it is doubtful whether this was anything more than a tentative adaptation of their standard anti-aircraft gun predictor. In any case it did not meet with favour in the Air Ministry and fell through together with the entire Vickers' fighter scheme. It was not until the autumn of 1939 when the subject was revived again, and R.A.E. were persuaded to take it up, that things began to move.

If technical details are disregarded the story of the R.A.E. design falls into four clearly defined stages: the early experiments, the emergence of Mark I, the design of Mark IIC as a turret sight, and finally, the adaptation of Mark II to fighter use, including Mark IID and the preparations of Mark III. An experimental gyroscopic sight with a rudimentary pneumatic control was ready towards the end of 1939, but the development made little progress until the spring of 1940. By that time, in pursuance of Air Vice-Marshal Tedder's list of 'war winners', a 'cell' for remote control and automatic sight design had been established in the R.A.E. Several designers, Group Captain H. Ford, Mr. M. Hancock, Mr. B. Sykes and Dr. Wheeler Robinson, at first under the supervision of Mr. L. H. Carpenter, and later under that of Mr. A. A. Hall, had been gradually absorbed into the project. By late spring 1940 an experimental model was flown for tests. By the summer of 1940 a more workmanlike version had been made, embodying a great deal of new fundamental work and giving trail correction as well as speed correction. It worked reasonably well when air-tested and was developed into the Mark I sight, limited production of which began at the end of that year.

The development did not stop at that. Though quite a number of these sights were manufactured, they were still far from perfect. There were two main defects: (a) the limited eye-freedom of the prismatic telescope around which the sight was built, and (b) a

[1] The idea was apparently suggested by Professor Cunningham and Mr. M. Hancock of the R.A.E.

[2] See p. 109.

tendency to instability of aim in inexpert hands, which was inherent in the fundamental design of the sight, but which was not revealed until extensive air-firing trials had been made. So, by the end of 1941, the Mark IIC was designed. It was free from these defects, easier to operate, and of a much more refined design. It was ready for tests in March 1942, and production began to be laid down in the summer of the same year.

Before 1942 higher priority had been allotted to sights for bomber defence than for fighters, and both the Mark IC and the Mark IIC were turret sights. The requirement for use in fighters began to be considered more urgently in the summer of 1942, and preliminary designs of a Mark III suitable for fighter use were prepared. In the meantime a turret version, on Mr. Hall's suggestion, had been fitted to a Spitfire and proved such a success that by the middle of 1943 the R.A.E. were presented with an urgent demand for the use of this sight in fighters. The result was a Mark IID—essentially the Mark IIC with minor modifications for fighter use—a highly successful sight which raised the chances of success for combat from 20 per cent., hitherto regarded as normal, to 50 per cent. A still further development in the gyroscopic gun sight and an extension in its use took place in 1944. At this time the Royal Air Force were introducing the use of rockets in air attacks of ground targets, and particularly tanks. The rockets were difficult to aim, and concerted attempts were made to design a rocket sight. In the end Mr. Hall was able by means of relatively simple modification to adapt the gyroscopic gun sight for the purpose. The adaptation allowed not only for the large gravity drop of the rocket but also for the influences of wind on the aircraft, and for the movement of the target, and thus made it possible to aim rockets with precision. Yet it did not impair the usefulness of the sight for aiming guns in air combat and enabled the same aircraft to be used in either role without a loss of operational efficiency.

In all this development private firms took little part. When brought in they had to be given much guidance and assistance by the R.A.E. A private firm was for the first time introduced in the summer of 1940, when Elliot Brothers, instrument makers, were asked to manufacture the first batch of Mark I sights to the designs of the R.A.E. This contact was not wholly successful. In spite of their very considerable standing in the industry and previous experience in making fire-control equipment for the Navy, the firm found the gyro-sight 'heavy going'. One snag after another had to be cured for them by the R.A.E., and the development was not successful until a representative of the R.A.E. had been boarded out with the firm for several months to help them with initial problems of manufacture. More successful were the contacts with the manufacturers over the production of the first batches of Mark II. In March 1942 the first order (a highly experimental and speculative one) was pushed through the somewhat hesitant M.A.P. by Mr. A. A. Hall. The first contract was placed with Ferranti Ltd., followed by a further contract with Reyrolle Ltd. (Newcastle). When the capacity of these firms, even allowing for a new factory specially to be built by Ferranti, appeared still insufficient, Mr. Hall persuaded the M.A.P. to bring in a third firm—Hall Telephone Accessories—a firm of electrical engineers who, though small, possessed a specialised engineering knowledge and were able to introduce many small but important improvements in the course of production. But here also the assistance from R.A.E. was constantly sought. On their part the R.A.E. designers spent the whole of the following year—1942–43—in removing snags, in designing testing equipment for firms, in getting people in the firms educated in the principles and construction of gyro-sights, and in teaching the Services all they needed to know about maintenance and installation.

This development, so successful in practice and, at the same time, so wholly concentrated in the hands of a government establishment, stands in contrast to the history of the automatic sight in America. In America the development of gun-sighting aids had been largely in the hands of an important and highly influential firm of instrument makers—Sperry's. Indeed, so powerful was the Sperry influence that when in late 1940 samples of Mark I were sent to the United States through the British Air Commission, they failed to arouse any interest in American technical circles. Such tests as were later, in mid-1941, carried out at Wright Field did not turn out well and created the general impression that the sight was 'no good'. At the end of 1941, Dr. Wheeler Robinson took with him to the United States sketches of the Mark II. These were not liked either. The American technicians and Army Air Force preferred the Sperry sight, which was apparently a workmanlike contrivance, quite accurate in assessing deflection, but assuming steady flight and therefore of a somewhat limited practical value.

The American firms, both Sperry and General Electric Co., were also experimenting with the gyro principle, and had several gyro-sights in development, but so far the equipment they had produced was more elaborate, bulkier, more expensive and not as efficient in action as the British. Yet it was not until the summer of 1942, after Mark IIC had been sent over, that opinion in American official circles began to change. By the end of 1943 they had completely gone over to the British sight, which they proceeded to adopt without substantial alteration. In the middle of 1944 the American production programme for the British type of gyro-sights was greater than the British, and the sights were being fitted to fighters and bombers alike.

(v)
Conclusion

This concludes our account of the relation of State and industry in design, and our attempt to allocate between them the credit for the quality of British aircraft. The argument it unfolds is somewhat circular for it merely supports the contention with which this chapter has been introduced—the contention that in the technical progress of British aircraft officials and technicians, both public and private, co-operated and combined in a variety of ways. Indeed so intricate and continuous was the combination that no historian will ever be able to support the single and more exclusive views sometimes propounded from the platform and the press. Individual designs were more or less private or more or less official: some of them, e.g. the Mosquito and the Merlin, were wholly due to private firms; others, the gyro-sight and radar, almost entirely due to the Air Ministry, M.A.P., Telecommunications Research Establishment or R.A.E. Most of the designs, however, were indebted to Government agencies and private firms in equal, or almost equal, measure.

CHAPTER VI

THE QUALITY OF BRITISH AIRCRAFT COMPARED WITH DOMESTIC EXPECTATIONS

(i)
Introductory

We have surveyed the improvements in the British fighters and bombers between 1940 and 1944, and have shown that great advances were made. Though the race with the enemy was very close, he was very seldom able to draw ahead. On the other hand the progress appeared somewhat more disappointing in comparison with domestic expectations. From some points of view divergencies from domestic hopes need not be taken too seriously. They were more noticeable in relation to certain new types than in relation to the general progress of quality. Above all, they bore witness to excessive hopes in official quarters rather than to failures in aircraft design. These divergencies, nevertheless, deserve special study, for such a study will help to point certain important historical lessons; to focus attention on the political, administrative and industrial setting of war production from which the divergencies arose; and to bring to light the improvised measures adopted to alleviate them. For while long-term plans for brand-new types often resulted in failure, short-term improvisations and modifications to existing types largely succeeded in filling the gaps. And it is in these improvisations that the main achievements of British technicians and designers will be found.

(ii)
Fighter Plans, 1936-40

If between 1941 and 1944 new British designs failed to come up to expectations, the failure was only a relative one, i.e. relative to the comparable achievements of the preceding period. We must, therefore, begin the story by recapitulating the achievements of the earlier period and re-assessing them in the light of the plans of the Air Council and the expectations of the designers. Broadly speaking, it would be true to say that between 1935 and 1940 the design and development of aircraft proceeded more or less according to plan. Nearly all new aircraft appeared later than expected and some also disappointed the hopes of the Air Ministry when they appeared, but generally speaking the overall progress of quality was as great as the general plans of the Air Staff required. If the detailed projects of individual aircraft were disregarded, there would appear to be two such general plans to be taken into account: one was the plan for the re-equipment of the Air Force, especially in fighters, as formulated between 1934 and 1936; the other was the plan for heavy bombers, as embodied in the bomber programmes of 1937 and 1938.

We have already shown how the hesitancy of the Air Ministry before 1936, and their detailed plan under the Scheme F of 1936, were founded upon the expectation that by the spring of 1939 the British fighter squadrons would be equipped with fighters of the quality of the Hurricane and Spitfire.[1] These hopes were somewhat delayed, more especially in the case of the Spitfire, but the overall delays were not greater than about seven months. Under the Programme F it was expected that 600 Hurricanes and 300 Spitfires would be delivered to the R.A.F. by March 1939. In actual fact these totals were achieved in October and August 1939 respectively, but the first aircraft of either type was in production little later than the date promised by the firms and expected by the R.A.F.

Viewed in detail, some of the other contemporary hopes failed to come true. The much hoped-for cannon fighter—the Whirlwind—came into production eight months after its expected date, and was not very successful when it appeared.[2] Even greater difficulties were encountered during the development of the Tornado/Typhoon, with the result that this type came into general service with a delay of about twelve months.[3] Yet, disappointing as these expectations were in detail, they did not destroy the general plan of providing the Air Force with a cannon-firing two-seater fighter for night and long distance duty and with a single-engined aircraft carrying cannon in its wings. The gaps in the programme were filled by the Beaufighter and the cannon-firing Hurricane. Both these innovations

---

[1] See pp. 3–4.

[2] The firm had promised they would bring the aircraft into production 9 months after the production order. The order was given in January 1939 but the first Whirlwind was not delivered until June 1940, that is 8 months later than the firm's promise.

[3] According to the July 1939 programme the first Typhoon production aircraft was expected in July 1940, but the first Typhoon was not delivered until July 1941, a delay of 12 months. See also table on p. 127.

were available in sufficient numbers and approximately at the time at which the appearance of suitable types of aircraft for these functions had originally been expected.

(iii)
Bomber Plans, 1936-40

More serious and more difficult to remedy were the delays in the progress of bombers. Already in 1936 and 1937 great disappointment and considerable delay in the re-equipment of the Air Force resulted from the slow development of the Hampden and the Wellington. The history of both, and more especially that of the Wellington, was beset by a series of accidents, (the development of the Wellington was greatly delayed by the destruction of a prototype during trials). In the end, the Hampden and the Wellington appeared in production about a year later than originally expected, and nearly six years after their tender design stage.[1] In the case of both aircraft, however, the harm done by the delays was more than compensated for by the improved quality. The Wellington and the Hampden, as they appeared in service in 1939, were larger and better aircraft than those originally ordered from the firm; they were capable of heavier loads, longer ranges and (in the case of the Wellington) greater development, than were expected when the specification was drawn up by the Air Ministry.

Somewhat similar was the balance of disappointment and fulfilment concerning the heavy bombers. From the middle 'thirties onwards the Air Staff plans for bombers were anchored on the heavy bombers. Several developments converged on this point. On the one hand there was the growing belief in bombing as a strategic weapon. By 1937 it came to be considered in the Air Staff as England's chief striking arm and indeed her chief instrument of defence. This point of view found its clearest and fullest expression in the 'Newall memorandum', submitted in October 1937 by Sir Cyril Newall the Chief of the Air Staff at that time. In that memorandum bombers were treated not only as the best weapon of the air offensive but as the chief and in some senses the only defensive weapon available to this country. This view had not been previously expressed in a form quite so extreme, but there is every sign of its having become the general doctrine of the Air Staff long before then.

[1] At the production conferences in 1936 it was estimated that the first production Wellington would be delivered in June 1937. The first production Hampden was estimated to be delivered in August 1937. The first Wellington was not delivered until October 1938 and the first Hampden until September 1938, that is 16 months and 13 months late respectively. The tender design conference for the Wellington and Hampden was on 29th May 1933, that is nearly 6 years before the delivery of the first production aircraft.

To this strategic idea there came to be added in the course of time a set of tactical and technical notions which led inevitably to the conception of heavy bombers. If bombers were to be used as an independent striking weapon they had to be given a greater range and carrying power than the medium and medium-heavy bombers then under development. The underlying technical ideas were worked out in a series of papers on the 'Ideal Bomber', which have already been mentioned elsewhere.[1] In the document prepared by Mr. Wallis of Vickers-Armstrongs, and circulated by the company to the Air Staff, the optimum size was put at about 50,000 lbs. all-up weight or some 66 per cent. more than the greatest weight to which the Wellington had then been developed.[2] In the official Air Ministry memorandum on the ideal bomber of March 1938 the optimum size was put up to 65/70,000 lbs.[3] At this size the aircraft was expected to attain the maximum carrying power and range compatible with the greatest possible capacity for defence. It was also thought to be more economical than smaller types in crews and ground maintenance. Neither of these documents, however, did more than justify what by then had become the accepted trend of official requirements. By February 1937 the Air Council definitely made up their mind in favour of the super-bombers; already in the previous autumn there had appeared the two specifications with which the history of the heavy bombers begins, the B.12/36, from which sprang the Stirling, and the P.13/36 to which the Manchester and the original Halifax were both designed.[4]

We have already shown elsewhere how each of the heavy bombers then projected came to be delayed by failure of their engines, hazards of airframe design and by other accidents.[5] The prototypes of the three heavy bombers—the four-engined Stirling (B.12/36) and the Manchester and the Halifax (P.13/36)—were ordered in the spring months of 1937, and it was expected that all three would be in production during 1940. Under the expanded Programme L, as sanctioned in October 1938, some 3,500 heavy bombers of all three categories were to be delivered to the R.A.F. by April 1942.[6] As we now know, the heavy bombers, in the form in which the R.A.F. could safely use them, did not begin to appear in service until 1941, and the total of 3,500 delivered was not reached until the spring of 1943. The overall delay was thus about a year. Yet it was

---

[1] See pp. 78–79.
[2] The Wellington IC weighed 30,000 lbs. all-up.
[3] See p. 79, fn. 1.
[4] Specification B.12/36 issued 15th July 1936; four-engined bomber. Specification P.13/36 issued 8th September 1936; twin-engined medium bomber.
[5] See Ch. IV, Section (ix).
[6] In October 1938 it was planned that the following heavy bombers were to be delivered before April 1942: 1,500 Manchesters, 1,500 Stirlings, 500 Halifaxes.

not all a dead loss. In the case of only one bomber—the Stirling—was nothing gained from the delay, and the bomber, as eventually delivered, was no better, and probably worse, than the aircraft the Air Ministry had hoped to get. But both the Handley Page and the A. V. Roe bombers appeared in the end in a form greatly superior to the original Halifax and the Manchester designs. To an historian the episode is therefore bound to appear as a blessing in disguise. Although the numbers available by the spring of 1942 were much less than that forecast, the average bomb-load by that date (to say nothing of the qualities which could not be so easily added up) was much higher than that provided for in the original Halifaxes and Manchesters.

(iv)
June 1940 and after

Thus until 1940, and possibly even to 1941, plans and achievement synchronised well: in bombers, as well as in fighters, earlier hopes were not greatly belied by subsequent achievements. But the general impression is that after 1940 hopes began to outrun achievements. How wide the gaps were over the whole range of British aircraft no historian will ever be able to tell. After 1940 it becomes more difficult to compare the general progress of quality with the general expectations, for the simple reason that between that date and the end of 1943 no such general expectations were formulated. The conditions in M.A.P. under Lord Beaverbrook and his immediate successors were unpropitious to long-term programmes. The R.A.F. itself was pre-occupied with its day-to-day needs, and new tactical requirements were faced only as they occurred. In these circumstances, inevitable in war-time departments working under pressure, it was found impossible to direct future progress to general objectives as clearly defined as those of the fighter programme of 1936 and of the heavy bomber programme of 1938. Changes in design and improvements occurred more or less piecemeal, and successes and failures must, therefore, also be judged in detail.

One such detailed plan on which great expectations were based in 1940 and 1941 was that for the Spitfire/Hurricane replacement. Much was hoped of the Tornado/Typhoon, and as we have seen the hopes were continually delayed by the shortcomings of the Sabre engine. The aircraft was planned to appear in service early in 1941, but it did not get into service in considerable numbers till late in

1942, when its deliveries compared with the original plans as follows:

Typhoon Deliveries Expected and Actual
Programmes dated

	July 1939*	January 1940*	March 1941	*Actual*
1st aircraft .	July 1940	October 1940	March 1941	July 1941
500th aircraft . (approx.)	September 1941	January 1942	February 1942	October 1942

* These two programmes only show the estimated rate of output at quarterly intervals. In this table the build-up of output has been calculated by basing the quarterly figure on the average monthly output for the quarter.

What is more, the Typhoon, as it appeared in service, was not quite the aircraft originally expected. It was clearly a fast, sturdy aircraft, which turned out to be useful for low level attack, and eventually was to prove especially suited for the installation of rocket armament. But it was not a replacement of the interceptor fighter class which was its designed role. Its speed in operation proved to be a whole 30 m.p.h. below the M.A.P. forecasts, and about 60 m.p.h. below the figure which the designers themselves had at one stage suggested.[1] Its climb and ceiling were inferior not only to the contemporary German aircraft, but also to the contemporary Spitfire, and the unreliability of its engine, the Sabre, was a great handicap. The result was that the gap in the development of single-engined pursuit fighters had to be filled by other means, mostly by further developments of the Spitfire itself.

Fulfilment and promise were somewhat more closely matched in the development of the Typhoon's offspring—the Tempest—though even there, as with the Typhoon, the Sabre engine proved the worst obstacle. The Tempest did not appear in January 1943 as expected; first deliveries only began in October 1943. Its final performance, though very high indeed, was somewhat lower than originally expected, and was by that time soon to be exceeded by the latest Spitfire, the American Mustang III and possibly one or two contemporary German fighters.[2] It was however able to play an important, perhaps a crucial, part in a critical episode in the closing

[1] The Air Ministry estimated the speed of the Typhoon could be 428 m.p.h., whilst the Hawker Aircraft Co. estimated a maximum speed of 464 m.p.h.; but according to official performance figures issued by M.A.P. the actual speed was 400 m.p.h. The designer's forecast was partially based on Napier's estimated performance of the Sabre engine.

[2] The firm estimated a speed of 455 m.p.h. for the Tempest I which was confirmed by M.A.P.; but according to official performance figures issued by M.A.P. the actual speed was 427 m.p.h. The Spitfire XIX had a speed of 457 m.p.h. and the Mustang III a speed of 450 m.p.h.

stages of the war. Both the Typhoon and the Tempest were brought in to fight the V.1 flying bomb. Both proved sufficiently fast for the task, especially when 'hotted up', brought down a very large number of the missiles, and were largely responsible for winning this particular campaign.

Other plans in the field of fighters concerned the high-altitude fighter. We have already noted that as regards bombers the Air Staff were never wholly converted to the idea of sub-stratosphere operation, and that plans for the specialised bombers of this kind were never pressed very hard.[1] The same is largely true of the high-altitude fighter. The idea was not adopted for general application, and the specialised high-altitude fighter continued to be regarded as a largely experimental weapon of limited use. At the end of 1940 the Air Ministry and M.A.P. sponsored the Westland design of a twin-engined high-altitude fighter—the Welkin. This aircraft finally appeared in production in September 1943, and by that time neither its performance nor its tactical usefulness appeared fully up to the more optimistic expectations of 1941. It turned out to be not only heavier than the designers originally estimated, and some 15 to 20 m.p.h. slower than what they hoped to achieve, but also slower than the Mosquito NF.30[2] which was shortly to make its appearance. Nevertheless, the Welkin should not be regarded as a complete failure. The advantage of a few thousand feet in altitude which it possessed over the Mosquito was thought to be valuable, and it also proved somewhat more stable in flight at extreme heights than the Mosquito. Also its pressurised cabin proved to be technically superior to most other pressurised cabins then in existence. Thanks to these advantages it was maintained in production in spite of the existence of the Mosquito and was, in its later version, made to compete with the Mosquito still more closely by being converted into a two-seater.

So much for the plans and achievements in the history of fighters between 1941 and 1944. The progress was marked by some disappointments, some serious, others not. Judged by domestic expectations the development of bombers in the same period was considerably more disappointing. As we have already said the progress

---

[1] See Ch. IV, Section (v).

[2] The specification (F.4/40) called for a speed of 400 m.p.h. which was presumably in accordance with the firm's expectations, but the Welkin's actual speed according to official performance figures issued by M.A.P. was 385 m.p.h. At the design conference on 17th October 1940, Capt. Liptrot estimated the weight would be 17,500 lbs. and the firm's estimates were a little below this, but the actual weight was 19,500 lbs.

The speed of the Mosquito NF.30 was 400 m.p.h. At the time when the Welkin specification was issued the possibilities of the Mosquito were barely realised and the high-altitude version had not been thought of. The Gloster F.9/40 jet propelled fighter was originally designed for similar duties to the Welkin but was eventually produced as a low-altitude version.

of bombers after 1940 was not subordinated to any general plan.[1] The ideas and calculations underlying the ideal bomber theory in 1938 were brought up-to-date by 1940, and it became generally assumed that the ideal all-up weight of maximum size should be raised from 60,000 to 90,000 lbs. But little was done to plan a general advance towards that goal. The need for ever greater numbers to feed the bombing offensive made a general re-equipment of the bomber force impracticable. The new projects conceived in those years came into existence piecemeal and in relation to the immediate tactical need to make use of passing technical opportunities. The act which inaugurated the post-1940 phase was in itself symbolic. One of the projects cancelled in the prototype stage during Lord Beaverbrook's ban on new developments was that of the B.1/39 aircraft which had been designed to answer the full requirements of the ideal bomber plan.[2] All the subsequent bombers owed their rise to special, and often accidental, circumstances.

In the heavy bomber class nearly all the new designs of that period were associated with the firm of Vickers. One of them was the B.1/35 Warwick, a carry-over from the earlier period. In the spring of 1941 Vickers were encouraged to proceed with another project, a 4-engined pressure cabin bomber known as the B.5/41, which was a development of the Warwick. A short while before, they had proposed as a private venture a 50-ton, high-altitude, 6-engined bomber, to carry a single enormous bomb, but this never received much official support. Another Vickers' project blessed by M.A.P. was for a Wellington replacement—a high-speed, twin-engined bomber powered by Centaurus engines; in June 1942 on M.A.P's initiative this latter project was merged with the B.5/41 and became the B.3/42, high-speed, 4-engined, heavy bomber, known as the Windsor. The history of most of these Vickers aeroplanes was marked by disappointments and broken by continuous interruptions and delays.

Of the types which reached the production stage, the Warwick was the most spectacular failure of all. It was originally designed as a replacement for the Wellington when the weight restrictions on bombers were removed in 1934, but after the Wellington had been substantially redesigned and the first heavy bomber specification (the P.13/36) issued, the requirements for the Warwick became obsolete. Consequently Vickers redesigned it with engines of improved performance. In this form the Warwick provided a more satisfactory replacement for the Wellington, but in this form it also competed with the Manchester, the new twin-engined heavy bomber

[1] See Ch. I and M. M. Postan, *British War Production* (H.M.S.O. 1952), Ch. IV, Section (3).

[2] Specification B.1/39 issued 5th January 1939; four-engined bomber.

project. Even powered with two Centaurus engines the Warwick still compared unfavourably with the four-engined bombers. Nevertheless the need for a replacement for the Wellington, together with the production advantages of continuing geodetic construction at one of the Vickers' factories, earned for it the support of M.A.P. which persisted in spite of its unpromising technical prospects. Its prospects were further disturbed by delays in production due to competing demands for Wellington bombers. It was not until July 1942 that the Warwick bomber came into production,[1] and by that time it was well behind the Air Staff requirements. Moreover tests of the first aircraft revealed great weaknesses in the design; the aircraft was heavy, slow, underpowered and unable to maintain flight on one engine. In January 1943 (by which time the firm were committed to 57 unwanted bombers) the final decision was made to convert the type into a transport, and an air/sea rescue aircraft; and it was for these unpremeditated uses in unplanned for branches of the aircraft programme that the Warwick began to be produced in numbers in the summer of 1943.

The latest of the Vickers' bombers, the Windsor, could not be judged by the end of the war in Europe for the aircraft was not by that time in production. As described above,[2] it grew out of two entirely different projects for the new Vickers' bombers—one a four-engined, pressure cabin, high-speed, bomber with Merlin 60 engines, known as the B.5/41, developed from the Warwick pressure cabin project, and the other a project based on M.A.P's requirements for a fast medium bomber replacement for the Wellington Mark X. This latter aircraft was to have two Centaurus engines and was to be roughly similar to the Bristol Buckingham.[3] The two Vickers' projects had little in common except the requirement for high speed. As the turret presented the main obstacle to increased speed in bomber aircraft, many alternative schemes for arming the aircraft were discussed, ranging from the new idea of remotely controlling the guns to no guns at all. In the end Vickers were entrusted with a scheme containing the residue of both types, e.g. a fast geodetic bomber to replace the Wellington, powered with four Merlin 61 engines, and the design became known as the B.3/42 or the Windsor.[4] But many changes in the specification, together with the difficulties in the development of the remotely controlled armament,

[1] The first prototype redesigned with Vulture engines flew in August 1939 and the second with Centaurus engines in April 1940. The production order was finally placed in December 1940. Owing to a shortage of Centaurus engines considerable numbers of early Warwicks were modified to take American Pratt & Whitney Twin Wasp engines.

[2] See p. 82.

[3] That is to say similar in its operational characteristics. The Bristol Buckingham medium bomber is described below, see pp. 131–132.

[4] In the winter of 1942–43 the War Cabinet sanctioned its inclusion in the aircraft programme.

delayed the early prototypes and also the early production. By that time the preview of the Windsor's qualities no longer suggested the possibility of any spectacular advance over contemporary heavy bombers.

Into the same category of disappointed expectations should be included the only new medium bomber to be produced in that period—the Bristol Buckingham. Other projects of new medium bombers were considered during the winter of 1941–42 and one of them—the fast Hawker unarmed bomber[1]—came, at one point, very near fruition. If only one of the projects, that of the Bristol Buckingham was allowed to come into production, the chief reason was again the shortage of suitable high-powered engines. The origin of the Buckingham goes back to the proposals which the firm made in early 1939 for a development of the Beaufighter—the Beau-bomber. The Air Staff showed no enthusiasm until it was resuscitated at the end of 1940 in connection with the abortive requirement for an Army Close Support Bomber. Its low performance caused it to be converted in early 1941 into a medium day and night bomber powered by two Centaurus engines, with a torpedo-carrying version. The firm were given a prototype order and were allowed to proceed with development, although the fate of the type was constantly discussed by M.A.P. and the Air Ministry. The Air Staff themselves were on the whole in favour of the new type. Although undecided as to the tactical future of the medium bomber, they were in no doubt as to the rapidly approaching obsolescence of all existing British and American medium bombers and demanded a replacement. On the other hand M.A.P. were at a loss to provide capacity for the required peak output on top of the recent heavy bomber programme. Discussions continued from May 1941 until July 1942, while the firm complained that it was losing interest in the project. In November 1941 a preliminary order was at last given.

It is possible that had the Buckingham gone into production as first planned, late in 1942, the results might have justified the original decision. But, instead of appearing in late 1942 or early 1943 (and this was as much the firm's responsibility as it was the Government's), the first Buckingham prototype did not fly until July 1943, whilst the first production aircraft was not delivered until February 1944. These delays were to some extent due to the shortcomings of the early Bristol Centaurus engine, which was about 10 per cent. to 20 per cent. inferior in power to that originally planned. Another circumstance which prejudiced the future of the Buckingham was the somewhat unexpected excellence and versatility of the Mosquito. From the very first the Mosquito was able to do

[1] Specification B.11/41.

more than the Buckingham ever aspired to, and much more than it in fact achieved—it could travel faster over ranges only slightly shorter and could carry a load equally heavy, if not heavier (see col. (*b*) of table below). The result was that at the beginning of 1944 the R.A.F. were about to receive a brand new bomber, designed to fulfil a largely obsolescent tactical function, and furthermore barely equal in performance to the Mosquito. Except in range, it was little superior to the American medium bombers, some of which were, at that time, at least two years old. However, in justice to the designers of the Buckingham, to the Air Staff and to M.A.P. it may be worth noting that the contemporary American Douglas Invader, a medium bomber scheduled to appear in 1944, was from some points of view as much a disappointment as the Buckingham.[1] Compared to the other aircraft the qualities of the Buckingham were as follows:

Comparison of British and American bombers in light and medium classes

Type	(*a*) *Max. speed m.p.h. at ft.*	(*b*) *Max. load at range*	(*c*) *Max. range at load*
Buckingham (2 Centaurus VII)	345 at 11,250	4,000 lbs. 1,570 miles	2,850 miles Nil
Mosquito B.IX (2 Merlin 72)	397 at 26,000	5,000 lbs. 1,370 miles	1,870 miles 1,000 lbs.
Boston IV (U.S.A.) (2 Cyclone R.2600)	320 at 11,000	4,000 lbs. 710 miles	1,570 miles 2,000 lbs.
Marauder II (U.S.A.) (2 Pratt & Whitney R.2800-43)	305 at 15,000	4,000 lbs. 900 miles	1,200 miles 4,000 lbs.
Invader (U.S.A.) (2 Cyclone R.2800-27)	340 at 15,000	4,000 lbs. 1,360 miles	1,630 miles 3,000 lbs.

The most outstandingly successful medium or light bomber of the period was without doubt the Mosquito, but its achievements cannot fairly be compared with expectations. It did not come into existence in fulfilment of any previously laid official plans, and from the point of view of the Air Ministry and the M.A.P., its appearance was utterly unpremeditated.[2] Like the Spitfire, it also succeeded in maintaining its superb quality in all its subsequent developments and modifications as a night fighter, as a high-altitude photographic reconnaissance, as a fighter-bomber and as a special purpose fighter

[1] In 1942 official estimates given to the Fedden Mission gave promise of a really high speed, 372 m.p.h., but, as was the case with the Buckingham, this speed, one of the chief attractions of the type, was not realised.

[2] See pp. 84-85.

mounting heavy armament. In this way the Mosquito not only exceeded the original estimates of its designers, but also made it possible for the R.A.F. to outstrip all its foreign rivals and the original estimates of its designer in the field of light bomber and twin-engined fighter throughout the later stages of the war.

(v)
Plans for Naval Types

The field in which failures occurred and hopes were deferred most frequently was that of naval types. So far, the naval types have hardly been discussed. The reasons for this are several. In the first place, until Japan's entry into the war British achievements in this field could not be profitably compared with the enemy's, since Germany did not pay much attention to specialised naval types and Italy was also deficient in carriers and carrier-borne aeroplanes. In the second place, naval types cannot be discussed against the general background of air war and of the Air Force requirements arising from it, but have to be related to naval tactics and naval architecture. For this reason alone the failures which mark the history of naval types (and they were both grave and continuous) cannot be fairly grouped together with the failures or successes of the land types. So grouped they would inevitably throw a shadow on the entire picture —a shadow which is not only blacker than the aircraft history as a whole, but also irrelevant to its main outline. For, as we have just said, the design of naval types was affected by troubles peculiarly its own in addition to the troubles of aircraft design in general.

These troubles were very nearly as old as the expansion itself and prejudiced the quality of naval aircraft even in the halcyon days of British design between 1934 and 1940. Naval requirements throughout this period were focused on two special types: the torpedo-spotter-reconnaissance and the fighter-dive-bomber or fighter-reconnaissance. The very hyphenation of the titles points to the character of naval requirements. A Fleet Air Arm aircraft even more than land-based aircraft had to be capable of a multiplicity of functions since the number of carriers available for attachment to any particular fleet or station was very small; indeed much too small to allow the Navy to plan to use a wide assortment of aircraft. Moreover, whatever their function, naval types had to satisfy certain special conditions regarded as essential for naval purposes, but often inimical to good design. To begin with, all carrier-borne aircraft had to be adjusted to the limitations of storage in aircraft carriers. This meant that their wings had to fold in order to facilitate the storage of the largest possible number of aircraft in their hangars.

This provision added slightly to the weight of the aircraft as well as to the complication of the design. Naval aircraft were also subjected to limitations of wing loading (and therefore of speed) to facilitate take-off and landing, and these limitations were only partially overcome by the development of arrester gear and the accelerated take-off. There were also other requirements springing from the current notions of naval tactics. Thus for a very long time the Navy insisted on an additional cockpit for a navigator in fighters, even though the general character and dimensions of the design were best suited for single-seater aircraft.

These technical problems prejudiced the design of aircraft operating from floating aerodromes compared with those operating from land aerodromes. This did not appear to matter much so long as the strategic assumption was that the Fleet Air Arm would not be required to operate within range of enemy land-based aircraft, but became very serious when circumstances of war pitted the Fleet Air Arm against enemy land planes. Finally, to the disadvantages inherent in the naval function of aircraft and to the disadvantages resulting from the tactical ideas behind a naval requirement, we must also add certain unfortunate features of design which sprang from the shortcomings of the firms specialising on naval aircraft production.

This combination of adverse circumstances affected almost every new project. The series of torpedo-spotter-reconnaissance aircraft produced during the expansion period began with the very excellent biplane—the Fairey Swordfish.[1] This type was already in production in 1936, when it was included in Scheme F. During the same year requirements were issued for its replacement,[2] which was scheduled to come in in 1938. Fairey's, on account of their experience with Fleet Air Arm types, were selected to produce the design and submitted both monoplane and biplane projects. But even at that late hour the risks of monoplane design appeared to be too great, and the order which went out in May 1937 was for the biplane version with an expected speed of no more than 180 m.p.h.

This was the genesis of the Albacore. Its subsequent history was in most respects behind expectations. One of the reasons why a biplane was preferred was that it was thought that this would make it possible to go into production speedily without elaborate trials. But as it turned out, the Albacore was greatly delayed, mainly by the tardy progress of its engine (the Taurus). The first available for tests did not fly until the spring of 1939, and production began so late that aircraft were not available for service until the spring of 1940.

---

[1] Designed to Specification S.15/33.

[2] June 1936.

Soon after the Albacore had been ordered the Admiralty, aware of its shortcomings, had issued requirements for a much improved monoplane,[1] and out of this requirement the Barracuda was eventually to come. From a wide selection of firms Fairey's was again chosen as the best. Prototypes were ordered in May 1938, production orders followed a few months later, and the aircraft was planned to go into production in the summer of 1941. In ordering it the Admiralty and the Air Ministry had every hope that in 1941 it would be far in advance of both the Swordfish and the Albacore, and well up to contemporary technical standards. But hopes were soon belied. The type was continually delayed by events outside the Admiralty's control—especially by a change in the engine and the Battle of Britain break in development—and it was not until 1941 that the prototype was delivered, and not until 1942 that aircraft began to come off the production line.[2]

Thus the Fleet Air Arm entered the war in 1939 and fought on the seas until 1943 with the majority of its squadrons equipped with the Swordfish, a type which was obsolescent in 1938. With the help of these aircraft the battles of Taranto and Matapan were won, the *Bismarck* crippled, Malta maintained as an offensive base throughout her siege, and convoys in the Atlantic and on the Northern route to Russia were served. The following table will show the relative performances of naval torpedo-bomber aircraft produced during the period. The Avenger (the U.S. Navy torpedo-bomber)[3] and the Bristol Beaufort (a land-based torpedo-bomber to a 1936 specification) are also shown for comparative purposes.

Comparative performance of torpedo-bombers

	Max. speed m.p.h. at ft.	*Max. load lbs.*	*Range miles*	*Date in service*
Swordfish	138 at 5,000	1,500	875	1936
Albacore	161 at 4,500	2,000	710	1940
Beaufort I	257 at 5,500	1,650	1,720	1940
Barracuda I	235 at 11,000	2,000	524	1943
Avenger (U.S.A.)	248–252 at 14,000	2,000	950	1943

The story of the fleet fighter is even more melancholy. What eventually saved the naval fighter force was that, contrary to the Admiralty's belief, converted single-seater land fighters proved

[1] Specification S.24/37, 6th January 1938. Requirements were issued to firms in October 1937.

[2] First production aircraft was delivered in July 1942.

[3] Too much attention need not be paid to the higher speed of the Avenger. In the Admiralty's view the British tactics of torpedo attack did not at that time need speeds higher than those of the Barracuda.

excellent fleet fighters. It was they and the American Navy fighters, the Martlet, later known as the Wildcat, the Corsair, and the Hellcat, that formed the backbone of the Fleet Air Arm fighter force from 1941 onwards.

Until 1938 the standard fleet fighters in service remained the antiquated biplanes, Nimrod and the Osprey. The first monoplane fleet fighter was the Skua, a two-seater fighter-dive-bomber, designed by Blackburn's as early as 1934 to Specification O.27/34. This Blackburn design was the first to overcome the special problem of monoplane wing folding, but unfortunately this and other technical problems so delayed the type[1] that the Admiralty were faced in 1938 with a serious deficit of fighter planes as well as the prospect of having to rely in war on the antiquated Nimrod and Osprey.[2] This serious lack of fighters called into being the Fairey Fulmar, a two-seater fighter conversion of a single-engined light bomber.[3] This type was ordered 'off the drawing-board' in the spring of 1938 and deliveries were hoped for in the autumn of 1939, but in fact not achieved until six months later. The Fulmar was a stop-gap type of low performance. In addition, in order not to delay delivery, many design concessions were permitted which served only to increase the gap between performance required and performance achieved.

The prospects of having Fulmars in 1940 were thus insufficient to relieve the picture which the fleet fighter force presented in 1939. The latter had nothing but the by now all-but-obsolescent Skua and a few additional Gladiators modified for deck landing. Projects for a new and much better fighter were therefore advanced with every show of urgency. Unfortunately the Admiralty requirements were not complete until the spring of 1939 and, when issued to the firms, they still embodied the disputed two-seater cockpit. By now there was a considerable body of opinion within the Admiralty itself which demanded single-seater fighters in order to achieve comparable performances to R.A.F. types. In spite of this the new N.8/39 and its companion, the turret fighter N.9/39, remained specified as two-seaters, and the Admiralty did not re-open the question officially until the tender designs for the two-seater fighter turned out to be deficient in performance and three months of war experience had shown decisively that high performance for fleet fighters was of paramount importance. Yet even now, minds were not ripe for a single-seater or a converted land fighter type. The

---

[1] The Skua prototype should have been delivered in 1936 and production aircraft should have been delivered in 1937.

[2] The other Fleet Air Arm fighter under development was the Roc, a turreted version of the Skua somewhat on the lines of the Defiant. Since it was dependent on the technical progress of the Skua, however, the Admiralty could not expect any relief from that quarter and in fact it did not turn out to be a success.

[3] This single-engined light bomber had been designed by Fairey's to Specification P.4/34.

Fairey two-seater design to Specification N.5/40 (afterwards named the Firefly) was accepted for production and 200 were ordered in May 1940. As a concession to the opposite doctrine two prototypes of a Blackburn single-seater design to Specification N.11/40 (the Firebrand) were also ordered experimentally and a small production order followed. The performance expected of these two types (350 m.p.h. for the Firefly and 400 m.p.h. for the Firebrand) promised a considerable improvement on the existing types, but unfortunately technical troubles, production difficulties and other snags held back production and reduced performance of these types until it was too late for them to be of service to the Fleet Air Arm in the war as first-class interceptor fighters.

The following table gives (A) the performances of the fleet fighters compared with (B) contemporary single-seater fighters for the R.A.F., (C) single-seater R.A.F. fighters converted for naval use and (D) American naval fighters.

Comparative performance of naval and other fighters

	Max. speed m.p.h. at ft.	*Range miles*	*In service*
(A) *Naval Fighters*			
Osprey III (Two-seater)	157 at 10,000	561	Before 1935
Nimrod II (Two-seater)	189 at 10,000	493	Before 1935
Skua (Two-seater)	224 at 6,500	1,000	1939
Fulmar I (Two-seater)	246 at 9,000	810	1940
Firefly (Two-seater)	321 at 17,000	572	1943
Firebrand	353 at 18,000	647	1944
(B) *R.A.F. Fighters*			
Gladiator	245 at 15,000	523	1937
Hurricane I	316 at 17,750	585	1938
Spitfire I	356 at 19,000	580	1938
Spitfire Vb	374 at 13,000	480	1941
Spitfire XIV	456 at 26,000	1,260	1943
Tempest V	414 at 18,500	650	1944
(C) *R.A.F. Fighters converted to Fleet Air Arm use*			
Gladiator	245 at 15,000	523	1939
Sea Hurricane	308 at 18,000	555	1941
Seafire IIc	356 at 20,000	453	1942
(D) *American Naval Fighters*			
Martlet	313 at 14,500	870	1940
Corsair	374 at 23,000	673	1943
Hellcat	380 at 23,000	762	1943

This table epitomises the entire story of naval fighters. But for the modified R.A.F. types and the American fleet fighters which filled the gap from 1941 onwards, the British Fleet Air Arm would have had to face the enemy utterly unprovided with a modern fighter force.

By the third year of the war the insufficient progress of naval types became apparent outside Service circles. A debate in the House of Lords,[1] and a series of more fragmentary discussions in both Houses drew from the unofficial political spokesmen of the two Services a certain amount of explanation mixed with mutual recrimination. But although political discussion for a time succeeded in focusing public attention on the slow progress of naval types, it did little to reveal its causes. Had a proper inquest then been possible it would probably have shown that the difficulties over naval aircraft were partly due to special causes and partly sprang from causes common to all new designs of aircraft. The latter will more appropriately be discussed in the next chapter.

[1] H. of L. Deb., Vol. 125, Cols. 794–829, 27th January 1943.

CHAPTER VII

THE TIMETABLE OF DESIGN AND DEVELOPMENT

(i)
Introductory

SOME of the disappointments over new types were doubtless due to technical defects of the designs themselves. In so far as they were purely technical and sprang from inevitable hazards of scientific and engineering progress, they need not concern us here at all. But by no means all the disappointments could be regarded as legitimate technical risks. Viewed historically, the most damaging cause of disappointment was not technical deficiency but delays. For in the design of aircraft hopes deferred were hopes disappointed. Designs which, on technical grounds, appeared most promising at the time of their inception could turn out to be total or partial failures, merely because they had been delayed in development and were out-of-date by the time they reached the squadrons. Even when the aircraft, in spite of the delays, were still 'employable' at the time of their emergence, they were sometimes too late to meet the strategic and tactical needs for which they were first conceived. The Defiant, the Whirlwind,[1] the Warwick[2] and the Buckingham[3] are all well-known instances of aircraft whose usefulness was impaired by overlong development periods, but other and less conspicuous examples were to be found by the dozen. It is therefore proposed to go into the question of delays in greater detail.

The length of time which new types took on their way from their first inception as a project to their first operational use in a squadron, was determined by two sets of causes: one was largely administrative and concerned the number and the length of the different stages in the progress of a design; the other was largely industrial and was concerned with the introduction of a new type into a production line.

---

[1] See p. 123.
[2] See pp. 129–130.
[3] See pp. 131–132.

(ii)
Normal Procedure

The number and the length of the stages in the design and development of new aircraft will be dealt with in greater detail in an appendix.[1] The normal procedure, which was customarily followed before the early years of the expansion, involved six or seven separate phases. The first phase, that of inception, covered the period when the Air Staff compiled the operational requirements for a new type or when the aircraft firms gave birth to preliminary designs in anticipation of a coming operational requirement. The second phase covered the period when the Air Ministry, or later the M.A.P., formulated the official technical specification embodying the operational requirements of the Air Staff, and possibly also the technical forecasts of the industry. The third phase covered the competitive tender, and was largely devoted to a discussion, preceding the issue of the prototype orders, of the relative merits of the tender designs. The fourth phase was that of the construction of the prototype aircraft. This was followed by the fifth phase, that of tests and trials of prototypes. The sixth, and in some cases the seventh, phase covered the development and production orders.

As long as a new design had to pass through all these phases much delay was inevitable. What made it worse still was that some of these phases were in themselves unnecessarily long. The first phase, that of operational requirements and of technical forecasts, was, of course, inevitable and could not be subjected to any definite timetable. Some technical ideas and operational requirements arose very quickly, as in the case of the Mosquito,[2] the Beaufighter,[3] or the Whirlwind.[4] But often they took a long time to mature, as in the case of the Buckingham.[5]

The second phase, that of the specification, was subjected to a more regular timetable, and the timetable was long as well as regular. In the Air Ministry, and later in M.A.P., more than one technical branch were interested in new designs and insisted on having their interests represented in a new specification. So it is not surprising that the preparation of a specification took on an average from five to six months and frequently even longer.

---

[1] See Appendix II, of which this section is a summary.
[2] See pp. 84–86 and 132–133.
[3] See p. 94.
[4] See p. 123.
[5] See p. 131.

Considerable time was also taken up by the next phase, that of the competitive tender. After the specification was approved it went to the Director of Contracts whose business it was to invite competitive tenders. This stage used to take sometimes as much as a whole month, after which two to three months were allotted to the firms for the preparation of their tenders. Having received the tender designs from competing firms, the Director of Contracts sent them back to the Directorate of Technical Development and there the designs had to be first analysed and then submitted to a 'tender design conference'. After the Air Staff had received and discussed the conference's recommendations, the Director of Contracts was instructed to place orders for the prototypes.

The fourth phase, the construction of the prototype, was, for technical reasons, long and arduous. The first step which a firm had to take towards building prototypes was to erect a 'mock-up', i.e. a full-scale model of the fuselage and as much of the wing and tail as was necessary to demonstrate the pilot's view from the cockpit. The 'mock-up' was supposed to take about two or three months, and then another month or two, and sometimes more, were taken by the inspection of the 'mock-up' and criticisms and suggestions from different technical standpoints. This was followed by the design of detailed parts, the assembly of major components, and perhaps by tests in a wind tunnel. The prototype phase then culminated in the main assembly, but this in its turn was often followed by improvements and the redesigning of parts of the prototype in accordance with the lessons of the first flight. Altogether it was quite usual for the prototype phase to take two years up to the time of delivery, and very few aircraft passed over the prototype phase in less than eighteen months.

The duration of the next phase, that of official tests, depended very largely on the excellence of the design and the absence of accidents. Where, as in the case of the Wellington,[1] a prototype happened to be destroyed during tests, the whole business had to be suspended until a new prototype was constructed. Ordinarily this phase lasted from six months to a year. The sixth phase was that of the development order. At the conclusion of the prototype tests the Ministry as a rule placed a development order for a small number of aircraft which later was, or was not, followed by a production order. This stage also took about a year.

Considering the leisurely progress of new aircraft through the seven stages of design it is no wonder that new types took so long to mature. The duration of design and development of standard

---

[1] See p. 124.

R.A.F. types in normal peace-time conditions is shown in the following table:

Stages of Design and Development

	Time Allowed (months)		
Stage	*Small aircraft*	*Medium aircraft*	*Large aircraft**
1. Air Staff notify Director of Technical Development of requirements for new type	Zero	Zero	Zero
2. Director of Technical Development prepares specification.	5	5	6
3. Competitive tender (tender invitation; tender analysis and placing of prototype orders)	8	9	10
4. Construction of prototype	12	16	24
5. Tests and trials	9	14	16
6. Development orders	13	13	17
Development trials	12	12	12
7. Production orders	6	8	10
Approximate total time	$5\frac{1}{2}$ years	$6\frac{1}{2}$ years	8 years

* Excluding large flying boats.

The average was thus expected to be about seven years, and sometimes more. The interval was obviously too long, even for peace-time conditions, and was impossibly long in war. Strategic and tactical needs, which might have prompted a design at a certain stage, could not possibly have remained unchanged through the years of design and development. And to make all necessary allowances and to forecast the tactical and strategic needs six or seven years ahead was beyond the powers of the most prophetic of air strategists.

(iii)
Abridged Procedure

For all these reasons the six or seven year span could not be, and never was, taken for granted by the Air Ministry or by the industry even in peace-time, and remedies began to be thought of from the early days of the expansion period. To begin with, the steps taken were not very drastic, for the Air Ministry continued to rely on the optimistic promises of aircraft firms which made it appear as if quicker progress was possible under existing routine arrangements. Thus the Whitley, Battle, Wellington, Hampden, and Defiant prototypes—to take them in this order—were delivered six, ten, nine, eleven and nine months later than their makers had promised. It was the same with almost every other aircraft, with the possible exception of the Mosquito, Lancaster and the Welkin. But sooner or later, these facts were bound to impress themselves on both the Air Ministry and the industry, and the Air Ministry began to look for measures to shorten the period.[1]

There were two ways of bridging the gap: one was to speed up the procedure of some of the stages; the other was to cut some stages out altogether. The former—the general speed-up—was attempted all along the line, but the more drastic, i.e. the surgical, method was only possible at three stages: the competitive tender, the prototype and the development order.

The various abridgments of the prototype stage, including its complete elimination in some cases, came to be described in the Air Ministry as orders 'off the drawing-board'. The Ministerial Sub-Committee on Air Parity, reporting in May 1935, put it down as a general policy that, in order to shorten the development period, orders for new types should be placed in bulk before the prototype had been tested. On 21st May 1935 this recommendation was approved by the Cabinet who accepted the inevitable financial risks. In accordance with this policy, in 1936 four new types were ordered in quantity before handling and performance tests had been completed by the Air Ministry pilots. They were the Battle, the Hampden and the Wellington bombers, and the Spitfire eight-gun interceptor fighter. In these instances the prototype stage was not wholly omitted, for prototypes had, in fact, been constructed and in almost every case delivered before the production orders had been placed. In addition the prototypes had flown at their contractors' aerodromes some months earlier still. Somewhat greater savings of time in the prototype stage were achieved in the case of the Armstrong-Whitworth Whitley and the Boulton Paul Defiant. Production orders for the former were placed in August 1935, a whole year before the prototype was delivered, and in the latter case a large production order was placed in 1937 at least four months before the prototype flew, and eight months before it was delivered. Similarly, contracts for prototypes which afterwards became the Halifax, the Manchester and the Stirling bombers were quickly followed by production orders.

However these economies, valuable as they were, could not make a really great difference to the timetable as a whole. In the end the Air Ministry adopted the more drastic policy of cutting out the prototype stage altogether and ordering 'off the drawing-board' in the

[1] As early as August 1934, the A.O.C.-in-C., Air Defence of Great Britain, expressed dissatisfaction with the excessive time lag and he was not alone in his sentiments.

narrower sense of the term. Instead of ordering a prototype and testing it, the Air Ministry now placed orders for quantity production on the understanding that the first two machines produced would be rushed forward as prototypes. If, as a result of the tests, modifications appeared necessary, they were incorporated into the remainder of the production series. The earliest example of an order 'off the drawing-board', pure and simple, was the Bristol Beaufort, for which a production order for 78 machines was given in August 1936. Since then many other types have been ordered in this way. Examples are the Bristol Beaufighter, designed late in 1938 and ordered in quantity in April 1939, the de Havilland Mosquito, designed in December 1939[1] and ordered in quantity in January 1940 and several Fleet Air Arm types.[2]

The other stage to be abridged and eventually to be cut out was the competitive tender. For many reasons competitive designs came to be regarded as a luxury which the country could not afford under the stringent conditions of rearmament and war. Competition could be cut out in two ways: either by allowing full play to private initiative in the initial stages (so-called 'private venture') or by the policy of special orders to earmarked firms. The history and the character of some of the private ventures have already been dealt with.[3] It was always recognised in the Air Ministry that good ideas were often born in the firms in advance of official specifications. It was very fortunate that three of the most important aircraft introduced during the expansion period—the Bristol Blenheim, the Hawker Hurricane and the Supermarine Spitfire—all turned out to be, at least in part, 'private ventures' in the sense in which this term is used here.[4] By adopting private ventures the Air Ministry were able to save from six months to a year which would otherwise have gone on the preparations for competitive tender and the discussion of competitive designs.

Even greater savings were aimed at, and sometimes achieved, by means of the 'special orders'. The peculiar relationship which existed between private design and official requirements made it possible to develop a system which in fact provided the real alternative to competitive tender. Under this system the Air Ministry, or the M.A.P., entrusted the design and production of a new type to a firm which, in the Ministry's view, was at the moment best able to create a new type of the necessary kind. Isolated instances of this could be found very early. In 1934 the Air Ministry took the unprecedented step of giving Armstrong-Whitworth an order to build a

---

[1] See Ch. IV, Section (vii).
[2] See Ch. VI, Section (vii).
[3] See pp. 83–95.
[4] See pp. 86–92.

heavy bomber to the B.3/34 specification, without issuing an invitation to tender. For the time being this remained an isolated instance. Gradually, however, circumstances made competitive tender difficult and undesirable. As war approached it was clearly uneconomical to expect the overworked design departments to spend their time on designs for competitive tenders if only one or two were going to be taken any further. So, what with the desire to save the time hitherto spent on organising competition, and with the imperative necessity to spare the efforts of the drawing offices, special orders gradually became the prevailing system at M.A.P.

For its success the system required close and constant contact between the firms and the Ministry, and throughout the war years this condition was apparently fully satisfied. The Air Ministry always knew what each designer was doing at any given point of time, while the designers themselves had always made it their business to know what the Service needed. This intimate understanding enabled the designers sometimes to produce designs at a short notice just when they were needed by the Air Ministry.

Special orders of brand new designs easily merged into designs which were little more than radical modifications of some older types and were therefore, as a matter of course, committed to the firm responsible for the original type. This was, in fact, the history of several aircraft produced to special order. Perhaps the earliest was the Fulmar fleet fighter conversion of the P.4/34 light bomber;[1] this was rapidly followed by the Beaufighter cannon-fighter version of the Beaufort torpedo-bomber. Once the precedent was established, the exigencies of war made it the established method of obtaining new types, and examples are almost too numerous to mention. The Lancaster, the York, the Tempest, the Brigand and the Spitfire may be quoted as the most important war-time examples.

So much for the cuts and abridgments in procedure. What of their effects? Did they result in economies of time great enough to bring the new types out as fast as the war strategy demanded? The table below setting out timetables of development of most of the more familiar types will show that in 'special order' types and the true private ventures, the development period was reduced. Yet on the whole the savings were not sufficiently great as to be wholly satisfactory in war-time. In spite of the abridgments and long after they had been introduced into the development procedure, new types continued to be delayed on their way to quantity production. As the table below will show, the gestation period of the early bombers took up to seven years, whilst that of the heavy bombers of later vintage took at least four years; fighters took nearly as long.

[1] See p. 136.

Development period of the principal types of aircraft

	(a) Date requirements formulated	(b) Date production deliveries started	(c) Length of development period (a)–(b) years	months
Fighters				
Hurricane*	December 1933	December 1937	4	0
Spitfire	June 1934	June 1938	4	0
Defiant	April 1935	September 1939	4	5
Whirlwind	February 1936	June 1940	4	4
Typhoon	November 1937	June 1941	3	7
Beaufighter*	November 1938	June 1940	1	7
Mosquito*	November 1939	June 1940		7
Welkin	April 1940	September 1943	3	5
Tempest*	September 1941	October 1943	2	1
Bombers				
Wellington	October 1931	October 1938	7	0
Hampden	October 1931	September 1938	6	9
Battle	August 1932	May 1937	4	9
Whitley*	March 1934	March 1937	3	0
Warwick	January 1935	July 1942	6	6
Blenheim* (Bristol type 142)	May 1935	March 1937	1	10
Beaufort	August 1935	October 1939	4	2
Stirling	July 1936	May 1940	3	10
Manchester	August 1936	September 1940	4	1
Halifax	August 1936	October 1940	4	2
Albemarle*	January 1938	April 1940	1	3
Lancaster*	September 1940	October 1941	1	1
Buckingham*	May 1940	February 1944	3	9
Fleet Air Arm				
Skua	September 1934	November 1938	4	2
Albacore*	June 1936	February 1940	3	8
Barracuda	October 1937	July 1942	4	9
Fulmar*	January 1938	May 1940	2	4
Firebrand	March 1939	June 1943	4	3
Firefly	March 1939	July 1942	3	4

* Special order and private venture types.

Thus to all appearances the problem remained largely unresolved and in the end it came to be regarded as all-but insoluble. In the discussion about the heavy bomber for the Japanese war, which took place at the turn of 1943–44, representatives of M.A.P. felt it necessary to warn the representatives of the other interested departments that a brand-new heavy bomber type could not be brought into operational service in under five years from the date of the specification and preliminary design. It is therefore impossible to escape the conclusion that the cuts were not as effective as they were at one time expected to be. Many months were doubtless saved but, in order to synchronise the progress of design with the changing war demands, years, indeed several years, would have had to be docked off the prevailing timetables.

(iv)
Delays at the Inception of Production

This could not have been done by mere cuts in procedure. As has been said at the outset,[1] the new types were delayed partly because the timetable of design and development was too long, but partly also through causes not directly connected with the business of design, which were largely industrial in character. That delays occurred at the industrial end of the timetable will be clear from the story of most aircraft scheduled for appearance under the expansion and wartime programmes. It was in the final phase, i.e. that of the production orders and first production deliveries, that the delays proved most stubborn and least amenable to cuts. Examples of types, the first deliveries of which were severely delayed, were the Wellington, the three heavy bombers (Halifax, Manchester and Stirling) and later, of course, the Typhoon, the Buckingham and the Tempest. A similar delay occurred in the period after first deliveries had appeared during the build-up to peak production. In each of these cases delays occurred after the business of design and development proper had been completed.

Some blame for these delays attaches to official agencies. The Air Staff attitude to all these aircraft, while they were still under development, changed so frequently that it was bound to delay the jigging and the tooling and all the other industrial measures necessary for their introduction into production. The fate of the Warwick[2] hung in the balance for nearly two years, that of the Buckingham[3] for about a similar period, and that of the Windsor[4] was never wholly

[1] See pp. 141–142.
[2] See Ch. VI, Section (v).
[3] See Ch. VI, Section (vi).
[4] See Ch. VI, Section (v).

secure. But even more important than the changes in the official requirements were the purely industrial problems of switching production to new types.

The problem was largely that of quantity versus quality. In theory the time a firm must take to introduce a new type into production is limited only by the speed at which the necessary buildings, plant and machinery can be provided; or, where the buildings are available, only by the time necessary for the jigging and tooling-up. This in itself lead to delays. And in war-time, when the capacity for the manufacture of jigs and tools and for the making of production drawings was overloaded, the delay was bound to be longer than in peace-time. But what retarded the introduction of new types most was that in factories fully employed on well-established types new types could only be produced at the expense of old ones. While new types were coming in, the losses in the old types were for a time bound to be greater than the output of new aircraft, with the result that total output declined.

This difficulty could never be wholly resolved and could only be tackled by dovetailing new production with the old—a process which came to be known as the 'splicing-in' of production. The theoretical alternative to 'splicing' would presumably be a clean cut of the old production followed by a fresh start of the new production. The fact that this procedure never received a nickname is sufficient evidence of its rarity and unpopularity. The Air Ministry and M.A.P. seldom contemplated replacing types in production in such a wholesale manner for the simple reason that at no point since the expansion were they able to allow as great a sacrifice of output as would result from a complete *hiatus* in production. Even at times when the quality doctrine reigned supreme a complete stoppage of output to enable a new type to come in was more than anybody in M.A.P., and still less in the aircraft firms, could contemplate. For, apart from the monthly records of production upon which for reasons of politics and prestige great store was set, there was also the labour problem. Even in the earliest stages of expansion, and long before the general scarcity of labour developed in industry, the firms and the Ministry took the view that a clean break in production would lead either to a dispersal of the labour force or to an excessive amount of idle time. Either course was distasteful to Government and industry alike.

The general policy, therefore, was gradually to 'fade out' the old types and to introduce the new types in their stead equally gradually and with the least possible disturbance to total production and to the employment of labour. Thus, in the very nature of things, new types could not come into production, still less reach their maximum rates, for a very long time. It is therefore not surprising that, as the table below will show, the interval between the production order or the beginning of the tooling-up on the one hand and the maximum rates on the other was sometimes as long as two years.

Production Periods

TYPE	(a) 1st Production order	(b) 1st Production deliveries	(c) Period between (a) and (b) yrs	m'ths	(d) Peak production	(e) Period between (b) and (d) yrs	m'ths
Bombers							
Wellington (Vickers)	15.8.36	Oct. 1938	2	2	May 1940 (65)	1	7
Whitley (Armstrong-Whitworth)	23.8.35	Mar. 1937	1	7	June 1940 (40–50)	3	3
Blenheim (Bristol)	22.8.35	Mar. 1937	1	7	Sept. 1938 (45)	1	6
Beaufort (Bristol)	22.8.36	Oct. 1939	3	2	Mar. 1940 (30)		5
Stirling (Short)	11.4.38	May 1940	2	1	Feb. 1943 (20)	2	9
Halifax* (Handley Page)	7.1.38	Oct. 1940	2	9	Jan. 1943 (35)	2	3
Lancaster* (A. V. Roe)	15.11.40†	Oct. 1941		11	Sept. 1943 (120)	1	11
Buckingham* (Bristol)	18.11.41†	Feb. 1944	2	3	—		—
Windsor* (Vickers)	—.4.43†	—		—	—		—
Fighters							
Hurricane (Hawker)	3.6.36	Dec. 1937	1	6	Feb. 1939 (40)	1	2
Spitfire (Supermarine)	3.6.36	June 1938	2	—	Feb. 1941 (66)	2	8
Defiant (Boulton Paul)	28.4.37	Sept. 1939	2	5	Feb. 1941 (60)	1	5
Typhoon (Gloster)	14.10.39	June 1941	1	8	Dec. 1942 (100)	1	6
Beaufighter* (Bristol)	—.2.39†	June 1940	1	4	Mar. 1942 (42)	1	9
Mosquito (de Havilland)	—.1.40	July 1941	1	6	Feb. 1943 (80)	1	7
Fleet Air Arm							
Barracuda (Fairey)	—.3.39	July 1942	3	4	Mar. 1944 (45)	1	8

* Aircraft whose production was 'spliced-in'.
† Direct order by Air Ministry requisition.

Needless to say the authorities were aware of the problem and it worried them not a little. The Air Ministry or M.A.P. did everything they could to press the firms to expedite the transition, and often succeeded in extracting from the firms optimistic promises. In a few, but very few, instances these promises were kept. In an overwhelming majority of cases the promised span was exceeded, as it had to be, by a very wide margin. So, before long it came to be realised in the government departments that mere promises were not enough; that the problem was one of policy and industrial organisation; and that as such it could only be solved by general measures and a general policy of production.

At quite an early stage in the history of expansion, in 1938, 1939 and 1940, various people in the Air Ministry and the M.A.P.—in the production departments as well as in the various planning agencies—made tentative studies of the problem and suggested tentative remedies. At the height of the war, in the spring of 1942, Sir Ernest Lemon was asked to investigate the length of time necessary for the introduction of a new type.[1] In August of that year he submitted a report which covered the whole process from design to maximum production, and contained a number of recommendations. In so far as the delays were due to shortages of draughtsmen or insufficient planning, the remedies he proposed were fairly simple. They mostly consisted of various measures to economise labour in the drawing offices, or to expedite the different stages preparatory to production. As for the main problem, that of 'splicing-in' new production with old, he had few radical measures to suggest. He admitted that in order to minimise the total losses in output, new aircraft would have to be introduced into production very gradually, and proposed an 'ideal' schedule under which the process could be telescoped into about fifteen months. Behind this schedule was the fundamental assumption that what made it impossible to jig-up new production without affecting the old was the shortage of floor space. One of his recommendations, therefore, was that additional floor space should be provided either by new building or by economies in the utilisation of existing floor space. His expectation was that new production would rise accordingly as the necessary floor space was cleared or added.

It is at this logical and historical point that the problem came nearest to that of general industrial policy and industrial organisation. The manufacturers needed no government advice to convince them that additional floor space would make the introduction of

---

[1] The direct origin of this investigation appears to have been the anxiety of the Air Staff during the winter of 1941–42 for new types to be introduced (i.e. the Buckingham, the B.8/41, the B.11/41 etc.); M.A.P. were unable to introduce new types within their existing capacity on top of the recently agreed Bomber Programme of December 1941.

new types easier. Nor was that point at any time lost on the Air Ministry or M.A.P. Now and again in the expansion years additions to floor space were sanctioned expressly in order to facilitate the introduction of new types, and the policy was carried over into the war years. Within a month of the outbreak of war the Director General of Production insisted upon creating additional floor space at A. V. Roe's works 'to allow local management to arrange the planning of the old and new types on a long splice basis'. The Director General of Production at that time was Sir Ernest Lemon, and in this way his recommendations in 1942 were consistent with his earlier policy.

Indeed so consistent was this policy that it is difficult to see why shortage of floor space should have figured at all in 1942 amongst the obstacles to rapid development. Throughout the years of expansion and war the industries' demands for additional accommodation were, generally speaking, satisfied, and in this way the industrial capacity measured in floor space and, to some extent, in machinery was greatly expanded. Judged by standards adopted in the pre-war schemes of war potential, floor capacity in assembly shops was well in excess of what the industry needed to produce the aircraft which it was in fact producing in war-time. Under the 1938 and 1939 plans of war potential, output was planned on the assumption of continuous shift working in assembly shops as well as in machine shops. But when war came, the average shifts worked were not more than one long shift in the assembly shops and not more than two incomplete shifts in the machine shops.[1] Had the aircraft factories found it possible to introduce continuous shift working, as the Royal Ordnance Factories did in 1941, not only would the surplus floor space which Sir Ernest Lemon demanded have been available in practically every aircraft factory, but great economies would also have been achieved in jigs and machine tools, both new and old. If so, the insoluble difficulties and the insurmountable delays in 'splicing-in' of production must be put down to the failure of the industry to create a fully balanced capital equipment and to work it with multiple shifts.

A slight digression may be necessary here, for the same factors (the unbalanced character of the industrial equipment and its incomplete utilisation) also entered into the allied problem—that of transferring factories engaged in the production of one type to that of better types in production elsewhere. Indeed, the whole story of the substitution of the Stirling and the Halifax by the Lancaster was beset by the same difficulties which slowed down the introduction of new types. As has been shown elsewhere[2] the general superiority of

[1] William Hornby, *Factories and Plant*, (H.M.S.O. 1958), pp. 247–250.
[2] See pp. 21–22.

the Lancaster over the other heavy bombers had come to be formally established by the beginning of 1942, and the advantages of substituting it for the Halifax and the Stirling came to be, in theory at least, taken for granted by the end of that year. Unfortunately, the substitution could not be carried out without sacrificing for a time a number of heavy bombers. In this way the M.A.P. ran into the same problems with which it had to deal in arranging for the introduction of brand-new types. It was found impossible to 'splice-in' the production of the Lancaster with that of the other heavy bombers so as to fade the latter out altogether, for the resultant losses in total production would have been too great for the Air Staff to allow.

A partial and very gradual programme had, therefore, to be adopted. But here, as in the case of brand-new types, the programme need not have been quite so partial and gradual had the industry and the Ministry been able to dispose of vacant floor space in the factories, or of idle machine tools. In 1943 neither the one nor the other were to be had. Yet even at that time the floor space and the machine tool capacity was fully employed only in so far as the industry continued to be run on a basis of one, or at most one-and-a-half, shifts. In theory it is possible to argue that, had the assembly of Lancasters at the end of 1943 been conducted on a three-shift basis, something like 50 per cent. of the necessary jigs and 30 per cent. of the necessary tools would have been available for employment elsewhere. By the same reasoning, had the production of the Stirlings also been run on a three-shift basis, the existing Stirling factories would have been able easily to find the floor space on which to put up the Lancaster jigs and tools without interrupting production of the Stirlings.

However, by the beginning of 1943 this remedy was more convincing in theory than possible in practice. The industry was set in its ways; labour had already developed something akin to a traditional opposition to multiple shifts, and was not very mobile, while the M.A.P. had given up all hope of controlling the utilisation of floor space and capital equipment, or even any attempt at measuring them. In fact so impracticable the remedy appeared in the conditions of 1943 and 1944 that in all the discussions it was not officially mentioned.

Thus the technical hazards of new designs, the vacillation of official policy, the protracted timetable of initiating, testing and ordering new types and, above all, the industrial difficulties of dovetailing new production with old—all these factors combined to cause delays in the development of new types. Thereby they also disappointed the hopes and expectations which officials and Ministers entertained every time a new type was proposed or a new phase of aircraft development opened. Had the general progress of quality of

British aircraft been entirely dependent upon brand-new types, the delays would have caused irreparable damage to the chances of victory. But as we have suggested at the beginning of this chapter, the delays were in practice less tragic than a superficial reading of this story might lead one to believe. They primarily affected the new types designed *de novo*, but fortunately the quality of British aircraft did not wholly, or even partially, depend on the introduction of new types. As we shall presently have to show it depended very largely on modifications of older types. This process will form the subject of another chapter.[1]

(v)

Gliders and Aircraft for Airborne Forces

Some of the reasons why, in spite of all the efforts to expedite the design and the development of aircraft, the progress of new types from project stage to operational employment was very slow, are indirectly brought out by the expeditious and trouble-free progress of the gliders. When the airframe was single in design and construction; when its design was not linked with the hazards of a parallel engine development; when the operational requirements were simple and above all did not impose on the design a multiplicity of operational roles; when the 'users' made up their minds early and did not find themselves under the compulsion to modify the original design by stages; where new and identical capacity not previously engaged in the design and production of other types could be brought in, it proved possible to put airframes (in this case gliders) into the air with very little trouble and delay. For it is clear that it is this combination of fortunate circumstances that is largely to thank for the relative ease and success of the glider design.

The success is all the more considerable for the suddenness with which the demand for gliders arose and the lack of previous experience or preparations. Gliders, and indeed the possibility of airborne forces, had no place in pre-war plans or schemes; they were entirely neglected until June 1940 when Mr. Churchill directed that we should proceed with equipping a parachute troop of 5,000. To provide the troops with air transport appeared an impossible task, since the only suitable aircraft was the Whitley, and the number available would carry not more than 800 men. Gliders were obviously the solution, for towed gliders had already been adopted by the Russians and the Germans. The Russians had carried out large-scale trials with towed gliders, and the Germans had used glider

[1] See Ch. VIII.

landings on a small scale in the advance into Belgium. But for this country the solution was as yet largely theoretical, since there were no gliders available; there were not even any preliminary designs or firm specifications.

What turned out to be even more fortunate was that the technical problems of glider design were very limited. The user requirements for types of gliders were straightforward. They were confined to the use of gliders as transport for airborne forces; they were in no way comparable with the complexity of aircraft specifications which had to combine the performance of an aircraft as a vehicle and as a weapon of warfare. On this point the 'users' did not take long to make up their minds. Despite the recent formation of the Airborne Forces the specifications for all types were available to the designers by the end of 1940. The detailed specification was provided strictly by the Airborne Forces. The most advantageous size was quickly determined; the 8-seater type was at an early stage selected primarily as a trainer glider and the 25-seater Horsa was adopted as the most useful operational type. The requirement for the tank-carrying glider arose before the end of 1940 as a War Office tactical requirement. It was only for this glider with a specialised load that any major problems of design arose. But these did not delay development to any significant extent.

In general (and this was an additional advantage enjoyed by the designers of gliders) preliminary design work had not been held up by lack of a detailed specification; the design of the main structure could proceed without the detailed specification, provided there was sufficient general information about load and function. It could be assumed that the construction would be substantial and mainly of wood and canvas; the wing lift was similar to that for monoplane aircraft. In general most of the principles of design could be readily derived from aircraft design; the sporting glider was in general too small to provide any useful data, though one of the design firms—Slingsby Sailplanes—was a sporting glider firm. By August 1940, the Director of Scientific Research and R.A.E. had reviewed the general problems of design and of towing. Wind tunnel tests had been held for an experimental design for an 8-seater. This was prepared jointly by R.A.E. and General Aircraft, and a prototype was soon under construction. For most types of gliders the design work was sufficiently advanced within a few months for preparations for production to be made. Indeed the design and manufacture of the production jigs often took longer than the basic design work for the glider.

Four main types of gliders were manufactured in the United Kingdom. The Hotspur an 8-seater troop carrier designed and built by General Aircraft (Mk. II was similar to Mk. I except for the addition of a parachute hatch). The Hengist, a 15-seater troop carrier designed and manufactured by Slingsby Sailplanes. The Horsa, a 25-seater troop carrier designed by Airspeed and built by Harris Lebus. This glider could also carry a light motor vehicle, and a second type of Horsa was designed to carry a 4 ton bomb-load. The Hamilcar glider was the largest glider used by the Allied forces. This glider which was designed by General Aircraft could carry a light tank, or a 25 pdr. or 17 pdr. gun and towing vehicle, or as was often done, heavy engineer equipment including a bulldozer.

Special problems arose mainly in connection with towing equipment and selection of towing aircraft. But these were fairly quickly settled, mainly by continuous trials made by the users at the Central Landing School of the Airborne Force. Several types of aircraft were suitable for the lighter gliders—Wellingtons, Stirlings, Albemarles and Whitleys were all used. For the Hamilcar the Halifax was the only type that proved suitable. The Horsa glider—the main United Kingdom type—was about the same size as the Wellington with a wing span of 80 feet and length of 67 feet; the weight fully laden was up to 13,600 lbs. including the pay load of 6,900 lbs. The Hamilcar, with a wing span of 110 feet and length of 68 feet, was wider than the Halifax and almost as long. Its fully laden weight of 36,000 lbs. and its pay load of 17,500 lbs. were more than twice the weight and pay load of the Horsa. The wing loading of 21.7 lbs to the square foot, much greater than anything previously contemplated for a glider, gave the Hamilcar many of the characteristics of an aircraft without engines. In fact, the probable difficulty of towing the Hamilcar in the Far East led in September 1943 to the demand for the installation of an engine. This proved a rather long job. The prototype was not on trial until August 1945. With the end of hostilities orders for powered Hamilcars were cancelled, but a number of conversions were completed with the engines installed in the existing type of glider. The two years from specification to prototype, despite the use of an existing glider airframe, in part reflects low priority and is also in contrast with less than twelve months needed for unpowered gliders.

More significant for this general design story is the way in which the Airborne Forces' requirements were filled within the current range of aircraft. Medium and heavy bombers were adapted for parachute troops, and were used as glider tugs. Specially designed transport aircraft would have been more economical, but in fact most of the existing transport aircraft were themselves adaptations of existing bombers. Bombers lent themselves easily to use as transports and thus also for employment as carriers of parachute troops, and until nearly the end of the war they remained load-carrying aircraft of conventional design. In this respect British experience matched that of the United States. Both for glider towing and for parachute troops the United States forces used the Dakota—this was a 1941 military version of the Curtis commercial airliner first flown in 1936. The Dakota was also used by British forces to tow the Horsa and also United States WACO gliders used by British forces.[1] The new post-war types could not be adapted in this way. The high-altitude, high-speed bomber aircraft were neither in performance nor in aerodynamic design suitable for use by Airborne Forces or as glider tugs.

(vi)
Summary

The constant progress in the quality of British aircraft in spite of frequent delays and failures of new designs has been described here as paradoxical. Yet the paradox is not as great as it might at first sight appear. The quality of British aircraft was largely maintained by means of modifications and new marks of established types. But to contrast the disappointments over new types with the solid achievements of the much modified old types is to overstress the real difference between modifications and brand new designs. From the point of view of aerodynamic and thermodynamic principles, the main engineering devices embodied in all the aircraft designed between early 1934 and 1944 differed relatively little. The real differences, and a real turning point in the evolution of military aircraft, occurred with the introduction of all-metal monoplanes of integral (monocoque) construction, with stressed skins, and of the high-efficiency piston engine exploiting the possibilities of the new high-octane fuels. All these fundamental innovations date to the early 'thirties; in the subsequent ten or twelve years, i.e. the years of rearmament and war, the newly designed aircraft merely exploited and developed the technical revolution of the early 'thirties. Thus viewed, the different aircraft designs of the time were but successful modifications of the same basic design.

This fundamental affinity of the various aircraft has been obscured by a variety of factors. Designs differed according to the tactical functions, be it bombing, pursuit or reconnaissance, or according to the idiosyncrasies of independently working firms and design teams and the fortuitous accidents in the history of individual types. But the affinity was well understood by a number of people in M.A.P., the R.A.E. and the industry, especially its engine branches. Mr. Ord,

[1] The Dakota was not adequate for the Hamilcar.

who played so forceful a part in the shaping of the aircraft industry on the eve of the war, tried to exploit the fundamental similarity of all military aircraft by inducing firms to make use of 'common denominator' sub-assemblies: especially of standard wings. And it would not be an exaggeration to say that the power plant, such as the Rolls-Royce engine with its standardised bed (the 'egg') used in a number of different aircraft, came very near to Mr. Ord's dream of a common denominator sub-assembly.

It is very largely because of the technical affinity of most aircraft that mere modifications sometimes sufficed to earn for an aircraft a 'new mark', and that new marks were so often deemed to be important enough to deserve the dignity and the name of new aircraft. And it is for the same reasons that the contrast between the delays of some of the new designs and the successful progress of modified aircraft may appear to be somewhat over-simple. Both represented successive derivations from established technical principles. And such progressive derivations were possible because the history of war-time airplanes happened to fall within the chronological limits of a single stage in the technical evolution of aircraft.

This stage came to an end with the entry of the gas turbine. The beginnings of the gas turbine and jet propulsion will be told in another section of this study.[1] Here, it will suffice to note that although by the end of the war the Whittle project of a jet engine had been under development for at least three years, an aircraft embodying the jet engine was not ready for operational use until summer 1944, and even then in small numbers and in a limited role.[2] Had war in the Far East lasted as long as it had sometimes been expected to last, jet aircraft would have played their part in operations. But as things turned out, the war against Japan came to an end while nearly all the aircraft in production and under development were still propelled by reciprocating engines.

The latter's days were however counted. Nearly all the projects launched in the closing months of the war in the West, and nearly all the plans for post-war types, were based on engines of the new type. And with the change in the principle of propulsion came a host of other innovations which often required fundamental technical departures from established principles of design. Aircraft could now be designed to travel at a speed approaching that of sound, and new speeds raised aerodynamic and constructional problems of the sound barrier. The M.A.P., and the Ministry of Supply with which M.A.P. was soon to be merged, thus found themselves administering what, to all intents and purposes, was a new and revolutionary

---

[1] See Ch. IX.
[2] See p. 175.

phase in the history of aircraft. Before long the very idea of manned aircraft became obsolescent, the airplane lost its position as the sole weapon of air warfare and rockets entered into the strategic plans of nations and into the business of aircraft firms. In this period the problems of design, of its administration and of the relations between Government and industry, could no longer be wholly identical with the similar problems thrown up by the war, and they were perhaps solved in a somewhat different way. Yet even now the difference was one of degree. Design and development still continued to be a joint enterprise of Government and industry, even if the exact share of the Government and the point at which projects passed out of the hands of government establishments into those of firms were no longer the same as in the ten years between 1935 and 1945.

CHAPTER VIII

PIECEMEAL IMPROVEMENTS

(i)

Introductory

THE previous chapter poses a riddle. The story of the general progress of the quality of British aircraft makes it clear that the Government and the industry between them succeeded in maintaining the performance and most other qualities of British aircraft on a very high level. On the other hand, in the chapters dealing with the design and development of new types, we found that for a number of causes, avoidable and unavoidable, new types were slow in coming and were below expectations when they came. If so, how did the high quality of British aircraft come about? The answer to this riddle is that new types were not the only, and in the long-run not the chief, means of raising the quality of British aircraft. In spite of all the thought and worry expended over them the salvation came not so much from new types, as from the piecemeal improvements of the old ones.

The story of the piecemeal development of existing aircraft cannot be told here in all its detail. We must therefore confine ourselves to a brief sketch of its general progress, illustrated by a few oustanding examples, and to a discussion of the industrial and the administrative problems to which it gave rise.

(ii)

Modifications, Marks and New Designs

Piecemeal improvements of existing types fall into two broad classes. There were changes in aircraft which, in the first place, were radical enough, or comprised detailed changes in numbers sufficiently large, to justify the allocation of a special 'mark' of an aircraft. In the second place there were changes which were not, taken separately, of very great importance in themselves, and therefore did not justify the allocation of a new mark number: these were 'modifications' in the narrow sense of the term. The line between marks and modifications is thus not very hard or fast, for many mark numbers represented no more than a collection of modifications centring round a special operational function. Nor was the line clear between modifications deserving that name, and the small routine adjustments made in the course of production, or by ground personnel on the airfields. But broadly speaking the commonsense distinction, which in fact prevailed, will also be adopted here. The marks will be taken to represent the more important improvements embodying a more thorough departure from the standard type than the improvements described as modifications.

This difference in degree means also some differences in technical and administrative procedure. Modifications in the narrow sense might come in at any point in the aircraft's life story. Some would be suggested and accepted even before the prototype was constructed; many followed the mock-up conference; many more resulted from the prototype test. Further modifications invariably came in in the course of production, as operational requirements changed and new instruments or technical devices came into existence. Even after the aircraft had passed into the squadrons it could still be subjected to modifications of every kind; some (the so-called 'retrospective' modifications) were introduced into the aircraft by R.A.F. personnel to serve the immediate purposes of operations.[1] Mark numbers, on the other hand, could only be introduced after production had commenced and were but rarely 'retrospective' in effect.

Nor was there a hard-and-fast line between 'marks' and brand-new designs. New mark numbers were mostly given to differentiate batches of aircraft modified in the production line for the installation of a different engine or of special equipment associated with certain operational functions (for instance, cameras, radio aids, deck landing equipment, etc.). But sometimes whole structural members, such as wings and fuselages, were redesigned, with the result that, although the aircraft identified by the new mark would appear to the lay spectator almost identical in shape to the aircraft with the previous mark, the detailed drawings would in fact be largely different. The new marks which covered these radical redesigns were usually tried out first as prototypes, and in that case a new prototype specification and Air Staff Operational Requirements might be issued.[2]

Some of the redesigns of existing types were so radical that even a new mark number was not thought to give sufficient recognition to the changes; in these cases a new name would be allocated and a

[1] Some retrospective modifications were introduced by the firm's 'working parties' specially sent from the factory for the purpose.

[2] The new mark numbers covered by the simpler modification procedure, on the other hand, would merely require a trial installation of the special equipment with its fixed and removable fittings. The specification to cover such a mark number would be a straightforward document for contract purposes merely listing the modifications that were to be incorporated.

separate set of master drawings would be assembled. Illustrations of such occurrences are not hard to find. Thus the Lancaster outgrew the bonds of the Manchester, the Tempest those of the Typhoon, the Lincoln those of the Lancaster and the Spiteful those of the Spitfire. On the whole, the point at which the redesign was radical enough to deserve a brand-new name was not well defined. A firm with a successful type like the Spitfire would prefer to cling to it and to assign mark numbers to improvements, however radical. On the other hand, a firm with an unsuccessful type, like the Manchester, might be more anxious to change the name on the first available occasion.

Yet closely as some marks approximated to new designs, the principal distinction between the two (which is also the justification for new marks as against new designs) was that a new mark, however radical, required for its design, or for its jigging and tooling, or for both, much less time and effort than a brand-new design. The history of the Spitfire is the best illustration of this. Vickers (Supermarine) have tabulated the man-hours expended on the principal marks of the Spitfire, and the results have been set out in the following table.

Effort in Man-Hours

Mark	*Design*	*Jigging and Tooling*
I	339,400	800,000
II	9,267	no figures available
III	91,120	75,000
V	90,000	105,000
VI	14,340	50,000
IX	43,830	30,000
XII	27,210	16,000
VII	86,150	150,000
VIII	24,970	250,000
XIV	26,120	17,000
21	168,500	no figures available
F.1/43	21,460	25,000
PR.XI	12,415	no figures available
Seafire I	10,130	18,000
Seafire II	3,685	40,000
Seafire III	8,938	9,000
Seafire XV	9,150	no figures available
Spitfire on Floats	22,260	35,000

Source: *Spitfire History*, by Vickers-Armstrongs Supermarine Works, Southampton, September 1943.

It will be seen from the above table that no single mark required an expenditure of man-hours on design as great as that originally spent on the Spitfire Mark I. The highest was that devoted to the Spitfire F.21 which was 168,500 man-hours compared with 339,400 man-hours on the Mark I. The average man-hours spent on design of the first 10 marks tabulated was 75,240 per mark. The total design man-hours devoted to these 10 Spitfire marks over a period of 5 years was 752,407, only sufficient to design two new aircraft of the Spitfire Mark I type.

The economy was even more marked in jigging and tooling: the highest expenditure incurred was on the Mark VIII, and possibly the F.21. Both would be very much below the 800,000 man-hours reached in jigging and tooling-up the Spitfire I. The average man-hours was 165,900 and the total was 1,493,000.[1]

The Spitfire figures happen to be the ones available, but indirect evidence suggests that the figures for the other much modified types, such as the Wellington and the Lancaster, will differ little from those of the Vickers (Supermarine) Spitfire. Viewed as a whole, the figures reveal the immense effort which the British industry devoted to the modification of its successful types, and yet at the same time prove the remarkable economy of the method compared with that of brand-new designs. By this means also the quality of aircraft was much more closely linked with the changing tactical needs and technical ideas than was possible under the existing timetable of brand-new designs. By a series of progressive changes, almost metabolic in their continuity and in their cumulative action, British aircraft kept abreast of the lessons of air battles and of the changing conditions in the industry.

(iii)
Some Examples of Piecemeal Improvement

What this meant to the history of individual aircraft is best illustrated by the same history of the Spitfire. The whole development of that aircraft is one unbroken record of improvements, as a result of which its speed rose from 356 m.p.h. to 460 m.p.h. and its other features of performance were transformed to match.[2] Very nearly

---

[1] The average and total man-hours are only taken for the first 9 marks for which figures were available.

[2] See Appendix V.

1,100 modifications in the technical sense of the word were incorporated in the aircraft between 1938 and the beginning of 1945,[1] and in addition a certain number of modifications were embodied in the initial design of fresh marks, for which there were at least 19. In fact, the whole story of that type can best be described as a continuous series of modifications now and again signposted by the introduction of new mark numbers.

For the smooth and continuous progress of these improvements the designing department of Vickers (Supermarine) was largely responsible. More especially it was due to their foresight and imagination that new marks of Spitfire came in with relatively so little disturbance in the general flow of the Spitfire progress and at a comparatively small cost in man-hours. Looked at superficially, all the more important marks, such as the V, VIII, XIV and 21, represented successive changes in the engine. But the reason why the engines could be installed with so little trouble and why continuous progress in performance and fighting efficiency was possible was that the airframes themselves were changed throughout the period, usually in anticipation of the new engine to come. As a result of the close co-operation between Supermarine and Rolls-Royce, which has already been mentioned elsewhere,[2] the Supermarine engineers always had sufficient warning of the coming of a new Rolls-Royce engine and could plan in advance the necessary modifications of the airframe.

In this way the evolution of the Spitfire can be traced through the succession of airframes—about four in all—modified and expanded for installation of new engines. The airframe A, that of the original Spitfire of 1938, accommodated the Merlin II, III and XII, and formed the basis of the Spitfire Marks IA and B, IIA and B and PR.IV. Although the original airframe could have been stretched to accommodate the next engine group, and in fact was so,[3] a stronger frame was needed to carry the engine with any degree of efficiency and with a margin for further development. As a result the airframe B (already designed for the abortive Mk. III with Merlin XX

---

[1] The net figure for Spitfire modifications is calculated as follows:

Gross	1,612
less amendments, proposals withdrawn, cancelled modifications and proposals in abeyance	527
Net	1,085

Of these 1,085, 667 were non-retrospective and 418 were retrospective. Of the retrospective modifications, Class 1 = 1; Class 2 and Special Order Only = 269; Class 3 = 148. It should be noted that many modifications were limited to specific marks, and that many of the withdrawals were due to the inclusion of the modification in the initial design of a fresh mark.

[2] See Ch. IV, Section (viii).

[3] The Spitfire Mark VA and B (with its variants the F.VI, the hooked Spitfire, the Seafire I and PR.VII and XIII) accommodated the Merlin 45 family.

engines) came into existence to form the basis of Spitfire Mark VC, with its variants.[1] Then came the 2-stage, high-altitude, Merlin 61 family which promised great additions to speed and ceiling. This again could with some difficulty be accommodated into the airframe B.[2] But the need for a satisfactory margin led to the design of the third airframe C (Spitfire Mks. VII and VIII). In the same way, when by successive modifications a limit was reached to what could be achieved with airframe C, a new airframe D to take the Griffon engine came into existence with the Spitfire F.21. Some early Griffon engines had, however, been carried in the airframe B (Spitfire Mk. XII) and in airframe C (Spitfire Mk. XIV). The final stage was reached with the radical redesign of the Spitfire wing for laminar flow, and this, coupled with the installation of an improved Griffon engine, led to such a drastic redesign of the airframe that even Supermarine designers felt that a new aircraft was being brought into existence and a new name, the Spiteful, was given to it instead of a new mark number.[3]

In addition to improvements in quality resulting from new engines and corresponding changes in airframes, great improvements also resulted from modifications introduced largely at the instance of the Air Staff and M.A.P. Amongst these were the continuous changes in armament from 8 machine guns in 1938 (Marks IA, IIA and VA) to 2 cannon and 4 machine guns in 1940 (Marks IB, IIB and VB, etc.) and 4 cannon in 1943 (Mark VIII). There were the variations in wing shapes, resulting from the clipped and extended wing tips required for increased manoeuvrability and high altitude performance respectively (Marks VC, VI, VII, XII, XIV, 21); the improvement of cockpits, including bullet-proof wind screens, sliding hoods, special streamlined frames for improving aerodynamics and pilot's view, as well as pressure cabins; the redesigned controls (ailerons, rudder and elevators) for improving manoeuvrability and strength factors; the variations of undercarriage to take the increased weight of the loaded aircraft; the series of changes connected with long-range tanks; not to mention the use of the Spitfire as a fighter-bomber, as a photographic reconnaissance aircraft and as a naval fighter. As a result of all these piecemeal improvements the Spitfire remained one of the most versatile fighters in production, as well as one of the fastest propeller-driven aircraft in the world. In its Spiteful version it maintained its place amongst orthodox fighters in 1945 and beyond, and bridged the

---

[1] The Seafire II and III were variants of the Spitfire VC.

[2] The Spitfire IC and its variant PR.XI were also accommodated into the airframe B.

[3] The evolution of the airframe was described to the writer by Mr. Smith, Chief Designer of Vickers-Armstrongs (Supermarine). The main structural development can be traced in the diagram given at Appendix V.

transition from piston-engined aircraft to the jet-propelled fighters of the post-war era.

In the field of fighters another example of continuous improvements by modifications is that of the Hurricane. Enough has already been said about the Hurricane to make it clear that but for its continuous development it would have been out-of-date in 1940, and numerous functions for the support of the Army and the Navy, for which no other aircraft was available, would have remained unfilled during the critical years of 1941 and 1942.[1]

The development of the de Havilland Mosquito is an equally remarkable story,[2] but it had certain distinctive features of its own. On the one hand, the structural development of the Mosquito to meet increases in weight was much less striking than that of the Spitfire, and the modifications did not result in similar increases in the disposable load.[3] On the other hand, the flexibility of the design for which the firm must receive credit proved quite outstanding. Developing the original unarmed bomber design, de Havilland's were able to modify the Mosquito to fulfil no less than four other operational roles with widely different requirements. To achieve this amazing versatility, two basic fuselages were designed: one, the original, known as the 'bomber', for the Photographic Reconnaissance Units and the unarmed high-speed bomber functions; and the other, known as the 'fighter', for the night fighter and fighter-bomber roles. Little structural alteration in the fuselage was found necessary in the course of development.[4] The first fighter version (F.II) and the original bomber photographic reconnaissance version (PR.I and B.IV) had slightly different wings, but it was realised that all versions would require wings of greater strength and accordingly the firm designed what was known as the 'basic' wing. From 1943 onwards this was built into all versions of the Mosquito.[5]

Within this structural framework a very considerable improvement in performance was achieved by the installation of better engines—the speed of the night fighter was increased by 30 m.p.h.

---

[1] See Ch. IV, Section (viii).

[2] See Ch. IV, Section (vii).

[3] The all-up weight of the night fighter was only increased by 4,300 lbs. (F.11 = 18,400 lbs.; N.F.30 = 22,700 lbs.); of the fighter bomber 900 lbs. (FB.VI series 1 = 21,100 lbs.; series 2 = 22,000 lbs.); photographic reconnaissance 4,300 lbs. (Pr.I = 18,050 lbs.; Pr.XVI = 22,350 lbs.) and of the bomber 6,000 lbs. (B.IV first series = 19,200 lbs.; B.XVI = 25,200 lbs.). The increase was therefore between 23 per cent. (night fighter) and 34 per cent. (bomber). The all-up weight of the Spitfire was increased by 3,180 lbs. (Mk.I = 5,820 lbs.; Mk. F.21 = 9,000 lbs.) or approximately 55 per cent.

[4] Perhaps the only exception being the strengthened bomb beam in the bomber fuselage necessitated by the carriage of the 4,000 lb. bomb.

[5] Mk. NF.XIII (night fighter); FB.VI (fighter-bomber); PR.IX (photographic reconnaissance aircraft); and the B.IX (high-speed bomber) and all subsequent marks.

and its ceiling by 2,000 feet;[1] the bomber improved its speed by 25 m.p.h. and its ceiling by 3,000 feet,[2] and the photographic reconnaissance version was improved in a comparable way. The specialisation of the several versions was also continued by the addition and improvement of equipment: the night fighter version carried successively improved marks of radar air-to-air interception devices; the fighter-bomber carried different types of fuel tanks, which could be dropped near the target so that both long-range and maximum combat performance could be achieved; the bomber carried highly specialised radar equipment to enable it to achieve amazingly accurate bombing results, whilst both bomber and the Photographic Reconnaissance Units versions were modified to take the pressure cabin designed by de Havilland's.[3] The offensive power of all versions was equally improved. In addition to the four .303″ Browning guns and the four 20 mm. cannon carried by the fighter-bomber as a normal armament, eight rocket projectiles could be carried and some versions were armed with 6-pounder guns. Certain aircraft of this version were also equipped to carry a 2,000 lb. bomb-load.[4] The final bomber version carried one of the heaviest bomb-loads of any aircraft of its size and range in existence—one 4,000 lb. bomb stowed internally in the fuselage, and smaller bombs under the wings.[5]

The Avro Lancaster was the backbone of the offensive against Germany in both numbers and performance.[6] Developed from the Avro twin-engined heavy bomber, the Manchester, the Lancaster, powered with four Merlin engines, operated at increasingly heavy take-off weight to carry both a larger total bomb-load and larger individual bombs, as well as a more powerful defensive armament and a wide range of specialised and miscellaneous equipment, such as radar aids to bombing and navigation, bomb sights, communications equipment, and auxiliary fuel tanks. The take-off weight increased from the 50,000 lbs. of the Manchester to the 60,000 lbs. of the Lancaster I, whilst the take-off weight of the Lancaster itself went

[1] According to official performance figures the Mosquito F.II with Merlin 21 or 3 engines had a maximum speed of 370 m.p.h. and a service ceiling of 35,000 feet; the latest night fighter Mk. NF.30 with Merlin 72 engines had a maximum speed of 400 m.p.h. and a service ceiling of 37,000 feet.

[2] The original Mosquito bomber Mk. B.IV with Merlin 21 engines had a top speed of 383 m.p.h. and a service ceiling of 33,000 feet. The bomber Mk. B.XVI, the last mark of Mosquito bomber to see extensive service in the Second World War, had a speed of 408 m.p.h. and a service ceiling of 36,000 feet.

[3] Mosquito Mks. PR.XVI and B.XVI, PR.32, PR.34 and B.35.

[4] Rocket projectiles and 1,000 lb. load were an alternative.

[5] The Mosquito was also converted in small numbers to perform various specialised functions for which its particular characteristics made it eminently suitable—the civil transport version for certain routes crossing enemy occupied territory; the dual control trainer and the ship and U-boat buster in which a six-pounder gun was installed, are but some examples of Mosquito use in the R.A.F. and the Army. In addition a naval version was also designed for both fighter and torpedo carrying duties.

[6] See pp. 92–94.

up by stages from 60,000 lbs. to 68,000 lbs., and 72,000 lbs. for exceptional operational cases; and the Lincoln development carried this trend even further. The maximum total bomb-load of mixed bombs was gradually increased from 14,000 lbs. to 22,000 lbs. and the size of the large individual bombs went up from 4,000 lbs. (of which two could be carried at the same time) to 8,000 lbs., then 12,000 lbs. and finally 22,000 lbs. The original nose, mid-upper and tail turrets, with two, two and four ·303″ machine guns respectively were gradually replaced by turrets with guns of heavier calibre and with better sighting equipment.

These changes, dictated by operational needs, were made possible by engines and propellers of improved take-off power. The Lancaster I and III aircraft were fitted respectively with British-built Merlin engines giving plus 14 lbs. boost to raise the all-up weight to 63,000 lbs., and with American-built Merlins giving plus 18 lbs. boost to raise the all-up weight to 68,000 lbs. But these new installations were also accompanied by numerous structural changes. The Lincoln development included many radical structural alterations to wings, fuselage and undercarriage in order to continue to increase the offensive performance of the type.

In the 'medium' class the most remarkable case of improvements by modifications was the Vickers Wellington twin-engined medium bomber. It was first brought into production in 1938 and remained in production until 1945: a most remarkable example of continued progress of a design basically the same. The all-up weight of the Wellington went up from 22,000 lbs. on the prototype to no less than 36,000 lbs. on the Mark X, the last bomber version. Its range and speed were considerably improved; its total bomb-load and the size of the individual bombs it could carry increased; its defensive armament and its miscellaneous equipment also kept pace with changing operational needs. The large and capacious airframe, designed and built on 'geodetic' principles, proved physically capable of accommodating the extra equipment and also capable of being strengthened to carry the extra weight of the equipment and the more powerful engines. Originally powered with Pegasus XVIII engines, the main bomber variants were successively powered by Merlin X engines (Mark II), Hercules III engines (Mark III), Pratt & Whitney twin Wasp engines (Mark IV) and Hercules VI engines (Mark X). Concurrently with these developments, from 1942 onwards, the Wellington was continually modified for service with Coastal Command in the U-boat war. There were torpedo-carrying versions (Marks IC, VIII and XI), long-range reconnaissance versions carrying the Leigh searchlight and submarine detecting radar devices (Marks VIII, XII etc.), and others with less specialised equipment. In addition there were freight-carrying aircraft and a small number of machines specially modified to fly at high altitudes with a pressure cabin (Mark VI) and to deal with the magnetic mines laid in 1939 (Mark D.W.1). This list is by no means exhaustive, but shows clearly how indispensable the Wellington was to the R.A.F., how versatile its use and how elastic its design and structure.

These five aircraft—the Spitfire, the Hurricane, the Mosquito, the Lancaster, and the Wellington—are but examples of successful modifications. A similar story could be told about almost every other aircraft in service between 1938 and 1944. Some aircraft lent themselves better to piecemeal improvements than others. For example, the Air Ministry and the M.A.P. did not subject either the Defiant or the Hampden to the same policy of continuous enlargement and redesign as the Spitfire or the Wellington, for the simple reason that neither aircraft was considered capable of much radical improvement. In the same way the Whirlwind twin-engined fighter, unlike the later Mosquito, was not given a new lease of life by the installation of new engines, because its fuselage was too small and its entire layout was unpromising. Nor was the Stirling carried forward as a heavy bomber by successive emendations, while the modifications of the Halifax did not in every case produce the results expected from them and did not lift it to a position of operational parity with the Lancaster. But whenever an aircraft lent itself to progressive development its life was prolonged beyond the span originally allotted to it. Indeed to be able to accommodate modifications and to lend itself to continued rejuvenation came to be regarded as a test and a hallmark of a basically good design.

(iv)
Control of Modifications

Needless to say continuous modifications, and more especially those sponsored by M.A.P. and the Air Staff, were much disliked by the industry. Although, as has been shown, compared to brand-new types they were economical in time and effort in the stage of design and development, they undoubtedly interfered with the flow of production. The appended graph shows that the trend of Spitfire production was continually broken by sharp recessions.[1] The graph also shows that these recessions were sharpest of all between October 1941 and February 1942, when the Mark VC and Mark VI were coming into production, and the Mark VB was running out; between

---

[1] See Appendix IV.

June and August 1942, while the Seafire I and Mark IX were being introduced into the factory, which was already engaged on turning out three other different marks of Spitfire and again in the late autumn of 1942, while the Marks VIII, XI and XII were being introduced. The output graph of each individual mark is also broken by recessions which can in part be attributed to the introduction of modifications in the narrow sense of the term. In a somewhat smaller measure, the production curve of every successful aircraft in this war showed the same tendency.

Indeed nothing militated more against the very introduction of quantity methods than the policy of piecemeal modification. It is true of several aircraft in quantity production by 1942 that, had their spate of modifications been anticipated when production was planned and tooled-up, a much less elaborate capital equipment might have paid better than the one actually installed. As a general rule it can be said that most British operational aircraft were never allowed to be produced undisturbed in quantities large enough to reap the full advantage of their jigs and tools. In his memorandum already quoted,[1] Sir Ernest Lemon, basing himself on the Spitfire data, computed that, whereas for the uninterrupted output of 1,000 components the jigging and tooling-up on quantity lines would pay best, a series of 500 or less might more economically be produced with a far larger proportion of bench tools. Yet, very few unmodified batches of Spitfires were greater than 500, so that many components must have been produced under conditions which were better suited to bench methods than to the jigs and tools actually used.

It is therefore no wonder that on the whole piecemeal improvements were most unpopular in the industry. The firms, however, were not alone in objecting to them, or in blaming them for drops in production. Modifications early became a favourite subject of criticism in Parliament, and even without these criticisms the damage they did to production was well understood in the Air Ministry and the M.A.P. But here, as in every other field of development, quantity and quality had to be delicately balanced, and on the whole the needs of quality were never seriously sacrificed.

In theory the American procedure could have been adopted. The American treatment of modifications followed naturally from their partiality for undisturbed quantity production. Not only did they jig and tool-up their standard types more elaborately than was customary and possible in this country, but they also took special measures to prevent the flow of production from being disturbed by changes in design and modification. The measure they adopted to this end was to 'freeze' large batches of aircraft under

---

[1] See pp. 37 and 150.

order. By an arrangement with the Services the aircraft manufacturers were allowed to produce large quantities, varying from 500 to as much as 1,500 aircraft, without any modifications in the production line. The modifications would in that case be all grouped and timed to come in at the end of a batch thus frozen; and when introduced, they would be again followed by another frozen batch. For modifications which might become inevitable in the intervening period special modification centres were set up, and in this way most of the changes in aircraft were what would in this country be described as 'retrospective'.

In theory this procedure had much to commend it. It enabled quantity production to go on undisturbed for long periods at a time, and made it possible for American aircraft figures to make a brave showing in official returns. But where and when tactical experience was accumulating rapidly and continuously, as in 1942, 1943 and 1944 in the case of bombers in use in the European theatre of the war, the Army Air Force demanded urgent improvements all the time, and the modification centres were soon choked up with aircraft awaiting modification. When this happened, the flow of aircraft to squadrons was much more meagre than the impressive figures of production suggested, and in the end it was difficult to escape the impression that the advantages of the system from the point of view of quantity were not as great as they at first promised to be. In addition, the sacrifices in quality were probably greater than they would have been under the more flexible and looser arrangements adopted in this country.

The prevailing method in this country[1] was to introduce modifications as far as possible when and where required, but at the same time to control them in order to reduce their effect on current output. From the early expansion days, a special body in M.A.P., the Airframes Modifications Committee, subjected all proposed modifications to a close scrutiny, classifying them in accordance with their urgency, and laying down a different treatment for each class of urgency. By the beginning of 1943 these rules composed themselves into something of a system, and were enshrined in one or two codifying documents.

The system, however, always remained rough and ready and more perfect in some respects than in others. To begin with, the control over retrospective modifications, i.e. those recommended for aircraft in service, was much more thorough and effective than the control over modifications suggested for introduction into the current production line. The rules operated by the Airframes Modifications Committee were mostly concerned with changes required in the

---

[1] See Appendix III.

aircraft already in service. For this purpose modifications were officially classified into four divisions: class 1, comprising modifications dictated by extreme safety precautions and justifying a cessation of deliveries and the grounding of aircraft in the squadrons until the necessary changes had been introduced; class 2, comprising modifications of great, but not of exceptional, urgency to be incorporated in the production line as soon as practicable, and to be retrospectively introduced into the aircraft in service as soon as the parts were available; class 3, comprising modifications which were expected to be introduced into new production as soon as convenient but which were optional for retrospective modification, i.e. they could be accepted or rejected by Commands at their discretion; and class 4, consisting of 'production-line-only' modifications. Thus, in each class, with the exception of class 1, production line modifications were allowed 'as soon as practicable' or 'as soon as convenient'. In this respect there was no marked difference between classes 2, 3 and 4, and it would not be therefore an exaggeration to say that modifications in the production line were not the main object of the classification.

The chief pre-occupation was thus with retrospective modifications. Needless to say, retrospective modifications had some effect on the current production which the Airframes Modifications Committee tried to reduce to the minimum. The modifications of class 1 involved complete cessation of production and were not permitted except on special authority of the Controller of Research and Development acting in consultation with the Chief Executive and the Chief of the Air Staff. In fact, in the whole experience of the Committee up to 1944 there were only 35 cases of this kind among all types.[1] The modifications in class 2 necessitated the manufacture of parts for replacement, and might have entailed a serious diversion of material and labour from new production. The Committee, therefore, subjected them to a close scrutiny, and required the special approval of the Controller of Research and Development.[2] Altogether about ten to twelve per cent. of the total number of modifications came under that class.[3] In class 3 the necessary safeguard was found in re-interpreting the discretion originally allowed to the Commands. As long as the use of modifications remained optional—as it was in the first year of the war—considerable quantities of parts prepared for incorporation were not used and were thus wasted.

[1] Thirty of these cases occurred before July 1940 and only five between that date and 1944. See Appendix III, Note 3.

[2] The Director General of Aircraft Production, the Director of Operational Requirements and the Director General of Equipment were given the opportunity to object on grounds of special difficulty.

[3] The total number of Class 2 modifications under this classification system was 3,730, an average of 14 a week. See Appendix III, Note 3.

To avoid this the Airframes Modifications Committee confined the discretionary powers of the Commands to those parts which did not require manufacture by contractors. To compensate for this restriction the Commands were allowed to devise modifications in the light of their own operational experience and to make their own parts for them.

The system did not, and could not, make effective its direct control over modifications in the production line. As we have already said, the official theory was that no modifications involving considerable loss of time or scrap were allowed except in special circumstances. Modifications in the production line were subject to a stringent local control, and in theory could not result in serious losses of output or of resources. As will be shown elsewhere[1] the primary responsibility for ensuring that modifications, especially those in class 4, did not result in loss of time and output was delegated by the Airframes Modifications Committee to the Local Technical Committees.

The latter were set up at all parent aircraft firms, including those responsible for the design and sub-contracting of specialised major components, and consisted of representatives of both the firms and M.A.P. It was their duty to consider each proposed modification and to weigh extra work, delay in production and scrap, against the advantages, operational and economic, which might accrue from it. If these preliminary findings of the Local Technical Committees were alone to be trusted, from 60 to 70 per cent. of the total number of modifications normally considered by them were thus sanctioned as capable of being introduced into the production line without disturbance: only 30 to 40 per cent. were, as a rule, referred to the Airframes Modifications Committee at headquarters, on the grounds that they might need retrospective incorporation, that they interfered with production deliveries, that they involved a great deal of scrap, or affected supplies of certain components and sub-assemblies. As we have seen the Airframes Modifications Committee on their part very seldom sanctioned modifications, other than those of Class 1, if they were known in advance to involve considerable hold-ups of production or considerable waste of raw materials.

Yet in actual fact the losses in time and scrap were greater than these figures would suggest. Some loss of time and resources followed from almost every modification, however small and innocent, and the aggregate effect of a 'year's ration' of modifications was to delay production even when little measurable delay could be attributed to any individual modification. In addition there were a number of modifications which were urgent enough to be sanctioned in spite

---

[1] See Appendix III, Section 9.

of the delays and the scrap they caused. In other words, production suffered from modifications much more than it should have done in theory.

In the light of the experience of the war years, it is difficult to say how the position could possibly have been remedied. The major difficulty in controlling modifications in production was that of measuring its two main variables, i.e. the importance of the modification and its cost in dislocation and scrap. In theory no modification was allowed to interfere with production unless some urgency could be claimed for it, but urgency is a relative concept. As we have already said, it was merely a special instance of the general conflict between quality and quantity.[1] Would the R.A.F. have preferred, say, 90 modified aircraft to 100 unmodified, and if not what other ratios would be acceptable? If the question were ever put to the Air Ministry, the answer would almost invariably be 'a hundred modified aeroplanes'. In the words of Mr. Cowlin, Chairman of the Airframes Modifications Committee, the industry had in some measure 'to thank itself for this situation because on occasions and by making a special effort it has achieved the alleged impossible'. Yet without some sort of scale of conversion of this kind, measuring the importance of the modification against loss, control of modifications was difficult. The M.A.P. could not ever persuade the Air Staff to arrange the modifications in order of urgency.

The fault, however, did not lie wholly with the Air Staff. Often quality could not be balanced against quantity merely because, in the treatment of modifications even more than in the design of new types, difficulties were bound to arise from the separation 'between quality control and quantity control in the organisation of the industry and the ministries, plus the fact that practically all of us must be specialists in some limited field, and therefore unable to see the picture as a whole'.

The other difficulty was that of estimating costs. It was clearly impossible to know and to judge in advance the extent to which production would be dislocated and scrap created by a modification. For such information as there was, the Local Technical Committees and the Airframes Modifications Committee had to rely almost entirely on the forecasts of the firms, but hardly any firm could tell accurately beforehand what a modification would cost in delays of production. So, in the absence of such estimates, to quote Mr. Cowlin again, 'how can one do better than impose a generalised resistance towards all modification proposals, tempered by "spot guesses" as to probable dislocation value?' In fact the effects were sometimes difficult to judge even in retrospect. Almost all estimates

[1] See Ch. I.

of the past effects of modifications needed careful sifting to separate the influence of modifications from that of other factors. Without such an analysis it was possible for the M.A.P. officials to argue that some delays were due not to the nature of the modifications, but to inefficiencies in the firm's own organisation.

Rough and ready control was all that was in practice possible. Here, as elsewhere, approximate balance between quality and quantity had to be struck, and the fact that, in spite of continuous and repeated disappointments over new types, the quality of British aircraft was in fact maintained at its remarkably high level, may perhaps be taken as evidence that the rough and ready rule, like so many other rules of this kind, did not after all work out too badly.

CHAPTER IX

GAS TURBINES AND JET PROPULSION

(i)

The Initial Stages

(a) ORIGINS AND EARLY RESEARCH AT HOME AND ABROAD

In July 1944, as part of the defence measures against the German flying bomb attacks on Southern England, the Gloster Meteor, a fighter aircraft powered with two Whittle jet propulsion engines, first went into operational action. This Whittle jet propulsion engine (known as the W.2.B/23C) was a combination of the gas turbine with jet reaction through a propelling nozzle.[1] In tracing the early history of what is known popularly as 'jet propulsion', it is necessary to make clear the distinction between these two features, which need not necessarily be combined.

For many years scientists and engineers in many countries were aware of the possibility of propelling aircraft by means of jet reaction.[2] Propulsion by a thermal jet is based on a heat process of three stages; compression of air, combustion by the injection of fuel into the compressed air and expansion of the resulting mixture released to the atmosphere to provide thrust. In the past different combinations of prime movers were contemplated to achieve the compression stage. One of these employed a conventional piston engine whose cylinders were used only to compress the air and not to deliver useful power from a crankshaft; another contemplated a rotary compressor driven by a reciprocating engine. In both these cases the remaining stages of the heat process envisaged the compressed air being delivered to a combustion chamber and expansion taking place through specially shaped jet discharge nozzles. None of these early schemes for compression were of a practical nature, and jet propulsion designs remained paper projects or laboratory

---

[1] As a pure jet propulsion unit it was ante-dated in operations by the German flying bomb. See p. 221.

[2] A jet-propelled carriage based on Newton's 3rd Law of Motion (action and reaction) was contemplated in the 17th century; in this the propelling jet was a simple steam jet produced by a boiler.

experiments until the possibility of using more revolutionary methods of compression began to occupy the minds of inventive engineers. The revolutionary idea which eventually bore fruit was that of a rotary compressor driven by a 'gas' turbine.[1]

It is impossible to place the idea of the application of a gas turbine to jet propulsion to the sole credit of any one individual or country. In this country the pioneer of jet propulsion as a practical scheme was undoubtedly Air Commodore (as he then was Flight Lieutenant, later Sir Frank) Whittle, and the first definite proposal to use a gas turbine for jet propulsion was contained in a patent taken out by him in 1930.[2] In 1928, when he was a young R.A.F. Cadet,[3] Air Commodore Whittle realised that a gas turbine working on the internal combustion cycle would be an efficient means of providing compression, combustion and expansion for jet propulsion. A part of the expanding stream of gases from the combustion chamber would be employed to drive a turbine which would mechanically drive a rotary compressor through a common shaft.

The gas turbine itself of course was not a new idea. Experimental work had been done upon it both in France and in Switzerland in the first decade of this century. Thereafter interest appears to have languished during the 1914–18 war, only to be revived subsequently. So far as aircraft were concerned the difficulty of improving piston engines for aero-engine work, because of the limitations of cylinder size and the consequent multiplication of working parts and the cooling of existing cylinder materials, directed attention towards the possibilities of the internal combustion turbine. As yet its only application was considered to be a means of driving a normal air-screw through reduction gearing and not in connection with jet propulsion. Compared to the piston engine, the turbine offered many striking advantages, but also some disadvantages. The possibility however was sufficiently interesting to cause a good deal of useful work to be done in Switzerland, the United States and Germany.

In Britain however little enough had been achieved before the mid-twenties. Although the Aeronautical Research Committee (A.R.C.) had occasionally discussed the prospects and in the year 1920 had sponsored a very full report of the position, the difficulties of improving blade materials and compressor design appeared so overwhelming that they were not willing to recommend the Air Ministry to take action. The writer of the report himself gave the following opinion of the prospects of internal combustion turbine

---

[1] A 'gas' turbine is one in which the working fluid is a mixture of air and the products of combustion.

[2] Patent No. 347206.

[3] See article 'The Whittle Jet Propulsion Gas Turbine' by F. Whittle, *The Engineer*, 12th October 1945.

progress. 'The internal combustion turbine will not be rendered practical by a revolutionary design of some lucky inventor. The steam turbine engineer and the metallurgist of wide experience are the people with whom the future development must rest.' As it turned out the metallurgist played the part foreseen for him, but the steam turbine engineer stood, or was left, well outside.

The first important step was taken by Dr. A. A. Griffith, a Principal Scientific Officer at the Royal Aircraft Establishment (R.A.E.) who, in 1926, put forward a paper entitled 'An Aerodynamic Theory of Turbine Design', which had little immediate practical result but was of far-reaching interest in that it directed attention to the crucial importance of the shape of blades and established the theoretical foundations for treating the blades of turbines as aerofoils. Dr. Griffith can thus claim to have been the first person to have interpreted the theory in precise scientific terms for particular application to gas turbines and air compressors. Further, he and his department at the R.A.E. can claim to have been solely responsible for the development and eventual success in this country of a compressor design, i.e. the axial-flow compressor. Around this axial compressor Dr. Griffith laid out the basic features of a gas turbine harnessed to drive a conventional aircraft propeller.

Air Commodore Whittle did not see Dr. Griffith's paper.[1] He was well aware of the potential importance of aerodynamics to turbine design, but his idea of the method by which the power of the gas turbine would propel an aircraft was fundamentally different from Dr. Griffith's. Air Commodore Whittle must have realised very early that if he were to design a jet propulsion unit he must also design his own gas turbine; and the particular objective at which he was aiming led him to conceive a turbine fundamentally different from the one designed by Dr. Griffith at the R.A.E. The useful work which his turbine would be expected to do for jet propulsion would not be as great as that needed to drive a propeller. Consequently, he was able to use a much simpler single-stage axial-flow turbine than Dr. Griffith, whose conception required a multi-stage axial-flow turbine with all the attendant mechanical complications. So far as the compressor was concerned Air Commodore Whittle was content to use a simpler and well-tried type—the centrifugal blower. He added, however, several novel features of his own by which he claimed, and achieved, an efficiency substantially higher than in current practice. Therefore it may be seen that in their initial stages, i.e. until about 1936, both Air Commodore Whittle and Dr. Griffith, whose interpretations of the use of the gas turbine were so different,

---

[1] First James Clayton Lecture by Air Commodore Whittle, see *Journal of Institute of Mechanical Engineers*, March 1946, p. 427.

worked separately and wholly independently of one another. To this extent their individual contributions to gas turbine knowledge in this country are unique. As however between them they laid the foundations of gas turbine technique in this country, the chronology of their individual work must be set out.

(b) BRITISH RESEARCH AND EXPERIMENTS, 1926–40

Air Commodore Whittle did not achieve recognition for jet propulsion from the Air Ministry until he had actually demonstrated its mechanical success and had compiled scientific data to support his claims for the efficiencies of his compressor and turbine. This was in 1939, but by then he had been at work for eleven years.

Air Commodore Whittle had attempted to interest others in his proposals for a gas turbine associated with jet propulsion of aircraft as early as 1929, but failed to acquire either official or commercial backing. He approached the Air Ministry in 1929, when his scheme was shown to Dr. Griffith at the South Kensington Laboratory, but was rejected as impracticable. Early in 1930 he went to two firms—British Thomson-Houston Co. Ltd. (a firm connected with turbine manufacture) and Armstrong Siddeley Motors Ltd. (a firm interested in aero-engine development)—but without result. He filed his first patent in the same year[1] and in it revealed his aims as well as his methods, but his proposals were in those days somewhat crude, and it was not until 1934, when he went to Cambridge University, that he had the opportunity to work on his project in detail. In 1935 he filed further specifications for patents of his inventions and was at last able to interest a private group in his project and to obtain from them a modest financial backing which probably did not exceed £20,000. Early in 1936 a private company, known as Power Jets Ltd., was formed to exploit his inventions and to enable him to start development work and, a short time before then, a contract had been given to the British Thomson-Houston Co. to manufacture an experimental jet propulsion unit to his designs and instructions.

The main characteristics of this epoch-making design were two: in the first place, as already described, its propulsive action was based on the linking of an internal combustion turbine with a jet nozzle. 'The excess of the momentum of the jet over that of the inspired air provides the propulsive effort.' Its second characteristic was the combination of its three main components. The *compressor* was of single-stage, double-entry centrifugal type[2] and had the double advantage of simplicity and familiarity, for centrifugal compressors

---

[1] British Patent No. 347206, 16th January 1930.

[2] A *single-stage compressor* is a compressor having one stage of compression, i.e. the pressure of the working fluid is raised in one continuous operation without intermediate depression or cooling. A *double-entry compressor* is one in which the working fluid is admitted to both sides of the impellor.

of various kinds were already in use in other applications. The *turbine* was also of the very simplest type at that time possible; i.e. a single-stage turbine. The two components were connected by a single *combustion chamber*, into which liquid fuel was injected and burnt. The products of combustion thus generated passed to the turbine, which required only a part of the available expansion to drive it: the remaining expansion took place in the propulsive jet nozzle which led from the turbine exhaust.

The original unit embodying these features was under construction during 1936, and during this period Air Commodore Whittle kept in touch with the Air Ministry, where in spite of his perseverance he had not been able to arouse more than academic interest in his work. He had however one useful friend in the scientific world who also carried weight in the Air Ministry—Sir Henry Tizard, Chairman of the Aeronautical Research Committee and Rector of Imperial College of Science and Technology. It was due to his insistence that a programme of tests for the experimental unit was worked out in collaboration with the Air Ministry in October 1936. The unit was not ready until the spring of 1937, but the delay had one advantage. It enabled the tests to go forward not only with Air Ministry interest, but with their specific approval, as embodied in a report drawn up by Dr. Griffith.

The date of Dr. Griffith's report definitely marks the beginning of official interest in the project. The A.R.C., to whom it was submitted, thought 'the time was ripe for departures in power plant design of this type'; the Chairman (Sir Henry Tizard), especially, thought that a power plant based on an internal combustion turbine promised great advantages both because it was capable of higher powers than ordinary engines and because it would be easy to manufacture and would not require high grade fuels. Consequently the Air Ministry was urged to foster its development.

Meanwhile the completed unit was put on test at British Thomson-Houston Co's Rugby works under Air Commodore Whittle's supervision, and in the course of a few months the rotational speed went up from 8,000 to 13,500 r.p.m. At this point Air Commodore Whittle decided that no further useful data could be got from the unit in its existing form and gave details and sketches of a proposed redesign, but the sponsoring of the tests of the redesigned units was creating some difficulty. In April the A.R.C. had recommended the Air Ministry to take active interest in the forthcoming tests and to supervise them, but Power Jets ran out of money. They hoped the Air Ministry would help, but the Air Ministry was not willing to provide money without getting a return in the form of research results. How research payments should be made presented many problems, and negotiations dragged on during the latter half of

1937; it was not until March 1938 that a research contract of a novel kind was finally given to the firm.

The reconstructed unit was not completed as quickly as its sponsors hoped; it did not run until April 1938, when it functioned for only $4\frac{1}{2}$ hours before it broke down completely on 6th May. The direct cause of the accident had nothing to do with any fault in the design of the turbine or compressor themselves, but such running as had been done showed Air Commodore Whittle, and the Air Ministry agreed with him, that to rebuild the unit in the same form would be a waste of time. Thus a more radical redesign was agreed on.

This redesigned unit approved in May 1938 bore little resemblance to the original unit. Instead of one combustion chamber the new unit was to have ten, and the remaining parts (except of course the compressor impellor and turbine wheel) were to be altered and rearranged. This need for redesign and its character disappointed the private backers of Power Jets who were mainly interested in the commercial prospects of the Whittle engine. A financial crisis thus overtook Power Jets which might have ended disastrously if the Air Ministry had not revised their attitude towards the costs of construction and agreed to pay for the additional expense resulting from the redesign.[1]

Construction of this redesigned unit was again disappointingly slow, but by April 1939 13 hours test running had been done up to a maximum speed of 13,500 r.p.m., and Air Commodore Whittle had obtained the readings of performance and temperatures etc. required by the contract up to 13,000 r.p.m. In June the unit ran for 40 minutes up to 16,000 r.p.m., and on the 30th of that month the Air Ministry's Director of Scientific Research, Dr. Pye, went down to Lutterworth to see for himself the unit run. He was favourably impressed and in his report described the jet propulsion unit as 'a practicable piece of engineering, easily started and under perfect speed control'. He declared that with increasing confidence in mechanical design the unit would have to be seriously considered as a power plant, probably for a single-seater aircraft, and that the Air Ministry should be willing not only to purchase the existing unit but to order a new unit, similar in design and dimensions but lighter in weight, suitable for a test in flight in a specially designed airframe.

This report marks the real turning point in the official attitude to the Whittle unit; an attitude which largely reflected the personal views of Sir Wilfrid Freeman and Air Vice-Marshal Tedder.

The new attitude was soon followed by practical steps. By the end of August Air Commodore Whittle and the Air Ministry agreed about the main features of the airframe. The airframe was, to begin

---

[1] This will be described in the section dealing with the relations between Power Jets and the Air Ministry. See pp. 192–194.

with, conceived as a simple flying test bed. It was expected to have a speed at the operating heights of over 400 m.p.h. and an excellent rate of climb. Gloster Aircraft Company were chosen to design this aircraft, because most of the other firms were already overcrowded, and of the available design teams, Gloster's was probably the best. They were able by October to map out the rough proposals for a small experimental aircraft which agreed with the estimates surprisingly closely. Shortly after a draft specification (known as the E.28/39) was issued to Gloster's and Power Jets, and from this point onwards the aircraft proceeded like a normal prototype.[1] The installation of the engines and the first flight did not however take place until 1941.

Meanwhile during the winter of 1939 and early 1940 the work undertaken by Power Jets grew rapidly. Air Commodore Whittle's designs for new engines, developed from the experience on the experimental unit 'U', were encouraged by the newly-created Ministry of Aircraft Production.[2] One of the most formidable problems still outstanding was combustion, and it was not until the autumn of 1940 that the introduction of the 'controllable atomising' type of burner and a specially designed flame tube marked a real step forward in this direction. With this new component, it became possible to undertake for the first time on the Whittle unit long endurance runs, up to as much as ten hours at a stretch.

At this juncture the pioneer period of the Whittle engine may be said to close and the development period to begin. No such turning point occurred at that time in the career of the other pioneering effort, that of Dr. Griffith. Dr. Griffith's early contribution to the theory of compressors and turbines has already been outlined. His original aerodynamic theory of blade design was expounded in the paper presented to the Aeronautical Research Committee in 1926, in which he related the efficiency of rotary (i.e. axial-flow and radial-flow) turbo-units to the shape of the blades. He argued that in conventional methods of design the blades were treated simply as defining passages through which the working fluid flowed without any loss of energy. Their real purpose however was to transfer mechanical energy between blades and fluid, and in fact they were so shaped and placed as to deflect the course of the fluid. Yet they were not designed to prevent such disturbances of the fluid as would lead to further dissipation of energy. Dr. Griffith argued that the way to prevent these disturbances was to treat the blades as aerofoils.

---

[1] The specification was approved in January 1940, the mock-up conference was held in April 1940 and construction went ahead.

[2] See p. 194.

Dr. Griffith's theory largely determined the main characteristics of his turbo-unit. To begin with, the use of an airscrew as the rotary member pre-supposed a unit of axial-flow type. Furthermore, the treatment of each blade as an aerofoil shape placed at least three more limitations on design. Limits were set, firstly, to the angle to which the fluid could be deflected by a single row of blades without 'stalling' and dissipating energy; secondly, to the number and size of the blades in each row; and, thirdly, to the velocity of the working fluid. From this followed the main features of engineering layout. As one row of rotating blades could deflect the fluid only to a limited degree, several such rows had to be provided, if the turbine were to provide the maximum energy. Dr. Griffith's axial-flow turbine and compressor were therefore both multi-stage.

The construction of either of these units at that date was not seriously contemplated, and the Aeronautical Research Committee and the Air Ministry, who examined Dr. Griffith's theory, did no more than recommend that a proposed test rig composed of a single compressor stage and single turbine stage of aerofoil blades mounted on a common shaft should be built at the R.A.E. so that the theory might be verified. This was done, and tests began at the R.A.E. in January 1929. Reporting on the tests, Dr. Griffith made detailed proposals for the building of a suitable aircraft power plant, but at the same time drew attention to an important difficulty of design. As soon as the operating assumptions changed, and pressures altered, the behaviour of the airflow also changed, so that it was impossible to design blades for a compressor which would cover all the possible ranges of running conditions. The solution was thought to be either to have a series of high, low and medium pressure turbines, each driving a similar compressor, or to make the turbine driving the airscrew mechanically independent of the turbine driving the compressor. This inherent complication in the design of multi-stage axial-flow compressors was responsible for most of the doubts which for many years surrounded the project.

This paper of Dr. Griffith's presented in 1929 was examined by a special panel of the Engine Sub-Committee of the A.R.C. during the early months of 1930. They came to the conclusion that it was impossible to predict with any certainty that the turbine would be as superior to the reciprocating engine as Dr. Griffith claimed. They could not therefore recommend the Air Ministry to develop the internal combustion turbine as a power plant. But they thought an efficient compressor so important that the question of whether efficient compression could be achieved through a number of stages should not be left unanswered. The multi-stage test rig proposed by Dr. Griffith was thought capable of giving 'an unquestionable check on the theory, whereas a conventional type of compressor . . . might prove unsatisfactory'. The A.R.C. accordingly recommended that it should be built.

Although the A.R.C. experts wanted further proof, the steps they recommended clearly indicate that they wished to sponsor the sole British exponent of internal combustion turbines. This makes it all the more difficult to understand why their recommendations were never carried out. Direct work on the gas turbine at the R.A.E. in fact ceased from 1930 until 1937.

The knowledge that Air Commodore Whittle had his jet propulsion unit, which included an internal combustion turbine, probably helped to revive interest in the Griffith project. As a beginning, the R.A.E. obtained authority in July 1936 to build an axial-flow supercharger. This scheme was rapidly overtaken by others. In early 1937, acting upon a request from the A.R.C., Mr. Hayne Constant of the R.A.E. reported upon the prospects of the internal combustion turbine. He concluded that by using only components that had been proved by past experience, a turbine could be built for aircraft with a performance at least equal to the best modern water-cooled petrol engine, except at low altitudes. With improvements in materials and in air compressor design foreshadowed by recent research even superior performance might be attained. Mr. Constant ended this very important report by concluding that 'possible developments':

> suggest the possibility of constructing in the near future an internal combustion turbine whose specific weight would be *less* than that of any internal combustion engine at present in production *under all conditions of flight* and whose specific fuel consumption would be less than that of any spark ignition engine and comparable with that of any compression ignition engine, under all conditions of flight.

The Engine Sub-Committee of the A.R.C. discussed Mr. Constant's paper at the same time as Dr. Griffith's paper on the Whittle jet propulsion scheme. The Chairman (Sir Henry Tizard) pronounced himself in favour of 'a concentration of effort and large scale expenditure'. He was also in favour of 'a device which should result in a very fast machine driven by a jet or preferably by a combination of jet and airscrew'. This pronouncement is interesting, because the R.A.E. reports had always been concerned with propulsion by airscrew, and this persisted until the success of Air Commodore Whittle's jet propulsion had been demonstrated. The outcome was a recommendation:

> that the Air Ministry should take up the question of the development of the internal combustion turbine as a matter of urgency and make all possible arrangements for its production at the earliest possible moment.

Yet in spite of the urgent and categorical recommendation no complete unit capable of delivering useful work could be built for some time. The next three years had to be occupied with preparatory work, mainly with the building of various compressors and units of the advanced axial-flow type for bench tests. The first experimental unit was an axial-flow supercharger (known as 'Anne'). The second experimental unit was the high pressure rotor—the so-called 'B.10' (9-stage axial compressor and 4-stage turbine)—of the high and low pressure series of turbine compressors which were put forward by Mr. Constant in his report. This was completed in 1939.

The firm of Metropolitan-Vickers, with whom R.A.E. discussed in June 1937 plans for joint research and development, later agreed to undertake the work on the high pressure rotor, 'B.10', under R.A.E. supervision. C. A. Parsons Ltd., who had first tested an axial compressor in 1904 and abandoned it in 1908, made some small experiments again in 1935, but as these showed the need for more research and promised no immediate commercial application, they again dropped the idea. In 1938, on hearing about the R.A.E. work, they expressed the desire to be associated with Dr. Griffith in any new development of the axial-flow type, and were invited to construct an axial compressor with R.A.E. blade design. This compressor was known as 'Alice' and ran in 1939. Another turbine firm, Fraser and Chalmers, also co-operated with the R.A.E.

The various compressors built by that time, 'Anne', 'Alice' (built by Parsons) and 'Ruth' (built by Fraser and Chalmers) together with the 'B.10' turbine-compressor, all ran on test during 1939, with varying degrees of success. All however fulfilled that most necessary step which had been emphasised by the A.R.C. in 1930 and without which a successful internal combustion turbine could not be built—the practical proof of the theoretically claimed efficiency for multi-stage axial compressors. In addition to these units many other schemes were worked out and some were constructed: of these, notable examples are the contra-flow scheme which had originally been planned in 1929; known as the C.6, it was designed in 1938 by the R.A.E., constructed by Armstrong Siddeley and returned to the R.A.E. for testing in 1940. The E.5, a small compressor for an axial-flow supercharger, was built by Metropolitan-Vickers in 1939. The D.11 was a combined coaxial turbine and compressor of increased pressure ratio; it was designed in 1939 and later manufactured by Metropolitan-Vickers, who in fact did most of the detail design.

By this time, however, the interest had come to be centred upon a jet propulsion unit. The success of the Whittle unit in the summer of 1939 had shown the practical possibilities of such a system. The R.A.E. were quick to see the advantages in a jet propulsion unit with an axial-flow compressor. Even though the axial compressor entailed certain disadvantages such as length, weight and mechanical complexity, it would permit a smaller frontal area than the centrifugal compressor and thus be eminently suitable for aircraft. The R.A.E. accordingly suggested to Power Jets Ltd., in September 1939, that an axial compressor might be built into a jet propulsion unit; they proposed to design and construct the compressor themselves whilst Power Jets should do the detailed work on the turbine. However, it soon became clear that Power Jets were too busy to take on the work, and eventually, in July 1940, on the R.A.E's recommendation, Metropolitan-Vickers were entrusted with the work under the supervision of the R.A.E.

This point also marks the conclusion of the preliminary stages of the R.A.E. work on axial-flow turbines, corresponding to the early stages of Air Commodore Whittle's work on the centrifugal unit. The early development of the jet engine was thus a two-pronged effort. Although both the R.A.E. Engine Department and Air Commodore Whittle had the same objective in view—a workable gas turbine with a compressor driven by a turbine—they employed different methods and intended its power for different uses. The R.A.E. under the impetus of the original work done in the late 'twenties by Dr. Griffith, were responsible for revolutionising in this country the prospects of the axial-flow compressor which from the point of view of future developments was perhaps a more desirable type. But the claim to have been the first to build and run a gas turbine was indisputably won by Air Commodore Whittle, who used a simpler form of compressor, in 1937. His own way of utilising the gas turbine's power for jet propulsion also became practical before the R.A.E's system involving propeller with reduction gear.

The pioneer stage, now over, owed a little to private enterprise, and a little to the Air Ministry and the R.A.E. Both private enterprise and the State did much less than they could or should have done, had the possibilities of the gas turbine been fully appreciated. In fact, both private enterprise and the State failed more or less, and no historian can allocate to either their rightful share in the failure. All he can do is to account for the reasons for which the support from either quarter was no greater than it was.

The problem does not arise in the case of Dr. Griffith's axial-flow turbine. All the early work in this field was done in the R.A.E. while Dr. Griffith and Mr. Constant were on the establishment's staff. As head and member respectively of the Engine Department at the R.A.E. they had access to certain facilities necessary to perfect the theories and basic calculations upon which the design of their components developed. But their intimate involvement with the R.A.E's work was also a great disadvantage and largely explains why the work proceeded so slowly and was for a time shelved altogether. The gas turbine was only one of many projects competing for time, finance and facilities at R.A.E. Moreover the building of so elaborate a piece of machinery was a task for which the R.A.E. were not equipped; more especially they had none of the necessary testing equipment. This put them at a disadvantage from which they could only be rescued by the co-operation of turbine or aero-engine firms. And unfortunately the co-operation of private firms was small in scale and late in coming.

This does not mean of course that private firms showed no interest, or that no attempt was made to interest them. In April 1937 the Chief Superintendent of the R.A.E. reported that four firms (unnamed) had been approached in 1936 and had, when approached, refused to participate in the construction of 'Anne'. The report though accurate does not of course correctly represent the attitude of the industry as a whole. The R.A.E. complained that 'the manufacturing technique of most of these firms is inferior to that of the engine firms and . . . they required considerably more supervision'. What was probably at fault was not so much the technique of the firms as their private orders of preference. The experimental departments of the engine firms were too busy with their own development work to spare manufacturing facilities for research units. And we have already noted the participation of Armstrong Siddeley in the construction of C.6 in 1938 and of Metropolitan-Vickers in the construction of E.5 and D.11 in 1939.[1] But, in general, during this initial period in the development of axial turbines, the co-operation of private firms was not on a significant scale and was often lukewarm.

Air Commodore Whittle's project, on the other hand was, to begin with, set afloat by private backers and wholly unsupported by H.M. Government. But the private backing came rather late and was very meagre. Had the Air Ministry failed to adopt his project as they did eventually, the whole enterprise would have floundered. To add to this lack of financial backing Air Commodore Whittle's project was further handicapped by his personal position, and especially by his lack of leisure and facilities for research. Although he was an undergraduate at Cambridge University, and was encouraged by his tutor and his professor,[2] the facilities of the Engineering Laboratories were not of the type which could have contributed to his work. Even after the formation of Power Jets in January 1936 he had to do all his work in his spare time. Indeed the pressure of work for the Tripos Examination in June 1936 forced him to stop all work on the

---

[1] See p. 184.

[2] Mr. Roy Lubbock of Peterhouse and Professor Melvill Jones.

iet engine design for several weeks. Later in 1936–37 when he was doing a post-graduate year of research he had more leisure. The lack of facilities for basic research and for testing and proving his components also forced him to concentrate on designing the simplest possible mechanical structure.

However Air Commodore Whittle was able to turn his worst disadvantages to good account. His single-stage centrifugal compressor with single-stage turbine was, compared to the elaborate multi-stage axial-flow compressor and turbine designed at the R.A.E., almost elementary. But it was cheap to build[1] and although it suffered from mechanical failures, and never in fact achieved its designed performance, it worked from the first moment it was completed. Eventually certain parts, notably the combustion chamber, were redesigned, but the turbine and compressor were, in 1939 when the Air Ministry purchased the unit, substantially the same as in the design produced by Air Commodore Whittle in his Cambridge days. It was also a measure of his success that his unit was built first and it worked first. It is not therefore surprising that, in spite of influential opposition, the gas turbine finally designed by the R.A.E. was similarly linked to the jet propulsion unit. This engine was built by Metropolitan-Vickers Electrical Co. Ltd., in 1941.

(c) GERMAN DEVELOPMENTS

The peculiar conditions of the pioneering stage are brought out very clearly by comparison with developments abroad. In the pioneer period of the development of the jet engine in Britain, Britain was not of course alone in the field. In Switzerland considerable progress on gas turbines was made in the 'thirties, for which Herr Eichelberger and the engineers of the firm Brown Boveri were largely responsible. The problems of the axial-flow compressor were also tackled with some success by Professor Ackeret of the *Technische Hochschule* of Zurich and by Dr. C. Keller. Although the axial compressor was not developed for a gas turbine, but for a wind tunnel, Professor Ackeret was acknowledged internationally as a great expert on the subject, and it is clear that the R.A.E. in their investigations were covering ground similar to that covered at about the same time in research stations in Switzerland.

It is however with Germany, the future enemy, that the most important, interesting and fruitful comparison must be made.

---

[1] Power Jets gave British Thomson-Houston Co. a contract for construction of the experimental unit on a cost plus basis. They had a subscribed capital of only £20,000, but with this they paid British Thomson-Houston's monthly accounts (which also included some combustion experiments) for more than a year.

Chronologically, the first work to be associated with the special problems of gas turbines was that undertaken about 1930 by Professor Betz and Herr Encke of the aerodynamics research institute at Göttingen. These two gentlemen were working in the late 'twenties on the problems of axial-flow compressor design. Their aim was to develop the axial-flow compressor primarily as a supercharger for reciprocating engines, and there is no reason to suppose that Professor Betz was particularly interested in its use as a turbo-compressor, although he must undoubtedly have been aware of its possibilities in this direction. There are good grounds however for crediting Professor Betz with being the first person to build a bladed compressor. Dr. Griffith himself, in his report to the A.R.C. in November 1929, referred to Betz's compressor and to the fact that it had achieved an efficiency of 85 per cent. This work on the fundamental problem of axial-flow compressor design was unique in Germany and was pursued as a research project at Göttingen throughout the period 1930–37. By that time a young engineer named Schelp, engaged by the *Reichsluftfahrtministerium* to study the means by which the speeds of fighters could be increased up to the speed of sound, became interested in the prospects of gas turbines and began in 1938 to stimulate their practical development.

This was not however the first time serious interest had been taken in gas turbines. In 1935 Ernst Heinkel, of the famous aircraft firm, became interested in the proposals of a Dr. von Chain and gave him the backing of his firm to build and test his engine as a jet propulsion unit. Dr. von Chain was then in his early twenties and thus could not have been working for very long before 1933 on his ideas.[1] Like Air Commodore Whittle in this country, he employed a centrifugal compressor so as to avoid the difficulties of axial-flow design. His turbine was a radial-flow design and he appears to have wasted no time in finalising it. The engine ran in 1937; shortly afterwards an experimental aircraft was designed by the firm and built; it flew for the first time on 27th August 1939.[2]

The work was carried out as a private venture. Although General Udet was aware of its existence, the firm kept their work secret from the *Reichsluftfahrtministerium*. Dr. von Chain's early engines were not outstandingly successful (trouble with blade failures was especially experienced) and the engine was never put into production. The firm, however, allowed Dr. von Chain and another engineer named Müller to continue with their work. In addition to Dr. von Chain, other engineers were interested in the theory of gas turbines,

---

[1] Air Commodore Whittle's patent (No. 347206) had been published in 1932 throughout the world.

[2] Herr Heinkel himself, in interrogation, repeatedly stated that the aircraft flew first sometime in 1938.

especially Oestrich of Bayerische Motorenwerke and Müller of Junkers (who afterwards went to Heinkel's). They both made design studies between 1935 and 1938, but no engines were actually built.

Helmut Schelp, the young engineer in the research department of the *Reichsluftfahrtministerium*, having investigated the theoretical possibilities of a great many different types of unconventional power units, decided in August 1938 that the gas turbine as a jet propulsion unit was the right type to concentrate on. In spite of the many practical difficulties, Herr Schelp determined to develop the axial-flow compressor because it was theoretically more efficient than the centrifugal compressor. This led him to devote all his energies to persuading the aero-engine firms to undertake the design of axial-flow turbines. Naturally he failed to convince Heinkel's who had their own development; Daimler-Benz were sceptical and refused to take the work of a new development. But Junkers and Bayerische Motorenwerke agreed to design engines and Dr. Wolffe of the latter firm was very enthusiastic. These two firms were given the results of the theoretical work done at Göttingen and also were very rigidly directed by the *Reichsluftfahrtministerium* in the details of the engine design. Work began on these designs in 1939 and the pioneer period can be said to close at this point.

This briefly is the extent of the German progress up to the outbreak of war. At first sight, and considering that there had been no technical contacts between the two countries, it is surprising how closely events appear to have synchronised. In both countries theoretical interest and work on the problem of the axial-flow compressor at government research establishments first began in the late 'twenties. In both countries the problems were so stubborn that although experimental compressors had been built and tested, very little had been done on the practical application by 1939. The practical results had in both countries resulted from the work of young free-lance engineers—Air Commodore Whittle in England and Dr. von Chain in Germany—and the similarity between the two was carried further by their decision to avoid the unknown of the axial-flow compressor by choosing the well-tried centrifugal compressor.

A more detailed study will doubtless reveal marked divergencies. So far as the work of Professor Betz was concerned he probably had advanced further by 1930 than had Dr. Griffith—he had built and tested a bladed compressor with an efficiency of 85 per cent. and by 1938 had done sufficient work for Helmut Schelp to see that it was clearly the right line to go for, in spite of the practical difficulties. On the other hand there is no evidence that Professor Betz ever used his influence to show how important the axial-flow compressor was for the gas turbine or how important a gas turbine itself might be.

In this country on the other hand, Dr. Griffith and later Mr. Constant of the R.A.E. exerted great efforts and played a very influential part in the struggle to get the idea of a gas turbine as a prime mover accepted in this country. From the very earliest days when Dr. Griffith first formulated his aerodynamic theory of blade design, he envisaged the axial compressor as a component of a gas turbine and prophesied the eventual substitution of the latter in place of the piston engine. This became almost an article of faith at the R.A.E. even during the sterile years from 1930–36 when work languished for lack of support from the Air Ministry. Therefore in many ways one can say that the R.A.E. were in advance of Göttingen in their understanding of the potential importance of the gas turbine, even though their theoretical and experimental work was if anything slightly behind.

There were considerable differences too between the work done by Dr. von Chain at Heinkel's and Air Commodore Whittle at Power Jets. The most obvious respect in which the Germans progressed more quickly was that an aircraft powered by Dr. von Chain's jet propulsion unit flew in August 1939 nearly two years before one powered by Air Commodore Whittle's engine. Too little is known of the early testing of Dr. von Chain's engine to enable a detailed comparison to be made of the progress of the two units. It appears, however, that they were both run for the first time in 1937 and it is clear from their subsequent history that Air Commodore Whittle's design was in many ways superior to Dr. von Chain's.[1]

To sum up, progress in the two countries was remarkably close and at the points where the Germans drew ahead they were able to do so thanks to fortuitous circumstances rather than to greater scientific and engineering accomplishments. Any advantage that Göttingen achieved over the R.A.E. was most likely due to the fact that their work was allowed to continue uninterrupted throughout the 'thirties on a line of their own choosing, whilst the R.A.E. were forced to abandon their work for six years.

The faster progress of Dr. von Chain was due very largely to the fact that he had the great good fortune to be able to develop his jet propulsion unit in surroundings which, if not exactly perfect,[2] were considerably more propitious than those in which Air Commodore Whittle's unit was developed. Heinkel's was a large and important firm with many years of aircraft development experience behind it, even if it had few of the special facilities required for engine development. Power Jets, on the other hand, started with no material facilities

---

[1] Dr. von Chain himself is described as more of a theoretical designer than a practical engineer.

[2] Heinkel's works at Rostock were primarily for aircraft production.

of any kind; the firm was only formed in 1936 with the limited purpose of paying for the detailed design and construction of the unit and with no assets beyond its small capital and Air Commodore Whittle's patented inventions. The firm had no buildings, plant or technical staff. For many months all actual work, including the detailed design, took place under contract on the premises of British Thomson-Houston Co. Ltd. at Rugby under the direct supervision of Air Commodore Whittle. Very soon, however, it became cheaper and more convenient for Air Commodore Whittle to conduct his tests independently, and Power Jets rented, as a test house, a disused foundry belonging to British Thomson-Houston Co. known as the Ladywood Works, but they had only the most rudimentary facilities there.[1] Until after the end of the pioneer period manufacture of modified parts, including two major reconstructions of the unit, was still carried out by British Thomson-Houston Co., and the engineering drawings were still largely done in the British Thomson-Houston Co. drawing office.[2]

Similarly the financial position of Heinkel's was incomparably stronger than that of Power Jets. The exact sum spent by the firm on Dr. von Chain's work and on the specially designed airframe is not known, but it was without doubt a much larger sum than the whole of Power Jets' initial capital. The bare outline of the Power Jets' early financial difficulties has already been sketched out in the earlier section of this chapter.[3] But the main facts will bear recapitulating here to underline the comparison with the Germans' experiences. At the beginning of 1936 Mr. M. L. Bramson, the consulting engineer to whom Air Commodore Whittle and his two friends, Mr. R. D. Williams and Mr. J. C. D. Tinling, had shown his scheme, persuaded a firm of investment bankers, O. T. Falk & Partners, to find the money to pay for development. Accordingly Power Jets Ltd. was formed with an authorised capital of £20,000. This was to pay for the patent fees and expenses, for draughtsmen's fees and for construction of the first experimental unit. The option to subscribe a further £18,000 at the end of eighteen months was open to the shareholders who had provided the original money capital (the 'B' shareholders).

Air Commodore Whittle's financial backers, although aware of the highly speculative nature of their investment, were under the impression that once the unit had been built it would soon be clear whether it was going to fulfil expectations. If it should be a success it was reasonable to suppose that the Air Ministry would buy it, or otherwise contribute to its cost. In fact, of course, nothing like this

[1] When testing began at Ladywood Works fitters, welders and sheet metal workers were frequently borrowed from British Thomson-Houston.

[2] It was not until the end of 1940 that a large proportion of design work was done by Power Jets' employees.

[3] See Section (i) (b).

happened. The engine ran and broke down, was rebuilt and broke down again, was redesigned and rebuilt and then ran for some months before any success could be claimed. During the $2\frac{1}{2}$ years that tests and modifications went on the fate of the unit was quite uncertain; on each occasion of a breakdown the original shareholders became more uneasy and less willing to subscribe further. In fact after the first eighteen months they only subscribed £3,000 instead of the hoped for £18,000.

This shortage of ready money had a direct effect on technical progress. There is no doubt that the use of unsatisfactory components was the cause of many technical difficulties during the pioneer period. The condition of the engine steadily deteriorated through accidents and distortion, and many parts which should have been scrapped had to be used again and again.

In Germany the *Reichsluftfahrtministerium's* interest was not needed by Heinkel's. Financially and technically they considered themselves self-sufficient, and when, in 1939, they received contracts for the work under progress, the initiative came from the *Reichsluftfahrtministerium*. Herr Schelp, the responsible official, was to remain in close touch with the firm on technical matters, but Herr Heinkel, fearing that he would wish them to pursue a different line of development, appealed successfully over his head to General Udet, the Chief of Development, for permission to continue work behind sealed doors.

So much for private backing in both countries. The failure of the Air Ministry to give more active aid[1] to Air Commodore Whittle and Power Jets during the earliest stages of the engine's development is easy to understand, though not to excuse. Firstly, the expert opinion available to the Air Ministry was that Air Commodore Whittle's particular compressor design and his method of using the power (i.e. jet propulsion) was not a practicable project. Secondly, the Air Ministry was doubtful about the advisability of giving financial assistance to the firm itself. It was Sir Henry Tizard who in 1936 first convinced the Air Ministry of the advantages of conducting tests on the recently constructed unit under properly controlled conditions. He was also a supporter of the principle of jet propulsion for a practical power plant and had a high opinion of Air Commodore Whittle's personal qualifications for his chosen path. The A.R.C. also supported Air Commodore Whittle's jet propulsion scheme and in 1937 passed a strong recommendation for official encouragement.

In spite of this the Air Ministry for a long time remained unconvinced. Their doubts persisted, although it was admitted within the

---

[1] It must not be forgotten that it was the Air Ministry who gave Air Commodore Whittle the opportunity and leisure to concentrate on his scheme, e.g. by arranging for him to spend a year of post-graduate research at Cambridge (1936–37) and subsequently placing him on the Special Duty List.

Ministry that the project was theoretically sound and that the mechanical and material problems were not insuperable. For some time one of the most important reasons for promoting tests was admitted to be the collection of data which would be useful for the internal combustion turbine at the R.A.E. In the words of the Director of Scientific Research, the Whittle engine was 'the only thing of its kind . . . in the country' and was 'capable of giving data which [could] not . . . be got in any other way'. In addition it was a much cheaper way of getting the information than if the work were done at the R.A.E. or elsewhere at the Ministry's expense.

Dr. Griffith's views were similar and were no more optimistic about the practical use of the engine. The Ministry did not leave Power Jets in the dark on the subject. The Director of Scientific Research clearly stated the Ministry's attitude in a letter to the Managing Director of Power Jets after the second breakdown of the unit in 1938. He said that the Air Ministry were only interested in the unit in order to obtain data from properly planned and controlled experiments 'and not because we expect to see the present apparatus take its place as a practical aircraft power plant in competition with the normal type. . . . I still feel that the ultimate form of power plant in which jet propulsion is made use of may be along different lines'.

These doubts were reinforced by certain administrative objections to the method of financing expected of the Air Ministry. In the past, as a matter of principle and convenience the Air Ministry had given financial assistance only to the well-established firms in the aircraft and engine industry, and did not give financial backing to bankers, investment houses or promoters, no matter how close their connection with the aircraft industry. And it so happened that Air Commodore Whittle was being sponsored by a city firm, and financial assistance to them would have been a new departure and a precedent. Moreover, the Air Ministry did not rate the judgment or the resources of the firm very highly. The Director of Scientific Research had early expressed the fear that the directors of Power Jets were over-optimistic about the speed with which results would be obtained. When Power Jets began to ask for help at the first hint of development difficulties, which were no greater than those which experienced engineering firms would have considered inevitable and taken in their stride, the authorities in the Air Ministry felt confirmed in their low opinion of Power Jets.

The Ministry's judgment on this point may have been too harsh. It seems that Air Commodore Whittle's backers were guilty of nothing more than underestimating the magnitude of the project and its difficulties and expenses. When the real financial needs of Power Jets became apparent, the City backers 'sheared off' the project, and all but abandoned it. Thereupon effective control passed to the 'A' shareholders (Air Commodore Whittle and his two friends) although the Chairman retained his office. But the 'A' shareholders had no money while the Air Ministry stood aloof, and the company was forced to carry on a hand to mouth existence.

The historical verdict may be that the financial outlay was very low compared both with the value of the research work done by Air Commodore Whittle and with the cost of the work in the immediately succeeding period when jet propulsion was fully backed by the Air Ministry. In this respect both private business and H.M. Government failed to rise to the occasion. Private finance was too meagre and too timid. It was drawn into the project on wrong pretences, and withdrawn from it as soon as its true nature became clear. The Air Ministry was over-critical and unperceptive, and its assistance came very much later than it should have done.

(ii)

The Development Period: The Years of Promise, 1940-41

(a) THE GLOSTER/WHITTLE PROJECT

The pioneer period of jet propulsion can be said to have ended and the development period to have begun when Air Commodore Whittle successfully demonstrated that his experimental unit was potentially capable of fulfilling the design assumption. The Air Ministry expressed themselves convinced of the importance of jet propulsion, and proceeded to approve plans for the design of an experimental aircraft. But it was not until the New Year of 1940, i.e. some months after the outbreak of the war, that plans for jet propulsion had come to be conceived on a large scale. The Ministry of Aircraft Production and the Air Ministry formulated a short list of projects which could have an important influence on the war in the air. Prominent amongst these development projects, somewhat hyperbolically called 'war winners', was jet propulsion. By April 1940 the effects of the new policy could already be observed. Orders had been given for engines to be built to improved designs made by Air Commodore Whittle in the autumn and winter of 1939–40, and an investigation into the most suitable type of military aircraft for jet propulsion was already nearing completion whilst production itself was being discussed. The events of May 1940 and the emergency régime at M.A.P. checked the plans for a time, but did not cause them to be abandoned. In August 1940 they returned prominently to the foreground. By this time they had won support at the very summit of war-time government; and with this support proposals for the development and production of engines and airframes, so long discussed and deferred, rapidly matured.

Since the late summer of 1939, when he had proposed the W.1 engine (a lightened version of his experimental unit) for installation in an experimental airframe, Air Commodore Whittle had not rested on his laurels. In September 1939 he outlined proposals for another engine, to be known as the W.2, which was intended to embody all the improvement shown to be desirable during the running of the experimental unit.[1] This engine was almost immediately ordered by the Air Ministry. By the spring of 1940 the design of the W.2 engine was sufficiently advanced to become the starting point of the new plans for an operational aircraft.

The type of aircraft most suitable for jet engines was considered in relation to the special advantages and limitations of the new methods of propulsion. The most favourable application was at first thought to be a bombing and reconnaissance aircraft which would operate at high altitudes. The fuel consumption would thus be at an economical rate and would permit a reasonably long range. But the problems of pressurising the cabin were thought to be too complicated and the operational role insufficiently important. Gradually the opinion of the experts came to be centred on a high-speed lightweight interceptor fighter with a relatively short endurance, and in May 1940 M.A.P. directed that Gloster's should proceed immediately with the design.

The next stage in the Air Ministry's plan for jet propulsion was to arrange for the development of the batch of engines from the basic W.2 design. Air Commodore Whittle himself was optimistic about the speed with which development could proceed, but other responsible persons expressed the view that the main problems of the gas turbine were as yet but imperfectly understood, and foresaw that these problems could only be solved when the new engines were actually running on the bench. The general feeling was, however, that if the development were energetically undertaken the difficulties could be overcome sufficiently quickly to achieve the minimum thrust in time for the airframe.

What was not yet clear was the choice of the firm fit to undertake the task. By this time Air Commodore Whittle had built up at Power Jets a very strong design team who were recognised to be 'the

---

[1] Halfway between the design of the W.1 and the W.2 was the design of another engine, the W.1A.

key to the whole project . . . [whose] continued existence is vital'. But all their skill and ability could not make up for Power Jets' lack of manufacturing facilities, and to build up such facilities would take time. Moreover, the chosen firm would have to be capable of going 'over rapidly to production once a reasonable state of development had been reached'. On both, Power Jets were disqualified, but if they could not undertake the development or production they were still the mainspring of design and research, and whatever firm did the work would have to co-operate very closely with them. This weighed heavily against the British Thomson-Houston Co., for Power Jets had had cause to complain of their unwillingness to co-operate on technical matters. They were still retained as possible candidates for production, whilst given further orders to manufacture W.2 development units, but for the work of development the choice lay with one of the motor manufacturers, who had also experience of aero-engine work under the shadow scheme. Rover's became the preferred choice. Power Jets had already approached them privately as possible shareholders and as sub-contractors. Rover's were at first opposed to the proposal that they should work as sub-contractors to Power Jets, but when the Air Ministry approached them they agreed to undertake the work. Power Jets accordingly handed over the W.2 design to them, while the Air Ministry gave them a direct contract to build an experimental unit.

Thus by the end of April, in addition to the project for the jet-propelled fighter, plans for development of the W.2, with a view to its future production, were well advanced. Direct Air Ministry contracts for construction of W.2 units had been given to British Thomson-Houston Co., and Rover's. British Thomson-Houston Co. forwarded their scheme on the 20th April, but before it could be considered the events of May 1940 caused all preparations for production to be shelved. Development, however, was continued in spite of a general ban on long-term projects. On 13th June, within 24 hours of the removal of the ban on general development, telegrams were despatched to the firms to inform them that they might officially resume work. In addition, Dr. Roxbee Cox, who had been placed in special charge of jet propulsion under the Director of Scientific Research, quickly followed up this intimation of renewed activity by visiting British Thomson-Houston Co., Rover's and Power Jets.

It was clearly the intention of the Ministry of Aircraft Production that, if possible, the progress of the development of jet propulsion should not be arrested by the ban of the summer of 1940. The direct effects of the ban were not immediately felt, mainly because during the summer months, the problems of jet propulsion were still handled at an administrative level below that of the Minister and his advisers. Unfortunately the break in priority did considerably delay the construction of the Unit W.1 at British Thomson-Houston Co. This should have been completed by June 1940, but was not delivered until March 1941, and even then the components were not assembled. The W.2 at Rover's also suffered a slight delay. But the effects of the ban would have been considerably more damaging had the Minister's instructions not been interpreted with a liberality bordering on disregard.

By July 1940 production was again being discussed. There is no doubt that the interest taken in the project by Lord Cherwell, who had the direct ear of the Prime Minister, was an important factor in the remarkable renaissance in jet propulsion during the early and late autumn. An important event in this connection was a meeting at the Royal Aircraft Establishment in September 1940, when Lord Cherwell was won over by Mr. Constant and Air Commodore Whittle succeeded in demonstrating to Lord Cherwell the importance of jet propulsion.

The extension of interest beyond M.A.P. was undoubtedly one of the reasons why, when at last Lord Beaverbrook and his chief collaborator at M.A.P., Mr. Hennessy, became aware of the existence of jet propulsion and the aircraft designed for it, the project took such an important place in the discussions of the future development programme. These went on during the winter of 1940–41 between M.A.P. and the Air Staff. At that time the tactical ideas of the R.A.F. were being shaped by the massed night attacks of the *Luftwaffe*, and two new fighter requirements made their appearance as a result. These were the night fighter and the high-altitude fighter incorporating a pressure cabin. Providentially both these requirements seemed to be adequately met by Gloster's designs: the high-altitude fighter by the jet propulsion design—the F.9/40—and the night fighter by a redesign of an existing prototype.[1] Interest in both these projects was sustained, and it was not until the E.28/39 flew in May 1941 that the Air Staff finally interred the Gloster night fighter, leaving the firm free to concentrate on the jet fighter. However, it was clear by the end of December 1940 that if the jet fighter were required at all, it would be needed in very large numbers. This was sufficient excuse for Sir Henry Tizard, who was made an additional member of the Air Council in June 1941, to perform some of the functions previously exercised by Sir Wilfrid Freeman. He was now able to use his authority to push the production plans for the jet aircraft with the greatest enthusiasm and activity. Eighty airframes and at least 160 engines a month were laid down as the basis for planning.

[1] F.9/37 later F.18/40.

The next decision turned upon which firm should finally be chosen to undertake quantity manufacture of the jet propulsion units. The British Thomson-Houston Co., because they did not agree with M.A.P's policy for co-operative development, had gradually dropped out of the running, although they continued with their contract for experimental units incorporating certain features of their own design. Another firm, Vauxhall's, was considered, but their other commitments were too heavy. Rover's were therefore left alone to manufacture a large proportion of the W.2.B engines required for the Gloster F.9/40 airframe. This they were perfectly prepared to do, and Power Jets proceeded to give them all the drawings and information necessary to commence work.

Suitable terms on which Power Jets and Rover's could co-operate on the design and development work were however very difficult to formulate. It was M.A.P's intention that Rover's should be responsible for the detailed mechanical and structural design for production, and that Air Commodore Whittle should be responsible for thermodynamic design. The arrangement assumed that both firms would collaborate freely and would be prepared to abide by this 'gentleman's agreement'. Unfortunately the firms were by no means on terms of mutual confidence. The two firms had failed in April 1940 to come to any commercial agreement owing to Rover's refusal to admit the validity of Power Jets' patents (their chief assets) and to Power Jets' counter-claim for a large sum for post-war commercial manufacturing rights. The deadlock had only been broken by strong M.A.P. pressure as a result of which Power Jets gave Rover's the W.2 design without having reached any agreement which to their view could safeguard their position. They believed that they were being put in the hands of a big company with no more than the 'moral' obligation of the Air Ministry as a safeguard.

Simultaneously with these arrangements for the Whittle engines (the W.2.B version had been chosen for production) closely integrated plans for the F.9/40 aircraft were proceeding. On 24th January the Air Supply Board approved that the Gloster Aircraft Company should be given an order for twelve development aircraft. At the same time approval was given for jigging and tooling for an output of eighty aircraft a month as an essential measure to avoid delay when a production order should be approved. The final order did not in fact come until several months later, i.e. August 1941, although materials had been ordered in June. The organisation of the production of jet-propelled aircraft and engines, so far as M.A.P. were concerned, was therefore virtually complete by the late spring of 1941.

(b) THE GAS TURBINE INDUSTRY

Towards the end of 1940 and during 1941 the enthusiasm for jet propulsion was at its zenith. The special characteristics of jet propulsion fitted extraordinarily well into the new tactical requirements of the period and appeared to offer spectacular advantages over the conventional engine. There was thus every incentive to press forward with plans for its development and production off the drawing-board in time to play its part in the war. The extraordinary success of the first flights of the E.28/39 experimental aircraft, which were singularly free from any of the usual mishaps of first flights, helped to obscure the fact that development itself was still in its earliest stage. The enthusiasm now began to overflow into other fields of gas turbine development which had hitherto lain fallow. It was now realised in M.A.P. that the range of possibilities covered by the Whittle engine and the resources devoted to its development were not large enough. The R.A.E. researches into axial-flow compressors were recalled; in theory certain other types of gas turbine and jet propulsion units were adumbrated and one or two firms were beginning to show an interest.

Due largely to Sir Henry Tizard's efforts during 1941, the policy of inducing well-known aero-engine designers and other experts to lend their brains and the resources of their firms to the problems of gas turbine design gradually established itself. It proved to be a success. Its guiding principle was co-ordination; and in the first place co-ordination between industry and the Royal Aircraft Establishment. A further expression of this policy of multilateral exchanges in technical matters was the decision to make available to the United States Government all that this country had already achieved in the gas turbine field. In carrying out the policy M.A.P. played an increasingly active part both as convenors of the committee of collaboration and as the ultimate authority responsible for the direction of development projects and for their character.

By early 1942 eleven firms were engaged in work of one form or another. The firms were:

Power Jets Ltd.
British Thomson-Houston Co. Ltd.
Rover Co. Ltd.
Rolls-Royce Ltd.
Metropolitan-Vickers Electrical Co. Ltd.
de Havilland Aircraft Co. Ltd.
Armstrong Siddeley Motors Ltd.
Ricardo & Co., Engineers (1927) Ltd.
Joseph Lucas Ltd.
Bristol Aeroplane Co. Ltd. (Engine Division)
Gloster Aircraft Co. Ltd.

Of these firms, the first three, as we have seen above, had been concerned with the plans for the W.2.B although only one, Power Jets, was engaged on the design of original units. Two more of the firms were brought in in connection with the W.2.B detail design, one (Ricardo's) as consultant on the special problems of accessories, and the other (Joseph Lucas) as a sub-contractor to Rover's. The air-frame firm (Gloster's) was also directly connected with the W.2.B plans and had the additional distinction of being for some time the only airframe firm in this country to be engaged on the design of special aircraft for jet propulsion. Four firms, Rolls-Royce, Metropolitan-Vickers, de Havilland and Armstrong Siddeley, undertook new designs of complete jet propulsion units, whilst the last, Bristol's, was given a long-term basic research problem intended to improve the general efficiency of the gas turbine heat cycle. These five firms, together with Power Jets, had the lion's share in the development of the new power plant.

Chronologically the first large firm to be brought into gas turbine design was the Metropolitan-Vickers Co. In October 1940, the Company received a contract for two jet propulsion units incorporating an axial-flow compressor, and soon showed a desire to be more closely associated with the project. They began by making claims to a large proportion of the design and early in 1941 sought an assurance from the Ministry that they would be amongst the firms chosen to produce the F.2 (as the jet propulsion unit was called) in quantity if such a course should be decided upon. Thus in 1941, when M.A.P. were themselves anxious to broaden the technical effort on the gas turbine, they found at least one firm, originally brought in in a subordinate position, ready to occupy an increasingly important part in the future.

The second firm to make their appearance in the field of gas turbine design was the de Havilland Co. They had had no previous experience in gas turbine work and were chosen mainly because of their connection with Mr. F. B. Halford. Of the two engine firms to which Mr. Halford acted as Chief Designer, de Havilland's were the least heavily committed to war contracts; therefore, when Sir Henry Tizard set Mr. Halford the task of designing a new gas turbine, they rather than Napier's were chosen to undertake the development work.

When Sir Henry Tizard, in early 1941, inaugurated his policy of enlisting experienced and successful engineers, one of the first individuals he turned to was Mr. F. B. Halford, the designer of the Napier Sabre engine. Mr. Halford's contact with jet propulsion had been a very recent one. Vauxhall's had called him in (probably on M.A.P's advice) as a consultant on their projected W.2.B contract. Soon after this scheme was abandoned Sir Henry Tizard approached him with the suggestion that he should design a new jet propulsion unit. The type and choice of components were to be entirely his own, but Sir Henry Tizard wished him to take the advantage of the specialised knowledge accumulated by Power Jets and the R.A.E. before making his choice. Mr. Halford was able to see Air Commodore Whittle's centrifugal compressor unit; in addition he wished to utilise his own work on the Sabre supercharger. The proposals he submitted to Sir Henry Tizard were therefore for a jet propulsion unit using a centrifugal compressor similar in principle to the Whittle unit. The unit was an important step forward in that it was planned to give a greater thrust (3,000 lbs.) than any other unit yet designed.

Four Halford-de Havilland jet propulsion units (known as the H.1) were ordered in May 1941, and the first of these ran in April of the following year. The unit proved very successful in its trial runs. The firm's enthusiasm and energy in tackling this new enterprise also impressed the official observers, and as the centrifugal compressor type of gas turbine was at a more advanced stage of development than the axial type, (partly because its problems were simpler and partly because more time had been devoted to its development), an additional order for development units was given. Plans were made to flight test the H.1 and this was followed a few months later by a small production order. Thus although the firm had not been master of their own destiny to the same extent as Rolls-Royce, and had relied on M.A.P. initiative to enter the field of gas turbine design, they proved apt and enthusiastic pupils. By 1943 they were able to undertake on their own responsibility the outline of an airframe project of novel construction to be powered by their own jet propulsion unit.[1]

The third firm to be approached by M.A.P. in connection with jet propulsion design was Rolls-Royce. This was in June 1941, many months after Metropolitan-Vickers had been given an order and sometime after Mr. F. B. Halford had submitted his new proposals. It is however, misleading to take this date as Rolls-Royce's starting point, for they were the only firm who on their own initiative had taken active measures to promote gas turbine development.

It was in 1939 that Dr. A. A. Griffith, whose name will always be associated with the pioneer work of gas turbine theory in the 1920's and early 1930's at the R.A.E., left that Establishment for Rolls-Royce, who offered him a senior position on their research staff with a wholly unrestricted commission and with wide facilities for his own line of development. On their part this was a decision which was both imaginative and long-sighted. By 1939 Rolls-Royce had no need to

---

[1] The D.H. 100 afterwards known as the Vampire.

fear competition in the field of reciprocating engines, but in the long-run, should this type of engine itself be supplanted by other prime movers, the firm's position would be radically altered. In 1939 the run must have seemed very long indeed, but the men in charge of Rolls-Royce knew how to look ahead. They were moreover well provided with resources both human and material, and were thus in the fortunate position to be able to indulge in the luxury of long-sight.

This Rolls-Royce enterprise was harnessed to official policy in 1941. In June of that year M.A.P. requested that Rolls-Royce should adapt Dr. Griffith's contra-flow gas turbine as a jet propulsion unit suitable for flight testing in the F.9/40 airframe. Sir Henry Tizard's policy of associating all current development work with the same objectives, made it inevitable that Rolls-Royce projects should be brought within the field. The firm were asked to adapt their unit for jet propulsion and to plan their programmes so that flight tests in the F.9/40 could take place as soon as possible. From the first Rolls-Royce offered M.A.P. the utmost co-operation and, indeed, Mr. Hives, as he then was, went further and at one point advised certain action, about which more will be said presently, whereby technical activities of separate firms could be more effectively combined.

The initial progress on the contra-flow units was, if measured against that of Whittle's and Halford's units, and even against the more backward Metropolitan-Vickers' unit, disappointing. The first unit which had been promised for bench tests by January 1942 and for installation in the F.9/40 by the following summer was many months behind schedule and the large 22-rotor unit which was to follow was even further behind. But Dr. Griffith's contra-flow units were by far the most technically advanced and ambitious of all the other designs and were expected eventually to outstrip them all.

Moreover the interests of the gas turbine department at Rolls-Royce were not limited to contra-flow schemes. This gas turbine department was active, independent and wide-ranging. In early 1942, without prompting from M.A.P., Dr. Hooker and Mr. Howarth planned with Power Jets an improved version of the W.2.B. This unit, to which the R.A.E. was also able to contribute technical advice, was not a practical success and was abandoned after Rolls-Royce took over Rover's factory. But as a bench test engine it provided a certain amount of information and data for the common pool. Before long, as a result of their work on the C.R. unit (as the contra-flow unit was called) and the W.R.1 unit (as the Rolls-Whittle scheme was called) the Rolls-Royce team built up an important position for themselves; and the M.A.P. and other firms came to regard them as a major influence on gas turbine technique. This position was, of course, much enhanced when in 1943 Rolls-Royce took over Rover's shadow factory for W.2.B production.[1]

Armstrong Siddeley was the fourth firm to come into the field of jet propulsion, but they plunged more irrevocably into the new field than almost any of the others, for they abandoned completely the design and development of reciprocating engines in favour of gas turbines. Although the firm were themselves ultimately responsible for this momentous decision, M.A.P. made it clear to them that their place in the aero-engine 'family' was dependent upon such a change.

Armstrong Siddeley had for some years been closely controlled by Hawker Siddeley; the directors of the latter had shown an interest in jet propulsion ever since Gloster's, another of their subsidiary companies, had been engaged on the design of the E.28/39.[2] In 1941 Sir F. Spriggs and Mr. H. E. Jones, in whose hands the direction of Armstrong Siddeley's lay, appointed to the technical staff Mr. Fritz Heppner, a German refugee and a very brilliant engineer, who had specialised in gas turbine theory and had invented a system, which, while it was similar in principle to other designs, differed very considerably in detail. His acquisition was a clear sign that Armstrong Siddeley's intended to branch out into jet propulsion as a long-term policy. The existence of a nucleus of a gas turbine team undoubtedly influenced the decision of M.A.P. to 'push' the firm into a gas turbine field, though the firm's decision to foreclose on their interests in reciprocating engines was largely due to other causes.

As might be expected from the circumstances of their entry into gas turbine work, Armstrong Siddeley's first steps were guided by M.A.P.: the arrangement for the co-operation with Metropolitan-Vickers over the installation of the F.2 in the F.9/40 prototype, which has been mentioned before, was as much intended to give Armstrong Siddeley's some insight into gas turbine problems as it was to aid Metropolitan-Vickers. A more important step, however, was the choice of the gas turbine design for the firm's first venture. Discussions on this question continued well on into the second half of 1942. Should the firm be allowed to proceed with Heppner's design in the face of certain technical objections? Finally, the technical objections prevailed. The firm accepted R.A.E's advice and designed a unit on more orthodox lines, which offered a slight but definite improvement in performance over other existing designs.

What then of that unique institution, Power Jets Ltd.? We have seen how Power Jets' financial and industrial position made it

---

[1] See p. 215.

[2] This was not of course the first contact which the firm had had with jet propulsion. In 1930 the firm rejected Air Commodore Whittle's proposals. This was before the firm was absorbed by the Hawker Siddeley Group. See p. 178.

difficult for it to fit into the normal industrial framework. But equally we have seen that the skill and ability of Air Commodore Whittle and his team was such that their survival as an entity was acknowledged by M.A.P. to be essential.[1] The special plans of 1940 to develop the W.2.B for production as fast as possible provided for Power Jets a definite, though limited, field of activity, but Air Commodore Whittle's original design work and his research were not expected to stop short with this particular engine. In order that he and his team should be able to continue their work on a technically independent basis a way of overcoming Power Jets' main weaknesses of finance and facilities had to be found. Although the most obvious solution would have been to place Air Commodore Whittle and his team *en bloc* within the R.A.E. or another firm (this idea was discussed on more than one occasion) the personal problems that it raised were admitted to be too great. Accordingly the only alternative was to build up Power Jets into a self-contained unit at M.A.P. expense.

The Treasury granted the first capital assistance for the establishment of a 'centre of research and development' in September 1940. The technical staff of Power Jets were described as 'the only people in this country competent to explore this new field of research thoroughly'. Accordingly £24,000 was granted to provide the research centre with much-needed buildings, tools and test equipment. Working capital was a more difficult problem and the Treasury were persuaded to agree to the unusual expedient of the department defraying the current expenses of Power Jets by a monthly cheque.

Thus far, M.A.P. were responsible for Power Jets' survival. But the latter's work was still limited by their facilities which remained on a very small scale. Early in 1941 the next phase came: Sir Henry Tizard, in his plans for the new industry, was determined that Air Commodore Whittle should be given every opportunity to continue and extend his work. M.A.P. accordingly sponsored a small factory, specially laid out to enable Power Jets to build their own prototype engines as well as to have much improved research facilities.

The factory, near Leicester, went into operation and became Power Jets' headquarters in 1943. Power Jets took with them to their new factory a large programme of research and experimental work including the design of a new engine. In this way, by the end of 1942, largely owing to M.A.P. decisions and financial provisions, Power Jets had been assured of an important part in the industry as the foremost research centre. This part they played in spite of their complete financial dependence which required an approval for virtually every item of expenditure. The financial dependence

---

[1] See pp. 195–196.

continued until the summer of 1944 when the Government took over the assets of the company and formed a new company known as Power Jets (Research and Development) Ltd., with which organisation the gas turbine section of the R.A.E. Engine Department was amalgamated.

Thus by the beginning of 1942, it became possible to use the title 'gas turbine industry' to describe those eleven firms who were concerned with one or more aspects of gas turbine engineering. The infant industry needed nursing and directing. It is therefore not surprising that during the period of growth the relations of the Ministry with the firms, the firms with each other, and the R.A.E. with the firms, should have been noticeably different from those which prevailed in the aero-engine industry proper.

Some of these differences were symbolised in the bodies through which the M.A.P. direction was so to speak 'institutionalised'. The most important of these bodies was the Gas Turbine Collaboration Committee. On 3rd October 1941, the Controller of Research and Development issued an invitation to seven firms to nominate representatives to the new committee which was to be under the Chairmanship of Dr. Roxbee Cox.[1]

The Committee owed its inception to the determination of the successive chiefs of research and development at M.A.P. not to allow commercial considerations to stand in the way of gas turbine and jet propulsion development, but the shape it eventually took was due to a suggestion of Mr. Hives the head of Rolls-Royce. The object of the Committee was to ensure that the normal peace-time barriers between individual firms, erected by means of patents, secret processes, technological 'know how', were broken down and that the experience of each firm should be at the disposal of all. It was expected to ensure the pooling of new ideas, of testing facilities and of experience; and also to establish a mood of mutual trust. In the words of the Controller of Research and Development, not the least of the Committee's achievements would be to bring 'the various factions within speaking distance of each other'.

The clouds of mutual suspicion were not, however, too black; most firms were happy to join the new committee. Amongst these were, of course, Rolls-Royce, Power Jets and Ricardo's. Other firms (de Havilland's and Rover's) showed some reluctance but did not refuse to join. At the outset there emerged one difficult problem concerning mutual relations of firms, i.e., the problem of patenting the new ideas and inventions which appeared during the period and as a result of technical collaboration. For reasons which are not relevant

[1] The firms were: Power Jets, British Thomson-Houston Co., Metropolitan-Vickers, de Havilland, Rolls-Royce, Rover Co. and Ricardo & Co.

here, no agreement was reached on this point either at the first meeting or on subsequent occasions. But in the interests of the progress of gas turbines the question of patents was banished for all time from the agenda of the Gas Turbine Collaboration Committee, and all firms agreed that technical collaboration should proceed on the assumption that the patent question would be solved (as indeed it was later) to everyone's satisfaction.

The Gas Turbine Collaboration Committee, or G.T.C.C. as it was called for convenience, survived the experimental stage. The firms 'played the game'; meetings did not take place too frequently; it was tactfully and efficiently led by its M.A.P. contingent, and primarily by its Chairman and the Secretary. Soon other firms were invited to join or themselves asked for invitations. In November 1941 Bristol's asked to be admitted, and Armstrong Siddeley were invited, and early in the New Year of 1942 the invitation was extended to Joseph Lucas. Frequently, other firms and bodies were asked to send representatives to meetings when special questions were being discussed. The Committee and its policy were loyally supported by the firms. Cases of withholding information were infrequent and, with one notable exception, were easily dealt with by the personal intervention of the Controller of Research and Development or his staff.[1]

The other institution embodying the policy of co-ordination was the R.A.E. Their influence in this field was largely due to their early pioneering work in the late 'twenties and the 'thirties which in some respects placed them, together with Power Jets, far ahead of the newcomers. In addition the wide range of the research work of the Establishment included subjects like aerodynamics, stresses and materials, which were directly related to the problems of the gas turbine. As a result a vast body of relevant theoretical knowledge was assembled at R.A.E., which gave to the R.A.E. a position of unique authority in the technical development of the gas turbine.

Apart from their own particular field of research,[2] the R.A.E. were also able to render many services to the industry. They were made responsible for the census of test equipment in the country suitable for gas turbines and components; they also undertook to compile the standard glossary of gas turbine terms for the use of the Gas Turbine Collaboration Committee. But the most important of the 'common services' they performed for the industry was the

---

[1] The notable exception was of course the construction of the B.26 version of the W.2.B by Rovers.

[2] Among the research work carried out by the R.A.E. were the following items: compressibility effects in compressor blading, combustion research, including the development of a technique of gas analysis, mixing of gases at different temperatures, blade vibration investigation, gas temperature measurement, work on pressure losses in combustion chambers, etc.

analysis and criticism of the firms' designs. Finally the R.A.E's expertise fitted them for another all-important task: that of investigating the types of jet propulsion units most suitable for certain classes of airframe.

In the opinion of M.A.P. the special value of the R.A.E's judgment on existing and future designs lay in the fact that they were:

> divested of any responsibility for decisions . . . and free of all the sordid business of turning a conception into a piece of hardware to be made by and bought from contractors, issued to and knocked about by the R.A.F.

There was, however, even inside M.A.P. another, less enthusiastic, view of the R.A.E. role. Some people thought that the R.A.E. was intruding into the fields which were the traditional preserve of either the headquarters staff or the industry itself. Certainly, it can be said that the position of the R.A.E. in the gas turbine field was more influential than it had ever been in the design of conventional aero-engines since the end of the 1914–18 war.

The scope of the work undertaken by the R.A.E. on gas turbines soon outgrew the capacities of the Engine Department personnel, and a branch establishment was set up at Pyestock, some two miles distant from Farnborough. At Pyestock testing and research facilities were provided, as well as a small machine shop, so that all the R.A.E's new functions as well as their old ones were catered for. Eventually the staff of 'thinkers', designers, engineers, and skilled workmen amounted to about 50 men.

(c) COLLABORATION WITH U.S.A.

Britain was not of course to remain alone in the field. The United States were bound to enter it before long, and co-operation with the Americans became an essential part of British policy.

Although design studies of a preliminary character for gas turbines for jet propulsion had been undertaken by various firms in America early in 1941 under official encouragement, little progress had been made, and it is not surprising to find that in June 1941, a few months after Sir Henry Tizard had first given the American National Advisory Committee on Aeronautics a brief description of the Whittle engine, the United States Army took the initiative and officially requested the British Government for more detailed information on the stage of development and on the main features of design. In October the two Governments concluded a general agreement relating to the disclosures under which they agreed that the chief object would be 'to assist the joint defence plans of our respective Governments'. For this commendable, but somewhat vague, purpose the British undertook to release all details of the Whittle engine, to give the Americans a full set of drawings and also to lend a test bench engine. The Americans undertook (and it was agreed by both Governments that this would be their best contribution) to supply the manufacturing facilities for the Whittle engines.

Original research work in the United States was thus for some time strictly limited. A Whittle engine, W.1.X, and a full set of drawings of the W.2.B were flown to America in October immediately agreement was reached between the two Governments. They were accompanied by three experts from Power Jets, who assisted the General Electric Company in the early stages. Later in the year details of the Metropolitan-Vickers F.2 and the de Havilland H.1 engines were also made available to the Americans, whilst at the end of 1943 H.1 engines for installation in experimental aircraft were flown across the Atlantic. The flow of information and help from East to West was considerable from 1941 onwards: apart from a visit paid by Air Commodore Whittle himself in 1942, many British experts visited the United States on special missions of assistance, whilst representatives of all the American firms involved were welcomed at British firms and establishments. In this way, there came into existence channels both formal and informal through which day-to-day information, as well as firms' regular progress reports, could be placed at the disposal of the Americans.

Within the United States itself gas turbine manufacture on the Whittle principle was for some time confined to one firm, the General Electric Co., who were recommended to the United States Government by M.A.P. on the grounds of their previous experience on turbo superchargers.[1] It was not until the summer of 1943 that Allis Chalmers, the American licencees of Brown Boveri, the Swiss firm of industrial gas turbine makers, were brought in to manufacture de Havilland H.1 engines. It is interesting to note that no British axial-flow compressor designs were ever copied in the United States. Both the General Electric Co. and Westinghouse undertook the design of axial-flow compressors on lines which were quite independent of British development, and, in the case of the General Electric Co., also for a long time independent of the work on centrifugal design which was carried on by another team in the same firm. Although the disclosure of information by M.A.P. and the British firms was fully consistent with the declared policy of technical collaboration which was such a remarkable feature of British war-time gas turbine development, nothing of this kind was ever attempted, or ever considered, in the United States. As a result of the

[1] They had built several designs based, except for the combustion equipment, almost entirely on the Power Jets W.2.B, W.2/500 and W.2/700 designs. The General Electric Co.'s versions were known as the 'I', the 'I.16' and the 'I.20'. The 'I.14' was the 'I' design with improved turbine blades similar to Rolls-Royce improvements to the W.2.B/23. The later 'I.40' version was a larger engine similar in principle to recent centrifugal engines in this country.

'rugged independence' of individual firms and even of teams within firms the American method of approach to development fundamentally differed and perhaps differs still from the method adopted by the British and even more from the prevailing methods in France and U.S.S.R.

This very brief outline of the circumstances in which American firms entered the gas turbine field is sufficient to show that, except in the case of the axial-flow compressors, there was during the early stages in the history of the gas turbine no indigenous line of development in that country.

(d) RIVALRY WITH GERMANY

Allied plans and progress in the field were well-matched by those of the Germans. The handling of gas turbines by the Germans, however, differed in a number of important aspects which are worth noting.

German progress after 1939—earlier development was roughly parallel to the British[1]—was briefly as follows. We have seen how after Helmut Schelp, the young engineer at the *Reichsluftfahrtministerium*, had completed his survey of the possibilities of different prime movers for increasing the speed of aircraft, Heinkel's, who were already engaged on the construction of their experimental engine and airframe, appealed directly to General Udet, then in charge of technical development in the *Luftwaffe*, to be allowed to continue to work behind closed doors. Of the other firms approached by Schelp, Daimler-Benz were sceptical of the immediate possibilities of the gas turbine and declined to do any work. Junkers, though not very keen, agreed to Herr Schelp's proposals, and Dr. Wolffe of the Bayerische Motorenwerke expressed real interest. Herr Schelp therefore commissioned the two latter firms to do the design and construction of an engine each. In accordance with a scheme drawn up by Herr Schelp for a series of engines of increasing size, power and complexity the two original turbines (the B.M.W. 003 and the Jumo 004) were to be of a size comparable with the first British engines (between 1,700–2,200 lbs. thrust) and were to drive the aircraft by jet propulsion.[2]

In 1939 Herr Schelp left the research branch and was put in charge of a newly-formed branch under General Eisenlohn, the head of engine research and development at the *Reichsluftfahrtministerium*, which dealt solely with gas turbines and was on equal terms with the branch dealing with reciprocating engines. Although gas

---

[1] See above, Section (i) (c).

[2] It appears however that Herr Schelp contemplated that eventually propellers would be used on the bigger engines. Firms were therefore told to design engines so that they could be adapted later to propeller drive.

turbines were not accorded a high priority in the aircraft programme, he had the power as head of a branch to authorise small contracts on his own initiative and easily obtained the agreement of his superiors, Generals Eisenlohn and Udet, for contracts up to a considerable value. By 1941 Heinkel's were also asking to be allowed to join in under *Reichsluftfahrtministerium* guidance and were given the design of a new and larger axial-flow gas turbine (the HE 011), and Daimler-Benz were given the task of assisting them as they were not considered fit to design a new engine of their own.

In one notable direction however Herr Schelp failed to mobilise available resources. The research establishments throughout resolutely refused to join in the effort on gas turbines. Most of the research workers either felt that the gas turbine was not ripe for practical development or else wished to conduct the research themselves. Airframe projects during this period, as might be expected from the low priority accorded generally to gas turbines, did not keep pace with engine projects. The Messerschmitt 262 was the most important as it was intended to take the Jumo 004. It was designed in 1940, first flew with conventional engines in 1941 and with Jumo 004 engines in 1942. It was however a very brilliant design, and later in 1943 its performance attracted the attention of General Galland, the then Inspector General of Fighters, through whom the aircraft was brought to the notice of Goering and Hitler himself. This was in fact the beginning of a new era for the gas turbine in Germany.

These are the bare bones of German plans and progress up to 1942. Certain similarities in technical development and in the framework of government and industry will immediately occur to the reader, but the differences are almost equally prominent. During the period 1939–42 the Air Ministries of both countries played the dominant part in expanding the effort devoted to gas turbines and in determining the main lines of development, but perhaps the *Reichsluftfahrtministerium* began earlier to organise the wider industrial effort needed. Certainly nothing similar to Herr Schelp's evangelising tour of the German firms in 1938 happened in this country. At that time and well on into 1939 the Air Ministry were only half convinced of the immediate prospects of the gas turbines and by no means convinced of the practicability of jet propulsion. By early 1940 however the position was completely reversed. M.A.P. then developed a great interest in jet propulsion and became firm believers in the future of gas turbines, and this official interest was later heightened under Sir Henry Tizard; on the other hand Generals Udet and Eisenlohn, although they did nothing to hinder development, never 'pushed' the gas turbine in their plans for the aircraft programme. It is quite possible that Goering himself was unaware of the advanced stage that gas turbine development had reached. Such plans as there were took shape at a very low level, and it was not until 1943 that an interest comparable to that of the British air chiefs was taken by their German counterparts.

Although he did not have influential support, Herr Schelp however managed to do almost as much to foster industrial effort by government aid as did the Air Ministry, and later M.A.P., in Britain. In both countries firms were deliberately sought out, canvassed and enrolled in the government plans. The majority of firms in both countries entered the field as a result of government initiative. The field in Germany was narrower, for only four firms were approached, and they were all aero-engine firms.[1] In this country, at any rate towards the beginning, steam turbine firms were included, but it will not have escaped the reader's notice that the professional aero-engine firms with their accumulated experience of the installation and requirements of power plant for aircraft gradually assumed the leading position. Where, however, we may observe a fundamental difference between the policy of the two countries is in the treatment of the enrolled firms. Herr Schelp, as a result both of the early work of Professor Betz and Herr Encke at Göttingen and of his own independent calculations, had concluded that far higher compressor efficiencies could be obtained from the axial-flow compressor and consequently never gave any consideration to the centrifugal compressor which was mechanically much simpler. It appears also that the firms received from Herr Schelp and his assistants very detailed calculations and data, so that in fact they undertook little more than mechanical design to the requirements and specification of the *Reichsluftfahrtministerium*. Further, throughout the various stages of construction the firms were subject to the scrutiny and guidance of Herr Schelp's branch. The consequence of this was that the scope of development was a great deal narrower than in this country where both axial-flow and centrifugal types were encouraged and where the choice of type as well as the detail design and layout was very largely left to the individual firm to decide. One has only to think of Rolls-Royce's position and to remember the freedom of choice Sir Henry Tizard gave to Major Halford to realise how profoundly different was the atmosphere in which the German firms worked.

On the other hand, the collaboration between the German firms which Herr Schelp helped to bring about was superficially similar to the collaboration of the British firms. But in fact it was a much more

---

[1] It appears that, of the German steam turbine firms, none did any pioneer work, and A.E.G. and Brown Boveri of Mannheim were only asked to help on certain special aspects.

haphazard affair, and regular meetings to ensure adequate collaboration were not established till very late in the war. It may be that this was at least partly responsible for the technical superiority which the British jet propulsion engines achieved by the end of the European war, for in Germany mistakes by individual firms were apt to remain unchecked and uncorrected by the experience of other firms.

(iii)

The Development Period: Disappointed Hopes, 1941-42

By the end of 1942 much had been done in both Britain and the United States to tackle research and development of the new type of power plant for aircraft use. But, generally speaking, the prospects of the gas turbine had come to be regarded in a more sober light than in, say, January 1941. This was mainly because the Whittle W.2.B engine had made much slower progress than had been predicted. The disappointing progress was directly revealed by the fact that, by the end of 1942, the W.2.B unit had not yet developed on the bench the minimum power output predicted for it and required of it. Another disappointment was that the production organisation assembled at Rover's shadow factory for the purpose of manufacturing W.2.B engines in quantity 'off the drawing-board' was still in a condition bordering on chaotic. And, as no engines of sufficient power and reliability had been built, no flight trials had taken place and the plans for building prototype and production Gloster F.9/40 aircraft were completely upset. The jet-propelled fighter was thus of little more than academic interest to the R.A.F.

The effects of the protracted parturition of the W.2.B spread far. It came to be admitted by those in charge of M.A.P's wider policy that the gas turbine as an engine was not yet sufficiently mature to be produced off the drawing-board; the production plans for other jet propulsion engines besides the W.2.B were accordingly throttled back. Again, although normal development difficulties had played a large part in delaying the W.2.B, it was seen that there were other contributory causes whose inevitability was less easy to admit. But once admitted, they were bound to lead to important changes, such as the replacement of Rover's as managers of the shadow factory by Rolls-Royce, and a small but significant administrative re-organisation at M.A.P.

So far as the demands of the R.A.F. were concerned it was fortunate that the rapid improvement of existing engines and fighters had largely filled the Air Staff's requirements for a specialised high-altitude fighter which the Gloster-Whittle project had originally been planned to fill. The emphasis was in any case swinging over heavily towards lower-altitude fighters, more suitable for the offensive operations contemplated by Fighter Command. The ultimate effect of the failure of the 1940–41 plans to mature in time were therefore largely mitigated, and M.A.P. were able to pursue in 1943 the more leisurely course of step-by-step development without the constant pressure for production induced by urgent operational needs.

What had caused this setback and this reassessment? Instability of engine design was of course a main factor. The original plans made during 1941 for the simultaneous development and production of the W.2.B and the Gloster F.9/40 fighter envisaged that delivery of the first twelve development aircraft from Gloster's by March 1942 would synchronise with delivery of the thirty development engines from Rover's, and that a satisfactory engine with a power output of 1,600 lbs. static thrust could be in production by mid-summer 1942. Later in the year the production flow of engines and airframes was expected to get into its stride so that the winter of 1942–43 should have witnessed the appearance of the jet-propelled fighter in sufficient numbers to be operationally useful.

In fact the position in December 1942 turned out to be quite different, and the gap between plans and reality was a very wide one. The W.2.B engine, which had been chosen for production, was not capable of a power output under the most favourable circumstances of more than 1,400 lbs. static thrust and in fact on the test bench, under sufficiently rigorous conditions, had only produced 1,250 lbs. thrust. In so far as production was concerned, only a handful of development engines had been built by Rover's, and not one was fit to be accepted by M.A.P. for flight in the F.9/40 prototype.[1]

The industrial position precipitated by the slow development was even more depressing. The production organisation built up by Rover's at their shadow factory at Barnoldswick, consisting of 1,600 operatives, scores upon scores of machine tools, and representing £1½ million of capital investment, was lying virtually idle at a time when both labour and machine tools were urgently needed elsewhere in the aircraft and engine programmes. The position at Gloster's was hardly any better. Equally serious was the state of relations between the two firms responsible for design and development of the W.2.B. Never very cordial, the collaboration now broke down entirely under a mounting strain of distrust and disagreement.

The causes of this strain were complex. Broadly speaking the chaos at the works of the production firms was mainly due to the attempt to put both engines and airframes into quantity production 'off the

[1] One de-rated W.2.B had been flown in the experimental E.28/39 aircraft for the first time in November 1942.

drawing-board'. Whilst this practice was well-established in the manufacture of airframes, it was badly suited to a new type of prime mover incorporating many new and daring features. In the course of prototype construction and early bench running there arose a host of major and minor troubles requiring considerable development and constant changes of design. The effect of the persistent fluidity of design on the attempts to tool-up can be imagined.

The difficulties were enhanced by the nature of Air Commodore Whittle's design. It was brilliant and ambitious, and its quality can be judged from the fact that even in its early stages it was superior in specific weight (that is power per lb. of weight) to the Junkers Jumo 004 with which the Messerschmitt 262 was powered in 1944. But it introduced many new and untried features, such as the elaborate diffuser design (afterwards modified) and caused several grave difficulties of development.

The development difficulties of the W.2.B cannot be dealt with here in detail, but something must be said of the three most important inherent technical problems of the gas turbine. These were, first, surging; secondly reliability and performance of the rotary components; and thirdly combustion. The first of these problems was totally new, but its appearance in the W.2 and W.2.B prototypes early in 1941 so delayed progress that the magnitude of the research still required on the second and third problems was not fully revealed until early 1942. Surging was a phenomenon connected with the airflow through the engine and it can best be described as an intermittent reversal of airflow. It first appeared in April 1941 when the first W.2 engine surged at a comparatively low operating speed.[1] The prototype W.2.B completed in June 1941 also surged, although at a speed not so far below operating speed. Unfortunately the trouble proved most difficult to cure. Although the design of nearly every major component was sooner or later affected, and in particular the blower (or impellor) casing and the turbine nozzle ring, every remedy tried so reduced efficiencies of components as to lead to intolerably high temperature. Eventually its incidence was reduced by intensive development work and by improved manufacture. Furthermore, by holding up bench-testing of the W.2 and the W.2.B it 'masked' or delayed the showing up of turbine and impellor troubles.

The turbine troubles were essentially a matter of finding a material which would resist the very high temperatures. This was an intractable problem, but the answer was eventually found in 'Nimonic 80', produced by the Mond Nickel Co. The impellor troubles were even

[1] The 'operating speed' is the speed at which the rotary parts of the engine were designed to revolve, i.e. in the case of the W.2.B this was 14,500 r.p.m.

more prolonged. They lasted even up to 1944, and both the diagnosis (vibration was the root of the trouble) and its ultimate cure was to raise the speed at which the 'fundamental frequency' of the vibration occurred above the designed speed of the unit.

Methods of combustion and suitable design of the combustion chamber and its component parts had not by 1941 reached such an advanced stage that improvement was impossible. Indeed combustion research was proceeding vigorously in more than one direction, and the best methods and equipment were still a matter for opinion. But the same factor that had hindered turbine and impellor research —the delay in running the W.2.B at full speed—was also an obstacle to combustion development. The result of this was that the design was constantly being changed. There was at least one major change in design of combustion equipment—that of the part introducing the fuel and the compressed air into what were known as flame tubes where combustion occurred. The new design was known as the 'colander' design. It was the work of Messrs. Joseph Lucas and it replaced the original design of Power Jets, the so-called 'swirl vanes'.

Some of the production difficulties, however, arose, so to speak, on the 'shop floor'. Rover's, whose own extensive redesigning activities had not hastened matters, had successfully manufactured reciprocating engines under the original shadow scheme, and their competence in this field had been the chief reason why they were chosen to manufacture the Whittle engine. Generally speaking, manufacture of gas turbines was no more difficult than that of reciprocating engines. Some of the components however were of complicated shape and were made of materials with such difficult characteristics of handling and machining that special tools and methods had to be devised for their manufacture. In addition, some of these components had to be manufactured to very fine limits if the performance of production engines was not to be lower than that of hand-built engines. The solution of these problems of manufacturing technique was largely due to the efforts of Power Jets and Rover's, and the proof of their success came only later when Rolls-Royce, who took over the shadow factory at Barnoldswick in 1943, produced W.2.B/23 engines (the first production version) with only a very small variation from standard thrust. But these manufacturing problems had to be tackled during the period when production was supposed to be beginning, thus gravely overloading Rover's production organisation.

Rover's were, of course, mainly responsible for the production layout. Amongst other things, they were responsible for a series of highly complex sub-assembly jigs for assembling the static entry guide vanes on to the air intake spinnings, the diffuser vanes on to the blower casing and the nozzles on to the turbine nozzle ring. The exact position of these organs in assembly was critical to the performance of the engine and probably also to the incidence of surging. Not the slightest deviation in the angle of incidence or of the throat area through which atmospheric air, compressed air, or gas, respectively, passed was permissible. The design of jigs whereby the rigorous requirements could be achieved was therefore no mean task. Rover's also devised new and more searching inspection methods, which made it impossible for faulty assembly to be passed.

Unfortunately Rover's high qualifications for production did not necessarily suit them to the work of engine development. To begin with, except perhaps in the limited field of motor car engines, they had had little previous experience in engineering development. When they undertook to build a Whittle engine in 1940, and later when they received an order for thirty development W.2.B engines to precede quantity production, it was clear that considerable bench development was inevitable. It was so arranged by M.A.P. that development should be jointly undertaken by Rover's and Power Jets. Rover's, as the manufacturers, were to have the responsibility for the purely structural and mechanical aspects, and Power Jets, as the designers, were to have the responsibility for the aerodynamic and thermodynamic aspects upon which the principles of the engine were based, with Air Commodore Whittle as the expert to advise and comment on all matters which might involve design changes. To play their part Rover's had to organise a considerable development organisation, practically from scratch. Some of their personnel were drawn from their permanent staff on a part-time basis, some were specially engaged for the W.2.B work. This tended to split the staff into two camps. Owing to the imprecise and informal way in which Rover's received their authority for development work, the firm felt themselves virtually free to pursue whatever line of development appeared to them promising without special reference to Power Jets or M.A.P.

It is therefore not surprising that though some of Rover's development work was good, much of it was not, and led to a waste of precious time and effort. In addition, the independent way in which they tackled the problems appeared to violate the spirit of the informal terms of reference under which Power Jets and Rover's were supposed to collaborate. It may well be that Rover's took little trouble to establish good working relations with Power Jets and did not make nearly enough use of the very valuable work being done there and of the very great knowledge and experience of Air Commodore Whittle, the designer. Much of the blame for the lack of confidence upon which satisfactory relations could have been built must therefore rest with Rover's. On the other hand, the attitude of Power Jets was one of suspicion and resentment—both excessive, even if understandable. The technical liaison was inevitably a very 'one-legged' affair since there was little that Power Jets could learn from Rover's. Moreover Power Jets had handed over their design and secret patents to Rover's at M.A.P's request, without any commercial agreement and without recognition by Rover's of the validity of the patents. This was a bad beginning to any form of business relations. When, during 1941, it became clear that Rover's were not asking Air Commodore Whittle's advice nor informing Power Jets before making design changes, the latter began to put the worst construction upon Rover's motives.

Rover's on their part cannot be blamed entirely for wasting their time and for not adhering to the terms of reference given them by M.A.P. The wording of these terms of reference was extremely ambiguous and failed to place the responsibility for development squarely on anyone's shoulders. The reluctance with which Rover's and Power Jets submitted to these 'terms of reference' and the difficulty which Sir Arthur Tedder and Sir Henry Tizard, and later again Air Marshal Linnell (Controller of Research and Development) had in finding a form of words to which the firms would agree, testifies to the delicacy of the problem.

It is however doubtful whether the problem could ever have been settled in this way. Nor were the various official efforts to bring the firms together successful. Rover's claimed considerable financial as well as technical independence and resented attempts at control. Nor was M.A.P. altogether of one mind on the desirability of control. There was at M.A.P. a conflict of views between those who saw that special measures were needed to guide the first steps of the gas turbine firms and those who thought that the existing tradition of non-intervention was suitable also for the new field of aero-engine development. Thus, what with the superior claims of reciprocating engine work, and the refusal of the department to take an active part in the actual direction of the firms, Rover's were able to pursue their independent path and even to feel that they were encouraged to do so.

The position of the gas turbine at the beginning of 1943 was thus admittedly anything but satisfactory. The setback had to be accepted, and an 'agonising reappraisal' had to be made. The prospects of the Whittle design brought to the forefront of discussion the claims of the jet-propelled fighter as compared with the fighters with reciprocating engines which were planned for the next two years. There was no evidence that the jet propulsion engine could not surpass the reciprocating engine, but it was now tacitly accepted that, with the exception of the de Havilland H.1, the only gas turbine which had reached a sufficiently advanced stage to be worth installing in an aircraft was Air Commodore Whittle's W.2/500 design. A comparative curve of the performance expected of the 'best' jet fighters and the two orthodox fighters planned for 1944[1] only showed the Meteor with W.2/500 engines and a projected Gloster fighter with the de Havilland H.1 engine. And although these jet fighters promised a marked predominance in speed at high altitudes, this was largely off-set by their inferior rate of climb. In addition the fuel consumption of all jet propulsion engines was still much greater than that of reciprocating engines.

The conditions therefore in which a jet fighter would be operationally more useful than a normal fighter appeared to be extremely limited; they were *either* a high-altitude fighter *or* a low-altitude interceptor fighter with very short range, i.e. suitable only for home defence. The first set of conditions was of course those in which the R.A.F. had been operating during 1940–42, but which had already begun to pass away. The Air Force was now passing from the defensive tactics requiring high-altitude interceptor fighters to the offensive tactics requiring both high speed and great endurance at comparatively low altitudes. Thus although M.A.P. were prepared to continue with the development of gas turbines and appropriate airframes, there was no pressing demand for the jet fighter from the Air Force such as had influenced the earlier plans for the W.2.B, or was to influence the development and production of German jet engines and fighters in 1944 and 1945.

This changed scale of R.A.F. demands was to prove very fortunate in the long-run for it permitted a much slower and more deliberate course to be planned for the development of the gas turbine in this country, the 'step by step' development. In this way it was possible to insist that the main objective should be reliability of the highly stressed parts, a quality in which British engines eventually were to outstrip the German ones. The British were also able to devote time to improving fuel consumption. In the short-run, however, the lack of an Air Staff demand made it difficult to justify any attempt at production on however small a scale, and there was also opposition from some quarters to the diversion of drawing office effort for the design of a de Havilland experimental fighter.

Apart from the hard lesson that an order 'off the drawing-board' could involve risks too costly even for war-time circumstances, there were other issues in which M.A.P. realised that they had followed a wrong policy. The first was their deviation from the principle that the firm which designed a piece of equipment should also be charged with the initial production. The second was the attempt to put the responsibility for the development of the gas turbine at headquarters

---

[1] A Folland design with Centaurus engines and a Spitfire with a Rolls-Royce R.M.15 S.M. engine.

into the hands of the branch responsible for reciprocating engines, on the assumption that because both were prime movers for aircraft they should be dealt with in the same way and by the same people. The recognition of both these points resulted in a re-organisation of industry and at headquarters.

To correct their first error the policy-makers at M.A.P. were prepared to take a bold step. In the opinion of the Controller of Research and Development one of the main causes of the W.2.B troubles was the division of design and production between Power Jets and Rover's. And the logical step, in view of Power Jets' possession of unequalled knowledge of centrifugal flow compressors, would have been to provide them with production resources by amalgamation with a production firm. But as working co-operation between these two firms had broken down this was out of the question. It was in any case clear that Rover's could no longer be used for gas turbine work, nor did the firm themselves wish to continue. Rolls-Royce's name had been suggested (by the Director of Scientific Research) as long ago as April 1942. It became increasingly plain that the W.2.B could only be developed satisfactorily by a firm like Rolls-Royce who combined both experience and resources in the triple fields of research, development and production.

The choice of Rolls-Royce was thus both simple and inevitable. Both the Controller of Research and Development and the Chief Executive (Air Marshal Sir Wilfrid Freeman) agreed that Rolls-Royce should take over Power Jets and run the Whetstone factory as their turbine section. To this the new Minister (Sir Stafford Cripps) agreed readily.

This solution, however, which seemed logically the best to almost everyone who considered it, was not adopted. What in fact happened was a compromise of the same nature as that adopted earlier in the relations of Power Jets and Rover's. Power Jets maintained their autonomy and their factory at Whetstone in order to continue research on, and development of, centrifugal type units. Rolls-Royce took over the responsibility for production of W.2.B and W.2/500 engines and the existing organisation and facilities at Barnoldswick as from 1st April 1943.[1] Power Jets' work was to be directed towards the W.2/500 unit and subsequent engines. Rolls-Royce were to produce these engines and were to give all the technical and research assistance that they could. In addition Rolls-Royce were to be responsible for such development, subject to Air Commodore Whittle's agreement, as was necessary to prepare engine designs for the M.A.P. type test standard.

[1] Rolls-Royce engineers virtually took charge from 1st January 1943.

The alliance with Rolls-Royce was welcome to Power Jets. They had not wished to be absorbed by Rolls-Royce for they treasured their independent status, but they had long been in favour of Rolls-Royce undertaking production of W.2.B engines. Indeed Air Commodore Whittle had suggested this to Sir Henry Tizard in 1940. Although the relationship was very similar to that previously undertaken by Rover's and Power Jets, the atmosphere in which Power Jets and Rolls-Royce worked was from the first a much freer and happier one. To use Air Commodore Whittle's own words—'Power Jets had the greatest respect for the technical quality of the Rolls-Royce team and the latter were much more ready to recognise and use the work of Power Jets'. The obstacles to a commercial agreement however remained, and because Power Jets had no clear idea (until the patent question was settled) what their assets were, negotiations for such an agreement never went beyond an early stage.

Thus, although those responsible for policy at M.A.P. from the Minister down had realised that ultimately the best solution would be to rationalise the structure of the industry, they were not able to enforce their decision in face of the firms' own reluctance to do so. But the fact that the identity of the firm in charge of production was changed was to prove a turning point in the pace and scale of gas turbine development.

The internal re-organisation at M.A.P. had long been discussed, but for one reason or another the Controller of Research and Development had hesitated to alter the existing finely balanced division of responsibility for research and development. Whatever the merits of the existing system (and the arguments for preserving for firms engaged on development of gas turbines the same freedom from direction as was enjoyed by reciprocating engine firms) the arrangements finally broke down because of the crushing load of work which had become concentrated on the desk of one individual, the Deputy Director Research and Development Engines (1). There is no doubt however that other cogent arguments for a re-organisation existed, especially the difficulty of drawing a line of demarcation between the research and development of the infant gas turbine, and the 'undoubted feeling of discontent that there [was] not one person charged with the specific task of jet engines alone' which was prevalent in the industry. The consequence of the admission that the existing organisation at M.A.P. was insufficient was that a new post of Deputy Director Research and Development Engines (Turbines) (DD/RDE(T)) solely charged with research and development of gas turbines was created. The Deputy Directorate was for the sake of form within the framework of the Directorate of Engine Development but was directly responsible to the Controller of Research and

Development himself. It was intended that close relations with the Director of Scientific Research's branch should be maintained by the appointment of 'a man who . . . has a real knowledge and understanding of the research point of view'. The man chosen was one who well fulfilled this condition, and who, at the same time, had had a part in a gas turbine development since 1940. He was Dr. H. Roxbee Cox who had up till that time filled the post of Deputy Director of Scientific Research, and who had been chairman of the Gas Turbine Collaboration Committee since its inception.

(iv)

The Later Development Period: Renewed Progress, 1943-45

(a) 'ANOTHER WAY OF PUSHING AN AEROPLANE ALONG'

The last section showed that plans for an immediate operational use of the gas turbine proved premature, and that accordingly a more leisurely attitude to development was encouraged. But the new attitude did not degenerate into one of indefinite postponements. By the middle of 1943 there were already signs that the research and development work of 1941 and 1942 was at last bearing fruit and that the industrial re-organisation of early 1943 was likely to fulfil the hopes of its sponsors. That the gas turbine was to be of increasing importance to aeronautics in the not-so-far distant future was revealed by the report of a special committee which had been investigating the requirements of the next generation of engine design.[1]

The timing of this report coincided with the first definite intelligence from Germany of the types and progress of unconventional power plants which had caused some alarm to the Cabinet. The Controller of Research and Development and his advisers accordingly felt it necessary to review the objectives of research on similar projects in this country and above all to question whether the co-ordination of unconventional power plant research and aerodynamic research, which in the future were clearly interdependent, had been sufficiently provided for. In fact it is from this moment that we can trace the first serious attempts to tackle the aerodynamic problems of supersonic flight; problems which had to be solved before the unconventional power plant could be fully exploited.

It was these events, occurring during the middle of 1943, which put the gas turbine development into the main streams of aeronautical research. By the summer of 1944, therefore, not only was

---

[1] See pp. 224–225.

the W.2.B/23 engine sufficiently developed to be worth installing in the Meteor I airframe, and for this aircraft to be used operationally for the first time against the German V.1 attacks, but some of the other projects were nearing the point where practical use could be made of them. A few months later the plans for intensifying the scale of the war effort in the Far East brought the jet-propelled fighter to the forefront of operational requirements again. Orders for the production of airframes and engines were increased manifold.

The main line of development in 1943 and 1944 was still of course the original W.2 design, and Power Jets and Rolls-Royce therefore played the most important part. From the beginning of 1943, when Rolls-Royce took over from Rover's, they made a great effort to try and turn the W.2.B/23 into a reliable aero-engine. Their attitude was, as they told M.A.P., to regard the Whittle gas turbine as just another engine to be fitted to an aircraft and not as a 'piece of scientific apparatus' to be handled in a special way. They added that 'we do not look upon the turbine engine as a new secret weapon, it is just another way of pushing an aeroplane along, except that at the present time it is not as good as with the conventional engine'. Accordingly they intended to start right away to work on the 100 hours type test. Rolls-Royce's method of developing a reliable engine was a simple and a successful one. It was described simply as 'run and bust'. An engine was run on the test bench at increasing speeds till a component broke. This component was then examined, the fault located and ways of improving it devised: then the engine was run again until another weakness was exposed and so on until the 100 hours type test was achieved.

The Whittle W.2.B/23 as bequeathed to Rolls-Royce by Rover's was a basically good and practical design. In addition they made the greatest possible use of Power Jets' knowledge, and took over with the Barnoldswick factory all Rover's staff who had been specially engaged for gas turbine work. Rolls-Royce were, however, entirely responsible for the development of the next engine known as the W.2.B/37 (afterwards named the Derwent Series I). This engine was based on an engine designed and built by Power Jets known as the W.2/500.[1] The W.2/500 was very like the earlier W.2.B/23; it had the same overall dimensions, but was more robust and had greater power and efficiency. The B.37 or Derwent I was the first of a series of developments of the Whittle W.2 design which carried the simple jet propulsion engine with centrifugal compressor to the limits of its capacity and power. In this Rolls-Royce were influenced and aided by Power Jets, who had themselves designed and built one other W.2 engine, known as the W.2/700, which carried the

[1] Design began 13th March 1942, engine first run 13th September 1942.

improvements of strength and capacity (through a larger turbine) even further than in the W.2/500. This engine influenced in particular the design of the later Derwent V engines and the giant B.41 or Nene.

Once the W.2.B/23 was ready for flight testing, the F.9/40 aircraft could also be developed; increased flight experience from the summer of 1943 onwards enabled the Meteor I (W.2.B/23 engines) to be evolved and the Meteor III (W.2.B/37 engines) was planned to follow when the engines were ready for production.

Although Rolls-Royce, thanks to the size of their development team,[1] as well as by virtue of the organisation they inherited at Barnoldswick, quickly established themselves as the dominating influence in the industry,[2] the other firms were working steadily and well. Of all the designs, de Havilland's was the most advanced. It will be remembered[3] that Mr. Halford had chosen for his engine the relatively simple Whittle principle, i.e. the centrifugal type of impellor with single-stage turbine. Full design performance was not in fact achieved until 1945, but the engine appeared so promising in 1942 that plans were immediately set on foot for installation of the H.1 engine in an F.9/40 airframe and for an enquiry into the industrial capacity which would be required for pilot production. In March 1943 an F.9/40 prototype flew with two H.1 engines installed (incidentally this was the first flight of the F.9/40). The main task of the de Havilland Co. during 1943 was to clear the engine on type test at increasing speeds and thrusts up to that of the design, for the engine had so far only done full speed running for 'spot' tests.

The Metropolitan-Vickers' axial-flow compressor design, the F.2, which sprang (it will be remembered) from the R.A.E's early research, had also made good headway.[4] Unlike the H.1 it was not considered fit for 'pilot' production because it was a less successful piece of aero-engineering due to the firm's inexperience in this field. But its potential advantages over centrifugal type design (greater efficiency, better fuel consumption and the possibility of further advantages in installation and aerodynamics) made it of great importance for bomber aircraft. Nevertheless, in 1944 the Rolls-Royce/Power Jets series and the de Havilland engine were still the only gas turbine engines sufficiently developed to make it possible

---

[1] Under the direction of Dr. Hooker, assisted by Mr. Herriott, Mr. Lombard and many others who came over from Rover's when Barnoldswick changed hands in 1943.

[2] In 1944 Rolls-Royce had 6 different types of simple jet propulsion engines under development; de Havilland's had 2 and Metropolitan-Vickers and Armstrong Siddeley only 1 each.

[3] See p. 201.

[4] See pp. 184–185 and 200.

for the Air Ministry and M.A.P. to centre the operational requirements round jet propulsion.

Meanwhile the Germans had not been idle. A special jet-propelled aircraft had been designed by Messerschmitt (the Messerschmitt 262) and had first flown in 1942. From this time onwards the higher command became aware of the possibilities of jet propulsion, and development and production of the Jumo 004 and the B.M.W. 003[1] were put on high priority. The Germans encountered some very severe technical problems,[2] but these were not allowed to interfere with production. The Jumo 004 was actually put into production long before development had reached a satisfactory stage with the inevitable result that the engine had a low performance and was extremely unreliable compared to the W.2.B/23. There was a very pressing operational need for high-speed fighters as a defence against allied bombing attacks, and, for all its shortcomings, the Messerschmitt 262 with Jumo 004 engines was the first jet-propelled military aircraft in the world to become operational.

Other engines and other fighters were also under development and in production by 1944, and the gas turbine was not the only form of motive power to be experimented with. In the summer of 1943 reports from intelligence sources were revealing to this country Germany's progress and effort on all types of unconventional power plant—their various V-weapons, rocket-propelled as well as jet-propelled. One immediate result of these reports was to revive the requirement for a fast short-range interceptor fighter. By the directive of the Prime Minister, Meteor production was restored and an order for 120 Meteor I's was given. This was later increased to 300 to allow for a number to be fitted with de Havilland H.1 engines (Meteor II). But a further result was M.A.P's determination 'to widen and increase the effort' devoted in this country 'to jet propulsion to include other forms which so far we have not touched'.

The new prospects found their expression in an important report on the future technical characteristics of gas turbines. This was the interim report of the departmental committee, set up to study in detail the requirements of size and power of the next generation of gas turbines. It became available in M.A.P. in June 1943. The report fell into two parts: the first discussed the considerations determining the size and form of propulsion of gas turbines suitable for (a) a short-range interceptor fighter and (b) a medium-range high-speed bomber. The second part was an analysis of the actual designs put forward by contractors. The recommendations on both parts also indicated the points upon which future research should be focused in order to improve the less favourable aspects of the gas turbine's

[1] See above Section (ii) (d).

[2] The most important of these were compressor design and turbine blade materials.

performance in relation to reciprocating engines.

In the case of the fighter, the committee agreed that for the optimum size of engine a single-engined aircraft was most suitable. To achieve a high rate of climb they agreed that a larger engine (i.e. one giving over 4,000 lbs. static thrust) was needed than the size which would give the highest top speed (i.e. about 3,000 lbs. static thrust). For the bomber, the committee had greater difficulty in determining the size and type of engine because the bomber requirements were less precise. On the assumption that the bomber would be of the Lancaster type, they agreed that four ducted fan gas turbines of nearly 7,000 lbs. static thrust each would give a higher speed than four fully developed Merlin engines, and (if the bomb-load was a heavy one) a longer range; but if the bomb-load was smaller, the range would be better with the Merlins than with the gas turbines.

Of the designs which had been submitted, a Rolls-Royce and an Armstrong Siddeley contra-rotating project were considered, and both were thought to offer promise after further research as bomber engines. Designs submitted by Power Jets and de Havilland's were to be suitable for fighter aircraft. Finally, as a general aim, the committee wished to improve the jet propulsion engine from a specialised to an all-purpose power plant, so that it would outclass the reciprocating engine in all conditions of flight.

This report, with its direct recommendations for construction of proprietary designs, its broad specifications giving engine designers guidance as to the requirements of capacity and methods of propulsion and its demarcation of the outstanding problems of research and development, may be considered as a landmark in the evolution of informed opinion, and to this extent also a landmark in the history of the gas turbine itself. Engine prospects for the near and more distant future were now clearly linked up with definite airframe requirements, and aerodynamics of compressibility were presented as an urgent problem requiring speedy solution if further progress of jet aircraft was to be sustained.

But the various plans arising out of the report (and some firms had actually anticipated the report in starting work on these) were still on paper when the long-expected flying bomb attacks began in the summer of 1944. The Gloster Meteor I was the only jet-propelled fighter in existence. This aircraft, powered with W.2.B/23 engines, was in production and did in fact go into operation in July 1944, but it had only a limited opportunity, for there were so few aircraft that they were allowed to operate only over English territory. The main reason that there were so few Meteors was that the long-range escort fighter, the Tempest, which was needed for the invasion of Europe, was also being built at Gloster's. As in the immediate future the latter was operationally more important, Meteor production was bound to suffer in consequence. But, except for this instance, the overriding priority which equipment required for D-day was now given did not interfere with the orderly development of gas turbines. By ideal standards the effort on airframes to take jet engines was small, but in the circumstances, i.e. at a time when this country had no urgent operational need for a jet fighter such as spurred the Germans on to produce the Messerschmitt 262 before the Jumo 004 engine was fully developed, jet propulsion types had a fair proportion of the available resources: a fact admitted by at least one interested authority.

Moreover, the tactical and strategic requirements soon changed in favour of the jet. Towards the end of 1944, as production for European operations slackened off, plans for the war in the Far East came to the front. A jet fighter, especially for naval use, was required for this theatre of operations. There were, in addition to the Meteor and the Vampire, many airframe projects under development by the end of 1944; some of these were considered by the Cabinet for operations in the Far East. Amongst these were a development of the Vampire, the Gloster E.1/44 and the Supermarine E.10/44 (the jet-propelled version of the Spitfire). All three were single-engined fighters designed to take either the Rolls-Royce B/41 (Nene) or the de Havilland H.2 (Ghost), simple jet propulsion engines of 4,500 lbs. thrust.

Production of the Meteor III (powered with W.2.B/37 engines) and of the Vampire was just beginning at the end of 1944, and output was expected to work up to useful proportions during 1945. By December it was decided to increase many times the scale of production of engines and airframes. The necessary extension to manufacturing capacity was approved for Meteor III production to be doubled and for Vampire production to be quadrupled: de Havilland H.1 (Goblin) and Rolls-Royce B.41 (Nene) engines were to be increased in proportion. Early in the New Year of 1945 these plans were reinforced by a direction from the Minister of Aircraft Production that all jet aircraft work was to have absolute priority: 'we want . . . as many high quality jet aircraft as quickly as is humanly possible'. Thus the wheel turned full circle, and for the second time jet propulsion engines and aircraft occupied a predominant position in the plans for the R.A.F. Things remained thus until the war in the Pacific suddenly ended in the following summer.

(b) POST-WAR ADJUSTMENTS

After the end of the war production of jet aircraft and engines was heavily cut together with all other contracts under war-time programmes of production. But if production had to be cut, development was to continue in peace-time. The share of resources available for development in British aero-engine firms and devoted by them to gas turbines had been steadily growing as the existing reciprocating engines approached the limit of their potential capacity and performance. The development activities in the field of gas turbines was therefore bound to remain at a high level and even to grow.

The first batch of problems which had beset the pioneers—inefficiency of rotary components, unreliability of highly stressed materials, combustion and mechanical problems—had largely been solved. In the new stage of development other problems came to the fore. The first task was to design more powerful engines, based on existing principles, suitable for all conditions of flight and for all types of aircraft. The second task was to design and develop gas turbines beyond the narrow field of aeronautics for practical use where operating conditions were totally different, and perhaps less stringent. All firms in the aero-engine industry were by now mobilised for the task. Napier's and Bristol's were now also set to work on complete engine designs, and several industrial turbine manufacturers were drawn in to develop gas turbines for marine work and for power generation.

The firms engaged on marine and industrial uses were largely new to the particular problems of gas turbines and were naturally anxious for advice on research and theoretical matters. This threw a greater amount of work on the central establishment responsible for basic research and also considerably widened the scope of that research, for the types and sizes of compressor and turbine for marine and industrial use were different from those for aeronautical use. There had been a time when firms would have sought advice from Power Jets Ltd. or from the R.A.E., according to whether the problem was connected with centrifugal or axial compressors. But from 1944 such advice was exclusively supplied by Power Jets (Research and Development) Ltd., the government-owned company which incorporated the old organisation of Power Jets, together with the section of the Engine Department of the R.A.E. which specialised in gas turbines. In 1944 this broadly constituted body, which combined some of the freedom of operation of a private firm with the duties of a central research establishment, had undergone a radical re-organisation, and had reverted to the status of a government establishment, the National Gas Turbine Establishment. This change of status is an important event in the story of the gas turbine industry and will be dealt with in the next section.

(v)

Acquisition of Power Jets by the State

The existence of the original firm of Power Jets, with its sole function of building Air Commodore Whittle's experimental jet propulsion engine, was an anomaly from the beginning. Had one of the old-established aero-engine firms or the R.A.E. adopted Air Commodore Whittle's ideas, the new invention could have been developed in a conventional setting, and all the subsequent controversies could have been avoided. But both these channels were closed to Air Commodore Whittle, and the means by which he eventually secured finance and technical facilities were forced upon him by the exigencies of his position. The incorporation of Power Jets Ltd. and the placing of the actual contract for construction in the hands of British Thomson-Houston Co. Ltd., have been told in detail earlier. It has also been told how the slow progress at the British Thomson-Houston Co. led Power Jets to assume responsibility for testing the unit in a disused workshop.[1] This step with its obvious result, the direct employment by the company of technical staff, established Power Jets as an engineering firm. Its largely accidental development, its gradual rise to a position where it was indispensable to the continued development of the gas turbine, and its unconventional relationship to the Ministry and to other firms employed by the Ministry, created problems which were of a fundamental nature and which were never satisfactorily solved. Eventually its continued existence was found to be incompatible with M.A.P. policy towards research and industry.

The relations between Power Jets and Rolls-Royce were cordial from the first and the joint work on the W.2.B and the W.2/500 progressed throughout 1943. But the position of Power Jets was still subject to criticism. In the past, this criticism had been directed to the firm's anomalous position, halfway between a research establishment and a commercial firm. There had also been criticism of its attitude of prickly independence. This time the criticism came from quite a different quarter. When the Minister, Sir Stafford Cripps, visited Whetstone, skilled workers at Power Jets complained to him of inefficient management. The Minister ordered an investigation into the internal management of Power Jets. This was carried out in September 1943 by the M.A.P. regional controller of the North Midland Region and Mr. Eric Mensforth, then acting as Chief Production Adviser to the Chief Executive. Their report did not

[1] See p. 191.

confirm the allegations of inefficiency to any serious extent. It was their opinion that the management could be 'strengthened' in various ways, and they made some detailed recommendations for an internal re-organisation to achieve that effect, which the board of Power Jets were quite willing to accept. But the Minister's attention had been already drawn to the problem of Power Jets which had long defied a solution acceptable to all the opposing viewpoints. It was generally agreed that Power Jets deserved reward for their work during the pioneer period when the Air Ministry expressed no interest in it, but that the subsequent heavy investment undertaken by M.A.P. must be compensated by special rights on behalf of the nation. It was known that Air Commodore Whittle had been in favour of nationalising the whole industry if necessary, and after the report on the management of Power Jets and the discussions on the safeguarding of the large public capital outlay, opinion in M.A.P., led by the Minister, veered round to favour public control of Power Jets itself.

Apart from considerations of finance and equity there was also an increasing need for a single central research establishment on a strictly non-commercial basis whose services would be available to all firms alike. As then constituted, neither Power Jets nor the R.A.E. entirely filled this place. But the Minister did not wish to do anything to thwart Power Jets' independent policy or to force on them a re-organisation on Civil Service lines. He therefore proposed that the firm's assets should, with the approval of the board of directors, be acquired by the Government[1] on behalf of the nation and that a new board should be appointed, to include certain members of Power Jets' original board, and that the general structure of the firm should remain unchanged.

There was however the position of the existing government research establishment to be considered. The turbine section of the R.A.E., expanded in the previous year, had specialised mostly in axial-flow compressors, but its interest in this particular development had lessened as Metropolitan-Vickers' share in the F.2 increased. It consequently assumed, or tried to assume, a new function, that of a centre for theoretical work to serve all the firms engaged on gas turbines of whatever type. This function was totally different from those undertaken by Power Jets, but was of a nature which made it impossible to exclude them from a central establishment such as Power Jets was in the future intended to be. It had long been foreseen that the two would have to be amalgamated, and now the

[1] Air Commodore Whittle had previously given his shares in the company to the Government as he felt their possession to be incompatible with his position as a serving officer. See statement by the Government quoted in *The Times Trade and Engineering Supplement*, May 1944.

chairman-designate of the new company made it a condition of his acceptance.

The fusion of two bodies containing highly placed scientists and engineers was bound to be a delicate operation. The conditions of service in government and private establishments were different in many respects, of which remuneration was only one. The particular solution of the problem, which the Minister chose, made it inevitable that the R.A.E. personnel would have to bear the burden of the adjustment, and many members of the R.A.E. elected to transfer to headquarters at M.A.P. rather than join Power Jets (Research and Development) Ltd. In the main, however, the operation was carried out without friction. What may have smoothed it was that the Chairman was Dr. Roxbee Cox, Director of Special Projects at M.A.P., and for many years a member of the scientific staff at the R.A.E. The R.A.E. team of course had to remain at Pyestock, many miles from Whetstone, so that the effects of the fusion were for a time confined to direction and co-ordination and not day-to-day operations. This was later to prove a disadvantage.

The combined organisation was larger, more influential and independent than either of its constituent bodies had ever been. Yet it had reached the limit of its expansion, and the seeds of its disintegration had already been sown. Under the new arrangements work at Whetstone went ahead without very much need for adjustment. The R.A.E. however suffered a sudden break in established relations with M.A.P., upon which much of their work depended. During the few months prior to the fusion the R.A.E. turbine team had been on closer terms with the policy-making staff than before, which was partly due to the personal efforts of the Head of the Engine Department, Mr. Hayne Constant.

The most conspicuous drawbacks of the new set-up, however, were those of scope. When the Government took over the assets of Power Jets and the new board of directors assumed office, the Minister wrote to the new chairman setting out the objectives which he wished the board to pursue. This short statement of aims was afterwards announced in the House of Lords.[1] The Minister wished the firm, (1) to conduct research on gas turbine engines; (2) to design, construct and develop such engines; (3) to devise methods of manufacture and to manufacture small batches of engines in the development stage; (4) to test such engines; (5) to make available to those concerned the knowledge so obtained.

At the time when it was first formulated this statement of the new authority's tasks appeared to be unexceptional. But almost immediately some of its implications—those relating to manufacture—

---

[1] H. of L. Deb., Vol. 132, Cols. 230–232, 14th June 1944.

were to prove a source of friction and a cause of dispute. It will be remembered that since 1940 many large and influential aero-engine firms had become interested in gas turbines, and none were more influential or more interested than Rolls-Royce. Before even the details of Power Jets (Research and Development) Ltd., were complete the news of the manufacturing clauses reached Mr. Sidgreaves and Mr. Hives of Rolls-Royce. They sought an interview with the Chief Executive and asked to be assured categorically that the Ministry had no intention of 'competing' with the industry in quantity manufacture. To give the industry (for whom Rolls-Royce was the spokesman) the assurance that Power Jets (Research and Development) were not going to act in competition with the industry and were to render only 'communal' services, the Minister authorised the setting up of the Technical Advisory Committee, in addition to the Gas Turbine Collaboration Committee, under the chairmanship of the chairman of Power Jets (Research and Development), at which all firms were to be represented. At the first meeting the chairman endeavoured to allay the industry's fears about any aspect of Power Jets (Research and Development) work which might be judged to be in competition with manufacturing firms and to show the advantages the firms might gain from using the products of their activities. The firms' fears were temporarily quieted but remained very near to the surface.

In spite of the definite policy of the Ministry and the warning of the hostile attitude the industry were likely to adopt, Air Commodore Whittle continued to hold the view that Power Jets should have more freedom to build engines up to production standard. In this he was supported by the chairman, Dr. Roxbee Cox, and by most of the engineering team of Power Jets. In March 1945 Power Jets (Research and Development) officially asked for 100,000 square feet of additional manufacturing capacity and 400 machine tools. Dr. Roxbee Cox and Air Commodore Whittle in a personal interview with the Chief Executive explained why they needed this capacity. It was their idea that Power Jets (Research and Development) should develop an engine up to contemporary standards, and, after 'manufacturing a large enough trial batch to standardise production, hand over their work to one or other of the major engine firms who would thereafter carry out manufacture. Any subsequent development work would, however, be under the direction of Power Jets'. They put forward various arguments to support this view; that it was necessary for reasons of prestige; that larger numbers of engines were needed for testing; and finally that it was necessary as an incentive to research teams to keep them from straying into academic by-paths. The Chief Executive (Sir Edwin Plowden) sounded the leaders of the three most influential firms. Their reaction was immediate: the industry would most certainly regard manufacture of 'contemporary' engines as direct competition, and they stated that they could not collaborate with Power Jets (Research and Development) on technical matters if such competition existed.

This attitude of the industry was bound to affect the Ministry's policy. It was obvious that the value of Power Jets (Research and Development) as a central research establishment would be impaired if industry believed them to be in direct competition. Moreover, the very rapid strides which firms, like Rolls-Royce, had made meant that it was no longer as necessary for Power Jets (Research and Development) to be concerned with contemporary engines in order to maintain Britain's position *vis-a-vis* other countries. Power Jets' demands were therefore rejected in spite of a final appeal to the Minister. Although Air Commodore Whittle considered production vitally necessary, and was strongly supported in this by the chairman, Dr. Roxbee Cox, the rest of the directors and many of the staff of Power Jets (Research and Development) were not equally insistent on the importance of manufacture.

Negotiations with the Ministry on the re-definition of the functions of Power Jets (Research and Development) continued throughout 1945 without any satisfactory conclusions. Air Commodore Whittle and the chairman were fighting a losing battle. For not only was the opposition of the firms too strong to overcome, but, for other reasons as well, the basis upon which the status of the firm had been built was crumbling away. Long before this particular issue arose, critics had repeatedly assailed the independence of the management of Power Jets. But in the past the usefulness of Power Jets won them enough support in influential quarters to enable them to resist attempts to reduce their status to that of a government research institution. In addition, the war had always provided an overwhelming argument against major disturbances which might be caused by turning a large number of important scientists and engineers into civil servants. These arguments however had in the meantime lost much of their strength. Opinion in M.A.P., especially from the administrative and contracts branches, hardened into the determination to break the dilemma of public financial backing without public administrative control. In addition, Sir Stafford Cripps, the chief architect of the existing arrangement, had left the Ministry.

Before any radical change in the constitution of Power Jets (Research and Development) could take place, Sir Stafford Cripps (now President of the Board of Trade) had to be consulted. It was eventually agreed to convert Power Jets (Research and Development) into a normal research establishment under direct government control. Air Commodore Whittle resigned,[1] and although he stated at the time that his resignation had nothing to do with the decision to wind up Power Jets, it is clear that it was connected with the Ministry's refusal to permit manufacture of engines on an increased scale. On the 26th January 1946, Power Jets (Research and Development) were formally notified of the Government's decision to turn Power Jets into the National Gas Turbine Establishment. A few weeks later this decision and also Air Commodore Whittle's resignation were made public.[2] Less than two months after the formation of the National Gas Turbine Establishment, almost the entire team of engineers built up by Air Commodore Whittle resigned. The chairman Dr. Roxbee Cox, however, remained as director of the establishment, in spite of his disagreement with the policy.

This was the end of Power Jets.[3] After 1946 the National Gas Turbine Establishment concentrated more and more on long-term research projects and has added marine and industrial applications to its programme.

---

1 26th January 1946.

2 *The Times*, 15th April 1946, p. 2.

3 There is still nominally a firm called Power Jets (Research and Development) Ltd. It is the legal guardian of patents only.

PART II

Army Weapons

CHAPTER X

PHASES AND BASIC PROBLEMS OF ARMY WEAPON QUALITY REQUIREMENTS

(i)

Phases

As with other aspects of war history, the quality[1] requirements for military equipment fall into three broad phases. First comes the long and lean period between the end of the First World War and 1936, when British foreign policy began to change and serious rearmament was decided upon. Second there is the period of rearmament itself stretching from 1936 over the first year of war to the end of 1940. And third, starting six months or more after Dunkirk, there are the five years of full war effort, when the mounting resources of the community reflected the urgency and insistence of battle. These phases are approximations, like all historical periods. But their general validity is established not only because of the diplomatic and strategical background into which they fit, but also because they have a rough correspondence with the incidence of military experience (and resulting changes in Army weapon policy) and with the main changes made from time to time in the machinery of control over weapon development.

In peace-time, responsibility for weapon research and development rested in the War Office with the Master General of the Ordnance, who was guided on broad policy by the Army Council and in more detail as far as weapon development was concerned by a body known as the Chief of the Imperial General Staff's Specification Committee, which met at irregular intervals to discuss both particular projects and the equipment of certain formations as a whole, such as the Tank Brigade or the A.A. regiment. The Master General of the Ordnance was, of course, responsible for the whole of army stores, and for production as well as design. On the weapon side he was advised by the Director of Artillery and (after 1928) by the Director of Mechanization, each of whom worked largely through a

[1] See p. 1, fn. 1.

committee (Ordnance Committee and Mechanization Board) and drew on the resources of the Departments for Research and Design.[1] This hierarchy was disturbed by the decision to rearm and in the years after 1936 important alterations were set on foot.[2] In 1936 the office of Director General of Munitions Production was created which soon took over the functions of the Master General of the Ordnance, first of all on the production side and then (in 1938) on the design side as well.[3] Similarly, the crisis of Dunkirk and the anxious months which followed carried organisational consequences. Intended at first to secure greater productive efficiency, these changes were most clearly expressed in the formation of a Cabinet committee (the Defence Committee (Supply)) which was presided over by the Prime Minister in his capacity as Minister of Defence. It would be mistaken to suppose that the periods outlined above fitted in exactly with the history of organisation: the most important change, the transfer of the Director General of Munitions Production and his departments to the new Ministry of Supply in 1939, for example, comes before the full effort of 1940 and yet is scarcely a rearmament device, though it might be argued that it was only towards the end of 1940 that the full results of this drastic step were seen; equally the 1941–42 re-organisations at both Ministry of Supply and War Office are of great importance, representing as they do a considerable change from the administrative arrangements of the first year of war.

The usefulness of distinguishing the three periods is, however, to be found in the light they shed on quality considerations pure and simple. The Army is a barometer more sensitive to changes in strategical policy than the other Services. There are two reasons for this. First, the Navy has traditionally assumed the chief role in the defence of Britain and its strength never fluctuated in the way the Army's did; once airpower came to the fore a somewhat similar attitude was taken with regard to the R.A.F. Ships and aircraft could not sink below a certain degree of efficiency if the basic protection of Britain was to be assured, while the Army tended to rise and fall in importance on the basis of its overseas commitments. Such overseas commitments have, it is true, had their effect on the Navy and Air Force; but the security of communications and the maintenance of scattered bases remained more constant factors for the oldest and the newest Services than they did for the Army. This aspect, it is true, affected in the first place the numerical strength of the three Services, but, as we shall see, quantitative

---

[1] As noted hereafter, the Director of Mechanization had no tank designers in the Design Department after 1930. See p. 305.

[2] See also J. D. Scott and Richard Hughes, *Administration of War Production* (H.M.S.O. 1955), Ch. II.

[3] See pp. 244 and 260.

questions had a direct influence on quality of equipment. And in any case the provision of equipment for the Army was more directly conditioned by terrain than was the case with Services which were essentially not tied to the land. Certain basic equipment apart, a campaign in the Malayan jungle, another in the deserts of North Africa and another in France, had each their own problems of *materiel*.

There was another reason why the general political situation affected Army equipment more than that of the other Services—the highly specialised nature of most of the modern soldier's weapons. Apart from its wheeled transport and some of its radio equipment the Army uses munitions which have no place in peace-time life. This, of course, is true of the guns and torpedoes used in sea warfare and of the bombs and automatic weapons carried by aircraft. But in the Navy and the R.A.F. the performance of the ship or 'plane is regarded as of equal importance with efficiency of its armament as such. In ship design, and in the development of marine engines in particular, the Navy can draw on civil experience and industrial research. The same is true of aeroplanes and aero-engines: these were developed irrespective of their war-time uses and they have advanced rapidly in peace-time, albeit not as rapidly as in time of war. In the case of the guns, mortars and tanks of the Army, peace-time research had on the contrary to be maintained artificially and this was especially the case in the period after 1918, when there was virtually no international armament trade, and the private manufacture of armaments declined almost to vanishing point in an atmosphere of public suspicion which was world-wide and of undoubted sincerity. In this situation the Army was almost completely dependent for research and development on the facilities it could organise for itself or which it could persuade a very few firms to undertake. Clearly design activity of this kind could only be prosecuted when ample funds were available and in this way the contraction of the Army in the 'twenties and its expansion in the late 'thirties influenced the quality of its stores in a much more decided fashion than was the case with the equipment of the R.A.F. or Navy. This weakness was aggravated not only because Army equipment ceased, by and large, to be manufactured by specialist firms but because much of it was becoming uncommercial in a larger sense, a trend which was to be accelerated as time went on: the tank (for example) proved to be distinctly unlike the products of all the British heavy engineering firms (except the one armament firm, Vickers-Armstrongs); the motor industry, though it might appear suited to tank development and production, was in fact highly unsuited for either and the unsuitability increased as tanks grew bigger and heavier.

In the interwar period before 1934, as explained elsewhere[1], the Army was organised on a hypothesis which placed major expeditions and a national war third and fourth respectively in the four broad categories into which military commitments were divided. Imperial policing and minor expeditions and guerilla warfare were the two tasks for which the Army had mainly to prepare itself. The results of this, so far as quality considerations are concerned, were that wherever a choice existed between equipment suitable for a European war and equipment primarily of service in Colonial warfare, the second type was given preference. Tanks are the most signal example of this. Light tanks and armoured cars were in fact developed to the point of active production; but heavier tanks were the subject of more or less academic investigations.[2] It was preoccupation with the defence of the Egyptian border during the Italo-Abyssinian war which largely influenced the development of the Anti-Tank rifle, a weapon which was to prove ludicrously inadequate against the tanks of major European powers.[3] Similarly, the opinions of senior officers in the forces engaged in imperial policing were given very great weight: the views of the Commander in Chief, India, could consequently delay the substitution of H.E. shell for shrapnel despite a consensus of technical opinion at the War Office. That the hypothesis was influential in these and other ways cannot be denied, but one must also remember that behind it lay a long tradition of public sentiment which rejected completely the doctrines of continental military efficiency: the peace-time soldier was in Britain a fish out of water; British army manoeuvres were singularly unrealistic; British factors of safety were high and consequently led to equipment which was cumbersome compared with the foreign equivalent. Within the Army the Technical Officer was generally despised. Within the country as a whole military expenditure in peace-time was regretted. Hence the hypothesis was allowed to exercise a conservative influence as far as the evolution of quality requirements was concerned. It is certain that expenditure on military research and development was rigorously scrutinised by the Treasury and no doubt the War Office was more hampered in this respect than either the Admiralty or Air Ministry. But it would be wrong to blame the Treasury for this. The Treasury was merely reflecting a general and deep-rooted attitude on the part of the community as a whole. No better illustration of this can be found than the almost total absence of any examination by General Staff or technical experts among the general public of the equipment lessons of the 1914–18 war.

---

[1] See M. M. Postan, *British War Production* (H.M.S.O. 1952), Ch. I.
[2] See Ch. XIII.
[3] See p. 259.

This attitude was modified by the decision to rearm which was taken in 1936, but it was modified gradually and with a typical optimism: the equipment of a force of only 5 divisions was at first contemplated, raised later to 10 and later still to 30; the men for these units were to be found by voluntary recruitment; the productive capacity for re-equipment was to be found without disturbing existing industrial arrangements. Modest as the first steps were, they upset the leisureliness which had hitherto prevailed in deciding equipment questions, for two facts stood out: the task which was to face the Army was clearly no longer to be imperial policing, even if this hypothesis was not formally altered until 1938; and, even for a small army, the existing equipment was totally inadequate from a quantitative point of view. Thus the period of rearmament is marked by a growing tension between the demands for new designs and up-to-date models on the one hand, and on the other the desperate urgency to obtain supplies of any equipment at all. This quantity-quality dilemma in weapon provision is to some extent inherent at any time, but from 1936 to 1940 it was exacerbated by the absence of concrete plans for re-equipment at the start of rearmament and by the regularity with which the size of the Army was increased. Nor was the peak shortage in men and munitions reached when war began in September 1939, for at that time it was still possible to count on the French Army and French industrial and design resources. The height of the crisis came after Dunkirk, when the country had been denuded of allies, and its Expeditionary Force stripped of the meagre harvest of such rearmament as had borne fruit up to that date. In the summer of 1940 quantity urgencies loomed larger than at any other point during rearmament and, in guns and tanks, production at all costs was the order of the day.[1] 'The best is the enemy of the good' was a ministerial argument which brooked no reply as early as April 1939. The B.E.F's demands for changes in equipment were rejected if they threatened to upset current production; in June 1940 the Cabinet ruled that:

> the immediate task to which more distant requirements must be subordinated was to expedite delivery during the next five months of everything required to make good deficiencies in essential items of equipment.

The provision of 'deficiencies' was in fact to take a good deal longer than five months, but the hand to mouth policy of production at all costs was less damaging than it might seem. First and foremost was the desperate need for weapons. In 1939 and 1940 the soldier in the field had a claim at least to protection and clearly he had to be

[1] See p. 321.

given what there was and not what there ought to have been: the Prime Minister was right to argue against 'strivings for perfection which would lead to further delays', in such a situation. In this sense the production achieved during rearmament was doomed to be experimental but the success of the experiment itself depended on equipping the Army which could only be done by resolutely foregoing the luxury of placing quality above quantity. In any case, as events were to show, it would have been tragic if the quality considerations of the rearmament period had been allowed to determine new design. As far as the Army was concerned, although mobility had its advocates and the mechanization of the Army was approved, the tactics of trench warfare on the 1914–18 model still dominated high places, and the relevance of this seemed at the time to be proved by the impregnable concrete fortification of the Maginot and Siegfried Lines. More than one influential officer in the Ministry agreed that 'we were back where we were in 1914'; looking back from the relative security of 1942 a senior member of the Armoured Fighting Vehicles Division of the Ministry wrote that 'the public at that time, and in fact the General Staff, thought in terms of . . . Somme mud'. A more advanced design and development policy during the years 1936–40 might well have been disastrous in the ensuing period: as far as quality factors in many military equipments are concerned a proper start was perhaps not really made until after 1940, but at least a false start was avoided. Nor indeed would finalised designs over the whole range of later military stores have been possible if industry had not been at first geared to the war effort on the side of production rather than design: as we shall see later,[1] only one non-government source was available for armament design prior to the expansion in tank production in the years 1939–40:[2] it is easier to build a factory than to gather a design team, and in the stringencies of 1940 it was more sensible to do what was of immediate fruitfulness. Besides, over a wide range of standard stores, the main design task of the years of total effort was to redesign stores in such a way as to make for ease of production. This had been an aim throughout the rearmament period, but only production experience could determine the exact lengths to which such redesign could go.

Yet the reason for the acute concentration on production at all costs, which reached its height in 1940, was the desperate shortage of basic field force equipment, and although we have seen that it was not without ultimate benefits for research and development, there is no doubt that it had on the whole a singularly bad influence on design. The last period, covering the years 1941 to 1945, was in fact

[1] See Chs. XI, XII and XIII.
[2] Vickers-Armstrongs.

taken up very largely with reversing this attitude and its qualitative consequence and in a sense returning to the quality considerations which had prevailed before rearmament began. In the pre-1936 Army the specification had always demanded the 'best possible weapon' which could be 'readily manufactured'. The dominance of production considerations during 1936–40 was thus an aberration, but it proved hard to re-establish the old relationship of quality and quantity.

To begin with, the structure of the Ministry of Supply was not suited to such a change. The creation of the post of Director General of Munitions Production in 1936 was the first of many steps, accelerated after the creation of the Ministry in 1939, to put production in control of development.[1] This might not have been critical, for in any set-up the resources of industry must in the last resort determine the feasibility of new design, had not the temper of the time consciously aimed at reducing the independence and authority of research and development. Some illustrations of this have been given; others will occur in later pages; here a brief indication of further difficulties must be considered.

The relationship between development and production prior to 1936 ensured the autonomy of each. The evolution of new weapons was a responsibility of the technical branches of the War Office; though occasionally outside firms designed, it was always to a War Office specification, and often in competition with an official design. The model or models of the new equipment were then scrutinised by the Army and, when finally settled, the detailed production drawings were passed by the Directors of Artillery or Mechanization for bulk manufacture. There was thus a sharp distinction between the War Office and its control of quality requirements and industry, whether official as at Woolwich or Enfield, or private as at Vickers or B.S.A. During rearmament this distinction gradually blurred, and with the transfer of both production and development branches to the Ministry of Supply in the autumn of 1939 it was for a time almost totally obscured. The War Office was deprived at a stroke of all its technical advice and, though it remained the main channel of user requirements and criticism, it could do nothing but pass such quality problems over to the Ministry for solution. In the range of equipments for which the Director of Artillery was responsible the results were not catastrophic. This was partly because of a sensible *modus vivendi* arranged by individuals in the two departments: the Director of Artillery had, after all, anticipated just this situation. Partly it was due to the relatively stable character of artillery and small arms development, and the relative absence, at all events

---

[1] See p. 238.

before the last months of the war, of any major changes in Army policy with regard to these stores. On the other hand the dislocation was critical in tank development; here the Director of Mechanization had long lost any design organisation such as the Director of Artillery disposed of; tank design had been entirely in commercial hands for some years before the war[1]; to remove the Director of Mechanization to the Ministry of Supply thus cut the last link between the War Office and control of specification policy. There was thereafter a danger—and more than a danger—that the War Office would ask only for what the Ministry of Supply could provide, a complete reversal of the balance which had seemed desirable prior to 1936. Meanwhile the new Ministry, staffed mainly by recruits from the production side of industry, swallowed the technical directorates. The Director General of Munitions Production, who had controlled all production and design at the War Office, gradually built up new departments which took over from him control over large groups of stores; and progressively the development organisations of the Ministry were placed under production directorates. Air Defence Research, Signals, Bridging and Demolition Experimental Establishments were put under the Director General of Mechanical Engineering Supply (D.G. Mech. E.(S)); Chemical Warfare research was one of the responsibilities of the Director General of Explosives Production. Under the new Director General of Tank and Transport Production, the small Department of Tank Design, recreated in July 1940, was for long restricted merely to modifications in current production. Even the Director of Scientific Research came in October of 1940 under the Director General of Explosives Production. The Director of Artillery alone continued to report direct to the Director General of Munitions Production and was not placed under one of the new weapons production directorates; this was no doubt partly due to his control of the interservice Research and Design Departments and because there was not much industrial design of the equipments for which he was responsible. Yet a situation having been achieved by 1941 where in most stores development was firmly controlled by production, a reaction soon set in which was to end by once again emancipating research and design and re-establishing their autonomy. What precipitated the changed attitude was the volume of field experience of equipment reaching home during 1941, the character of user criticism, and a change in the balance of forces in the opposed armies.

As noted above, the brief campaign in France in the spring and summer of 1940 had done little to instruct opinion in the equipment lessons of the new warfare. After Dunkirk problems of A.A. defence

---

[1] This simplification will be elaborated below, see pp. 317 et seq.

were, it is true, closely studied and a number of important innovations were stimulated by the experience of large scale air attack; radar in particular was more efficiently harnessed to the needs of target prediction.[1] These developments were, however, largely obtained by transcending both the traditional Civil Service hierarchies and, to some extent, the hallowed channels of military command. A.A. Command was an *imperium in imperio*, often negotiating directly with the Ministry of Supply and recruiting, independently of the War Office, the scientists and engineers needed to advise its Commander-in-Chief. The public awareness of the danger of air attack made such novelties tolerable; the devices of enlisting the production side in problems of tactics and of forming operational research groups were to be of more general use later in the war. But in general the watertight nature of A.A. Command made its unorthodoxies inapplicable in more distant theatres of war. It was from North Africa that user experience was transmitted in increasing volume during 1941 and it covered the whole range of military equipment.

As we shall see, much of the criticism of serving soldiers was favourable. But in certain cases (in particular mortars and tanks) there was clearly much amiss with British designs. Though at first experts hesitated to make general inferences concerning weapon policy from the somewhat odd conditions of desert warfare, it was evident that many of the assumptions which had guided development during the rearmament period were outmoded. Sufficient experience had been obtained with A.F.V's, for example, for an accurate forecast to be made of future design requirements. Whether these purely quality considerations would have been as influential as they were had not the whole strategy of the war changed in 1941, it is hard to say. At any rate, with German armies occupied in Russia, with the United States in full alliance after Pearl Harbour, the desperate days of 1940 were over. Numbers of equipments at any price were no longer essential. The relaxation was, of course, most influential in those stores where production had been undertaken of equipments known to be unworthy. Of such stores A.F.V's were the most important: it was possible to end that series of interim models which had dominated the rearmament period. It was not so easy to decide on a method of ending it. The mounting disquiet first expressed itself in the 'Tank Parliament', a gathering of experts called by the Prime Minister in May and June 1941, and later by the increasing preoccupation of Parliament itself with the problems of British A.F.V's.[2] The detailed changes which were embarked on

---

[1] See Ch. XV, Section (iii).

[2] H. of C. Deb., Vol. 385, Cols. 1771–5, 15th December 1942.

during and after 1942 were provoked mainly by concern over tank development, but they affected the development of all stores. They will be discussed in greater detail in a separate section of this volume[1] and need only be referred to briefly at this point. In the first place the Research and Design Directorates in the Ministry were accorded a markedly increased prestige. In September 1941 a Controller General of Research and Development was appointed with the Director of Scientific Research as his deputy and, ranged under him, the Director of Artillery, the Director of Tank Design, the Controller of Projectile Development, and the other technical directors. This vigorous re-arrangement was too logical and lasted for a little less than a year. But when, following the report of the Guy Committee,[2] a more practical arrangement was arrived at, and, for instance, tank design came once again under the head of the tank production division, the authority of development as against production was not further questioned, while the strengthening of the Armament Research and Armament Design Departments gave increased status to all the other official development organisations. In the second place, during 1942 and 1943 the War Office re-established technical weapon directorates which made it easier for General Staff policy to be framed independently of purely production considerations. In the third place, there was much closer integration from 1943 till the end of the war between Ministry of Supply and War Office on weapon development policy. These steps were not taken all at once nor without producing in their turn various strains and stresses. What was indeed far more important than mere administrative changes was the changed outlook which characterised the last three or four years of the war. The harvest of experience came at a time when Britain was no longer alone in the war and when a less desperate atmosphere prevailed; when the hope of survival had been replaced by the certainty of victory. The basic equipment had by now been settled and there was time to make refinements which could aim at achieving final superiority in battle.

The period 1941 to 1945 was one of continuous warfare and in areas which tested to the full the response of Army equipment to difficult terrain. Troops were in action in the North African desert, in the Malayan jungle, and finally in Western Europe, with its man-made hazards, towns, bridges, canals and hedges. In the new spirit which prevailed from the end of 1941, and which counselled adaptability at the expense of a rigid production programme, these changes of environment involved major changes in weapon policy: equipment had to be lightened for the jungle, strengthened for the campaign through the rocky mountains of Italy. Moreover the very

---

[1] See pp. 322–323.
[2] See pp. 474 et seq.

enthusiasm for development characteristic of this period produced novelties independent of formally expressed requirements, designed to anticipate the tactical situation. Much of this ferment was admittedly concerned with minor equipment: the basic artillery and infantry weapons were hardly affected by it. But, as will be seen below, there was, over a wide range of equipment, more radical change in the last years of the war than there had been in the period 1918–40.

Discussion of military equipment in the following chapters thus falls naturally into three periods: peace-time, rearmament and war. But the impact of each period, expressed in both requirements for new equipments and resources for their development, did not produce identical reactions in all types of weapons. In some there is a steady continuity; in others there were violent changes. With the reasons for such differences we must concern ourselves, before embarking on a discussion of the evolution of the weapons themselves.

(ii)
Basic problems

In a later chapter[1] we shall see that the 25 pdr. was a weapon gradually evolved during the 1920's and was one of the few new stores ready by the time of rearmament. Put into production before 1940, the equipment formed the basic divisional artillery of the British Army throughout the war and the modifications to its design introduced from time to time are so minor as to be almost negligible. The story of the No. 4 .303″ rifle is much the same: it was a standard equipment before the war and remained standard during the war. If we look at some other weapons, however, we are met by a very different picture. Not one British tank in production at the start of the war was in production at the end of it;[2] a similar fate overtook the anti-tank weapons of the rearmament period, the Boys Anti-Tank Rifle and the 2 pdr. A.T. gun, while pre-war tank armament was equally superseded. Nor is this difference merely due to the absence before the war of new designs of tanks and anti-tank guns. Tank design, it is true, was not well placed during rearmament; but no fewer than eight different infantry and cruiser tanks which were in production in the first half of the war had been abandoned by the end of it. On the anti-tank side, the 6 pdr. replaced the 2 pdr. and was in turn replaced[3] by the 17 pdr.; and had the war lasted

---

1 See Ch. XI and Ch. XIV, p. 355.

2 With the exception of a handful of Valentine tanks.

3 In A.T. regiments Royal Artillery, the 6 pdr. continued as an infantry A.T. gun.

longer an even larger anti-tank equipment might have been produced, making the 17 pdr. obsolete. Why was it not possible to make an anti-tank gun, if not a tank, so thoroughly good that it would remain a basic equipment, as the 25 pdr. did, throughout the war?

The answer to this question involves asking, what makes one weapon better than another? How may one compare the efficiency of two roughly similar weapons? These queries may sound simple enough but in fact weapon comparisons are extremely complicated and their study was not far advanced by the end of the war. The aim of any weapon may be defined as maximum lethality, giving lethality a broad connotation to include moral as well as physical effects. This may indeed be measured with a fair degree of precision in the case of projectiles, whose area of detonation, fragmentation, piercing qualities and so forth may be ascertained empirically; and a further range of variables (physical variations of terrain and temperature, vulnerability of the target in various protections, for instance) may also be determined. But before the projectile can hit its target this has to be identified (perhaps on a map), the gun has to be aimed and given the correct range, allowance being made for travel of target (if moving): all these being factors in which human error can play a part. Finally the internal ballistics of the gun (jump, throw-off, temperature, degree of wear and others) and the external ballistic factors (meteorological conditions, ballistic coefficient of the projectile, drift) also help to determine the actual point of impact of the projectile. The enumeration of such a list of variables would be greatly extended if we were to consider the behaviour of a gun mounted on a tank. In any case it will be evident that hitting the target is a difficult business: if it were not, wars would not last as long as they do.

Even apart from the refinements just considered, there is a range of alternatives which condition the efficiency of an equipment. Some simple examples of these will come readily to mind: the choice between weight of shell and range, between speed of tank and thickness of armour. Who is to say precisely how to measure the superiority of the Bren gun of 1940 with its nearest German equivalent, the M.G.34?—the German gun had a higher rate of fire and a much greater maximum range; its feed was a 50 round belt compared with a 30 round magazine. But the Bren could offset such advantages by its light weight (19 lbs. instead of 26 lbs.) and though less good as a medium machine gun it was better as a light machine gun. Again, in achieving a rifle (No. 5) two pounds lighter than both its British predecessor and the German equivalent, the British Army had to accept a marked drop in accuracy.

None the less comparisons have to be made, and had to be made by rough and ready methods in the field itself when troops captured new equipment from the enemy. Much work was done by the Ordnance Board in the period immediately after 1918 in establishing the exact performance of German weapons and in general great attention was paid to information on the capacities of foreign equipments throughout the interwar period. When such comparisons were attempted they related the most obvious of the factors discussed above: weight of equipment, range, number in detachment and so on. The result was a form of absolute comparison which, useful as it was up to a point, could prove very misleading in all cases where the tactical role of the weapon was at all fluid, where (in short) an element of surprise was still left open to the weapon designer.

In the case of many weapons their tactical role was clear enough. Rifles and artillery, for example, were no new inventions and a very great deal indeed was known about the ballistics of bullet and shell. The tactical functions of field and medium artillery had been established over centuries of experience and the variations in equipment which were possible fell within a fairly narrow range. The same was true of rifles and machine guns. Such weapons remained relatively stable because of the relative stability of the functions of the artillery in a division and a corps, and of the accurate small arms of the infantry. That is not to say that new problems did not arise: the field gun had on occasion to fight tanks; the rifle was superseded in hand-to-hand fighting by the sub-machine gun. But the basic function was not seriously modified.[1]

Tank tactics were in a different position. The tank was a product not of the sixteenth century but of the 1914–18 war, and had arrived then in the fighting too late for its potentialities to be thoroughly explored. It had formed the centre of much peace-time speculation but its employment had been negligible is such warfare as occurred between the two World Wars. Germany was known to contemplate the large-scale employment of armoured vehicles in a future war but even when the war came various dilemmas remained. Was the tank primarily of service in breaking through prepared positions or in exploiting a break-through after the manner of cavalry, or both? Was it intended in the first place for the engagement of soft targets or opposing armour? Was it essentially an infantry or an artillery weapon? It cannot be said that the course of the war from 1939 to 1945 solved these problems: it may with truth be said that they were shown to be misconceived; that armoured units had a tactical role which did not comply with the tactics of either infantry or artillery; that (to put the matter in another way) there was not one tank role but several, not one tank type but more than one.

---

[1] As it was in the case of heavy artillery, where the bomber aircraft largely took over.

There had of course not been wanting prophets and even a few practitioners of this attitude before 1939. But for them, as for the bulk of army tacticians, the variables in tank construction were scarcely appreciated until the war was well under way and the supreme lesson was only learnt as time went on: that, unlike field artillery, the essence of successful tank employment in the field was a virtuosity which had to be matched in tank design. The equipment of a tank regiment had in fact to be undertaken in the certain knowledge that the duration of the usefulness of any type of A.F.V. was limited; that re-equipment would sooner or later become essential. Throughout the war there was a positive race between the armour of the opposing forces. Far from being content with the rough approximations in efficiency achieved with small arms and infantry weapons, each side strove to make its armour superior in some critical respect: to sacrifice speed to greater armour or gun power; to forego protection in order to achieve maximum manoeuvrability; to turn the tracked chassis into the carrier of a large gun or in other words to reduce armour in the interests of fire power. Further development was called for because the tank unit aimed at self-sufficiency: it laid bridges, waded, detected and exploded mines.

In the train of these revolutions in tank development came similar changes in anti-tank artillery. Here again there was a race on each side to secure advantages. This race was, however, not quite the same as the contest between the armour of the opposing armies, where (rightly or wrongly) tank tended to be compared with tank. The anti-tank gun had to be superior not to the anti-tank guns on the other side, but to the tanks on the other side and so was committed to increases in calibre, muzzle velocity and general efficiency which involved a history very unlike that of the traditional artillery it resembled in so many other ways. Nevertheless, the general equilibrium inherent in all artillery stores exercised a restraining influence on A.T. gun development, and there were by no means as many different types of guns as there were of tanks, even allowing for a considerable variety in the ammunition developed from time to time to increase the performance of existing weapons. It was, in other words, possible to take more certain and steady steps in A.T. gun design than in tank design.

Two other groups of weapons were to a lesser extent involved in changes which distinguish them from the placid artillery story. Mortars were more important in operations than had been anticipated during peace-time, for they had been used during the First World War as emergency trench-warfare weapons. As a result, very little was known in Britain about mortar ballistics until urgent demands from the field forced a rapid development in performance and an extension of knowledge upon which to base this. Though it proved possible greatly to extend the range and effectiveness of British mortar equipments there were clearly limits to this, and it may be supposed that, as experience was assimilated, mortar development would gradually become similar in pattern to that of traditional artillery.

This is not the case with A.A. artillery. The history of its development is strikingly similar to that of A.T. artillery, for the very good reason that the A.A. gun, like the A.T. gun, had to attack a target which improved in performance. The aircraft of the 1914–18 war were slow, had a low ceiling, and were unprotected: by 1939 aircraft had improved out of all recognition. The progressive steps which were necessary to keep the guns in step with this progress are discussed below.[1]

At the two extremes of development we can thus place those equipments which, due to the experience behind their use and the steadiness of their tactical role, remain stable, and those which, because of their comparative novelty both in construction and operation, present a bewildering variety of changing types. Between these two extremes are various groups of weapons which share some of the characteristics of each. Consideration of the host of minor weapons supports these distinctions. In small arms development there is a continuity which is displayed in other weapons than the rifle which has been instanced already: pistols and grenades, for example, both have a long and steady history. The infantry weapons which did present original and unorthodox features were precisely those developed for use against tanks. Equally, the rocket weapons which were evolved during the war were designed primarily for use against tanks and aircraft; their only traditional role was in fact as a sort of massive mortar barrage.

Accordingly the following discussion of the development of military equipment is divided into three sections, roughly corresponding with the three categories outlined above, and roughly reflecting in length the greater complexity in the development of the A.F.V. It is hoped that this division will enable the mass of equipments to be considered more fruitfully than would be possible with a plain chronological account which attempted to enumerate all stores as they were called for and developed. It is also to be hoped that the more detailed analysis of equipment history which follows will justify some of the generalizations which have been made in this introductory chapter.

---

[1] See Ch. XII.

CHAPTER XI

ARTILLERY AND SMALL ARMS DEVELOPMENT

(i)

Prior to 1934

REFERENCE has already been made in the previous chapter to the long history which lies behind artillery and small arms. The evolution of guns and rifles must, indeed, be spread over more than 500 years and these weapons are as familiar to the soldier, and almost to the civilian, as his boots and braces. Nothing reflected this sense of continuity so much as the title Master General of the Ordnance given to the officer who was responsible at the War Office for the design and production of all weapons during most of the interwar period. Directly responsible to the Chief of the Imperial General Staff and with a seat on the highest policy-making body in the War Office, the Army Council, the Master General of the Ordnance could trace his predecessors back to the sixteenth and seventeenth centuries. In its essentials the organisation which the Master General of the Ordnance controlled was also of considerable antiquity, though it had made room for more recent developments, such as mechanization and chemical warfare.

As far as weapon development was concerned, the Master General of the Ordnance had as his deputy the Director of Artillery. The Director of Artillery disposed of considerable resources for research and design. The largest groups under his control were the Departments of Research and of Design, housed at Woolwich; associated with the heads of these Departments, the Chief Superintendent of Research and the Superintendent of Design, was a Superintendent of Experiments; the whole of this organisation was, as explained elsewhere,[1] at the disposal of all three Service Ministries. These were the oldest component parts of the Director of Artillery's hierarchy since, in one form or another, they had existed prior to 1914;[2] the experience of 1914–18 added a Mechanization Experimental Establishment, an Air Defence Establishment, a

---

[1] See pp. 435–446 and 449–451.

[2] The Design Department was, however, an extremely small body before 1918. See p. 255.

Signals Experimental Establishment, a Chemical Warfare Experimental Establishment and others. After 1928 the Director of Artillery's responsibility for the whole range of military equipment was divided. A Director of Mechanization was appointed in that year who took over the Mechanization Experimental Establishment and similar bodies for Air Defence, Signals, Bridging and Demolition; the Director of Artillery was thus left with weapons in a narrow sense, including chemical warfare.[1]

In the case of most stores the Director of Artillery, and later the Director of Mechanization, called on the assistance of specialist advisers in various Boards and Committees. The oldest and most influential of these committees was the Ordnance Committee. This body, whose origins go back almost to the origins of artillery, was put on a permanent footing in 1797 and, in various guises, it then had a continuous history, reassuming in 1938 its older title of Ordnance Board. The Ordnance Board (which was an interservice body) was staffed by senior officers, usually over the age of active service, and through it the Director of Artillery transmitted his research and design enquiries, though the Board was in no sense responsible itself for research and design. Rather it 'progressed' such work, keeping elaborate records and printing numbered *Proceedings* giving a permanent record of the experimental work which was being carried on and with which it was most closely associated. This system of the Ordnance Committee or Board was widely imitated as new technical developments called for new machinery. A Small Arms Committee hived off from the Ordnance Committee, for example, only to return to the parent body in 1938; and similar committees were later established for Chemical Warfare, Mechanization, and Royal Engineers and Signals Equipment.

Few of these committees survived into the Second World War and the significant point that emerges from the preceding paragraph is that the Ordnance Board, responsible primarily for artillery and small arms, did so survive, thus illustrating the permanence of the machinery for the development of these stores. This permanence is equally reflected in both higher and lower administrative organisation. The Directorate of Artillery also persisted throughout the Second World War, though the range of responsibilities attached to the office fluctuated somewhat, and the title was heightened to Director General in response to the normal processes of war-time magnification. At the other end of the chain of research and design, the Departments concerned also survived in a surprisingly conservative way. It is true that during 1942 remarkable changes were made

[1] Chemical warfare equipment is not discussed in this book. Although it absorbed a great deal of energy and many notable developments occurred, the fact that gas warfare did not take place makes its omission less serious.

which tended towards a greater secularization of both armaments' design and research; even their divorce from Woolwich was more than a merely geographical break with the past. But increasingly lay, as opposed to military, control, greater liberty of initiative, and many other features of the two departments in the later years of the war must not conceal their fundamental resemblance to pre-war machinery: both before and after re-organisation the Research Department contained branches covering explosives, ballistics and metallurgy, and the Design Department branches corresponding to the main types and assemblies of small arms and artillery.[1] These two departments, like the Ordnance Board, were (as already mentioned) interservice as far as their work went, projects being undertaken on priorities agreed between the three Services, and doubtless this was partly responsible for the remarkable conservatism which retained in all its essentials a pre-war organisation throughout years of war which saw revolutions in the control and direction of almost all development departments which were under only one Ministry. But this is far from being the most important reason. Guns and shells, rifles and bullets are the hardy perennials of warfare: the evolution of new stores of this kind inevitably stems from previous experience; the element of novelty is so small as to be inconsiderable.[2] Explosives, ballistics, metallurgy are the raw ingredients which go into any gun and the comparative stability of the research and design departments concerned mirrors the stability of the problems involved in the evolution of such equipments.

One further point may usefully be made here. Later pages will no doubt give rise to a feeling that, if the basic elements in development machinery remained fairly constant, the higher control varied in a confusing way: the Director of Artillery was responsible first to the Master General of the Ordnance and then to a Director General of Munitions Production; later both the Director General of Munitions Production and the Director of Artillery were shifted from the War Office to a new Ministry of Supply; later still, while the Director of Artillery became the Director General of Artillery, the War Office recreated another Directorate of Artillery. These changes were important and (as we shall see) usually corresponded to important moments in the evolution of quality requirements. Yet they should not obscure the astonishing fact that the officer[3] responsible for artillery and small arms (Director of Artillery, later Director General of Artillery) from 1938 to 1945 was the same person. Doubtless this is partly to be explained by the personal abilities of the individual

---

[1] See Chs. XVII and XVIII.
[2] This is hardly true of high- and super-velocity A.T. shot, on which see p. 347.
[3] Major-General E. M. C. Clarke.

concerned, but it suggests again the basic continuity of developments in these fields. In what other spheres of armaments research and design would a pre-war competence have continued as a wartime mastery?

Having stressed the extraordinarily persistent nature of organisation in the field of artillery and small arms development and the light this seems to shed on the nature of the stores themselves, it is necessary now to sketch the pre-war resources for artillery and small arms development: the situation which will be revealed should reinforce the significance of the administrative stability just described. Prior to 1914, design and development of artillery and small arms was for the most part in the hands of industrial manufacturers of armaments, no fewer than sixteen separate firms habitually tendering for and receiving orders for guns, gun ammunition, small arms and small arms ammunition. In this period, and during the 1914–18 war itself, there was virtually no official development of conventional equipment, although for A.A. guns, as well as in certain other novel stores, traditional methods had to be abandoned. Thus, before 1918 the War Office called for the design of a weapon with certain qualities; those firms interested submitted designs, produced models 'competitively' and the War Office chose the one which best answered its requirements.

The creation of the Design Department in the early 'twenties as an independent body (as opposed to the small organisation at Woolwich which had prepared repair techniques and modifications) represents the most obvious comment on the changed situation in the interwar years. 'Normal' commercial resources for weapon design progressively dried up, and by the early 'thirties there was virtually only one all-round armament firm left in the country.[1] Vickers was, it is true, a bigger concern than any of the firms operating in the first two decades of the century; but the total industrial resources for weapon development had clearly shrunk. In this situation the Design Department, despite financial stringency, was bound gradually to grow, and the 'competitive' design, where it was still invoked, meant competition between the Department and Vickers. For the rest, the older methods were still applied. The War Office made its requirements known. The Design Department and Vickers each produced a design and an experimental equipment. These were tested in a series of elaborate user and technical trials. The favoured design was modified and finally the Director of Artillery issued his 'approval for production'. In the interwar years 'approval for production' did not, of course, mean that large orders were then placed or, indeed, that production started at all; it was precisely the

---

[1] B.S.A. was not in the same category.

absence of sizeable orders which discouraged armament firms from remaining in business. Too often the approved design was either laid aside for future manufacture, or manufactured in small token batches for issue only to certain selected units.

The reluctance to embark on a thoroughgoing programme of basic re-equipment was, needless to say, not due to complacency on the part of the Master General of the Ordnance, the Director of Artillery or their advisers, although it must be admitted that experience of the 1914–18 war had been very ill-digested at the War Office, and small efforts were made in the 1920's to master its lessons. True, Britain had been on the winning side and thus had less incentive to penetrate the reasons for success than the vanquished German Army had to ponder the causes of its defeat. But, though the military experts after 1918 could not but share in certain widely diffused notions about the equipment problems of any future war, there was a general lack of concreteness and system in the development work carried out. For this, as we shall show, there were sometimes sufficient reasons.

A consequence of the First World War which was drawn by the military experts of all participating countries was the likelihood that in a future war mobility would be far more important in equipments of all kinds than it had been in the days of slower, horse-drawn, vehicles. 'Mechanization' and 'lightening the soldiers' load' were thus two fundamental preoccupations of the interwar period and were responsible for some of the most important developments in the conservative fields of artillery and infantry weapons. A further problem which had to be met was equally a product of increased mobility: the tank might be expected not only by the infantryman at the forefront of battle, but considerably farther back and near the artillery, particularly the divisional artillery, employed in infantry support.

Some of these points are apparent in discussions of future policy from the early 'twenties and are reflected in the details of army requirements. Any new field artillery equipment, for instance, had to be capable of 'self-protection', i.e. by being able to attack a tank with open sights and with the maximum traverse. Preoccupation with A.T. weapons for infantry can be traced in all discussion of new development, and so can a general desire to streamline the infantryman's impedimenta. 'The British citizen walks less and less in peacetime', the War Office was informed by the departmental Kirke Committee (1932).

The 1914–18 war, however, had been predominantly a trench war and the influence of the static fronts which were then the rule made for a certain unreality and lack of urgency in discussing the mechanical and mobile army which, so far as Britain and most other countries were concerned, lay definitely in the future. When one remembers that the lance as a weapon of war was not formally abolished until 1927 it is not surprising that informed opinion urged as one of the most important requirements of the infantrymen a 'bigger and better trenching tool', to be carried in unit transport: this was another recommendation of the Kirke Committee, whose report has just been quoted. Moreover, the 1914–18 war was influential in restraining development of small arms and infantry weapons in yet another way. Considerable stocks existed of certain basic weapons, notably rifles and field artillery.[1] In the conditions of financial stringency which prevailed in the 'twenties and early 'thirties the wholesale adoption of new types of basic equipment, which would have had to be provided in large quantities, was viewed with disfavour.

Even without such pressures against change, the active role of the peace-time army exerted a drag on innovation. Troops were engaged throughout the interwar period in the traditional 'police-duty' which (as we have seen) was the first strategic task of the Army at this time. Such duty was by no means nominal. The Army in India, like the Army in Palestine, had occasionally to undertake active operations. Such responsibilities meant that re-equipment, if not undertaken by stages, might disrupt the efficiency of garrison forces abroad and naturally gave the views of the Commanders of such forces a weight in determining policy on weapons which was certainly disproportionate to the importance of such territories in the event of hostilities on the continent of Europe, the 'major war' of the 'fourth hypothesis'. Yet a major war was for long regarded as a distant contingency and accordingly the opinion of the Commander-in-Chief India was of direct relevance in reaching decisions on new weapons, despite the limited resources of any enemy troops with whom his forces might have to contend and the very special problems of Indian terrain. These factors were, of course, hardly operative in matters of basic research or in the development of the more restricted weapons, such as tanks. But they were of undoubted importance in the questions of field artillery and small arms, where the basic equipment of comparatively numerous units was at stake.

---

[1] *Stocks at November* 1918:

Small Arms and Guns	*Quantity*	*Ammunition (in round figures)*
Rifles	60,865	325,000,000 rounds
Field Artillery		
18 pdr.	3,144	8,000,000 H.E. and shrapnel
4·5″ how.	984	2,000,000 H.E.

Statistics of the Military Effort of the British Empire during the Great War. (H.M.S.O. 1923.)

Against the background sketched above, development of artillery and small arms equipment proceeded slowly in the years after the First World War.

Artillery was traditionally divided into three types. The Field Artillery had as its principal function the support of infantry and was employed at a divisional level. Medium Artillery, which was mainly used for counter-battery work, was allocated to Corps. Heavy Artillery, besides being valuable in counter-battery work, was intended to attack strong fixed defences. In the 1914–18 war two equipments had been found necessary in each of these categories, a gun and a howitzer, and the 'brigade' in which they were organised was usually a composite one, containing batteries of guns and batteries of howitzers. The need to modernise existing Royal Artillery equipments was well known. It had, the Chief of the Imperial General Staff reported in 1935, 'for many years . . . been the subject of theoretical study' and certain policies had already emerged before rearmament began. In the first place the replacement of shrapnel by H.E. was agreed (after a delay due to the opposition of the Commander-in-Chief India)[1]; a decision to 'pneumatize' (or fit carriages with pneumatic-tyred lorry wheels) and employ mechanical traction was part of the general policy of mechanizing the Army; and a good deal of preliminary work had been done on the development of new field artillery equipment.

Field artillery units were equipped in the 'twenties with an 18 pdr. gun and a 4.5″ howitzer. These had not only been out-distanced by the comparable equipments of continental armies, but such composite units were clearly more difficult to supply and maintain than homogeneous units. The 'theoretical study' therefore concentrated on evolving a weapon which would perform both roles. A concrete proposal to this end was first made in 1928 and by 1933 technical trials had established that a 25 pdr. H.E. shell of 3.7″ calibre gave excellent results. At this point it became possible for the General Staff to lay down their requirements more precisely. In May 1934 the 'General Staff Specification' was issued. This called for a weapon to take the place of both the old gun and howitzer; to have a weight in action of 30 cwts.; to fire a projectile of between 20 and 25 lbs. to a range of 12,000 yards (later increased to 15,000); and to be so designed as to be capable of mass production in time of war 'using only materials and plant readily available commercially'. This decision also involved the conversion of existing 18 pdr. guns, by relining them to the new calibre; this was necessary because it would enable a partial re-equipment to take place immediately and (since

---

[1] In 1931 all General Officers Commanding-in-Chief were in favour of substituting H.E. for shrapnel except G.O.C., India. See also p. 263, fn. 1.

stocks of the 18 pdr. were comparatively high) such a step would also be economical. By April 1935 the suitability of a 3.45″ calibre and a 25 lb. shell had been settled and a range of 13,500 yards agreed upon; this range involved the employment of a super-charge which could not be used with the converted 18 pdr. equipments. These were the only major developments in artillery prior to rearmament. When it had taken so long to establish the nature of a future field artillery equipment it is not surprising that medium and heavy artillery were even more neglected, the only noteworthy step being the research which was undertaken into a new medium howitzer, and preliminary work to step up the performance of the 60 pdr. gun.[1]

In contrast with the somewhat leisurely progress of artillery design, considerable advances were made in the field of small arms. The original .303″ rifle had proved difficult to mass-produce during the First World War. Design work and trials on a design to deal with this went on from 1924 to 1935 when the No. 4 rifle was finally approved —at a moment when (owing to financial considerations) the design had to be temporarily shelved. From 1927 onwards the General Staff were preoccupied with the question of an infantry weapon for use against tanks. This was regarded as a task for small arms, not artillery, and, largely under the impetus of the Italo-Abyssinian conflict, the .55″ Boys Anti-Tank rifle was developed and adopted for service in 1936. Considerable interest in a new light machine gun was also shown during the late 1920's and the General Staff expressed a formal requirement in July 1931. The following years witnessed extensive trials with British and foreign designs, from which there emerged, in the summer of 1935, the Bren gun, a British adaptation of a Czech weapon. The medium machine gun was also investigated, and the 7.92 mm. Besa gun was given extensive trials; the use of machine guns on tanks and in the A.A. role will be mentioned below.[2] For the rest, development was confined to fruitless efforts to stimulate the design of an improved self-loading rifle (by offering a prize of £3,000), and to consideration of a machine gun for use against tanks.

Most of the development work in connection with the equipments described in the preceding pages was done in the official Research and Design Departments. Vickers competed with the Design Department for the carriage of the 25 pdr., but the Design Department's version was ultimately approved; the same decision was reached over the two agencies' projects for the pneumatization of the old 18 pdr. carriage. In the field covered by this chapter the most important industrially designed equipment was the standard

---

[1] See pp. 261–262.
[2] See pp. 280 and 307.

Vickers water-cooled machine gun; other work was undertaken by industrial firms (notably continental firms) but the Bren gun was modified by the small arms section of the Design Department, while the Boys Anti-Tank rifle was entirely developed there.

(ii)

1935-1940

The relatively placid development of the 'twenties and early 'thirties was rudely disturbed by the 1936 decision to re-equip existing units with the most modern equipment. This decision was reinforced by changes at the War Office already touched on. The Director General of Munitions Production in that year took over the Master General of the Ordnance's production responsibilities, and two years later his design responsibilities as well. As far as the Director of Artillery was concerned, the change of his masters was in a sense small enough; but it typified a new attitude of mind, a new urgency and incentive to action. From the start the urgency was in the direction of production and for the first time in nearly twenty years there was a marked pressure for the finalisation of designs and the certainty that approved designs would go into bulk manufacture. This stressing of production was at first not at the expense of quality, and indeed in artillery and small arms the need for numbers was never predominant to the extent of impairing the efficiency of equipments. But the practical job of getting new equipments manufactured was brought home to the technical directorates by the production directorates and, in 1939, the Director of Artillery and all the bodies he controlled were removed physically to a Ministry of Supply. Such a move was not without its critics: the Director of Artillery himself regarded the transfer as of doubtful wisdom and felt that an equivocal position would be created if the War Office were advised by him on weapon questions from another Ministry. Such a situation certainly had its difficulties, as experience with tanks was to prove[1], but the less temperamental stores for which the Director of Artillery was responsible were scarcely affected by the transfer except that they were brought closer to the realities of manufacture, which at the time was desirable if not positively essential.

The need to be more in touch with manufacturers was intensified because the desperate effort to rearm without recreating an armaments industry (which was at first held to be desirable on economic grounds) meant employing capacity for production which, unlike

[1] See pp. 346-347.

Vickers, totally lacked the 'know-how' of armaments work. This is a topic which will properly be discussed elsewhere,[1] but its influence on design should not be forgotten nor the repeated instructions from the Principal Supply Officers Committee, embodied in most 'General Staff Specifications', that designs should be 'easy to manufacture' and contain 'no scarce raw materials'. 'Ease of manufacture' meant one thing to a specialist firm like Vickers; quite another thing to the engineering concerns new to armaments work which were now called on to produce gun barrels or gun carriages.

The intensified activity of 1936 and the next few years was not, of course, spread evenly over the whole of artillery and small arms but was concentrated on the items which seemed, from time to time, to be most urgently needed.

Of these, field artillery was at first the most important. The rapid stabilization of design of the 25 pdr. gun and carriage was undoubtedly due to the exigencies of rearmament. The carriage for the new equipment proved more difficult than the piece itself. It had indeed been the need to keep the weight in action down to 30 cwt. that had convinced the General Staff of the need to accept a range of 13,500 yards instead of the desired 15,000. Nevertheless, after initial delays due to debate about the relative merits of box trail and split trail types, the prototypes of the split trail carriage which were produced in 1938 proved to be considerably in excess of the stipulated weight. The box trail was then reverted to; this late change in basic design was less drastic in its effects, since there was in existence a box trail carriage design which had been prepared from an abortive 4.1″ how. project. Thus it was possible to stage trials in October 1938 and proceed at once to place orders. The delays in finalising the carriage design, however, impeded the final appearance of the new equipment as a whole. This was not as serious as it might have been, since the 18/25 pdr. conversion proved a straightforward operation, though the design of modifications to the carriage was not firm until the spring of 1938.

As and when field artillery re-equipment policy settled down, the question of medium artillery could be taken up and rearmament caused this also to be considered as a matter of urgency. Some piecemeal investigations had already been undertaken but the question of medium (or corps) artillery as a whole was not seriously investigated in the interwar years until the autumn of 1936. The problems that were then faced were in some ways similar to those affecting field artillery. The old equipments (the 60 pdr. gun and 6″ how.) were outmoded: were they to be replaced by a gun/how. in order to achieve a homogeneous unit? And (given the greater

[1] See Ch. XIV.

need to produce new field artillery) what immediate steps would be taken to improve performance, apart from the pneumatization already agreed on? The 60 pdr. gun proved amenable to conversion; a shell of slightly smaller calibre and weighing 55 lbs. was designed; the gun itself was provided with a loose liner. The results of trials in 1937 showed that the converted equipment, the 4·5″/60 pdr., was a success: at top charge it ranged over 20,000 yards compared with its old performance of 15,000. This was, however, an interim step and a large number of other projects were discussed in the next two years. Much of the uncertainty was due to a conviction on the part of the General Staff that decisions on the composition of medium regiments (or brigades) must necessarily depend on knowing for certain what the performance of new equipments would be. In the event it was not until January 1939 that the General Staff finally decided to ask for a gun/how., a demand which ultimately crystallised as the 5·5″ gun/how. (range 16,000 with a 100 lb. shell) and a new 4·5″ gun (2,050 with a 55 lb. shell), both to be mounted on a common carriage; such a carriage had been designed earlier to accommodate the 4·5″/60 pdr. and a projected 5″ gun/how., so that design work was rapidly completed and the equipment passed its proof and travelling trials satisfactorily by the summer of 1939. Subsequently the first carriages off production were found to be faulty and a new welded design was produced which was given approval in April 1941.

The need for mobility in a highly mechanized army was responsible, as we have seen, for some of the salient features of the new field artillery. In a sense it was a similar preoccupation, leading to the mounting of the 5.5″ gun/how. on a carriage which was really too light for it, which produced delays in the successful development of the medium equipment. And it was certainly the knowledge that heavy artillery was by definition of limited mobility which, together with the tactical use of air power in support of ground troops, led to the re-equipment of heavy artillery units being dealt with on a very low priority. There is also no doubt that in 1939 and 1940 such projects would have seriously interfered with work on medium artillery. This was a matter which was, like medium artillery, reviewed in 1936 at the start of the rearmament programme. It was then decided to modernise two of the heavy equipments (the 6″ gun and 8″ how.) and provide them with a new common carriage; a new howitzer design was also called for. The common carriage design was approved finally by April 1938, and work went on slowly with the design of a 7.85″ howitzer. Official opinion remained divided, however, not only on the question of bomber support but also on the merits of short range and heavier shell as against long range and lighter shell and by 1939 it was decided to drop the 7.85″ howitzer in favour of a new 9.2″ calibre, on which work slowly proceeded. It is of some significance that at no point during rearmament was there any demand for the design of super-heavy equipment, the War Office stating that 'these monster equipments had a very limited practical or even moral effect on field operations'.

It will have been noted above that three basic items of infantry equipment had been virtually established before rearmament began: the Vickers machine gun in the role of medium machine gun, the Bren gun in the role of light machine gun and the No. 4 rifle. There were, in fact, few outstanding developments in the rearmament period in this field. The most significant was the design of a streamlined bullet (the Mk. 8Z) for use with medium machine guns and having a range of 4,000 yards instead of the original 2,800 yards. This ammunition, which was factory-filled in belts, involved the design of a dial sight to take full advantage of the increased range. These developments were approved in 1938 and the need for large-scale production was responsible for the suspension of investigations into alternative types of medium machine gun.[1]

The divisional artillery and the most important of the infantryman's weapons were thus available during rearmament, the only real casualty of the rearmament crisis being a new design of medium machine gun. The 25 pdr., the new medium artillery, the No. 4 rifle, the Bren gun and the Vickers medium machine gun were all to last the years of war without serious modification. It is important to note that in so far as quality is concerned, the British Army had new and workmanlike weapons for its fundamental artillery and small arms tasks by the outbreak of war. There may not have been enough of such equipment: as late as 1941 13 pdrs. from the Boer War and 18 pdrs. from the First World War were still in limited service. The Lewis gun was made familiar to many recruits in 1940 who should have been handling the Bren. In a sense this was due to the leisurely way in which design proceeded during the interwar period, in a sense it was due to the absence before 1936 of funds which would have made bulk production possible. Yet, as far as quality is concerned, the weapons discussed were a sufficient tribute to the 'Master General of the Ordnance system' which had produced them.

Once more, the bulk of design work referred to here was performed by the departments under the Director of Artillery. Vickers' connection with the 25 pdr. and the 18/25 pdr. conversion has already been noticed. New design resource was, however, provided by the reintroduction of the firm of B.S.A. to small arms design and the evolution by this firm of the Besa machine gun, a weapon extensively employed in A.F.V's, as will later be noted.[2] It may be observed

[1] A further factor was the adoption by the Indian Army of the .303″ Vickers water-cooled medium machine gun.

[2] See Ch. XIII.

here that, as this period drew to a close in the campaign of the B.E.F. in 1940, both A.A. and A.T. attack ceased to be regarded, as they had previously been considered, as questions requiring a small arms solution.

This, indeed, was one of the few 'lessons' which could reasonably be drawn from the very limited experience so far available, though the B.E.F. demand for sub-machine guns for use in forward patrols in the Saar was a straw in the wind. It would be true to say that research and development of artillery and small arms had up to 1940 pursued the general lines which were determined almost entirely by the very modest anticipations of future needs currently held in the interwar years. There were virtually no 'novel' developments in this field; development was characterised by a cautious response to formally expressed General Staff requirements and no attempt was made on any scale to produce answers to problems which might never arise. This, as we have argued, was partly a feature inherent in the nature of the stores with which we are here concerned. The extremely unorthodox situations which soon developed were, in fact, to make demands to which the orthodox weapons and the orthodox machinery for development were somewhat less responsive.

(iii)

1940-1945

The collapse of France in the early summer of 1940 heralded a period of military effort which made the activity of the rearmament years and the phase of operations in France during the winter of 1939 and the following spring seem trifling. The B.E.F. had been evacuated but had lost most of its stores. Like the new divisions which were called for, it needed re-equipment and a demand for massive numbers of basic weapons was made all the more embarrassing by the decision to form the Local Defence Volunteers, the Home Guard, on an armed basis. From this situation arose a call for quantity which could not but affect the quality of the weapons themselves. This period of 'numbers at all costs' was, however, soon over and the characteristic of the last three years of war in artillery and small arms as in other fields, was a return to a policy of 'quality first'. Besides these broad characteristics of the period, it also saw a great extension in the operational experience of the Army. British troops were deployed in almost every conceivable kind of terrain and met tactical situations which had never before been envisaged. The major war which had always been a background preoccupation of planning, in weapon development as elsewhere, had always been envisaged as a purely European affair. Yet in fact for some years the main theatre was the North African desert, and later the tropical jungle of South East Asia was the scene of important operations. Moreover, the more orthodox terrain of Europe was fought over in new ways and a series of novel tactical situations called for new expedients. Despite these unexpected developments, it will appear that the basic equipment remained much the same and, with few exceptions, the trends in design already discussed were maintained. With the detailed consideration of these points this section will now deal.

Some of the consequences of the predominance of quantity considerations had more far-reaching effects in the development of other equipments, notably A.F.V's, than they did in the development of guns and small arms. But naturally the need for greater production was felt very strongly in the case of the artillery and small arms equipments which were required anyway in large numbers: for every cruiser and infantry tank produced in Britain during the war there were two guns with their carriages, ten Bren guns, a hundred rifles and a hundred and thirty Sten guns. There is small wonder that 'design for production' acquired a dominant status in artillery and small arms development as it did elsewhere, and that the very greatest efforts were made to secure revision of existing types in order to obtain greater output. These efforts were naturally more fruitful in the case of small arms, though larger equipments were also affected.

The 25 pdr. remained for a time the most urgently needed gun and, since carriage supply held up the delivery of the complete equipment, considerable redesign was undertaken to make manufacture (and inspection) more rapid. This took two forms. For a while a welded version was authorised and, more important in the long run, changes in contour and in the finish of outside surfaces were approved. The use of higher grade steel in the liners enabled the lengthy and expensive auto-frettaging process to be abandoned.[1] The adoption of a muzzle brake on the gun enabled higher charges to be used with increased range. While much of the Armaments Design Department's time was occupied in this unspectacular but vital work, the equipment was modified in a much more radical way to meet the demand for a lighter field gun, for use in the Far Eastern fighting. The result was the 'Baby 25 pdr.' The evolution of medium artillery equipments has already been touched on:[2] only the failure of the carriage led to design of the 5.5″ gun/how. being protracted into 1941. Medium artillery was not later seriously

---

[1] See p. 267.
[2] See p. 262.

changed, although in 1942 it was found possible to secure an increase of range to 18,500 with an 80 lb. shell, instead of a 100 lb., in the 5.5″ gun/how.

The slow investigations into new heavy artillery have been already described.[1] The good service of the old 8″ how. in France during 1940 led to a demand from the General Staff for a new weapon of similar character but increased performance. This was met, in the summer of that year, by the design of the 7.2″ how., which it was reckoned (significantly enough) would be twice as quickly manufactured as the 9.2″ equipment which had been on the stocks earlier; the 8″ how. was also relined to the new calibre. The shell of the new equipment weighed just over 200 lbs. and at top charge ranged to nearly 17,000 yards. Carriage design, however, ran into difficulties, and it was ultimately decided in the early summer of 1941 to convert the carriage common to the old 8″ how. and 6″ gun, large stocks of which were available in the United States. The relatively late development of the new heavy equipment, and the *ad hoc* nature of the carriage, suggest that war-time experience did not really alter the pre-war conviction that in normal circumstances heavy artillery had been rendered more or less superfluous. But there was throughout the war a steady demand for the 7.2″ how., which remained popular with troops however sceptical the Director General of Artillery and the General Staff may have been. Indeed a long range version of the weapon was finally asked for by the War Office in 1943, the development being rapidly finalised; the Mk. VI was a longer gun and enabled an extra top charge to be fired, stepping up the range to 19,700 yards. It too was mounted on an American carriage, the 8″ how. More certain evidence that the bomber had usurped the place of heavy field equipments is provided by the small part played by super-heavy guns, which had been of some importance during the First World War: a score of 9.2″ guns and two 18″ howitzers had been fitted on rail mountings by the end of 1944, but these cumbersome equipments were virtually relegated to static defence at home.

Redesign for easier production was more urgent in the case of small arms equipments than it could be with artillery. It would be true to say that for eighteen months after Dunkirk the small arms section of the Design Department was preoccupied with simplification of existing equipments rather than new design. This is no doubt undramatic work; but some of the results were significant enough in the strained production atmosphere of 1941, and will be touched on below.[2] With artillery, less striking economies were achieved by redesign, although many relaxations were permitted in

---

[1] See pp. 262–263.
[2] See p. 360.

contour design and in surface finishes, permitting not only of more rapid manufacture but also expediting inspection. Above all, artillery, both new and old, was benefited by the elaborate work undertaken by the Gun Design Committee of the Scientific Advisory Council.[1] Established in May 1941, the Committee was able to recommend, as a result of preliminary theoretical investigations, 'immediate relaxations in the minimum factors of safety specified for non-auto-frettaged and auto-frettaged guns'. The upshot of this was felt quickly: in the field, performance of existing guns could be increased; raw material supply was aided by the employment of steel of a lower yield point, containing fewer alloys; auto-frettage could in many natures be abandoned which saved man-hours and floor space; and design of future guns could produce lighter equipments for a given performance.

Similarly a wide range of redesign was called for by the small arms demands of the Far East campaign and of Airborne Forces. So far as standard equipments are concerned these demands were nearly all in the direction of lighter weight: the rifle was reduced from 9½ lbs. to 7 lbs. and the Bren gun from 23½ lbs. to 19¼ lbs.

If the bulk of small arms development was redesign rather than design, some novel weapons were in fact soon required by the Army. The first of these in order of time was the machine carbine; the 'tommy gun' or Thompson sub-machine gun (.45″ calibre) was obtained from the United States in considerable quantities as a stopgap measure. The War Office request, due, as we have seen, to the experience of the B.E.F. in France, was that a British version of the German Schmeisser should be produced, and the German weapon was in fact the basis of the Sten gun which resulted. But the Sten was a product of austerity, the Mk. II equipment being less than a fifth of the cost of the Thompson gun and nearly half the weight, though in common with continental machine carbines it fired a smaller calibre bullet (9 mm.). The Sten, with a rugged appearance which matched up to the emotional attitude of the crisis it was designed to meet better than a more immaculate weapon might have done, was in many ways a most influential departure, for it provided the basis of the Polsten 20 mm. equipment which compared favourably in the A.A. and A.T. role with its nearest rival, the Oerlikon, and was much easier to manufacture and to handle.[2]

The machine carbine was a new weapon designed to meet a new situation—the likelihood of hand-to-hand fighting in a war of movement. Such conditions raised a much greater problem for the

---

[1] Under the Chairmanship of Dr. Guy, the Committee worked through a small secretariat (S.R.1) and used the resources of the Design Department, Research Department and National Physical Laboratory.

[2] See p. 360.

infantryman, defence against the tank, and this problem accounts for nearly all the other infantry weapons which fall to be discussed here.[1] The Boys Anti-Tank rifle was clearly not adequate in this role (though it later was modified for inclusion in the weapons carried by Airborne Forces). Nor was the grenade No. 68, a hollow charge rifle grenade, fired from a discharger on the No. 1 rifle, much better owing to the use of low-rated explosives and the small size of the discharger cup which limited the use of a larger projectile. Other attempts to provide an effective grenade were relatively shortlived, although No. 74 (the 'sticky bomb') was popular even if its use was restricted largely to night actions; No. 75 was really an anti-tank mine, small enough, however, to be thrown from behind cover into the path of an advancing tank. These two stores, approved towards the end of 1940 and early in 1941 respectively, were superseded in most roles by a much more original weapon, the Projector Infantry Anti-Tank, or P.I.A.T. This followed on logically from the limitations on the No. 68 grenade. It was decided in 1940 to design a special projector which would fire the most efficient hollow charge bomb available. The result was a weapon which, as the Director General of Artillery later put it, 'had an excellent "press" '. By means of a spigot mechanism, the recoil stresses were spread over a longer period than would have been possible with a rigid weapon and in this way an infantryman could discharge a projectile weighing 1 lb. 14 ozs. from his shoulder to a distance of up to 100 yards. Final approval for the P.I.A.T. was given in May 1942.

The original version of the S.T.[2] grenade (No. 74), the 'sticky bomb', was not produced by the Design Department, but by an organisation attached originally to the Directorate of Military Intelligence at the War Office. This arose from a group of soldiers and technicians employed in the first months of the war to design specialised stores for use in irregular operations. Later the group, which was led by Major, later Major General, M. R. Jefferis, was transferred to the Directorate of Military Administration at the Ministry of Supply, though it continued to be technically under the control of the Minister of Defence and was entitled M.D.1. A good many of the stores which were invented by M.D.1 were less useful than the S.T. bomb; and even in this case the Director of Artillery's rejection was overruled by the War Office only on the instructions of the Ministry of Defence. But the very existence of such an unorthodox source of design, producing novelties in an attempt,

[1] The main omissions in the following account are No. 77 grenade (approved 1942) and 82 grenade (approved 1943)—the latter being issued with the (plastic) explosive in a separate container so that the grenade mechanism and the explosive could be assembled either as a hand grenade or as a demolition charge.

[2] Sticky Type.

however misguided this might sometimes seem, to anticipate military requirements, was a thoroughly useful thing. M.D.1 may have been disliked by the official design organisation: ginger groups are never precisely popular. And it doubtless sometimes attracted more public and political attention than organisations developing more prosaic stores, although these were the solid elements of military success while M.D.1's projects were sometimes merely ingenious. But a voluntary response to the weapons problems of war-time is healthy enough and on the whole the Director General of Artillery's fears that production and design effort would be seriously damaged were proved to be groundless.

In any case the design resources of the community were greatly extended by the middle years of the war as far as small arms were concerned. This was due partly to B.S.A's reintroduction to design work which has already been mentioned and which (in another connection) will be referred to again later.[1] Inventors, like Colonel Blacker and Sir Dennistoun Burney, were also employed on specific projects. The arming of the Home Guard produced a variety of weapons running from the archaic to the apocalyptic, from pikes to Molotov cocktails, and derived from a variety of sources both specialist and amateur. But perhaps the most important accession of strength was to the official Design Department itself. Here the staff was reinforced by a number of émigré engineers—the Polish group being commemorated in the 20 mm. Polsten gun. In fact, while the gun itself was largely Polish, the magazine was of Czech inspiration and the universal mounting Belgian.[2] The Senior Supply Officer of the Ministry of Supply told a War Office Committee in August 1943 that 'our team of designers of infantry weapons . . . was probably the finest that could be assembled'.

By this time the relations of the technical directorates in the Ministry of Supply with the ordering department and with the user in the field had also improved. The transfer of the Director of Artillery to the Ministry of Supply in fact deprived the War Office of its technical adviser on weapon questions; though in theory the Director of Artillery continued in that capacity, there is no doubt that had the War Office embarked to any extent on the design of weapons other than those in hand during the rearmament period and the first months of war, difficulties would have arisen earlier, as they did in the case of A.F.V's. But, as we have seen, field, medium and heavy artillery were relatively stable after 1940 and the bulk of small arms work was also concerned with adapting and modifying existing stores. By itself, therefore, the field of weapons under the

---

[1] See pp. 263 and 287.

[2] 12 Czech, 8 Polish and 4 Belgian engineers were employed at different times under the Chief Superintendent Armament Design.

Director General of Artillery would probably not have provoked the sharp change in War Office organisation which occurred in 1942.[1] It was mainly over A.F.V's that the War Office was forced to recreate an independent quality organisation of its own. Nevertheless it is significant that with the appearance of the Director of Infantry and the Director of Royal Artillery at the War Office a stream of new quality requirements emerged and regular and systematic consideration of future policy produced a series of General Staff specifications which were sufficiently fundamental to envisage a new field artillery equipment, a new rifle and the adoption of new ammunition for all small arms. These developments fall outside the scope of this chapter. The interesting thing is that they were only in part due to the digestion of campaign experience—admittedly not available to any extent before about 1943. They were due much more to a logical examination of future trends in armament development and derived from the greater part which was being played in the later years of war by the scientists as well as the soldiers in the Armament Research and Armament Design Departments.

How far was the decision taken in the last years of war to investigate a whole new range of equipments for infantry and artillery due to the relative deficiencies in British stores as compared with German? This is a matter to which the 'user' would have given different answers at different times. The equipments we have been considering were often criticised in detail and it was reported in 1943 by the War Office that in North Africa and the Middle East 'more complaints had been made against infantry weapons than against any other type of equipment'.[2] None the less infantry weapons (with the exception of mortars, which are discussed separately below[3]) and artillery were at any rate of the same order as comparable German equipments as the tables on pages 271–273 will show.

A careful study of the first table will show that there is little to choose between the two sets of equipments. The variables—weight of shell, range, total weight of equipment—have been differently arranged: the German medium gun sacrifices weight of shell for range; the British heavy equipment is more readily handled but its shell weight and range thereby suffer. Needless to say such absolute comparisons are dangerous. In particular, the superiority in battle on many occasions of the British field artillery was to a great extent due to the advanced technique of radio inter-communication, which had no rival in any other Army at the time, while the standard of gunnery training remained very high throughout the war. It is, of course, true that by and large British artillery equipments are

[1] See pp. 474 et seq.

[2] See also Major-General I. S. O. Playfair, *The Mediterranean and Middle East*, Vol. III (H.M.S.O. 1960), App. 7.

[3] See pp. 298–301.

always heavier than their counterparts in continental armies. This is not so much the result (as was sometimes claimed by German authorities) of the influence of naval technique, but of the peacetime vigilance of the House of Commons, ever ready to criticise the Army if safety tolerances were not rigorously maintained.

Only a small selection of small arms equipment can be illustrated in the tables on pages 272 & 273.

British and German Artillery 1942–43

	Weight in action (tons)	*Weight of Shell (lbs.)*	*Range (yards)*	*Total Elevation and Depression*	*Total Traverse L. and R.*
Field					
U.K. 25 pdr. Mk. 1 Carr.	1·75	25	13,400	45°	8°*
Ger. 10·5 cm. Le F.H. 18/40	1·9	32·6	13,479	46°	56°
Medium					
U.K. 4·5″ gun	6·25	55	20,500	50°	60°
U.K. 5·5″ gun/how.	6·1	80	18,100	50°	60°
		100	16,000		
Ger. 10·5 cm. gun K 18	5·5	33·3	20,860	48°	64°
Ger. 15 cm. how. F.H. 18	5·4	95·7	14,550		
Heavy					
U.K. 7·2″ how. Mk. 5 on 8″ how. carr.	10·25	200	17,000	45°	8°
U.K. 7·2″ how. Mk. 6 on 155 mm. American carr.	13	200	19,667	65°	60°
Ger. 21 cm. MRS 18	16·4	249	18,250	70°	16°

* 360° on firing platform.
The weight in action of 4·5″ gun and 5·5″ gun/how. refers to the Mk. 2 carriage. The Mk. 1 carriage is approximately 1 ton lighter.

Rifles—British and German

Rifle	*Weight (with empty magazine)*	*Magazine capacity*	*Rate of Fire*		*Range*		*Muzzle Velocity of ammunition*
			Rapid	*Normal*	*Marked on sights*	*Maximum battle range*	
British No. 4 Mk. I and 2 ·303-in.	9–9½ lbs.	10 rds.	15	5	200 to 1,300 yds.	600 yds.	Mk. 7 2,400 ft./sec.
British No. 5 Mk. I ·303-in.	7–7½ lbs.	10 rds.	15	5	200 to 800 yds.	300 to 400 yds.	Mk. 7 2,400 ft./sec.
German G.98a and K.98k 7·92 mm.	9–9½ lbs.	5 rds.	10–15	5	100 to 2,000 metres	760 yds.	Patr. S.S. 2,580

Light and Medium Machine Guns—British and German

Machine Gun	*Method of operation*	*Method of cooling*	*Weight of gun*	*Weight of spare barrel*	*Weight of tripod mounting*	*Magazine or belt capacity*	*Cyclic rate of fire*	*Rate of fire in action* *Rapid*	*Normal*	*Range* *Marked on sights*	*Effective battle range*
British L.M.G., ·303 in., Bren, Mk. 3	Gas	Air	19¼ lbs.	5 lbs.	—	28 rd. magazine	480	112	28	200 to 2,000 yds.	600 yds.
British Gun, Machine, Vickers, ·303 in. Mk. 1	Recoil assisted by gas at muzzle	Water	33 lbs. and 10 lbs. water	4 lbs.	Mk. 4B 52 lbs. Mk. 5 35 lbs.	250 rd. fabric belt	500	250	125	Iron sights graduated to 2,900 yds. for Mk. 7 ammunition and to 3,700 yds. for Mk. 8Z ammunition.	Up to 2,800 yds. with Mk. 7 ammunition. Up to 4,500 yds. with Mk. 8Z ammunition.
German 7·92 mm. M.G.42	Recoil assisted by gas at muzzle	Air	23¾ lbs.	4 lbs.	43¼ lbs.	50 rd. metal belt in L.M.G. role. 5 joined into 250 rd. belt in M.M.G. role. Some guns adapted to take 75 rd. magazine for use in L.M.G. role.	1,100 to 1,200	180	60	Iron sights 200 to 2,000 metres. Dial sight for use on tripod—0–3,000 metres for direct fire, and 300 to 700 mils for indirect fire.	As L.M.G. on bipod 600–800 yds. As M.M.G. on tripod up to 3,200 yds. direct and 3,800 yds. indirect.

The rifle comparison again illustrates the dilemma between range and weight: in saving 2 lbs. the British Mk. 5 rifle suffered a distinct loss in accuracy. Similarly, the German machine gun M.G.42 was a dual purpose weapon and in the medium role undoubtedly was better (in range and volume of fire) than the Bren; but as a light machine gun its greater weight gave the advantage to the British equipment.

To sum up: the very nature of artillery and small arms of the traditional kind precludes the sort of leapfrog advance which characterises some other weapons. The choice between fairly rigid alternatives is inevitable. The technical directorates at the War Office before the war, and in the Ministry of Supply later, hit on solutions so near those adopted by designers on the other side as to make it clear that artillery and basic infantry roles are, so to speak, unchanging. The weapons thus evolved were, it must be insisted upon, basic. It would have been useless to have had tanks of great virtuosity if the gunners and the infantry had been outranged.

(iv)

Royal Engineers Equipment and Transport

If this study were devoted to a full account of *all* military equipment, as opposed to *weapons* in a narrower sense, great attention would have to be paid to the engineering and transportation stores which form one of the main foundations of the modern mechanized army. As it is, even a narrative which concentrates on weapons must take a glance at Royal Engineers stores and motor vehicles. Whether they fit appropriately into a chapter which is devoted to stores which of their very nature are not susceptible of violent changes in development is, perhaps, a moot point, though with Royal Engineers stores there were few dramatic developments and as far as transport is concerned, the Army relied almost entirely on normal commercial designs which were not much affected by specifically military needs.

The two groups of *materiel* are linked in more than one way. Royal Engineers equipment is devoted to two paramount tasks: it assists the Army to advance and it delays the enemy during a retreat. Its three great fields of activity are the bridging of water obstacles, the development of demolition stores and field engineering. This last was of less importance during the war of movement of the 1939–45 campaigns than it had been in the trench warfare of 1914–18 and will not be further discussed here. 'Bridging' in its widest sense involves the provision not only of bridges, but of rafts and water propulsion units for ferrying men and machines and it is in 'bridging equipment' that Royal Engineers stores form their main connection with transportation problems. The second fundamental connection between the two is their close reliance on normal engineering experience. Unlike offensive weapons of any kind, unlike A.F.V's (as we shall see), 'bridging' and motor vehicles are both matters of everyday industrial concern so that a vast field of design and development resources was accessible to the bodies concerned with these branches of military equipment.

For the rest, development organisation in the Royal Engineers Equipment and Motor Transport was analagous to that described above for the Director of Artillery's stores. In the interwar period, under the Master General of the Ordnance, the Mechanization and Royal Engineer and Signals Boards, together with the Mechanization Experimental Establishment, the Experimental Bridging Establishment, and the Experimental Demolition Establishment, were under the Director of Artillery. After 1928, on the appointment of the Director of Mechanization, the machinery described was placed under the control of this officer; the history of the Director of Mechanization's office will be touched on again in discussing tanks[1]; it suffices here to note that under various masters the pre-war engineering development establishments continued much as before, while in motor transport itself, both before and during the war, there was virtually no development as such with the exception of the gun tractors which will be described shortly.

The bridging equipment of the Royal Engineers had to keep in step with the steadily mounting size of vehicles employed in the Army. During most of the interwar period only light tanks and 30 cwt. and 3 ton lorries were employed in mechanized units and the pontoon equipment developed during and soon after the 1914–18 war proved adequate. But during rearmament and still more during the years of war, the tonnage classification 5, 9, 12, 18, 24 which had been adopted for roads and bridges in 1939 had to be extended first to include tonnages up to 70 (in 1940) and later up to 100 (by the end of the war). This gives a measure of the much greater tasks which faced the engineers. The water propulsion units devised from time to time were ingenious and effective, but the ultimate solution to this problem lay in the provision of amphibious vehicles and tank landing craft and thus falls outside the scope of this narrative.[2] The great contribution of the engineers was a series of bridges, developed mainly by Mr. Bailey, Chief Designer of the Experimental Bridging Establishment, and bearing his name.

---

[1] See pp. 305 et seq.

[2] See M. M. Postan, *British War Production* (H.M.S.O. 1952), Ch. VI, pp. 284–287, and William Hornby, *Factories and Plant* (H.M.S.O. 1958), Ch. II.

The Bailey Bridge was a product of the urgencies of 1940 and it had the advantage of being designed from the start in an atmosphere where economies in production were essential. The bridge was designed as a 'through' structure, the roadway being placed between two main side girders, built up of panels 10 feet by 5 feet. Construction was so arranged that the girder could be one, two or three panels high and be composed of one, two or three trusses of panels side by side. Originally intended to carry Class 40 vehicles (the Churchill tank was being contemporaneously developed), the components could in fact be doubled in order to secure a Class 70 bridge. Detailed design was started in January 1941 and General Staff approval was obtained in July of the same year. Not only did the Bailey Bridge render superfluous a great deal of existing equipment, but it proved possible to design a number of further variations which were of considerable importance. A suspension bridge proved possible; a mobile bridge (for assault purposes) and a Canal Lock Bridge were the chief of these.

If the Royal Engineers equipment is one of the legs on which a modern army moves, motor transport is the other, and in a sense the few lines here devoted to motor transport are totally inadequate. Yet from the point of view of development motor transport is, for several reasons, unimportant; its dependence on pre-war and normal commercial designs make it most suitably discussed in this chapter.

Under the Director of Mechanization at the War Office and later at the Ministry of Supply, design of motor transport was controlled in much the same way both before and during the war. A section of the Director of Mechanization's staff was responsible for the preparation of detailed draft specifications which were then farmed out, sometimes on a 'competitive' basis, to existing commercial firms. Thus the development resources of military load vehicles were in a sense co-terminous with the development resources of the motor industry itself; not that that was very extensive, as the conditions of the trade led to greater importance being placed on annual redesign of external and superficial features than on fundamental development of engines, transmissions, suspensions etc. The concentration of general policy control in the Director of Mechanization's departments and the distribution of detailed design in industrial undertakings worked, on the whole, very well in the pre-war period, though it was to some extent wasteful of effort in view of the wide multiplicity of components involved in reaching the same end result in different drawing offices. Moreover, the comparatively early decision to mechanize the Army enabled detailed re-equipment plans to be drawn up in the 'twenties and early 'thirties. In this period some notable advances were made by the Army, independent of commercial use.[1] The 6×4 vehicle[2] and the use of low pressure tyres date from this period.

From the moment rearmament began, however, the need for great quantities of vehicles cut short the further elaboration of radically new types. True, as a result of a decision to employ a greater number of 4×2 vehicles a step was taken towards evolving the 4×4 vehicles, some of which were in fact ready by the outbreak of war, and which were soon put to other uses in addition to artillery traction for which they had first been developed. But this was to be the only noteworthy innovation. While designers were kept busy with minor modifications, involved in providing a very wide variety of bodies for special purposes, and while noteworthy steps were taken towards the standardization of such components as batteries, no fundamentally new designs of load-carrying motor transport[3] were evolved during the war; as the production of the 4×4 M.T. vehicles was strictly limited, the bulk of motor transport can fairly be described as basically commercial types.

This was at no time due to satisfaction in the War Office or the Ministry of Supply with commercial types nor (at any rate after 1942) to lack of user criticism. The user was, indeed, extremely vocal after the first major experiences of the Libyan campaign; and the mingling of American vehicles among British ones made the disabilities of the latter (especially in speed and load-carrying) seem disproportionately great. But by the second half of the war there was no chance of redeploying industrial capacity in the manufacture of new types of motor transport; the demand for numbers remained as urgent as ever and no one was prepared to face the drop in production which would have been involved in the adoption of new types. In any case there was a marked contraction in the total motor transport design resources of the country, for many motor manufacturers had to devote the bulk of their development capacity to tanks and aircraft components (especially engines). It was, in fact, the absence of engine development which really precluded the introduction of basically new types, so far as development was concerned; and it was mainly the superior engines in United States vehicles which gave them such advantage.

Yet, though much was heard of the inferiority of British motor transport (gun tractors in particular coming in later for much criticism), the reliability of British vehicles and their effective

---

[1] The 'subsidy system', whereby payments were made for limited periods to purchasers of War Office approved and essentially non-commercial designs, was discontinued in 1930. With the increased production of heavy commercial vehicles the subsidy system had become ineffective.

[2] The first figure gives the number of wheels, the second the number of power-driven wheels.

[3] Armoured wheeled vehicles are discussed below with A.F.V's, see Ch. XIII.

working life was put much higher than United States vehicles by competent observers. Where the British vehicle was in convoy with its American counterpart and striving to maintain equivalent speeds, it was clearly inefficient and inferior. But judged by the standards required of it in the first place, British motor transport, though conservative in design, was by no means unsatisfactory. In any event, it was a policy decision reached at the highest levels to rely to a great extent on trans-Atlantic motor vehicles and avoid the successive redesign of motor transport which might otherwise have become a necessity.

CHAPTER XII

THE PROBLEM OF ANTI-AIRCRAFT DEFENCE: WITH A NOTE ON MORTARS

(i)

To 1934

THE weapons discussed in this chapter have a history markedly more animated than those with which we have so far been concerned. The guns and lighter weapons developed for use against aircraft (like the mortars which are the subject of a separate note at the end of this chapter) emerged from the same machinery as that which controlled artillery and small arms. They were under the Director of Artillery in the War Office and later at the Ministry of Supply. Yet, even from the viewpoint of the organisation and control of development policy, anti-aircraft weapons are distinctly different from more conventional stores. The reasons for this are not far to seek.

A.A. weapons are designed to combat air attack and air attack was the most widely canvassed military problem of the interwar period. Few features of any future war could be envisaged so concretely as the much greater part to be played in it by the bomber aeroplane. The knowledge that this was so was far from being restricted to the administration. Every writer on military matters stressed the sinister consequences of a sudden air thrust at Britain, so that there was wide popular apprehension on the subject. For this was a military question which had implications going far beyond the Army and the other Services as such. Bombing would probably not be restricted to 'military targets' and, even if it were, these were normally to be found in densely populated areas.

Air warfare had played a small part in operations during the First World War, both at the front and at home. But the enormous advance of civil aviation left no room for doubt about the next war. It might equally have been anticipated that A.A. weapons would produce greater demands on research and design organisations than other artillery and small arms. The target of the A.A. gun is an aircraft, and it was easy to see that, especially under the impulse of war, aircraft performance would be progressively improved. A.A. guns are, like all artillery, subject to ballistic and other limitations which narrowly circumscribe the designer; but faced with a target which proved more and more elusive, the gun had to be pushed to the limit of its efficiency. If we find that in fact the German and the British gun were strikingly similar in their performance qua guns, we must remember that there were many other elements in the use of the weapon which could be improved—fuze setters, fuzes themselves, and—above all—methods of target prediction.'

Given the latent public anxiety and the certainty that air defence would be important in any future war, it is somewhat surprising that the crisis of the mid-thirties found the Army without any alternative A.A. armament to that which had been evolved by the end of the First World War. This was not due to lack of interest. A number of War Office and departmental committees reviewed the question from time to time and (being purely defensive) A.A. equipments were less subject to restrictions than other military stores. Considerable research and development had been devoted to elaborating new calibres to replace the existing 3″ 20 cwt. A.A. gun which, though a workmanlike weapon, was admitted on all sides to be inadequate to the task of engaging modern aircraft, for it had an effective ceiling of only 17,000 feet. Such a ceiling made it equally unsuitable for work against low-flying enemy planes, while the impact of normal small arms on such planes was clearly of smaller effect now that aircraft were capable of carrying armour. On the whole a machine gun of slightly greater calibre than the infantry .303″ weapon was favoured for the light A.A. role by interwar opinion in the General Staff; as for a heavy gun, a tentative decision in favour of a calibre of 4·7″ had been reached.

These somewhat negative results were in part the product of a division in the military aspects of A.A. work. Home A.A. defence preoccupied the public and the politicians and even in the War Office to some extent obscured the other equally important task of A.A. defence, its employment in the field. The establishment of A.A. in the field army prior to 1934 was small enough; the Air Defence Brigade was composed of two A.A. brigades Royal Artillery,[1] together with one searchlight battalion Royal Engineers and a signals brigade. There was, of course, a close parallel between the problems of A.A. defence at home and in the field. Protection of forward areas was comparable to defence of particularly important home targets which might be exposed to low level attack; the Army's lines of communication and bases were comparable to the large urban areas which would need defence against the high-flying

[1] 'Brigade' at this time was used to cover a unit resembling the present regiment.

bomber. Even the mobility of the heavy A.A. guns did not involve so big a difference between home and field requirements as might at first have been supposed: though mobility was absolutely essential in field equipments, it was highly desirable also in a large proportion of home defence guns, for it was impossible to conceive of adequate fixed defences being available for every vulnerable area of the United Kingdom.

The beginning of rearmament, then, found a diffused sense of the importance of air defence in the community at large and in the Service departments. But (as with other weapons) it needed the mounting anxiety of 1934 and later, to force decisions in qualitative requirements by impelling a more precise definition of A.A. strategy and tactics.

(ii)

1935-1940

In 1934 the provision of air defence units for the Field Force was doubled, and as rearmament progressed and an even larger army was planned for, A.A. requirements were multiplied with the creation of each new division. But the chief stimulus remained, not the requirements of the future Expeditionary Force, but what was technically known as the Air Defence of Great Britain—A.D.G.B.

To some extent the two sides of A.A. defence, in the field and at home, were linked and consequently estimates of the danger to Britain from air raids fluctuated with changes in the hypothetical responsibilities of the Army: the danger to Britain would be greatest if the enemy were to occupy the nearest continental bases. But independently of this, a threat remained and the Air Ministry pointed out in January 1937 that, if Germany aimed at delivering a knock-out blow against Great Britain at the outset, attacks might well be carried out for a limited period by practically the whole of the German air striking force, notwithstanding an alliance with France. This assumption, that in the first weeks of war the enemy would launch a crippling blow at Britain, was fundamental: to plan for anything else would have been foolish.

From the start of rearmament it was evident that the only effective defence against German bombing strength, estimated by the Air Ministry in 1934 to be rising annually to a total bomb-load of 2,000 tons by 1939, was air attack on the enemy: by fighter aircraft on his bombers, and by bomber attack on his 'immediate aircraft reserves, aircraft parks and aircraft assembly factories'. It was also appreciated that the success of the German attack would largely depend on:

> the degree to which the community and its supply system can be protected by passive measures. Adequate dispersion, a suitably elastic supply system, and, above all, the education and training of the general public in air raid precautions are, therefore, just as essential in an "ideal" defence system as the active defences.

It was within this framework—the desirability of building up a striking force of our own and the need for passive air defence as a bolster for civilian morale—that A.D.G.B. developed.[1]

The part played by the Army in A.D.G.B. was restricted to ground defences and the main element, the provision of fighter aircraft, was an Air Ministry responsibility. The supreme control of A.D.G.B. was appropriately vested in the officer commanding the fighter planes. This was the more reasonable as the function of ground A.A. defences is primarily the diversion of attacking aircraft to areas and altitudes where they can do least damage and be most readily engaged by defending planes; the maintenance of civilian morale and the physical destruction of hostile aircraft are secondary to this task. The guns and the defending fighters in A.D.G.B. were thus directly linked: the guns were to help the fighters by forcing a diversion of enemy planes and also by supplementing the lethal effect of the fighters. There was also another direct connection between guns and planes. It was critically necessary to give our own aircraft industry at least the same protection against low level attack as the Germans were able to give their industry; otherwise, as the Chiefs of Staff argued in 1940, 'the net result can only be to accentuate still further the comparative numerical superiority of the German Air Force'.

From the point of view of design, the domestic role of A.A. was stressed: as late as 1935 the feeling was expressed by the War Office that A.A. in the field army was being evolved as means would permit, and without any real regard for the roles it would have to undertake, because nobody was directly responsible for it. In fact, as indicated previously,[2] apart from the relatively higher stress laid on mobility in field equipments, the tactical roles at home and in the field were strictly comparable. The field army and A.D.G.B. both needed a light gun to deal with aircraft flying at a ceiling of about 6,000 to 12,000 feet: such a weapon obviously needed a very high rate of fire; and they both needed a heavier weapon able to engage aircraft flying between 20,000 and 30,000 feet. Development accordingly followed these lines.

When rearmament began, the choice of a light A.A. weapon lay between a .303″ machine gun, a .5″ A.A. machine gun and a 2 pdr.

[1] The military term P.A.D. (Passive Air Defence) was, of course, ultimately replaced by the civilian A.R.P. (Air Raid Precautions).

[2] See p. 280.

of the naval pom-pom type. The ineffectiveness of small arms fire on aircraft had been demonstrated. Apart from rapidity of fire, its sole advantage was that it readily admitted of 'hose pipe' fire, the direction of the trajectory on the target by the observation of tracer ammunition. The range of the .303″ machine gun (about 1,800 feet) was exceeded by the .5″ machine gun, but neither of them attained the 6,000–12,000 feet ceiling that was required. The doctrine that volume of fire was the prime consideration was however dominant in the War Office (despite the Director of Artillery's recommendation of a gun) and it was only in June 1936 that what was virtually a General Staff ban on research into calibres greater than .5″ was lifted. A 2 pdr. gun then became the principal light A.A. research project, at first for the Field Force and later, by November 1936, for A.D.G.B. as well.

Time by now was short and several ready-made solutions were promptly considered. The Navy had a 1½ pdr. in hand but it was at first hoped to secure quicker results by adopting a Vickers 40 mm. 2 pdr., drawings for which were complete. This was essentially a static gun, but it could be transported on a lorry and took only half a hour to be set up on the ground. In fact the gun gave disappointing results when it was tried out in 1937, but even before that the General Staff had decided that a fully mobile gun of about the same calibre was essential. In view of the urgency, another existing equipment, the Swedish Bofors 40 mm., for which designs on a mobile mounting were available, was rapidly investigated: it emerged that the performance of the weapon was not only adequate, but that it was even more suited than the 2 pdr. to the remote control system developed by Colonel Kerrison. The 2 pdr. project faded into the background and orders were placed for Bofors guns and ammunition from Sweden, while at the same time a licence was obtained to manufacture the weapon in the United Kingdom. Subsequently a Mk. III equipment was evolved which incorporated remote control.[1] Later redesign is touched on below.[2] The ammunition, H.E. with impact fuze and self-destroying tracer, was subsequently modified to incorporate more lethal fillings, a modified fuze and the use of flashless propellant.

In the period prior to rearmament, research into a heavy A.A. gun to replace the 3″ 20 cwt. equipment had, as we have seen, culminated in a 4.7″ project, under trial in 1933 and 1934.[3] This gun, while adequate from the performance point of view, had a total weight of 22 tons and its mobility was 'very limited'; it had,

---

[1] Mk. I—the original Swedish design; Mk. II (Mk. I adapted to remote control) was never actually manufactured.

[2] See pp. 291–292.

[3] See p. 280.

in fact, been embarked on very largely in order to meet Admiralty concern over the defence of naval ports.[1] The theoretical advantages of a 3.7″ gun had already been demonstrated and designs had already been called for from the Design Department and the trade as early as 1933. Rearmament caused a more urgent prosecution of this project. Meanwhile the Director of Artillery successfully urged that existing stocks of the 3″ A.A. gun should be modernised. In 1936 the Admiralty again raised the question of heavy A.A. defence of ports, pointing out that a 4.5″ A.A. gun had been accepted for mounting on warships and that, if the War Office were to adopt the same equipment for A.A. batteries at ports, the problem of ammunition supply would be simplified. The War Office agreed to take a certain number of 4.5″ guns. Thus the programme of heavy A.A. guns to which the War Office was committed by 1936 consisted of a modernised 3″ 20 cwt., a new 3.7″ and a 4.5″ of naval origin.

The 3″ 20 cwt. A.A. gun had originally had a two-wheeled carriage; this was replaced by a four-wheeled pneumatized carriage. In addition the ordnance was converted to a standard loose-liner type. The modernised guns were in the hands of the Army by the outbreak of war.

The draft specification for the 3.7″ equipment had originally called for a travelling weight of not more than 8 tons, a time into action of not more than 15 minutes, a speed on roads of 25 m.p.h. Designs were put forward by both the Design Department and Messrs. Vickers-Armstrongs[2] in January 1934. The project, coinciding as it did with rearmament urgencies, was pressed forward with commendable speed. After consideration of the alternative proposals it was finally decided to go ahead with Vickers' design. A pilot model was delivered and proved in April 1936. It completed its trials by the end of the year and by April 1937 the design was cleared for production. Even before the formal acceptance of the mobile 3.7″ gun, a static mounting for it had been mooted and soon the need for numbers reinforced other arguments (simplified design, better firing qualities) which the Director of Artillery had advanced and the static mounting was finally adopted for use in A.D.G.B. and defended ports abroad. The mobile mounting was an elaborate and difficult piece of engineering; the static mounting could be manufactured by general engineering firms without armament experience.

The adaptation of the naval 4.5″ gun to land use was a fairly straightforward operation. The naval equipments under trial in 1936 were all designed for twin mountings. The army design was for single mountings which could be easily transported to a war site on

---

[1] Air defence of ports was a naval responsibility.

[2] Messrs. Beardmore, who were invited to compete, replied that they had disposed of their experimental design staff. See also p. 255.

mobilisation. A 'sub-base' was accordingly prepared to form the chassis of the transporting vehicle, and in effect represented the ship's deck for which the equipment had originally been designed: the design for this was approved in September 1937.[1]

The shells for both the 3.7″ and 4.5″ equipments were high explosive[2] with a pre-set time fuze. Both mechanical and powder fuzes were designed in view of the shortage of capacity in Britain to manufacture the first type, which is the more accurate. The propellant charges in heavy A.A. are liable to give the enemy plane warning as well as to lead to heavy barrel wear: both of these reasons stimulated research into flashless propellants; shortage of flashless propellants, however, made the design of other charges necessary.

The development of the range of A.A. equipments described above was completed some time before war broke out. It will be noted, however, that of the four guns mentioned only one, the 3.7″, was *ab initio* a new army weapon. The Bofors came ready made from Sweden, the 4.5″ from the Admiralty and the 3″ 20 cwt. from the First World War. Yet it would still be true to say that A.A. development absorbed an immense amount of the research and design resources available. Research, in particular, was involved in the development of equipments which far surpassed those which had been used in the 1914–18 war, when A.A. in any case first made its appearance. The Research Department in fact concentrated a great deal of its attention, both for Army and Navy, on flashless propellants. These, as indicated above, were important not only from the tactical point of view, but also from the aspect of barrel wear, a matter particularly important in A.A. artillery, where a high rate of fire was essential. Another field of research was the evolution of tracer compounds. On the side of engineering the Design Department could, as we have seen, be reinforced by Vickers-Armstrongs; but the novel chemical work involved in the design of propellants and tracers had to be carried out almost exclusively at the Research Department itself: commercial chemical and explosives firms had little direct interest in such developments.

A further activity within the Research Department, of which this time there was not the remotest military, let alone commercial, past experience was the study of rocket projectiles. These were termed 'Unrotated Projectiles' or 'U.P.' at the time and during the early years of the war. In fact rockets in the A.A. role, and in the Army generally, were not of prime importance during the war. But rocket weapons were rising in value as the war progressed; the German use of a rocket missile (V.2) gave such stores an enormous advertisement; and there is clearly need to give some account of the genesis

---

[1] It should be noted that the actual calibre of the gun was 4·45″.

[2] A proportion of shrapnel shell was at first provided.

and development of a weapon which was both totally unorthodox and obviously destined to be important.

Knowledge that the French and German armies were interested in rocket weapons coincided with the increased anxieties about military re-equipment in and after 1934. The Research Department was formally concerned with the matter and by the end of 1935 special branches to study rockets had been formed in both the Ballistics Directorate and the Explosives Directorate. 'The original problem was to consider the possibilities of rockets for A.A. defence' and, though other projects (long-range defensive use in place of pilotless aircraft, assisted take-off for heavily loaded aircraft) were soon on the agenda, the A.A. use of rockets remained for long the chief preoccupation. The Ballistics Directorate was particularly concerned with the design of the main components,[1] while investigating fully the question of ballistic theory, methods of prediction and stability. The most complicated practical problems arose with the motor component, where the Explosives Directorate was faced with a requirement for 'a propellant which will burn at a steady controllable pressure; whose surface, during burning, will remain constant and which will leave, at the end of the burning, as little unburnt residue as possible'. The compromises involved in trying to meet these demands involved also a wide range of further problems; the charges had to be sheathed in non-inflammable material and cement had to be found capable of withstanding sharp acceleration and differential gas pressure: yet the acceleration which might dislodge cement was far slower than that used in normal projectiles to actuate a fuze mechanism and a novel type of fuze had therefore to be elaborated. But the most important desideratum was a suitable cordite propellant, for the complex shapes involved complicated extrusion processes. Yet by 1936 great progress had been made. The Director of Ballistics Research could report that 'a position has been reached in the general investigation of rockets which warrants their fullest consideration for war purposes'; above all, the new propellant was emerging, to be known later as Cordite S.C.[2] In July 1936 it was decided to concentrate research in a special unit under Dr. (now Sir Alwyn) Crow, Director of Ballistics Research, and from this point rocket projects received the regular attention of the Sub-Committee on Air Defence Research of the Committee of Imperial Defence.[3] The Sub-Committee on Air Defence Research

[1] It should, however, be added that in early development work an engineer from B.S.A. Ltd. was regularly consulted on production aspects.

[2] S.C.—Solventless Cordite.

[3] In the summer of 1939 Dr. Crow left the Research Department to become head of an independent department for the development of rocket projectiles: this new body was called the Projectile Development Establishment. This move was on the direct inspiration of the Sub-Committee on Air Defence Research.

was a very powerful body: presided over by the Air Minister, it was attended by the Minister for Co-ordination of Defence, Service Chiefs and technical experts.[1] Rockets were thus from 1937 developed under an interservice body and the unorthodoxy of the weapon was matched by the unorthodoxy of policy control.

The first concrete design was for a 2″ rocket. Work on this had gone some way when it was decided to press forward the development of a 3″ projectile which would be comparable to the 3″ 20 cwt. and 3.7″ A.A. shells and which would thus make a more useful contribution to medium and high-altitude A.A. defence. By October 1937 the Sub-Committee on Air Defence Research reached two important decisions: the 3″ U.P. was to be given general precedence over the 2″; and the aim was to be 'to obtain an initial supply of a type which, though it might not be ideal, would serve as a weapon of war'. In June 1938 the Sub-Committee on Air Defence Research urged the War Office to plan for quantity production. Trials up to the end of 1938 established that all components except the fuze were satisfactory and designs for service projectors, both twin and quadruple, were asked for from Vickers-Armstrongs, who thus joined B.S.A. in being connected with development work on the new weapon. Quite apart from its efficiency the rocket was attractive on the grounds that for the most part its manufacture would not compete with existing armaments with the exception of demands for S.C. Cordite, which could only be met by providing new capacity at R.O.Fs.

The developments we have been considering were viewed with perhaps more consistent interest at the Admiralty than at the War Office. True in December 1938, when pressed by the Sub-Committee on Air Defence Research to express its views, the General Staff was far from being unresponsive. 'Tentative requirements have been based on the assumption that the U.P. weapon will not attain the accuracy of the gun. It will, however, be invaluable as a means of producing heavy concentrations of fire over short periods and over relatively large areas, provided a sufficient density of fire can be developed.' Working from these assumptions the War Office calculated that it might require 285 troops, each with four quadruple projectors, together with 60 quadruple projectors as reserves; and it was an added advantage that this might also enable the 3″ 20 cwt. to be placed in reserve, a reserve which 'would be invaluable to meet immediate demands for further units at the outset of hostilities'. The final adoption of the weapon was, however, dependent on the extensive firing trials carried out in Jamaica in the spring of 1939. While these were on the whole satisfactory and the Sub-Committee

---

[1] Mr. Churchill attended the meetings of this body.

on Air Defence Research recommended the adoption of the 3″ U.P. for Service use, that decision was at the time not made. The Director of Artillery advised the General Staff that the degree of accuracy was not adequate for medium or high-altitude shooting and development of military U.P. proceeded slowly until the crisis after Dunkirk in 1940.

The explanation for this lies in the 'assumption that the U.P. weapon will not attain the accuracy of the gun'. It was, in fact, felt to be a wasteful weapon compared with a normal A.A. gun firing against a predicted target. This was no doubt true, in a sense. But it raised the whole question of whether the degree of accuracy in the predicted gun was itself of major importance. Prediction means anticipating the area in which the plane will be by the time the shell arrives in its vicinity; it is, in short, predicting the unpredictable. At the time, it was not possible to test empirically the number of rounds of 3.7″ A.A. and 3″ U.P. needed respectively to hit an enemy plane; and it was assumed that round for round the U.P. would be less efficient: not only because the trajectory was less stable, but because prediction was not so close. This tended to discount the much greater lethal charge carried by the U.P. (where the projectile casing was thinner than was possible in an artillery shell). An even greater repugnance was expressed to the main characteristic of the U.P., its concentration of expenditure on the ammunition as compared with the projector: it was felt that the repetitive, consumable element in a weapon should be cheaper than the permanent part; the U.P. was, so to speak, its own gun barrel and the projector merely a device on which it rested. This objection also depended on accurate estimates of the relative efficiency of shell and U.P. which were not available at the time.

To some extent War Office confidence in the accuracy of the predicted A.A. gun was based on solid grounds, for in the years when rockets were developing there was also developing the new radar technique which was to revolutionise A.A. fire control. Hitherto A.A. artillery had been aimed at its target from the indications provided by sound locators and searchlights. Sound locators were not of great use when enemy planes appeared in any numbers, and reliable prediction only became possible with the development of radar devices. These are described elsewhere[1] and will not be discussed here beyond recording that a primitive form of A.A. G.L. was available by the outbreak of war.

By 1940 the test which A.D.G.B. had been intended to anticipate at last came. How well did British A.A. stand up to air attacks on the B.E.F. in France and to the air onslaught of the summer which

---

[1] See Ch. XV, Section (ii).

followed Dunkirk? We are not here concerned with the part played by fighter planes, which, as we have seen, were from the first intended as the main answer to the German bomber; that part of the defence scheme certainly responded to the challenge with remarkable efficiency. The guns were also respectable in quality, however deficient they may have been in quantity.

True, as far as the troops in France were concerned, the new 3.7″ gun was considered by Lord Gort and his advisers to be too heavy. Indeed at one point G.H.Q. was demanding that the old 3″ 20 cwt. equipment should be manufactured again; or at least that all available supplies of this weapon should be sent to France on a fully mobile basis. But the real test of both light and heavy A.A. came after Dunkirk, during the months from July to August 1940.

There is no doubt that the deficiency was almost entirely quantitative not qualitative. The following table gives the simplest relation between British guns and enemy bombers; and the German guns and British bombers are added for purposes of comparison.

Heavy A.A. Guns 1939–40[1]

Gun						*Target*		
Type	*Total weight of equipment* (tons)	*Weight of shell* (lbs.)	*M/V* (f.p.s.)	*Effective ceiling* (ft.)	*Rounds per minute*	*Type*	*Maximum ceiling (unloaded)* (ft.)	*Maximum speed* (m.p.h.)
Br. 3.7″	10.3	28	2,670	32,000	10–12	Heinkel III	29,000	240
4.5″	[Static]	55	2,400	34,200	8	Dornier 17	27,000	255
						Junkers 88	32,500	291
Ger. 8.8 cm.						Wellington	19,000	235
(Flak 8)	4.92	20	2,690	26,250	15–20	Blenheim	25,000	266
12.8 cm.	12.8	57	2,890	35,000	8	Hampden	23,000	254

The maximum ceiling quoted in the above table is, of course, somewhat unrealistic: bombers habitually attacked at this time at altitudes of between 16,000 and 20,000 feet[2] which explains the popularity of the old 3″ 20 cwt. A.A. gun, with its ceiling of 17,000 feet. It is obvious that the higher ceiling of the British A.A. equipments compared with their German counterparts was necessary in view of the slightly superior performance at this time of German as compared with British bombers. Further, the efficiency of heavy A.A.

[1] In this, and the other tables in the A.A. section, the 'effective ceiling' for British equipments is the 'operational ceiling' defined as the height at which a 400 m.p.h. directly approaching aircraft can be engaged for a period of 20 seconds up to a quadrant elevation of 70°.

[2] Supplement to the *London Gazette*, 10th September 1946 (No. 37719), Appendix "C". Section 2, Enemy Tactics.

was directly related to the prediction equipment available. Engagement of unseen targets was greatly increased at sites where G.L. was available, and elsewhere a barrage defence was normally resorted to in night attacks. By day the prediction equipment worked well, as may be seen from the average number of rounds fired per enemy aircraft certainly destroyed: 298; the similar average for barrage and unseen fire was 2,444.[1] The extremely high mobility of the German 8.8 cm. gun should, however, be noted: it was less than half the weight of the 3.7″ equipment.

Light A.A. guns in the first year of war cannot readily be compared with the targets they might occasionally have to engage and the following table does no more than set side by side the comparable British and German equipments in service at this time.

Light A.A. Guns 1939–40

		Weight in action (tons)	*Weight of shell* (lbs.)	*M/V* (f.p.s.)	*Effective ceiling* (ft.)	*Rate of fire* (r.p.m.)
Br.	Bofors 40 mm.	2.4	2	2,800	12,000	120
Ger.	3.7 cm. (Flak 18)	1.53	1.4	2,690	5,000	60
	4.7 cm. (Skoda)	1.7	3.3	2,620	7,000	25

The advantage of the Bofors gun over indigenous German weapons is obvious: its high rate of fire more than compensated for the greater lethality of the 4.7 cm. It should however be observed that the Germans used the Bofors gun themselves:[2] ballistically the German Bofors was identical with the British version; but the enemy again achieved a very much greater mobility, the total weight of the equipment being only 1.7 tons—almost half the weight of the British Bofors. On the other hand the prediction equipment built into the Bofors justified itself; in the main area of the battle, guns with prediction equipment expended only half as many rounds per hit as those fired over Forward Area Sights. One important lesson was learnt in light A.A. The use of small arms fire from machine guns on A.A. mountings was surprisingly effective against low-flying attacks. Old Lewis guns, mounted on single, double or quadruple mountings accounted for nearly 20 per cent. of enemy planes certainly destroyed in the area round London during the Battle of Britain. This suggests that the original War Office view that 'hose

[1] Ibid., Appendix "C.C.", Section I. (These figures refer only to 6th A.A. Division covering the London Area and South East Coast.)
[2] 4.0 cm. Flak 28 Bofors.

pipe' fire was the answer to the low-flying aircraft was at any rate partly true of the situation as it existed in 1940.

The balance sheet that may be drawn at this stage is, on the whole, a satisfactory one. The equipment was too scanty: but it was up to its job. The 3″ U.P. equipments would have been a most welcome reinforcement to the barrages laid down against unseen attacks; the need for more and better G.L. was obvious. But the standard equipment provided had passed the test of battle.

(iii)

1940-1945

When the main guns for field, medium and heavy artillery had been settled there were, as we have seen, only minor changes aiming at light versions (for Far East and airborne employment) or at versions which could be more readily manufactured. In the years which followed Dunkirk these last two points affected the design of the light and heavy A.A. guns which we have been discussing. But over and above such changes in design, the tasks which A.A. guns themselves were called upon to face changed. The gun was aimed at a target which flew higher and faster, and which carried more armoured protection. Later, when the pilotless V.1 made its appearance, the gunner was faced with a target which was immune to assault on the morale of a pilot, hitherto the most immediate effect of A.A. gunfire on an attacking plane. To meet these new responsibilities development had to embark on novel designs and refurbish the existing types, though an ever increasing Allied air strength was, of course, the principal answer to the improved German planes of the central and last years of the Second World War.

First of the tasks which confronted the Army in the immediate post-Dunkirk period was a massive demand for equipment. The hypothesis of a war against Germany with no allies postulated by the Air Staff before the war was now completely fulfilled.[1] A.D.G.B. was therefore the first priority. To its demands for A.A. guns were added those of the rescued B.E.F. which were soon to be augmented by the decision to reinforce the Army in the Middle East. These quantitative demands involved qualitative consequences: existing types were simplified for production and alternatives were sought in the U.P. weapon which, as we have seen, had been virtually rejected in the previous period.

The redesign work carried out on both Bofors and 3.7″ A.A. equipments effected noteworthy economies. The mounting of the

[1] See p. 281.

3.7″ A.A. gun was a most difficult engineering job and could not be made much easier. But the Bofors was redesigned so that man-hours dropped from 2,420 to 1,500—a saving of 38 per cent.[1] As flashless propellants were progressively introduced there were further savings in barrel wear. As far as ammunition is concerned the only notable change was the introduction of shrapnel shell for both 3.7″ and 4.5″ calibres: this was called for because its employment by the 3″ 20 cwt. gun had shown it to have a marked effect on the morale of enemy crews, though it had small effect on the planes themselves.

The decision to employ rockets[2] was taken by the General Staff purely on production grounds.[3] It was considered that it was the only way to make good the deficiency in Bofors production without impinging on industrial capacity allocated to other guns; the first type approved for service was, in fact, a single projector which, it was felt, would fulfil this manufacturing requirement more readily than the twin or quadruple projector. Development and production of this very simple equipment was quickly put in hand. The operational ceiling of the 3″ rocket, 18,000 feet, was in fact much higher than that of the Bofors.

The rocket-ammunition itself proved more difficult when the designs, never before produced in bulk, were translated into the very large requirements of the summer and autumn of 1940. The tail, of light tubular construction, fitted at one end with stabilising fins and a Venturi and at the other end with a screwed ring to receive the shell, was deceptively simple to make: in attempting bulk manufacture some special features were overlooked with bad results. Manufacture of solventless cordite was still largely in the experimental field at Bishopton R.O.F. when the demand for quantity production was made. Thus the early days of bulk production were full of acutely urgent minor redesign and development work for the Controller of Projectile Development and the Departments of Research and Design. Later, multiple types of 3″ U.P. were designed—twin, nine and twenty barrel projectors coming into use. The intention of these multiple projectors was partly to supplement the 3.7″ deficiency.

Meanwhile the old feeling that the rocket was 'inaccurate' as well as purely wasteful was still prevalent in the authoritative departments controlled by the Director General of Artillery. As 'Z' batteries went into action rumour spread that the rockets were descending—as rockets traditionally do—only distinctly unspent,

[1] See p. 283.

[2] The security name 'U.P.' was dropped after 1942.

[3] But it also had attractions from the manpower point of view; a rocket battery needed 274 men to service 128 barrels; a 3.7″ A.A. battery needed 332 men to service 8 barrels; and the rocket battery could be, and was, serviced by comparatively untrained personnel, including Home Guards in home defence.

wrecking more damage than was reasonable here below. Such rumours were, in fact, without foundation. But, together with the demand for improved performance against low-flying attack, they stimulated research into a proximity fuze. This radio proximity fuze was developed during 1941, but development was slowed up by the move of the Air Defence Research and Development Establishment (formerly Air Defence Experimental Establishment) to Malvern and by delays in obtaining sites for recovery shoots. This work, however, proved to have a wider use. In 1943 the Army in North Africa expressed a demand for a proximity fuze for field artillery shells (more readily attained in the rocket than in ordinary A.A. shells, because of the slow acceleration) and the resulting radio proximity fuze was to be a vitally important step towards the use of radio proximity fuzes in A.A. artillery in the later stages of the war. The radio proximity fuze was developed mainly by the Air Defence Experimental Establishment (later Radar Research and Development Establishment) of the Ministry of Supply.[1]

Another device was also developed for use in rockets. This was a wire barrage intended for defence of airfields and other vital targets. The 'K' head was provided with an aerial mine instead of the normal H.E. filling and the main aim was to place considerable numbers of these mines in the path of aircraft, using the technique of predicted barrage. This development, which was closely supported by the Prime Minister (as indeed were all U.P. projects), was not put to considerable use as low level attacks did not develop after 1942 to any extent.[2]

The need for new equipments with a much greater performance followed on the Dunkirk crisis with astonishing speed. General Officer Commanding-in-Chief, A.A. Command (General Pile) made forthright requests for such developments during the summer and winter of 1940. In December the Air Staff gave the War Office an official estimate of the performance of future enemy planes. As far as altitude was concerned the figures communicated by the Air Ministry were alarming:

	Altitude in feet		
	Heavy Bombers	*Light Bombers*	*Fighters*
1941	25/30,000	30/35,000	35/38,000
1942	30/35,000	35/40,000	38/42,000
1943	Up to 45,000	Up to 45,000	Up to 48,000

[1] The first proposals to develop radio proximity fuzes working on a Doppler reflection from planes arose during discussions with the Projectile Development Establishment, War Office, in April 1940.

[2] Many other rocket developments fall outside the scope of this chapter—e.g. air-ground use and assisted take-off.

As early as October 1940 General Pile reported that high-flying enemy bombers were occasionally encountered up to 40,000 feet. To deal with these changes in the habits of the enemy bomber a new gun was clearly required, while the speed at which bombers were flying and the increases to be expected in speed, made existing prediction equipment seriously out-of-date. There was also a need, albeit not so urgent, for a new intermediate gun, to cover the gap between the Bofors and the heavy guns.

The first General Staff specification produced in December 1940, asked for a gun firing to a maximum height of 50,000 feet in preferably 30 seconds and not more than 45 seconds. For this high performance the Army would be prepared to accept a low rate of fire and barrel life. As a result of discussions between the War Office and the Ministry of Supply in January 1941 the specification was more concretely expressed as being for a maximum ceiling of 50,000 feet, time of flight of 30 seconds, and a rate of fire of 3 rounds in 20 seconds, including one round in the barrel. The Director of Artillery and his staff put forward a variety of solutions. The first was the existing naval 5.25″ gun, suitably 'hotted-up' with flashless propellant; the second was a 5.25″ gun lined down to fire a 4.5″ shell at a higher muzzle velocity than was possible in the existing gun; the third a similar lining down of the 5.25″ to fire a 3.7″ shell; and the fourth a 4.5″ A.A. barrel lined down to 3.7″. The estimated performance of such equipments was as follows:

	5·25″	4·5″/5·25″	3·7″/5·25″	3·7″/4·5″
Shell weight (lbs.) . .	80	55	28	28
Ceiling (feet) . .	52,000	55,000	54,000	52,000
Fuze ceiling . . . (30 secs.)*	44,000	46,000	46,000	45,000
Fuze ceiling . . . (40 secs.)*	50,000	52,000	52,000	50,000

* In both cases fuze ceiling estimated for Quadrant Elevation of 70°.

The heavier shell of the 5·25″ gun made it about three times as lethal as either of the 3·7″ projects and the General Staff accordingly decided for it, while requesting the 3·7″/4·5″ gun as a stop-gap measure. In April 1941 General Pile was told that the Admiralty had been requested to release from production between thirty and fifty of the 5·25″ twin equipments. Meanwhile, at the request of the Chiefs of Staff the Ministry was to investigate the possibility of making 500 twin mountings and 1,000 barrels. By May, however, the Chiefs of Staff had changed their policy; only four twin 5.25″ equipments were to be issued to A.A. Command for experimental use; a design of single 5.25″ mounting was to be pushed forward; and so was the 4.5″/3.7″ conversion. In fact, both the new and the stop-gap equipment encountered difficulties in production: the 5.25″ gun competed for capacity with the 3.7″ and the ammunition for the relined 4.5″/3.7″ held up the issue of the interim gun. As a result both equipments actually appeared in the field at much the same time, in 1943.

The story of the intermediate gun was far less happy. Officially it was required, as we have seen, to be effective at altitudes up to 10,000 feet, but behind this lay the desire to replace the 3″ 20 cwt. gun for altitudes above this. The suggestions put forward by the Director of Artillery were two-fold: on the one hand an adaptation of another naval gun, the 3 pdr., and on the other a new 6 pdr. It was calculated that these would have ceilings respectively of 15,600 feet and 19,500 feet (12 second fuze) and 17,600 feet and 22,100 feet (15 second fuze).[1] The advantage of the naval gun was that a predictor for it had already been designed by Colonel Kerrison; the attraction of the 6 pdr. was that it would be better suited to Field Force requirements for a highly mobile equipment, since its total weight was estimated at no more than about 6 tons. Both projects, it will be noted, had ceilings much greater than that specifically required, but this was perhaps connected with a prevailing view (expressed, for example, by Professor Blackett of A.A. Command in February 1941) that the future operational height of nine out of ten enemy bombers would not exceed 20,000 feet. This view was not officially shared by A.A. Command: that is clear from the decision to persevere with the heavy equipments we have just been discussing. But that the ceiling of 10,000 feet was felt to be on the low side is evident from the ultimate decision to proceed with the 6 pdr. equipment. This was, in any case, popular with General Pile and his staff for another reason: it offered much better chances of damaging the increasingly heavily armoured German planes. A new predictor was accordingly to be developed and in June 1941 a firm requirement for the 6 pdr. A.A. gun was expressed by the War Office. By December 1941, however, the Director of Artillery had developed a twin mounting and a three-wheeled carriage. The guns thus mounted were intended to be dual-purpose; they would fire H.E. shell with a delayed-action fuze as A.A. guns, and A.P. shot as anti-tank guns. In January 1942, General Pile complained vigorously that it had taken far too long to establish that 'a fully automatic 6 pdr. single was not a practical proposition'. In fact, the twin 6 pdr. proved a most unsatisfactory weapon and design reverted to a single mounting, which was not, however, finalised by the end of the war. This serious failure was to some extent compensated by the use of 20 mm. equipments. The first

[1] Quadrant elevation 70°.

of these was the Oerlikon. The Polsten, whose design has been already commented on,[1] was produced by the Chief Engineer Armaments Design, and a power operated twin mounting for the .5″ Browning heavy machine gun enabled that weapon also to be adapted to A.A. work.

Though rockets were useful for engaging intermediate targets, they were not found to be an answer to the sub-stratospheric bomber. By the use of a lighter shell the ceiling of the rocket could be raised from 18,000 to 25,000 feet but this increase in range, which was in any case inadequate, was estimated to involve a great diminution in both accuracy and lethality. As it was, the efficiency of the existing A.A. artillery was greatly increased by the development of ancillary equipment during 1941 and 1942. The prediction provided by G.L.I. was much improved in G.L.II and G.L.III[2] and besides these radar devices, the automatic fuze setter and the Molins loader for the 3.7″ gun were an appreciable help. These points were stressed in an important memorandum drawn up in the spring of 1942 by the Ballistics Committee of the Advisory Council on Scientific Research and Technical Development of the Ministry of Supply. Improved methods of radar control were also developed for use with searchlights (S.L.C.).

The concentration of development work into heavy guns with higher effective ceilings and into ancillary equipment to increase the effectiveness of all A.A. artillery was doubtless prudent. Yet the resumption by the enemy of intense air attack was to take a form which had not been foreseen, the use of pilotless aircraft. True, the likelihood of such attacks had been apparent as early as 1943, but it was reasonable to suppose that such aircraft would provide targets which the A.A. defences could engage with the very highest chances of success. Such anticipations were falsified, however, by the altitude at which the V.1 was employed. Flying at between 2,000 and 3,000 feet, the pilotless aircraft were too high for light guns and too low for heavy guns as far as existing G.L. and prediction equipment was concerned, while the mobile 3.7″ had not the requisite speed of traverse.[3] Searchlights were similarly handicapped. The one device which mitigated the effect of the V.1 attack was the radio proximity fuze.[4] For the rest, the situation was solved partly by the skilful tactics of Fighter Command and A.A. Command, who tried a variety of different forms of defence until the most efficient was discovered; partly by the immediate provision by United States

---

[1] See p. 267.

[2] See Chapter XV, Section (iii).

[3] See the despatch of General Sir Frederick A. Pile, 'The Anti-Aircraft Defence of the United Kingdom from 28th July 1939 to 15th April 1945', Supplement to the *London Gazette* of 16th December 1947 (No. 38149).

[4] See p. 293.

authorities of American G.L. of an improved type; and partly by the advance of Allied forces up the French coast.

The success of A.A. artillery during the war years as a whole was very largely to be accounted for in terms of the tactical employment of the weapons and their ancillary equipment (especially G.L.). This is, of course, to some extent true of all weapons. But in the case of A.A., enemy planes not only developed in themselves, but such development permitted techniques of evasion which had not been possible in the First World War or in the interwar years. The answer to this virtuosity on the part of the German Air Force could only be provided in part by the development of better equipment: the real answer was a similar virtuosity in the employment of the forces of A.A. and Fighter Commands. Perhaps this need, early foreseen, was the reason for the employment in A.D.G.B. of a large number of civilian scientists (the name of Professor Blackett has been mentioned above)[1] and the emergence in A.A. Command of the first 'operational research' in the Army. It may be mentioned as an illustration of the consequences for development work of such new scientific resources that the investigation into the comparative efficiency of rockets and heavy A.A. against unseen high level targets was undertaken by the Army Operational Research Group for the Scientific Advisory Council of the Ministry. With this aspect of the A.A. story we cannot here concern ourselves, but it is necessary to bear it in mind in turning to survey the results achieved by 1944 in a table comparable to that given for the state of equipment in the early days of the war.

A.A. Guns 1944

Gun						*Target (unloaded)*		
Type	*Total weight of equipment* (tons)	*Weight of shell* (lbs.)	*M/V* (f.p.s.)	*Effective ceiling* (ft.)	*r.p.m.*	*Type*	*Maximum ceiling* (ft.)	*Maximum speed* (m.p.h.)
Br. 3·7″/4·5″	[static]	28	3,400	45,000	6	Ju 86P	42,000	290
						Fw 200	28,000	240
5·25″	[static]	80	2,825	43,000	12	Do 217M	29,500	325
						He 129	29,500	275
3·7″	10·3	28	2,670	32,000	20	Ju 188	34,000	325
						He 177	32,000	305
Ger. 8.8 cm. (Flak 41)	8	20·7	3,280	35,000	15–20	Lancaster II	21,000	273
						Halifax II	21,000	253
15 cm.	[static]	88.6	3,450	40,000	6–8	Stirling II	22,000	263

[1] See p. 295.

It will be observed that the advance in British A.A. guns again corresponds with the advance in the performance of enemy bombers which, as we have seen, had been anticipated as early as 1940; moreover the superiority of German bombers to British bombers (from the viewpoint of avoiding land engagement) is also apparent, though it is important to recall that in the last years of the war the German A.A. guns needed their maximum performance to attack, not British bombers, but United States Liberators and Fortresses. In the last stages of the war the German defences were strained to an even greater extent than A.D.G.B. had been during the Battle of Britain. In the field, the improved 8.8 cm. German gun maintained its previous parity of performance with the 3.7″ (allowing lighter shell to balance greater range) but still managed to remain two tons lighter. If British heavy A.A. thus contrived to follow with some success the increased altitude of the target, in the field equipment there is no doubt that the advantage lay with the German gun. As for light A.A., Germany again had the advantage: the 5 cm. Flak 41 was a successful gun strictly comparable in intention to the abortive British 6 pdr.

A.A. design and development was thus faced throughout the war with the need to keep abreast, if not to keep ahead, of developments in German aircraft. So, of course, was German development in regard to the evolution of British planes. In fact, the revised 8.8 cm. Flak 41 made its appearance rather sooner than the 3.7″/4.5″ conversion or the 5.25″. It (like the older 15 cm.) was designed *ab initio* for land service, while both the British equipments were improvisations on existing weapons. But British defence against air attack, both at home and in the field army, was assisted by the provision of ancillary equipment, particularly radar devices, incomparably superior to that possessed by the enemy.[1] In that respect, as in the tactical handling of guns, rockets and other A.A. equipment, as well as in the performance of the fighter aircraft which were the main element in A.A. defence, Britain had no rival.

(iv)
A Note on Mortars

Mortars have no place in a story of A.A. weapons. But it so happened that the leap-frog game which had to be played with A.A. guns was to some extent paralleled in mortars and the experience of developing them was even more hand-to-mouth than was the case with A.A. guns. Indeed, far more was known about A.A. guns than was known

[1] See Ch. XV.

about mortars, for the A.A. gun was after all a gun. Its construction, ballistics and lethal possibilities were strictly analogous to other artillery pieces. It was the mutation of the target that caused the fluctuations in A.A. development policy.

True, mortars were far more used in the 1914–18 war than A.A. guns had been. The mortar is an infantryman's weapon and the bulk of the fighting in the First World War involved the sort of infantry engagement where the possession of localised and instantly realised artillery fire power in short-range actions was of great tactical value. The mortar, with its simple muzzle-loading action and relatively high H.E. content of bomb, was popular both in the trenches and at home, where it presented few manufacturing difficulties. Largely developed by Mr., later Sir, Wilfrid Stokes, the mortar consisted essentially of a 'drain-pipe' which projected an H.E. bomb for distances up to about 200 yards. In the years after 1918 the French officer, M. Edgar Brandt, carried the evolution of the weapon to a point where it could be employed by infantry, not only in trench warfare, but also in general mobile operations. This new type of mortar employment was generally adopted in all armies, but (at any rate as far as Britain was concerned) the extension of mortar practice was not accompanied by a corresponding knowledge of the ballistics of the weapon. Its external ballistics[1] are those of an unrotated projectile which, as velocity increases, tends to instability. Not much more was known of the internal ballistics; though it is clear that, for accurate results, the windage should be at a minimum, the bomb has to be inserted in the mortar so that it falls down the tube under gravity; unless there is some play it will not fall down freely, while the least fouling also acts as an impediment and results in misfires. A final group of problems arises from the vulnerability of the weapon to rain, which affects the efficiency of ignition.

No attempt was made in the interwar years to embark on a thorough long-term research into all the basic questions involved in mortar design, and development was concentrated on the production of two versions of the Stokes/Brandt type of weapon. The first of these was the 2″ mortar, which made its appearance during the last year of the First World War, but was made obsolete in 1919. A redesigned version (Mk. II) was then investigated and was introduced during rearmament. During 1938 and 1939 there were several attempts to improve this model, and by 1940 there were about a dozen marks, not all of which actually went into production.[2]

---

[1] External ballistics—the behaviour of the projectile after leaving the muzzle. Internal ballistics—behaviour within the barrel.

[2] Mk. III, a special tank mortar, is not here discussed; Mk. II* and Mk. II** incorporated some advantages of Mk. IV which only went as far as pilot production. Mk. V was not manufactured. Mk. VI and Mk. VII were further improved, but Mk. VI was not produced. Later production models were Mks. II***, VII** and VIII*.

The 3″ mortar was similar in design, but its larger calibre was intended to enable it to replace the 3.7″ howitzer as an infantry close-support weapon, a change which was decided on in 1932. These two weapons, the 2″ ranging just over 500 yards and the 3″ about 1,600 yards, were the standard infantry mortars at the outbreak of the Second World War.

The war saw both equipments heavily criticised, and, particularly during the campaigns in North Africa, demands for a greatly increased range began to come in. In particular the 3″ was regarded as inferior to the Italian 81 mm. mortar and the German 8 cm. weapon, both of which fired a bomb (of about 7½ lbs., as compared with the 10 lbs. of the British 3″ bomb) to much greater ranges, the German equipment to over 2,000 yards and the Italian to over 4,000 yards. The troops in fact experimented freely with German and Italian charges—and bombs—in British 3″ equipments, while desperate attempts were made at home to increase the performance of the weapon in a new design, once the War Office and the Director General of Artillery realised that the demand for greater range was not a transient freak of desert warfare. In retrospect it would no doubt have been wiser to start at once on the development of a new equipment. In 1941 and early in 1942 it seemed that modification of the 3″ mortar would produce a more rapid answer to the problem. As it was, a long series of investigations was needed to secure the strengthened base-plate which was a prerequisite of meeting the General Staff requirement for a range of not less than 3,000 yards. Eventually the Staff compromised at 2,750 yards which proved to be the maximum attainable range; greater range was certainly obtained in the field in the unorthodox ways referred to, but only with a loss of accuracy which the Director General of Artillery refused to sanction. The new mark of 3″ mortar (No. IV) involved a better sight and this was eventually designed by 1943. At the same time attempts were made to increase the range of the 2″ mortar. While various improvements were made in the equipment, it proved impossible to increase range without lightening the bomb. Despite its limitations the 2″ mortar was by no means unpopular with the troops. A lightened type was produced for paratroops (Mks. VII* and VIII). A similarly lightened version of the 3″ mortar (Mk. V) was designed to meet the requirements of Far Eastern warfare.

The Commander-in-Chief, Middle East, had asked in November 1941 for a mortar ranging 'in excess of 4,400 yards'. The satisfaction of this requirement was to be made by a new equipment, the 4.2″ mortar. This particular development originated as a chemical warfare requirement of the General Staff, expressed in March 1941, with an H.E. bomb as a subsidiary role, as well as for ranging purposes. When the need for a mortar with a range of over 4,000 yards was known in November 1941, the Director General of Artillery at once ordered an investigation of the Chemical Mortar, which had reached a satisfactory stage of development a month earlier. The design of a streamlined H.E. bomb (20 lb.) was quickly put in hand and was cleared by the spring of 1942. At this stage in the war, capacity for forging steel cases was strictly limited and a cast iron bomb had to be adopted. With this exception, subsequent development was small, consisting mainly in the adoption of extension plates for the base-plate, for use in muddy terrain, and in a wheeled design (development by Jowett Cars). The wheeled version solved two problems: the weight of the total equipment, which was too heavy for rapid manhandling, and the recoil on muddy terrain.

The upshot of this very haphazard development (and a more extended narrative would have to record a host of troubles not detailed here) was not altogether satisfactory. The war ended with British mortars very much better than they had been at the start, and the latest model of the 3″ mortar, officially rated at a range of 2,790 yards with its 10 lb. bomb was, no doubt, better than the 8 cm. German mortar, which had been stepped up likewise, but only to fire its 7½ lb. bomb to 2,625 yards. On the other hand in their 12 cm. mortar the Germans had developed an equipment which weighed less than the 4.2″, had a heavier bomb (35 lb. as against 20 lb.) and had a very much extended range (6,500 yards as against 4,100 yards).

The development of mortars, with repeated attempts to improve the performance of existing equipments, is thus markedly similar to the development of A.A. artillery. But a profounder understanding of mortar theory might have made the story a great deal more creditable; the designers of mortars had not the justification of the A.A. designers, that the target was developing, nor that experience in peace-time was hard to come by. Research had, in fact, been neglected and design paid the penalty. To that extent, as we shall see, mortars are somewhat parallel to tanks, which form the subject of the next chapter.

CHAPTER XIII

ARMOURED FIGHTING VEHICLES, TANK AND ANTI-TANK GUNS

(i)

Introductory

TANKS and their armament could be discussed fruitfully apart from anti-tank guns. This chapter is devoted to both topics because in fact British tank armament has been very closely connected with Anti-Tank Artillery. At any rate until 1942 the role of both tank and anti-tank gun was regarded as the same, i.e. to attack enemy armour. As a result, anti-tank performance was measured against enemy tank qualities and vice versa. Both anti-tank gun and tank have thus a constantly changing requirement to fulfil and are subject to a tempo of development which cuts them off from the equipments discussed in the two previous chapters. The Armoured Fighting Vehicle (to use its current technical name), is a comparative newcomer to warfare and, as the history of tank design which follows is scarcely intelligible without an understanding of the main engineering problems involved, a brief explanation must be attempted of the mechanics of tracked propulsion.

Long before the 'tank' was evolved, armies had given protection to vehicles by means of steel plate. Armoured trains existed before 1914 and in the early years of the First World War combatants on both sides employed motor vehicles which had been similarly protected. Originally the tracked vehicle was envisaged as affording a means of crossing rough country, shelled areas, trenches etc. as well as muddy terrain where a normal wheeled vehicle would have been immobilised.[1] Later, the great weight of armour itself suggested the inevitability of tracks, if mobility was to be achieved without constructing a very large and vulnerable target. In either case the function of the track was essentially the same: to provide in small space a moving and continuous surface equivalent to that which would be provided by a wheel of great diameter. The main difficulties in tank design arise entirely out of this basic problem: how to suspend, steer and power a mass of metal moving on two tracks. The suspension is critical because it has to provide a robust system

[1] See also *History of the Ministry of Munitions*, (H.M.S.O. 1920), Vol. XII, Pts. III and IV.

for dealing with the major shocks of cross-country employment, without being too rigid. Steering is critical because it can be achieved only by altering the alignment of the tracks ('bowing'), possible only for lighter vehicles and providing in any case only a wide circuit; or by reducing the tractive force in one track so that the vehicle is slewed round by the other, which at once reduces speed and imposes heavy loads on the engine unless the braking forces can be converted into additional energy for the 'free' track. The power unit's importance may be gauged, not only from the total load of men and metal, but also from the additional tasks involved in steering a tracked vehicle.

Something will be said in the following pages of these three main components, as well as of armour and armament. But it must be stressed that many other assemblies are involved in the A.F.V.—radio equipment, lighting units etc.—which need redesign if they are to survive in their new environment. Equally, the basic suspension, steering and power units can be broken down into a multitude of smaller items any one of which may be regarded as a separate problem. Little will be said of these smaller, though vital, elements in A.F.V. development, but it is essential to bear them in mind if simplification is not to result in distortion. It cannot be too strongly stressed that among military equipments the tracked and armoured vehicle had no antecedents prior to 1916, and that commercial tracked vehicles during the interwar years offered little experience relevant to the later evolution of the tank.

The absence of a long tradition of design in tanks, together with the complicated nature of the assembly, leads to a further background problem. This is the length of time needed in development and the danger that the equipment, which may have been adequate enough when originally envisaged, may prove obsolete by the time it finally gets into production. It is, of course, desirable that a quality requirement for any military store should be so framed that it is still valid by the time the store comes into service; but with tanks the possibilities of technical innovations and of novel tactical employment have been so great as to make this much more difficult of achievement than is the case with traditional artillery and small arms. Only two obvious ways present themselves for overcoming the difficulty. On the one hand, the requirement may be so framed that it covers all possible tactical roles, and allows of modifications to an existing 'common purpose' machine—somewhat like the Admiralty doctrine of the 'well-balanced ship'. On the other hand, it may sometimes be possible, particularly if the strategical commitments of the Army are firmly fixed, to forecast terrain, character of enemy armament, duration and extent of operations, in such a way that specialised vehicles may be prescribed with confidence.

Finally, it is clear that in a moving, armoured and armed unit, each of the elements in design may at any time appear as critically important. Yet each factor is related logically to the others. If speed is stressed it tends to involve lighter armour and armament; if armour is stressed it necessitates either a more powerful engine (and therefore a bigger tank) or a loss of speed; and if armament is to be increased, so must be the overall dimensions of the vehicle and the areas requiring armour. These elements have therefore to be balanced, and the following pages will show some of the concessions and compromises adopted from time to time. At the back of each solution lay, explicit or implicit, a conception of armoured warfare. What was the enemy of the tank—obstacles of terrain, artificial or otherwise? enemy armoured vehicles? or enemy anti-tank guns? Discussions of these tactical questions would naturally be out of place here, but changing military opinion on such problems will be reflected in changing military requirements and thus in the A.F.V's which we shall have to discuss.

(ii)
Prior to 1934

The tank was a British invention, designed to break the stalemate in trench warfare which had developed by 1915. The British equipments of the First World War were heavy, slow and only protected against small arms fire. As with other armaments at that time, detailed design was in the hands of industry, but the novelty of the concept and its origin in the Admiralty and the War Office ensured a strong official design organisation under the Superintendent of Design, ultimately under the Minister of Munitions.[1]

After the war British interest in tanks declined. For this there were many reasons. The Army was soon reduced to a handful of divisions, and included only one armoured brigade. Money was strictly rationed and the share allotted by the War Office to tank development was small. During the years 1927 to 1936 the sums available annually for tank development varied between £22,500 and £93,750—scarcely liberal when it is remembered that the manufacture of an experimental assembly might cost anything up to £30,000. This financial stringency often affected design in a less obvious way; it led to the trial of new components in obsolete

[1] A full and useful account of A.F.V. design in the First World War is given in the *History of the Ministry of Munitions*, Vol. XII, Part III.

vehicles, and thus unreliable results were sometimes obtained. In any case, 'mechanization' was unpopular with many senior as well as with some junior officers; the tank was regarded as a device for creating the conditions for mobile warfare rather than as a new manner of conducting mobile warfare itself. Thus while continental armies, and especially the German Army, as it was gradually recreated, concentrated much attention on tanks, such an interest by British soldiers was generally regarded as somewhat freakish and fanatic. To these background limitations were added others less compromising but still influential. Partly because of the tank's origin, partly because no other convenient parallels existed, the operational control and deployment of A.F.V's continued after 1918 to be regarded as analogous to sea warfare. 'Landships' and 'destroyers' were terms often applied to tanks, and the term 'cruiser' was (as we shall see) to have a long career; the almost total inappropriateness of these analogies needs little stressing. In addition, design was hampered by various restrictions on size and weight. The League of Nations convention limited weight to 16 tons and in any case the Royal Engineers bridging equipment had an even lower maximum.[1] Dimensions were further circumscribed by a firmly understood rule that British tanks must conform to standard loading gauge maxima on British railways, that is to say that they had to be transportable by rail without 'special working';[2] this meant in practice that 9 feet was a maximum width, which was more than enough for pre-war tanks, but was to be embarrassing later, as we shall see. But still more important than these factors, was the belief that the tank was essentially comparable to other heavy engineering projects, for it was this which prevented much fundamental research being undertaken and which saw the tank designers under the Superintendent of Design gradually dwindle in numbers and importance.

The resources for tank design before rearmament began may be stated simply enough: the small group under the Superintendent of Design and Messrs. Vickers-Armstrongs Ltd. Tanks were in this respect no different from other stores, except that the Superintendent of Design's departments in all other main armaments were inter-service, Navy, Army and Air Force being interested in small arms, and the Navy and the Army in all types of artillery. The Superintendent of Design's tank department was finally abolished in 1930; shortly before that (in 1928) a Directorate of Mechanization was established at the War Office and the Superintendent of Design's small staff of tank experts joined the Mechanization Board which advised the Director.[3] Under the Mechanization Board they no

[1] See p. 275.
[2] i.e. without working on one line while all traffic is stopped on the adjacent lines.
[3] See p. 237.

longer designed, however, but merely vetted, and suggested modifications to, the commercial designs submitted by outside firms—in fact by Messrs. Vickers-Armstrongs. This firm was one of the biggest heavy engineering firms in the country and (as we have seen) the last of the 'armament' firms.[1] Its tank design department was much stronger than the Superintendent of Design's which the War Office never considered (in the words of the Chief of the Imperial General Staff in 1937) as 'anything more than an addition to Vickers'; and a very close liaison between the War Office and the firm enabled the fullest use to be made of the firm's resources. Yet the War Office was no more than a customer, albeit a favoured one; it would ask for designs from Vickers but it could not do more than criticise them when they were forthcoming. Vickers produced tanks to sell to all comers: it merely happened that in the late 'twenties and 'thirties the international trade in armaments dwindled away and government orders were consequently more attractive, government specifications attended to more closely, than before. Moreover, the international tradition of this firm made it more active than official agencies in keeping abreast of foreign developments, while in Sir John Carden it had a designer of the very greatest ability.[2]

The resources for tank design which have been indicated above would have scarcely stood the strain of an active and progressive tank policy. The impediments to such a policy which we have indicated—size of army, reduced finance, relative distaste in the Army for mechanization—these were, after all, merely symptoms of official policy towards the role of the Army in a future war. The hypothesis upon which the War Office worked until rearmament was well advanced, as noted above,[3] placed a major European war fourth in the list of contingencies, a Colonial war remaining throughout the main task of the Army. This hypothetical assessment proved fatal for tank development. With the Army starved of money, with the lighter machines suitable for desert warfare and for shipping overseas available in relatively firm designs, there was small inducement to embark on an elaborate research into transmissions and power units. Moreover, the General Staff could plausibly argue that its policy could not be defined until prototypes were available for trial, and the Director of Artillery or the Director of Mechanization could feel that without strong General Staff policy directives ('specifications') such prototypes could never be produced. The Tank Brigade consisted of a battalion of light tanks (for reconnaissance) and three mixed battalions of light and medium (the medium,

---

[1] See p. 255.

[2] Sir John Carden's death in 1935 in an aeroplane accident was a serious blow to British tank design.

[3] See p. 240.

with a five-man crew and an anti-tank gun to be the offensive power of the brigade); this solitary formation was the sole consumer of such tanks as were produced, and a source of the 'user' opinion on the handful of new equipments.

Between 1924 and 1934, seven new projects were taken up by the War Office. With one exception,[1] these were all for medium or light vehicles, the equipment of the Armoured Brigade. Three of these were designs of light tank (A3, A4, A5) and three of medium (A2, A6, A7);[2] the Superintendent of Design's share in this was a design of light tank (A3) and a medium vehicle (A7) which were abandoned. The successful designs (A4, the 'Carden-Loyd' light tank, and A6, pilot of Medium Mk. III) were both designed by Vickers—though in close consultation with the Superintendent of Design. Yet even within the accepted categories of light and medium, only the light designs were regarded with equanimity: of the medium tanks in service in 1936 all but one or two were officially classified as obsolete; and the 'Carden-Loyd' was essentially a machine gun 'carrier', not a tank. It may be added that there was no significant design work taking place in armoured cars during this period: their functions were, in fact, largely usurped by the light tank. On the other hand, during the late 1920's considerable work was done on the Tracked 'Tankette' or 'Machine Gun Carrier', a specifically British development, which was to have (in the shape of the later 'Universal Carrier') a most successful future.

To compensate for the somewhat lethargic development of complete assemblies, considerable work was done in the field of component design and in armament. A process of welding hardened-steel plates was evolved by the Research Department at Woolwich between 1927 and 1930 which enabled a very much stronger tank to be built; and the quality of armour plate also improved in the 'thirties with the introduction of nickel-chromium-molybdenum steel. Standard commercial engines were in use during the period, but a start was made to master the steering problem. The development of a system of 'regenerative braking' was studied intensively from 1929 and was to culminate ultimately in the Merritt system.[3] It was towards the end of this period that the 2 pdr. tank gun was designed to replace the old 3 pdr. in medium tanks. Light tanks were armed with the Vickers machine gun. It will be recalled that anti-tank defence was still regarded as a small arms problem.[4]

---

[1] A 29 ton tank designed by Vickers in 1926—one pilot manufactured.
[2] Tank development numbers are listed in Appendix VII.
[3] See p. 315.
[4] See p. 259.

(iii)

1935-1940

The organisation sketched above lasted more or less unaltered during the rearmament period. The Master General of the Ordnance (later the Director General of Munitions Production) was the ultimate authority for A.F.V. design (and production). Below this level the Director of Mechanization, working through the Mechanization Board,[1] was in direct control of design. This, as we have seen, was by 1935 almost entirely in the hands of Vickers-Armstrongs. Design of tank and anti-tank guns was, of course, controlled by the Director of Artillery, also under the Master General of the Ordnance and his successor the Director General of Munitions Production. As rearmament gathered momentum the official structure of administration reflected the new situation: the very title of Director General of Munitions Production is evidence of the new spirit; but the transference of departments of design as well as of production to the new Ministry of Supply from the War Office in the autumn of 1939 is the main innovation of the period. With the formation of the new Ministry the Director General of Munitions Production devolved his responsibilities for tanks on to a new officer, the Director General of Tanks and Transport (October 1939), who in turn was in control of officers specially charged with responsibility for design and for production. Under this arrangement (which lasted till the crisis of the summer of 1940) a Controller of Mechanization Development was given the design hierarchy (Mechanization Board and so forth) hitherto under the Director of Mechanization. These changes, therefore, did little but elaborate the old 'M.G.O.' system of earlier days.[2] Their significance lies in the increasing emphasis placed on production as opposed to design. That this was a general preoccupation of the period will soon be evident.

The explanation of the concern for increased production is to be found partly in the expansion of the Army undertaken during rearmament, partly in the realisation that A.F.V's had been excessively neglected in earlier years. A fully mechanized army (in which cavalry units were to be 'tankised') became official Army policy by 1936. From May 1936 to May 1939 the financial requirement of the War Office tank programme multiplied threefold (from £12 millions to £36 millions); this was based on the steady increase in the number

---

[1] Divided into 'A' (tracked) and 'B' (wheeled) Committees; a similar division existed in the Mechanization Experimental Establishment.

[2] A note on the Special Vehicle Development Committee will be found below, p. 314.

of new divisions authorised, and was not actually expended, as the development of new designs did not keep pace with expansion. Both the numerical and the qualitative deficiencies as they appeared to the War Office at the start of rearmament are strikingly revealed in the following table which was compiled in 1936:

Tank Situation: Principal countries, 1936

	Light	*Medium*	*Heavy*
Britain	209(a)	166(b)	—
U.S.A.	135	19	—
Germany	1,600	300–400	50
France	500–600	180	Under trial
Italy	600–800	?	—
U.S.S.R.	2,000	4,000	—
Japan	450	150–200	—

(a) Two-thirds obsolete (b) 164 obsolete

The twin problems—lack of numbers, lack of adequate models—were completely understood by the highest officials at the War Office, by July 1936, when the Secretary of State for War expressed his concern to the Chief of the Imperial General Staff. And from then onwards they dominated the rearmament period. The resulting story is complicated, for production depended on design, and policy on design depended on the trial of experimental tanks, which could not be hastened without extending the meagre tank design resources of the country. In what follows policy has been dealt with first; but this is a somewhat overlogical approach if one remembers the dependence of policy on experiment. War Office requirements, it was stated in this same year 1936, could only be tentative 'until the first tanks are in the hands of troops'.

We have observed[1] that the only ways of securing up-to-date A.F.V's were to aim at 'common purpose' designs, or to forecast with accuracy the role of the tank at the time of its bulk production. On the whole it was possible for the British General Staff during much of the interwar period to follow the second of these two paths. The first commitment of the Army down to 1939 remained the 'colonial war' of the hypothesis already discussed.[2] This unquestionably accounts for the early concentration of attention on light tanks, which were suitable for employment in such conditions. As rearmament progressed, however, the light tank gradually declined in importance and heavier A.F.V's became the main aim of the General Staff. In October 1936 the War Office placed before the Cabinet a

[1] See p. 303.
[2] See p. 240.

statement of their quality programme:

(a) a 'light' tank for the cavalry;
(b) a 'cruiser' tank, more powerful than (a), for the light tank role in the Tank Brigade;
(c) a medium tank for the 'hitting' role in the Tank Brigade;
(d) an 'infantry' or assault tank.

Of these a satisfactory design existed only for the light tank; the remaining types were more or less projects. As the international situation deteriorated, as the likelihood of British participation in a major European war increased, the relative importance of these types changed, although the official hypothesis was not modified at first and there was still official uncertainty on Army commitments. The light and medium tanks gradually gave place to the cruiser and infantry projects. Comparison with continental A.F.V's became more pressing, and as a result the 8 mm. of armoured protection which had been accepted in the interwar period was abandoned: 14 mm. was regarded as essential as early as 1935; soon 30 mm. was a minimum standard for cruisers and 60 mm. for infantry tanks. These steps were a direct reflection of increases in both tank and anti-tank armament, and they produced immediate dilemmas in speed and manoeuvrability. By 1938 it was reported that, although the Germans were maintaining these qualities as primary in A.F.V's, the French had concentrated on defensive armour: 'all their machines can be classified as infantry tanks'. The strategical preoccupation of the two countries is plainly revealed in this divergence of policy; the middle way in Britain reflects a hesitancy due to the absence of a clear strategy at this time.

The medium tank, rechristened 'Battle-Cruiser', survived 1938 only as a remote research project and the drift to heavier vehicles was intensified since by this time the cruiser and the infantry types had become production possibilities, as we shall see. The outbreak of war in 1939 and the first winter of war in France gave every encouragement to a movement from light to heavy. The prophets of a repetition of the conditions of 1914–18 seemed to have been justified; the prime function of the A.F.V. was regarded as being the breaching of the Siegfried Line. Not only was the infantry tank more important at this stage than the cruiser; it was during the first months of war that several super-heavy equipments were investigated, which, with other detailed developments, will be considered shortly.

There was, it will be apparent, no overall statement of tank policy in this period by the General Staff, beyond the brief indication of types just mentioned. The many meetings which were held during 1937, 1938 and 1939 to define the 'tank programme' as a whole were concerned almost entirely with numbers and with the broad categories of 'cruisers' and 'infantry', with the 'insurance policy' of the 'interim' models which we shall shortly discuss. The position was clearly outlined in January 1939 by the Director General of Munitions Production: 'The difficulty about the tank has really been . . . to make up our minds exactly what we want . . . The type of tank you want depends very largely on the theatre of war in which it is expected to be used . . . Directly you begin to consider a war on a Western basis your tanks become a different business altogether from a war in Egypt.' The absence of such a general statement is due precisely to the conception of the tank as fulfilling a particular rather than a general role, and thus the General Staff's own uncertainties (merely part of a larger uncertainty in British foreign policy) were reflected in an ambiguity at the level of detailed design. Some basic notions there were, as, for instance, the insistent requirement that tanks should be able to 'fire on the move', but on the whole tank policy was hand-to-mouth. A policy of accepting what could be obtained was soon equally influential, and was indeed implicit in the absence of a general statement of detailed quality requirements. Some of these points will be illustrated from the consideration of the actual development work carried out prior to Dunkirk.

Light tanks may be dismissed fairly rapidly. The 'Light Mk. VI' was the logical development of the Vickers light tank adopted (as Mk. V) in 1935. Mk. VI was protected by 14 mm. of armour, and had medium and light machine guns coaxially mounted in a two-man turret.[1] At a weight of 5.25 tons Mk. VI had a speed of 32 m.p.h. But the armour was considered by users to be too light and dissatisfaction was equally expressed at the clutch-break steering and the absence of a gun. Subsequently Vickers undertook further light tank designs (Mk. VII and Mk. VIII) but by 1939 the cruiser was emerging as the prime vehicle for 'cavalry' units, while the armoured car was increasingly used in the reconnaissance role, and the light tank had little importance until airborne operations gave it a new lease of life.[2] The introduction of four-wheeled drive vehicles was largely responsible for the development of armoured scout cars and what were called 'Light tanks wheeled'; already by 1938 these projects were ousting the tracked vehicle in this role and contributing to its decline.

The demand for a cruiser tank coincided with, if it was not directly inspired by, the reports[3] of General Wavell's staff at the Red Army manoeuvres in September 1936,[4] where the British observers noted the successful employment by the Russians of the American Christie

[1] At first these were Vickers .5″ and .303″; later Besa 15 mm. and 7.92 mm.

[2] See pp. 341–342.

[3] See report in *The Times*, 22nd February 1945, p. 2, Col. 4, 'Nuffield Foresight'.

[4] The attention of the War Office had been drawn to the Christie tank before this by Mr. Oliver Bowden of Nuffields.

chassis. A.9, the first design produced to meet the staff requirement for a cruiser, had been designed by Sir John Carden of Vickers as a 'Woolworth medium tank' to a War Office specification of September 1934 for a close support tank. The machine was ultimately successful and was to lead, by way of A.10, to the later infantry tank Mk. III. But A.9 and A.10, prototypes of the later Cruisers Mk. I and Mk. II, were considered to have marked limitations, particularly in their speed of 25 and 20 m.p.h. respectively; nor was their design such that it could be mass-produced by non-armament firms. Hence they were regarded as stop-gaps and hopes for cruisers were pinned to the Christie chassis. This had (as subsequent investigations were to show) two important advantages—the power/weight ratio and the suspension. The engine was light and high powered, being based on the American Liberty aero-engine. The suspension consisted of a number of large wheels, each independently sprung. The engine had power enough to produce the higher speeds required of the 'cruiser' tank, while the large wheel movement and comparatively slow rotation of the wheels enabled the vehicle to withstand the shocks of fast movement. Trials of two American chassis were held in the winter of 1936–37; it was clear that much redesign would be necessary: '. . . in order to fit a 2 pdr. turret it is necessary to widen the machine by 5 or 6 inches and either to lengthen it 10 inches or raise its height 5 inches.' The development symbol A.13 was allocated to this work. Development was in the hands of Nuffield Mechanizations and Aero Ltd., and great difficulties were experienced. In part these were due to the additional weight of armour: a 14 mm. basis made the prototypes A.13 E1 and A.13 E2 over two tons heavier than the ten tons of the American original. In part the trouble lay with inherent defects in the main components. The engine needed a freshly designed carburetion and ignition system, and the air-cleaner, piping, fuel pump, cooling and starting arrangements had all to be redesigned—these items being later responsible for many further difficulties. Fresh designs of track, clutch and brakes had also to be prepared; the gear components proved too light; even the suspension units had to be fitted with hydraulic shock absorbers. This brief list only includes the major 'modifications'. But it was to be typical of the makeshift and piecemeal development of the rearmament period. The first production of what was later to be styled Cruiser Mk. III was delivered in December 1938.

The demand for 30 mm. of armour on cruisers was met in a variety of ways, none of them particularly satisfactory. Cruiser Mk. IV consisted of Cruiser Mk. III with additional armour. A fresh model (A.14) was developed by the Mechanization Board and L.M.S. Railway; this was to be powered by a Thornycroft engine, but it was soon dropped. Instead a modified version of Cruiser Mk. III was embarked upon: designed to have 30 mm. of armour (40 mm. on the turret), A.13 Mk. III was envisaged with a low hull, a flat engine and a front radiator. L.M.S. Railway detailed the general hull designs and produced a pilot; Henry Meadows undertook engine design and Nuffield Mechanizations and Aero the turret. The vehicle which emerged, Cruiser Mk. V or Covenanter, proved a great disappointment: deliveries began in the summer of 1940 but defects were so numerous and so fundamental that a large reworking programme had to be undertaken at once and in the event Covenanter never saw action as a combatant vehicle.[1] Finally, Nuffield Mechanizations and Aero embarked on a fresh design of Cruiser, A.15, which was intended as their own version of Covenanter. Crusader, as the new project was later called, had a more satisfactory career than Covenanter, but it will more properly be discussed at a later point.[2]

Infantry tanks were to have a somewhat more creditable history. In response to a request in 1936 for an assault or infantry tank Vickers produced an experimental model (A.11). This machine was powered by a Ford engine and had 60 mm. armoured protection. Originally the armament had been only a machine gun, but by the time the prototype was running a heavier main armament and a three-man turret were considered essential. As an interim measure A.11 was manufactured as Infantry Tank Mk. I, later known as Matilda. Parallel with this development an investigation was carried out into a similar vehicle, with a higher speed, a 2 pdr. gun and a three-man turret. Design of this, under the symbol A.12, was undertaken by the Mechanization Board and Vulcan Foundry and reached the mock-up stage in April 1937. Despite its many defects this A.F.V., Infantry Mk. II, known later as Matilda II or (after Infantry Mk. I was no longer in service) simply as Matilda, was the best of the tanks produced in the rearmament period. By the start of 1938 these two tanks were thus fairly clear, and Vickers were invited to manufacture Infantry Mk. II or a new vehicle based on their own cruiser model A.10. The firm opted for the latter and rapidly produced a design for a shortened, thickened-up version of A.10. Valentine, as the project was named by the firm, had a 2 pdr. and a coaxial Besa M.G., but it had only a two-man turret. The General Staff for a year postponed deciding whether this was adequate and it was only in the summer of 1939 that the argument of rapid production won the day and Valentine, or Infantry Mk. III, was accepted. It was to prove a successful and adaptable vehicle.

There remained the problem of the tank which could deal effectively with the major obstacles of the Western Front, a preoccupation

---

[1] See p. 337.
[2] See pp. 337–338.

which, as we have seen, was widely shared in the autumn and winter of 1939. One answer (A.20) was a revision of Infantry Mk. I, but longer, in order to secure improved trench-crossing and climbing qualities, and armed with a 6 pdr. Development was undertaken by the Mechanization Board and Harland and Wolff of Belfast, a pilot model being produced by June 1940, by which time the weight had risen from a planned 37½ tons to 43 tons, though it had proved impossible to accommodate a gun larger than the 2 pdr. Another answer was the super-heavy machines embarked on by the Special Vehicle Development Committee under Sir Albert Stern. The only one of the Committee's projects to reach a pilot model (T.O.G.2)[1] weighed 68 tons: its armament consisted of a 75 mm. gun in the front hull, a 2 pdr. in the turret, and machine guns mounted in sponsons. Both A.20 and T.O.G. were, however, swept aside by the crisis of the summer of 1940, though not before they had produced valuable experience and experimental data, particularly in component design.

The haste and anxiety of the period 1935–40 were, as can well be imagined, scarcely conducive to research and development of novel components. The tanks enumerated above were all so directly related one to another, that they form really two basic series rather than a number of separate types. This was, of course, intentional. The notion implicit in these developments was that known types would produce more reliable progeny than completely new designs, and would do so more quickly. Yet modification was always extensive and often new wine had to be poured into old bottles. In the event considerable work had to be done in the field of components. Of armour plate little need be said. Though various technical difficulties were involved in the increases of armour from 8 mm. to 14 mm., and 30 mm. and (for infantry tanks) 60 mm., the chief problem investigated was the relative advantages of homogeneous machinable quality armour and face-hardened plates, the latter being more effective in resisting capped shot. In fact, homogeneous armour was finally adopted, largely for manufacturing reasons. Steel for tracks also occasioned much research before a manganese steel developed by Hadfields proved adequate. The main development in suspensions was the introduction of the Christie system, but the use of rubber tyres in the Vickers 'slow-motion' suspension employed on Cruisers Mks. I and II and applied to Valentine should also be mentioned. Apart from the Liberty aero-engine, also in Cruisers Mks. I and II, all the tanks we have discussed were powered by normal commercial engines with the exception of Covenanter.

---

[1] The Old Gang.

For this vehicle Meadows designed the 'D.A.V.', with twelve horizontally opposed cylinders. This suffered from many faults which were only being overcome when Covenanter was obsolete; though a good deal of the trouble arose from Covenanter's main fault—a defective cooling system.[1] Two important developments were undertaken in transmission and steering. The regenerative braking system designed by Mr. Merritt was applied first in 1938–39 to an experimental cruiser A.16, and A.20 was designed to incorporate a Merritt-Brown gear box. T.O.G. vehicles sought to convert braking energy into tractive power by electrical devices in an exceedingly ingenious way, though one which needed a great deal of bulky equipment—a factor which proved disadvantageous compared with the purely mechanical principles involved in the Merritt-Maybach and Merritt-Brown designs.

Tank armament and anti-tank guns must be considered together, and the development of the 2 pdr. and 6 pdr. will show why. The 2 pdr. was first designed as a tank gun, to replace the obsolete 3 pdr. as the main armament of 'medium' tanks. It was adopted for A.T. artillery in 1934 when the General Staff realised that 'apparently all Continental armies were deciding on light guns firing shell for anti-tank defence'. In October 1934 the Director of Artillery informed the Staff that the 2 pdr. would be satisfactory; it would probably penetrate 25 mm. armour plate at a range of 1,000 yards. While some influential members of the General Staff considered so heavy an equipment undesirable, it was admitted to be unavoidable; curiously enough the debate hinged on the size of bursting charge in the shell; as yet solid A.P. shot was not designed, though this change was made in 1938 in order to improve penetrative performance. The A.T. design work was undertaken 'competitively' by the Superintendent of Design and Vickers. In July 1936, 'owing to the political situation', and because deliveries could be made fairly quickly, a limited number of the Vickers' design were ordered, but the Superintendent of Design's design was approved for the future, on grounds of ease of manufacture, inspection and handling. The carriage was designed for all-round traverse. Since the 2 pdr. tank gun was in existence before the tanks for which it was to be employed, no major difficulties were experienced with the tank mounting. The adoption of a 2 pdr. for both tank and anti-tank use was made in January 1935. For tanks in the role of close support for infantry a 3″ howitzer was developed to be fitted into the 2 pdr. mounting.

The thickness of armour was steadily rising during the ensuing period: by 1938 30 mm. armour was mounted by British cruisers and

---

[1] It should be noted that the General Staff in this period preferred oil to petrol engines in tanks, both on grounds of fire risk and economy in fuel. No heavy-duty oil engine of adequate power for tanks heavier than Valentine was available.

60 mm. by infantry tanks; these advances were not confined to Britain and there was clearly a case for a heavier A.T. gun. Working this time not from the needs of tanks but from those of A.T. equipments the Director of Artillery in 1938 initiated design of a 6 pdr. A.T. equipment. From the start design took account of possible employment of the gun in tanks, but no General Staff interest was expressed in either project until after the outbreak of war. In mid-September 1939 the War Office called for 'a heavier A.T. gun for the Artillery' which 'should be such as to ensure penetration of the thickest armour likely to be met in the next four or five years'. In January the General Staff accepted the performance of the 6 pdr. perforating 70 mm. 'with the proviso that if possible . . . the range should be something over 500 yards'. The Director of Artillery was unable to give this assurance and asked the Ordnance Board for solutions for 80 mm., 90 mm. and 100 mm. The Board recommended a 20 lb. shot of 3.45″ calibre which would have involved a gun not dissimilar to the 3.7″ A.A. gun and the General Staff dropped their request in March 1940, the 6 pdr. being accepted as a general A.T. equipment to replace the 2 pdr. The first attempt to incorporate the new gun in tanks was made with the projected A.20, where it was found to have too long a barrel; we shall have occasion to notice other attempts in the post-Dunkirk period.

Of the vehicles we have been considering only a few were available for service in the first French campaign in 1940: Matilda I, Cruiser Mk. I and the various types of Light Tank Mk. VI. Hasty as their development had been owing to the misplaced strategical hypothesis, lack of funds and reduced design resources, these tanks were not ill-matched against the German A.F.V's of the period, Pz.Kw.I, II and III.[1] Matilda I had heavier armour (75 mm.) than Pz.Kw.III (30 mm.), which was essentially a cruiser tank, and thus better protected than Cruiser Mk. I (14 mm.). As far as armament was concerned the 2 pdr. was superior to the 37 mm. gun which was the standard German tank gun at that time. Where the German vehicles had a distinct advantage (except over Light Tank Mk. VI) was in their reliability from a mechanical point of view: both Matilda I and Cruiser Mk. I frequently broke down—faults intensified by a lack of spare parts.[2] But broadly speaking the main British deficiency of the spring of 1940 was in quantity, not quality. Much the same is true of anti-tank guns. As yet the Boys Anti-Tank gun[3] and the ·303″ M.G. could penetrate the armour of Pz.Kw.I and II

---

[1] *Royal United Service Institution Journal*, Vol. XCI, No. 561, February 1946, 'Tank and Anti-Tank', by Brigadier R. M. P. Carver, C.B.E., D.S.O. M.C.

[2] These mechanical failures would probably have been much greater if tank crews had not been better trained mechanically than they were to be in post-Dunkirk tank units. See p. 363.

[3] See p. 259.

at ranges under 400 yards. The 2 pdr. and the 37 mm. gun were more or less identical: they were effective against 30 mm. of armour at about 500 yards and were effective against 14 mm. at twice that range; it was here that Matilda I's 75 mm. protection was valuable. But there was a shortage of A.T. 2 pdrs.; and there was a shortage of A.P. shot.[1]

A very brief mention must be made of other A.F.V's of the period. Apart from a few 6-wheeled vehicles (Rolls-Royce, Lanchester and Crossley) dating from the early 1920's, the Army had in the rearmament period only an adaptation of the standard 4-wheeled Morris 15 cwt. truck: without turret and intended for reconnaissance, the vehicle had mountings for Bren gun and A.T. rifle. This adaptation was designed by the Superintendent of Design, and, while it did good service with the B.E.F., it was essentially a stop-gap type. However, the Daimler scout car, developed by the Mechanization Board in co-operation with B.S.A. and Daimler proved a more lasting solution to the reconnaissance problem and production was beginning in 1939. The requirement for an armoured car, a 'Light tank wheeled' was only partly met by the Guy light tank, the only vehicle adopted for this role at the time; while armour and armament (14 mm., two machine guns—.5″ and .303″, or 7.92 mm. and 15 mm. Besa) were generally acceptable, vehicle performance was regarded as unsatisfactory. On the other hand an exceptionally sound design of 'Bren Carrier' or 'Universal Carrier' was developed by 1939. This largely superseded a variety of tracked carriers developed or contemplated during the early rearmament period for specialised roles with infantry and 'cavalry' units, and though the 'Universal' was not available in time for service in France, it may be counted the most successful tracked vehicle of the rearmament period.

However tentative and hesitant the A.F.V. designs of the years 1935–40 may appear, they represent a great intensification of effort compared with the preceding decade. The multiplication of design work nevertheless coincided, as we have seen, with the closing down of the official design department for A.F.V's under the Superintendent of Design (which, in effect, meant the restriction of the Superintendent of Design's participation in tank design to the 'fighting portion of the machine' rather than the chassis). What, then, were the tank design resources available and how were they extended?

---

[1] Absolute comparisons of A.T. equipments are misleading, as they were designed for specific tactical employment: the 2 pdr., for instance, was intended to be concealed and used at relatively short range. Designs of A.P. shot were available by the spring of 1939, but there were manufacturing difficulties.

The most important source of design was of course Vickers. Responsible for all the light tanks we have considered, for Cruiser Mk. I and Cruiser Mk. II, for Infantry Mk. I and Infantry Mk. III (Matilda I and Valentine), as well as for the basic designs which culminated in the Universal Carrier, Vickers had an overwhelmingly preponderant influence on tank development. This was due to their possession of a strong and independent tank design department, and to their long experience of heavy engineering in the armament field. The vehicles they designed were in every sense their own: user criticism and War Office 'specification' influenced the details of design, but in no sense controlled its execution. Moreover the firm's designs were intended for manufacture in their own factories, and there was thus an understanding that production problems were fully dealt with: were, so to speak, an internal matter which the Director of Mechanization could safely leave alone. Yet the rearmament requirements of even the modestly expanded army of 1936–38 were clearly beyond the manufacturing resources of Vickers; on the development side the necessity of producing firm designs over a wide range of vehicles involved a hunt for new 'design capacity', while as soon as large orders were involved which exceeded Vickers' productive capacity, the whole question of ease of manufacture became an integral problem of tank design. Vickers' designs were frequently of a kind which involved industrial skills and techniques not possessed by the engineering firms who were now to make tanks. There were thus two problems: how to obtain new design resources and how to ensure that designs should be readily manufactured. In the rearmament period we may discern the tendency to treat these two problems as one problem, which was to be characteristic of the post-Dunkirk years. If design were put into the hands of the firm which was to manufacture, would not the difficulty sort itself out? Design resources would be provided voluntarily by firms who were assured of later production orders, and they would naturally develop models compatible with their manufacturing experience and plant.

Yet, as described elsewhere,[1] rearmament was undertaken within the general government ruling that the recovery from the slump was not to be upset: normal production was not to be interfered with. The War Office was in the straight-jacket of what the Master General of the Ordnance in 1936 called the 'business-as-usual procedure'. Acceleration of design and production could, he said, only be achieved if 'the firms selected . . . put their backs into the execution of work entirely new to them'; if 'government work' were 'given priority'; if 'tank production' were 'given priority over other government work'. These steps were not taken and, as a result, the

[1] M. M. Postan, *British War Production* (H.M.S.O. 1952), Ch. II.

orders which began to flow from 1936 onwards went, on the whole, to firms with idle capacity, and it is hardly surprising therefore that the design resources of firms which found it difficult to survive the economic stresses of the early 1930's were often fairly tenuous. In November 1936 Vulcan Foundry were given the job of preparing designs for Matilda II. From then until May 1937 they employed only two draughtsmen on this complicated and entirely unfamiliar work: six months later the number had only risen to eight. When in 1937 the firm was asked to design a new medium tank, their representative replied that only after design on Matilda was completed would the firm have 'a small party of skilled designers', and he added that 'it was almost impossible to obtain more designing [*sic*] staff under present conditions'. In November 1939 Harland and Wolff were given the design of the projected infantry tank A.20 on the grounds that they were 'the only possible firm . . . with half-a-million pounds' worth of suitable machinery not being used': the firm was able to produce only 'three or four draughtsmen'. One organisation, it is true, was created intentionally to supply another specialist armament firm: Nuffield Mechanizations and Aero Ltd.[1] But the new firm suffered severely from its origin in the light engineering of the the motor industry, a type of enterprise which (as already noted above[2]) was notoriously poor in genuine design resources.

That despite these limitations the firms new to tank design produced vehicles which were capable of combatant employment is a tribute to their pertinacity and ingenuity. It is equally a tribute to the liaison established with the Director of Mechanization and the Mechanization Board. For, while it is true that the last 'official' tank design appeared in 1930, the 'official' element in the tanks produced by firms newly introduced to tank design must be stressed. Matilda II, for example, was in every sense a joint undertaking by Vulcan Foundry and the Mechanization Board. A.20 was similarly developed jointly by the Board and Harland and Wolff. Cruiser Mk. V or Covenanter was equally a collaborative effort: the Mechanization Board sketched out the general scheme and supervised the detailed design undertaken by L.M.S. Railway, Meadows and Nuffield Mechanizations and Aero.[3] But Nuffield Mechanizations and Aero who developed Cruisers Mks. III, IV and VI (Crusader) were more independent from the start. The proper place for a discussion of the somewhat unusual features of the Nuffield Scheme is the volume dealing with the expansion of industrial war

---

[1] William Hornby, *Factories and Plant* (H.M.S.O. 1958), pp. 183–190.
[2] See p. 276 on motor transport.
[3] See p. 313.

potential.[1] Here it may be noted that it was intended that the development of the Christie chassis should be in the hands of a 'single licensee', who would acquire the necessary patents and manufacturing rights. In fact, as noted above, the development of the Christie chassis with Cruiser Mks. III, IV and VI proved long and disappointing.[2] One is forced to the conclusion that this was by no means entirely due to giving the project to a firm not merely unfamiliar with tanks but also not experienced in heavy engineering; it was as much the absence of a strong official control. The Mechanization Board had no means of determining upon what lines Nuffield Mechanizations and Aero should proceed: the firm and the Board both proceeded on hand-to-mouth lines, but the result was the more dangerous since at no point was the necessity for basic redesign accepted. Indeed the notion that a reliable unit could be produced by combining a number of components of known reliability was generally adopted in the rush conditions of rearmament and applied equally to many of the Vickers' models. But Vickers' tanks were genealogically connected and the firm was adept at the redesign of existing types. When the same approach was employed by less skilled designers it led to Covenanter, which was incapable of fighting, and Crusader, which was made battleworthy with the very greatest difficulty, as we shall see.

Looking back on the early days of rearmament in November 1939 the Controller of Mechanization Development said that 'the trade did not take any interest in design unless they were given orders'. The need for A.F.V's was, of course, very urgent and the placing of small orders for 'interim models' not only gave the manufacturer some certainty in planning future production, it also gave the Army some tanks—even if they were faulty. Beyond doubt it also vastly increased the tank designing resources of the country as a whole. But it had serious weaknesses. It placed too much discrimination in the hands of the firm; and it led to an uncritical reliance on the 'drawing-board order'. The firms employed on the tank programme could not, of course, be compelled to undertake any particular project. It is, however, odd that Cruiser Mk. IV was manufactured by Nuffield Mechanizations and Aero as an alternative to the radical redesign of Cruiser Mk. III which was what the Mechanization Board wanted; and the design of Cruiser Mk. VI or Crusader was again due to the firm's preference for a design of their own model rather than manufacture of Cruiser Mk. V. In much the same way, when Vickers were invited early in 1938 either to manufacture Infantry Mk. II or redesign their cruiser model (A.10 or Cruiser

[1] Hornby, *op. cit.*, pp. 183–190.
[2] See p. 312.

Mk. II) they opted for the second alternative and produced Valentine. These decisions were based on production arguments, in the last resort. It was production, too, which led to the drawing-board order, first employed in the case of Covenanter, and soon copied in the cases of Crusader and A.20. The drawing-board order, intended to accelerate production and eliminate the gap between design and deliveries, will come to our notice in a later page.[1]

To summarise the position as it was during May 1940, when the German advance began which was to lead to the evacuation of the B.E.F. from France, we may note three points. First, in quality the tanks in service were about the same as their German opposite numbers, but no plans existed for future types of increased performance apart from A.20, the heavy infantry tank designed for the Siegfried Line. Second, design resources had been increased and to Vickers could now be added the individually smaller but cumulatively significant design departments of Vulcan Foundry, L.M.S. Railway, Mechanizations and Aero (previously Nuffield Mechanizations and Aero), Harland and Wolff. Third, production urgencies had led to 'drawing-board orders' and a general feeling that numbers must be obtained at all costs. By April 1940 there was no resistance from the General Staff or Ministry of Supply to a conclusion of the War Cabinet committee dealing with the co-ordination of defence: the tank programme 'must not be interfered with either by the incorporation of improvements to the approved types, or by the production of newer models'.

(iv)

1940-1945

The astounding policy revealed in the quotation at the end of the previous paragraph was made before the crisis of 1940. Within two months the B.E.F. was shorn of its small supplies of A.F.V's and Britain was committed to furnishing the equipment of a vastly bigger army. The call for increased production was even greater after the fall of France than it had been before. Yet if the decision to freeze types as they were in the spring of 1940 had been adhered to it would have gone far to losing the war. The central and later years of the war which we have now to consider in fact witness first, an intensification of the cry for output regardless of quality, and second, a period of steady insistence on the absolute priority of quality over quantity. These two moods, the first of short duration,

[1] See pp. 334–335.

the second, lasting from 1942 to the end of the Second World War, were reflected in every aspect of A.F.V. and anti-tank gun design—General Staff policy, organisation, design resources. There was, moreover, an ever-quickening public interest in A.F.V's. For a time there was also much parliamentary concern and the matters to be discussed below may be illustrated from a number of accessible published sources.[1] For this reason, as well as to reduce the story of war-time tank development to manageable proportions, it has been thought advisable in what follows to lay most stress on the critical period 1941–42 when quality replaced quantity as the main factor in determining policy.

'The best was the enemy of the good', was the advice of the Air Minister to the War Office as early as April 1939: 'it seemed better to have an inferior tank rather than no tank at all'. Before Dunkirk, however, it had been deliberate policy to sacrifice future improvements to present production. The labelling of so many types as 'interim' indicated that hope lay in the future. After the summer of 1940 a more intransigent attitude for a time prevailed. 'At this stage in tank production', wrote the Prime Minister in November 1940, 'numbers count above everything else. It is better to have any serviceable tank than none at all'. The precise meaning of 'serviceable' was somewhat ambiguous, as events were to prove. 'Serviceability' as a criterion was to lead to an insistence on 'reliability' which in the end was to replace quantitative values. But that was not till after the summer of 1941, when the danger of invasion was at last over, and when, in any case, North African experience had demonstrated the absolutely vital need for mechanical efficiency in A.F.V's. By then the main weight of German military strength, including German armour, was turned against Russia, and the United States had entered the war. Both of these events had a direct influence on tank policy in Britain, for Russia was for long supplied with British A.F.V's and the co-ordination of British and United States tank design and production policy had to be worked out in order to ensure the efficient employment of industrial resources. Though the first military task, the eviction of German forces from North Africa, took many months to accomplish, from 1942 it was clear that the final campaign would be an assault on the German-held continent. The North African desert had been a peculiar terrain, imposing on A.F.V's the strain of lengthy approach marches,

---

[1] Especially the reports (originally made in 1942 and 1944) of the Select Committee on National Expenditure printed as Cmd. 6865, *War-time Tank Production* (1946). Among several well-informed articles in periodicals may be mentioned anonymous contributions to the *Economist*, Vol. CLI, No. 5390, 14th December 1946, pp. 942–943, 'British and German Tanks', and *The Times*, 26th July 1950, p. 7, 'Tanks in Korea'. See also *Royal United Service Institution Journal*, Vol. XCI, No. 561, February 1946, Tank and Anti-Tank, by Brigadier R. M. P. Carver, C.B.E., D.S.O., M.C.

sandy conditions and great heat. The terrain of Italy and of France was different and the changing tactics of A.F.V's were reflected to some extent in design requirements.

The battles fought in France in 1940 upset the widely held theory that 'we were back where we were in 1914'. Support of infantry was apparently not the principal and certainly not the only function of an army's armoured formations; ability to surmount formidable obstacles and cross 'shelled areas' was no longer a prime requirement in an A.F.V. As early as June 1940 it was stated that the General Staff had agreed 'that future design of tanks need no longer be hampered by attempts to get a big trench-crossing performance'. Of the three main attributes of a tank—speed, armour, armament—it was the first two which acquired importance after Dunkirk: tanks had to be fast and well armoured. The results of this were not merely to change Army demands from a majority of infantry tanks to a majority of cruisers, but also to lead to the comparatively fast speed of the new infantry model (A.22 or Churchill) and the heavy armour of the new cruiser (A.27). This revolution in doctrine was hastened by the knowledge that conditions in the desert, the only field of major armoured engagement envisaged in the autumn of 1940 (apart from home defence), would favour the tactical employment of armoured striking forces. If any historical parallel was relevant, we were back where we were in 1936—the hypothesis of the 'Colonial war' was more appropriate, so far as geographical environment was concerned, than could have seemed possible at any point between 1937 and May 1940. But instead of the fast light tanks of the 1930's, the need was for fast tanks with armoured protection which rose from 30 mm. to 50 mm., involving a great increase in total weight.

This stressing of armour thickness was justified 'in France on a small scale and has again been demonstrated in the Middle East', it was stated in January 1941. Matilda II, limited in fire power, manoeuvrability and mechanical reliability, survived to fight again another day precisely because of its heavy armour. It is thus understandable that when the War Office in January 1941 drew up a list of 'some factors for consideration in future tank design', armour came first, then armament, and then 'simplicity of operation'. In May 1941, the Tank Parliament[1] was informed that insistence on speed and the addition of thicker armour were the two most troublesome pre-requisites in tank design. To some extent (as subsequent engine difficulties in Crusader and Cromwell were to show)[2] they were incompatible. But in the period 1940–41 the

---

[1] See p. 245.
[2] See pp. 343–344.

urgent call for numbers obscured this and mechanical difficulties, which were sometimes implicit in the specified qualities of the vehicle, were referred to increasingly under the rubric 'reliability'. Thus in the list of 'factors' mentioned above 'reliability' follows armour, armament and simplicity of operation as a desirable *quality* in a tank. This was the Prime Minister's criterion of 'serviceability' in another guise and that its oddness was not apparent to anyone at the time is the best possible evidence that quantity considerations had clouded quality criteria: no one ever specified that an artillery weapon, an aeroplane or a battleship should be mechanically 'reliable'. This notion of 'reliability' indeed survived the crisis of 1940–41 to become the main battle-cry of the later period, when quality was regarded as more important than quantity. During the summer and autumn of 1941 the changed attitude is revealed in various specific cases. In August, for instance, 'reliability' was stated by the War Office to be the most important requirement in the new Churchill tank. By January 1942 the General Staff applied the new criterion to all A.F.V's. 'In view of Middle East reports', General Weeks informed the Tank Board,[1] 'reliability must be considered more important than numbers'. Six months later the Staff were even more explicit. In August 1942 the Tank Board were informed that the 'qualities of a tank' should be put in the following order:

(1) Reliability;
(2) Armament;
(3) Speed;
(4) Radius of action;
(5) Armour.

By September 1942 the General Staff issued the following 'order of priority of requirements in design':

(1) Reliability;
(2) Gun;
(3) Speed;
(4) Endurance;
(5) Armour;
(6) Fighting compartment.

It is clear from these statements that 'reliability' and 'quality' were almost synonymous terms. The Army required tanks which would not break down.

It will also be clear from what has been said that 'armament' had taken precedence of 'armour' and 'speed' in the Army's requirements in A.F.V's. This was a direct consequence of the fighting in North Africa, and had repercussions on General Staff policy for

---

[1] See pp. 331–332.

both tanks and anti-tank artillery. The enemy increased the armoured protection on his tanks and he also employed tank guns of ever-increasing calibre: 5.0 cm. short gun, 5.0 c.m. long, 7.5 cm. short, 7.5 cm. long; in the anti-tank role the 8.8 cm. A.A./A.T. gun soon appeared, for long the best A.T. equipment in the field. We have noted above that the General Staff had expressed a demand for the 6 pdr. gun, designs of which were available;[1] soon steps were taken to improve the design of this gun and of the 2 pdr., as well as to improve the ammunition. These and other steps are described below,[2] where the development of the 17 pdr. A.T. gun, from the spring of 1941 onwards, is also discussed. The 6 pdr. and later the 17 pdr. were from the start envisaged as tank guns as well as anti-tank equipment. Hence the General Staff insistence on 'armament' involved the employment of the heavier calibre weapons in British A.F.V's: 6 pdr. tanks were the principal obsession of 1941–42, just as 17 pdr. tanks were of the later stages of the war. The A.T. equipments, as such, presented few difficulties, but tank mountings raised endless problems, to be considered later. The mere question of increasing calibre was, however, not the most significant aspect of the armament debate which developed during 1942, as far as A.F.V. policy was concerned, for the question was no longer envisaged as a simple competition between penetrative performance of A.P. shot and thickness of enemy armour. In fact, by the end of 1942 it was accepted that the tank and the anti-tank gun had fundamentally different tasks.

The North African campaigns from 1940 to 1942 had shown that armour was seldom pitted against armour. German tactics in advance were to bring tanks within range of the defence and, with flanks protected by A.T. guns, to open fire. The desert did not lend itself to easy concealment, and the 2 pdr. was ineffective at the ranges at which it could be employed, while being highly vulnerable to the H.E. shell which German tanks carried in equal proportions to A.P. Furthermore it was the experience of both sides that in making and exploiting a break-through normal targets for tanks were soft: infantry, motor transport, artillery crews. In brief, the main obstacle to the tank was the A.T. gun. In support of infantry, A.F.V's again needed H.E. rather than A.P. On these points user opinion crystallized during the winter of 1941–42, and a stream of requests for H.E. shell for tanks was the result.[3] It was for these reasons that

---

[1] See p. 316.

[2] See pp. 345–346.

[3] At the same time a request was made for A.P. shot with a small bursting charge—a variety of ammunition provided by the Germans which it was at first thought was responsible for epidemic fires in British A.F.V's during 1941. This demand was resisted by the Director General of Artillery, properly as events were to prove, since the fires were found to be due to faulty stowage of ammunition; the Germans progressively reduced the H.E. content of their A.P. H.E.

the 75 mm. gun in American tanks was popular with the troops; although its A.P. shot was inferior to the 6 pdr., it was provided with H.E. shell and, it was felt in the Army, its A.P. performance was adequate. The 75 mm. was, in fact, a dual-purpose gun and led to requests for precisely such a weapon in British A.F.V's. More detached consideration than was possible to the fighting soldier, suggested that a wholesale conversion to H.E. in tanks might be improvident. It was not certain till the summer of 1943 that long-range engagement of A.T. guns by tanks would be as feasible in the closer terrain of the European continent as it had been in the desert. Further, no dual-purpose gun could have a first-class performance in either of its roles: armour penetration demands high velocity and low trajectory; explosive lethality involves plunging fire. If British A.F.V's were to be issued with a gun of good H.E. performance might this not provoke the Germans into seeking tank versus tank engagements? If good A.P. performance were neglected might not the A.F.V. be inhibited from exercising its more *frequent*, but not more *important* task, the attack of soft targets? Finally, as German A.T. guns increased in calibre they were increasingly given mobile and armoured mountings, so that the A.F.V. in defending itself against S.P. (self-propelled) A.T. gun might in practice need armour penetration in its weapons. This summary of the tactical questions doubtless simplifies the actual arguments, fragmentary and partisan, which were bandied about at every level from technical staffs with the Field Forces to Cabinet Committees. The General Staff was slow to commit itself. As late as September 1942 the Staff (in the first comprehensive statement in tank policy to be made during the war) laid down their requirement as:

> an efficient weapon against enemy armour [which] must, therefore, be a first-class anti-tank weapon of the 6 pdr. or heavier type modernised to its highest performance, and one which can outclass enemy tanks of corresponding type. In addition, it should be as efficient a weapon as possible against personnel and lorries.

This policy—a dual-purpose gun with armour penetration as its main task—was, however, completely reversed by the end of the year. In a revised statement of policy the General Staff stated:

> *Gun*. Fulfilment of their normal role necessitates that the main armament on the greater proportion of tanks of the medium class should be an effective H.E. weapon; and, at the same time, an effective weapon against enemy armour of the type so far encountered in this war.

In a commentary on this change the War Office wrote:

> In view of the fact that evidence to date is that the 75 mm. tank gun, in use in American medium tanks, is the best dual-purpose

> tank weapon yet produced, and also in view of the advantages of standardisation, that gun should be adopted, as soon as practicable, as the main armament of the majority of British tanks.

To achieve this the War Office were willing to go to great lengths, 'if necessary, by the adoption in the United Kingdom of American medium tank design'; though a proportion of British tanks mounting a 17 pdr. was asked for at the same time, and infantry support was to be provided for with a 95 mm. how. mounted on Churchill tanks. By February 1943 these decisions were incorporated in the design and production programme of the Ministry of Supply. The wisdom of the step was, however, soon challenged. The Defence Committee of the Cabinet heard heated arguments at two meetings in April and May 1943 and it was finally decided that 30 per cent. of tanks should be fitted with the 75 mm. gun, 20 per cent. with the 95 mm. how. and 50 per cent. with the 6 pdr. (or a better A.T. weapon, such as a high velocity 75 mm., or 17 pdr.). A year later a not dissimilar statement of requirements was made by the War Office: 65 per cent. best dual-purpose weapon, 25 per cent. best A.P. weapon, 10 per cent. best close-support weapon.

By comparison with the vicissitudes in General Staff doctrine on A.F.V. guns, A.T. gun policy was much more straightforward. In September 1942 the staff issued a statement of their requirements: the 6 pdr. was accepted as the standard Royal Artillery equipment, entirely to replace the 2 pdr. as soon as possible; the 17 pdr. would in turn replace the 6 pdr., at any rate in part; while it was indicated that a heavier gun than the 17 pdr. would be needed in the long run. The 17 pdr. was to be towed by the Field Artillery Tractor, but a definite requirement was made for a self-propelled mounting. In October 1942 the General Staff stated their forward policy: an A.T. gun with 25 per cent. improved performance over the 17 pdr., on both a field carriage and a self-propelled mounting, with light armoured protection. In the event, the increases in A.P. performance sought by the Staff were to be found by improved ammunition for the 6 pdr. and 17 pdr., as will be seen.

General Staff policy with regard to tank and anti-tank guns was closely connected with tank policy as a whole. The final decision, to specify armament as a proportion of tanks rather than by types, reveals a change of approach, as revolutionary in its way as the change from A.P. to H.E., from vehicles with narrowly defined functions to a common-purpose A.F.V. As we have seen,[1] two varieties of A.F.V. were regarded as basic in 1940—the Cruiser, capable of long approach marches and with speed, armament and

---

[1] See p. 323.

armour appropriate to co-operation with the mechanized troops of the Armoured Division; and the Infantry Tank, formed into Brigades, designed for support of other arms and therefore needing less speed, a smaller radius of action and more armour. As cruiser tanks were not available in sufficient quantities, infantry tanks were in practice used in the Armoured Divisions during 1941 and 1942, but the trend towards a common-purpose tank was due to more than the limitations of supply. The prime inspiration was the need for mechanical reliability; this was reinforced by the influence of Anglo-American tank policy.

The notion of securing a high degree both of reliability and ease of maintenance by developing a basic type was, in a sense, already familiar enough, for most British A.F.V's were, as we have seen, developed from earlier models and not from basically new designs. If a tank had a set of basic components (engine, suspension, transmission etc.), thoroughly tested and proved, alterations to its armour, main armament, speed, radius of action and so forth, could be undertaken without the radical upheavals of making new prototypes and upsetting production. After all, the Germans had never adopted the specialisation of functions characteristic of British design: Pz.Kw.I to IV were constructed in such a way that the superstructure could be altered with a minimum of trouble.[1] British forces in North Africa saw the results of this: Pz.Kw.III successively mounted a 3.7 cm. gun, a short 5 cm., a long 5 cm., and a short 7.5 cm.; frontal armour increased from 30 mm. to 50 mm. and weight from 19 tons to 22 tons, with no loss of speed;[2] Pz.Kw.IV similarly grew from 20 tons to 25, 30 mm. of armour to 85 mm., a short 7.5 cm. to a long 7.5 cm. gun. These developments were only possible because of the capacity of the common-purpose chassis. In December 1941 the Tank Board was coming to a somewhat similar approach to that revealed in German design: 'design policy should be to develop tanks of this general type (Cromwell) with common power and transmission units, carrying different combinations of armament and armour'. Six months later General Ritchie, fresh from the Western Desert, 'was in favour of one general purpose tank of the Crusader type, with the biggest gun that could be mounted'.

The interaction of British and American tank policy cannot be considered here in any detail, but it is necessary to go back to the early days of the war in order to understand later developments. Before Pearl Harbour Anglo-American tank policy did not, of

---

[1] The hull of these tanks was constructed not in one piece (as in British designs) but in three: main lower hull, front superstructure, rear superstructure. Engine, transmissions and controls were in the lower hull which then became a mobile platform for the superstructure which was added later.

[2] The chassis also mounted a self-propelled 7.5 cm. assault gun.

course, exist as such. The relationship was essentially one of customer and retailer. True, the customer had some say in the design of his purchases: though the Americans refused to manufacture any current British A.F.V's, the British Mission[1] finally succeeded in getting the United States Ordnance to accept the criticism that the medium M.3, the only design in sight of production, should be modified since its main armament, the 75 mm., was in an old-fashioned sponson mounting. The resulting General Grant tank has been described as 'a British-sponsored version of the American M.3 (General Lee)',[2] but it still had its main armament in the sponson mounting. As soon as the United States was herself at war the need to co-ordinate policy was evident, particularly as it was clear that British troops would be to a great extent dependent on United States supplies of A.F.V's. The main United States tank, medium M.4 (General Sherman), was also influenced by British experience,[3] and as it reached British troops during 1942 it became, as we shall see, immensely popular, not only for its armament, but also for its ease of maintenance: it was the 'perfect conscript's weapon'.[4] The dual-purpose gun's success was to be sufficient practical proof for the American Staff's contention, explained to a mission of British experts in February 1942,[5] that 'the role of the Armoured Force' was to deal 'with the enemy communications and to attack infantry and artillery etc. from the rear'. But by the late summer of 1942 when an American Tank Mission[6] arrived in Britain the decision to concentrate on a common-purpose tank had brought British and American theory more or less into line. In September 1942 the following statement was accepted:

> British and American staffs are in agreement that the major requirement is an 'all-purpose' tank, the standard components of which should provide the degree of flexibility required to mount the various types of tank armament in use or under development. These components may also be utilized for the mounting of self-propelled artillery weapons.

It was upon this assumption that towards the end of 1942 the General Staff issued a full definition of the quality requirements in tank development. These were to rest, in the words of the official statement, 'upon the demand for a basic design of vehicle whereof the following components are reasonably "hard and fast": (a) Power Unit; (b) Transmission; (c) Suspension; (d) Method of propulsion

---

[1] Special tank mission appointed by the Ministry of Supply in July 1940 under the direction of Mr. Michael Dewar, later assimilated into the British Purchasing Commission.

[2] Capt. B. H. Liddell Hart, *The Tanks* (London, 1959), Vol. 2, pp. 490–491.

[3] Through the Canadian 'Ram' project.

[4] *The Times*, 26th July 1950, p. 7, 'Tanks in Korea'. See pp. 362–363.

[5] The U.K. Tank Mission under the leadership of Mr. G. Nelson.

[6] The Barnes Mission.

(whether wheel or track)'. The statement proceeded to say that upon this basis variation in gun power, speed, armour and radius of action could be made to produce a range of vehicles, 'all built upon the same or similar type of base':

(i) *Medium Cruiser Type*, as the standard tank.
(ii) *Self-propelled Mounting*, for Gun and Howitzer—up to Medium. Dual-purpose A.A./A.T. gun—up to Heavy.
(iii) *Tanks* for special tasks.
(iv) *Armoured Command Vehicles*.
(v) *Heavy Tank*, by sacrificing gun power, number of crew, radius and speed in favour of armour.

At the same time the Staff laid down that the tactical role of the cruiser tank was 'to obtain a decision in battle . . . by engaging in battle with enemy armour, by attacking enemy rear administrative echelons or by operating against infantry formations', and among the factors listed in the 'order of priority of requirements in design' after 'absolute reliability' comes 'a first-class anti-tank weapon [gun] of the 6 pdr. or heavier type': and in both these points we have a reference to the contemporary dispute concerning tank armament discussed above, which, as we have seen, was not resolved until early in 1943.[1] Finally it should be noted that no absolute characteristics were laid down in General Staff policy: definitions were related to enemy performance. Thus in armament it was stated that the 'gun must be an efficient weapon against enemy armour . . . and one which can outclass enemy tanks of corresponding type'; as for speed, what was demanded was a performance able to put 'the tank at least on even terms with the enemy'; finally armour must be 'proof against the main armament of the equivalent enemy tank at normal European battle ranges'.

The War Office revised its tank policy more than once later in the war, but no general statement of policy affected the war-time design of A.F.V's. Later effective changes in design requirements were all particular rather than general: the urgent need to mount the 17 pdr. on tanks, for instance; the tendency to seek superiority in armament by increase of velocity rather than increase in calibre. These, together with various other aspects of the policy changes of 1942–43 (self-propelled artillery and the heavy tank), will be discussed later under actual projects. Before turning to this, however, it is necessary very briefly to indicate the organisation which controlled tank development between 1940 and 1945. The changes made in organisation to some extent reflect the vagaries of policy outlined

[1] See pp. 325–327.

above, and—so contemporaries were convinced—had a direct bearing on design of A.F.V's themselves.

The 1939–40 organisation in the new Ministry of Supply has been referred to above.[1] During the spring of 1940 a number of criticisms were directed at it, ironically enough because (to quote one critic) we had 'no fighting tanks suitable for trench warfare'.[2] The solution proposed was a Tank Board, analogous to that formed in August 1918,[3] and, coincident with the change of administration in May 1940, a Tank Board was appointed (29th May). Sir Alexander Roger was its chairman. The other members were Mr. A. A. M. Durrant, Mr. H. J. Moyses and Mr. G. W. Thompson. The terms of reference agreed by the Minister of Supply and the Secretary of State for War make it plain enough that the Board was regarded as a temporary or at any rate an advisory body, somewhat like a Royal Commission. It was called upon 'to consider the whole situation regarding the production and design of tanks and to advise the Minister of Supply as to the future action'. The Board (which had thus a somewhat misleading title) conducted its enquiry with speed and reported on 7th June 1940, that:

(a) Army requirements should be confined to the minimum number of types in order to acquire standardisation of design.
(b) The Army must state its demands unequivocally and through one focal point. The fundamentals of these demands should be expressed in terms of armament, production, performance and numbers.
(c) Control of the organisation in the Ministry of Supply should be in the hands of civilians engaged in rapid commercial methods.
(d) Assuming that a civilian Director General remained in charge of both tanks and wheeled vehicles, a General Manager should be appointed to devote his entire time to the tank department, with subordinate civilians charged respectively with design and production responsibility.[4]

Broadly speaking, these recommendations were accepted. Under the Director General of Tanks and Transport,[5] civilian directors of production and design were appointed and, at the War Office, the

---

[1] See p. 238.

[2] The most pertinacious of the critics were Mr. S. S. Hammersley, M.P., Col. Gretton, M.P., Lord Lloyd and Sir Albert Stern.

[3] *History of the Ministry of Munitions*, Vol. XII (H.M.S.O. 1920), Part III, pp. 66–68.

[4] Other recommendations urged simplification of tank construction and the vesting of responsibility for complete assembly in the Ministry to avoid vehicles being issued minus vital equipment.

[5] Where Mr. G. Burton succeeded Mr. Peter Bennett shortly after the report was issued.

new post of Director of Armoured Fighting Vehicles was created.[1] The original Tank Board did not formally expire until November 1940, but, though it acted as an admirable forum for discussions which ranged over the whole field of tank design and provision, it was handicapped by the lack of any executive powers: it could only take action through its members as individuals.

In January 1941, the Board was reconstituted 'to consider the design, development and production of A.F.V's including their armament and equipment *and to take decisions thereon*, in order to meet, as expeditiously as possible, the requirements of the War Office'. Despite this last phrase, the reconstituted Board was not purely Ministry of Supply in composition. Under the Chairmanship of Sir James Lithgow,[2] there were four independent members; the Ministry was represented by the Director General of Tanks and Transport (Mr. Burton), the Director General of Mechanical Equipment (Mr. Weir) and the Director of Artillery (General Clarke) and the War Office by the Assistant Chief of the Imperial General Staff or the Inspector of the Royal Armoured Corps and the Director of Armoured Fighting Vehicles. It was thus an inter-departmental body, strengthened, through its independent members, by an infusion of industrial experience.[3] Later changes in the Tank Board first of all removed the independent members, and second, strengthened both Ministry of Supply and War Office representation. These tendencies reached their logical development in September 1942 when a Chairman, Armoured Fighting Vehicles Division was appointed (Commander Micklem) who was supreme executive officer for A.F.V's in the Ministry of Supply and who presided over a Tank Board thus constituted:

Ministry of Supply

Controller General of Munitions Production
Director General of Fighting Vehicles (Production)
Director General of Fighting Vehicles (Research and Development)

War Office

Deputy Chief of the Imperial General Staff
Assistant Chief of the Imperial General Staff
Director Royal Armoured Corps
Director of Mechanical Engineers

---

[1] To these posts were appointed Mr. Graff Baker, Mr. Durrant and Major General Pope.

[2] Sir Alexander Roger had left to lead a Supply Mission to India.

[3] The independent members were: Commander Micklem (Vickers), Mr. Moyses (Birmingham Railway Carriage Co.), Sir Albert Stern and Mr. G. Thompson (Trades Union Council).

It will be noted that in this arrangement the Chairman, Armoured Fighting Vehicles Division, and the other three Ministry of Supply representatives exactly balanced the War Office delegation. These later changes must, of course, be reviewed within the larger framework which gave 'quality' a greater independence of 'quantity' and which we have referred to above,[1] just as the first notion of a tank board is evidence of the overwhelming drive for production at all costs of the 1940–41 period.

The composition of the Tank Board is thus a revealing index of the mental climate affecting tanks during the three years from 1940 to 1942. Thereafter, as criticism of tank development increased, the Board became more formal while attempts were made to improve liaison between the War Office and Ministry of Supply at more effective levels. The two Ministries were unable to give joint evidence to the Select Committee on National Expenditure in 1943, so violently did they disagree at this stage on the ultimate reasons for the defects in tank development.[2] Indeed the very existence of the Tank Board, which shared responsibility between the War Office and Ministry of Supply, occasionally tended to produce rather than avoid friction. But if the Tank Board proved sometimes a mixed blessing, it coincided with the emergence of officials in the Ministry of Supply especially charged with responsibilities for tank design. The Director of Tank Design came first under the Director General of Tanks and Transport. Then, in February 1941, this post was superseded by the appointment of a Controller General of Mechanical Equipment (Sir James Lithgow), and the Director of Tank Design came under the Director General of Mechanical Equipment (Design and Development) (Mr. J. G. Weir). When Mr. Oliver Lucas was appointed Controller General of Research and Development in September 1941, the Director of Tank Design was placed under him—the complete split between design and production control being, as noted elsewhere,[3] the major symbol of the new insistence on quality considerations. In November 1941 the new attitude was further emphasised by bringing in Mr. Robotham as Chief Engineer Tank Design, to control all design and development (under the Controller General of Research and Development), at both the Department of Tank Design and private firms. When, in September 1942, design and production were once more reunited under the Chairman, Armoured Fighting Vehicles Division, the control of design was not materially affected: Mr. Lucas came under the new executive head as the Director General of Fighting

[1] See Ch. X.
[2] Cmd. 6865, *War-time Tank Production*, July 1946.
[3] See pp. 245–246.

Vehicles (Research and Development); under him the Chief Engineer Tank Design was responsible for new development and, under a Director of Fighting Vehicle Design and Liaison, came the Director of Tank Design and branches making contact with projects in hand in actual firms. We shall have to note elsewhere some of the tensions which survived these rearrangements,[1] just as we shall have to stress the steady growth of the design department under the Director of Tank Design, which in the long-run was to be such an immense accession to the tank design resources of the country.[2] The important point is that during 1941 and 1942 the Ministry of Supply began to speak more strongly than it could earlier on questions of design policy. The detailed discussion of new tanks and components will illustrate this. But it may also be illustrated by some more general points—the relationship of design and production, the question of loading limits as a factor in development, and the problem of introducing modifications into existing production.

'Design for production' was a natural policy in war-time—indeed at any time it may be regarded as desirable that new types of equipment should be capable of easy manufacture. The point at issue was to what degree development should be circumscribed by production considerations. At first, following on the rearmament pattern, the avoidance of *ab initio* new design is the best indication of the aim to use existing vehicles as a basis for future development: the cruiser type as it existed in A.13, Covenanter, and A.15, Crusader, logically led to Cavalier, Centaur, Cromwell and their derivatives, just as A.22 (Churchill) was the basis of infantry tank development. The arguments in favour of this were weighty: production was more readily secured since many sub-assemblies were common to actual and projected models; reliability of performance might be guaranteed by the use of tried components. But these two arguments in fact hung together: if tried components proved to be inefficient in new models, production was seriously interrupted. The occurrence of such troubles was only too frequent and, where it proved impossible to initiate any fundamentally original projects in time to be effective before the end of the war, it led gradually to the questioning by the Design Department of the Tank Division of the main device whereby the old policy expressed itself—the so-called 'Drawing-Board Order'. This had been employed in the case of Crusader, Covenanter and the abortive A.20. In the great rush to secure 500 A.22s (Churchill or Infantry Mk.IV) by the spring of 1941 the same technique was applied on a vaster scale: materials were ordered in advance of design; sub-assemblies were manufactured after little more than bench tests. The forecast was for the

[1] See pp. 351–352.
[2] See pp. 349 and 352.

delivery of a 'pilot' by November 1940, six months from the beginning of design, with production proper beginning to flow in December. This forecast was not met and evidence accumulated in 1941, from both A.22 and from Covenanter and Crusader, which led to a general scepticism as to the value of such lengthy short cuts.[1] If quality and mechanical efficiency were important rather than mere output, it was hardly economical to avoid trials: in fact, as a critic put it, we were not avoiding the manufacture of prototypes, we were manufacturing nothing else.[2] In response to the representations of the design officials, the War Office and the production departments in the Ministry of Supply gradually accepted the new position. In October 1942 it was laid down that at least six pilot models of new designs were 'essential' and to be produced 'concurrently'; such pilots were 'to take precedence over production', and were to be subjected to a 2,000 mile test at the Fighting Vehicles Proving Establishment. Moreover:

> A prototype having . . . passed its acceptance tests, the Department of Tank Design must ensure that . . . at least a small percentage of production vehicles is subjected to a protracted endurance test to make certain that the durability built into the prototype is reproduced in the quantity produced article.

These steps were, in fact, to bring British tank development more or less into line with what was apparently early German tank policy, the manufacture of considerable numbers of experimental types; and also into a somewhat similar procedure to that adopted in the United Kingdom development of aircraft.[3]

Another victory for design was the jettisoning of the old restrictions of the railway loading gauge. This, as noted above,[4] limited the width of tanks to 9 feet[5] and was quite acceptable so long as the hypothesis remained a 'Colonial war'. But as soon as a continental enemy emerged the picture altered. The loading width for express traffic in the main continental countries is 10 feet 6 inches, and the heavier tanks projected during and after 1940 forced a challenge to the validity of the old principle. The 9 feet maximum had, indeed, been increased to 9 feet 2½ inches in the case of Churchill tanks; and subsequent negotiation between the original Tank Board and the Railway Executive raised the maximum to 9 feet 6 inches.

---

[1] H. of C. Deb., Vol. 385, Cols. 1771–5, 15th December 1942.
[2] H. of C. Deb., Vol. 381, Cols. 224–476, 1st July 1942, and Cols. 527–610, 2nd July 1942.
[3] See Ch. III, Section ix.
[4] See p. 305.
[5] Width is here used as an indication of other limiting dimensions—height, under-clearance etc. The profile of the vehicle is at issue rather than its maximum dimensions, since the shoulders of tunnels provide the severest limits.

Churchill was, of course, envisaged at first as an anti-invasion vehicle so that ease of rail transport was more justified in that case than with other big tanks where, the Director of Tank Design stated in February 1942, it would 'impose an unacceptable limitation'. As early as December 1941 Mr. Lucas had informed the Tank Board that 'transport by road appears to be the only solution' and three months later it was decided that, despite the vigorous opposition of the Directorate of Movements at the War Office, new tanks should not be bound by railway limitations.[1] The use of wheeled transporters for A.F.V's was in any case urgently dictated at this time by African campaign experience, both to reduce long approach marches and for the recovery of damaged vehicles: a formal War Office requirement for these transporters was made in March 1941 and was readily met as the M.T. branch was ready with plans for the purchase of British and American vehicles.[2] The load-limits of bridging equipment, with a maximum on the Bailey Bridge of 70 tons[3], was a further limitation, but one which was not seriously influential in the range of vehicles which saw action during the war: the bridge-laying Churchill, and certain wading devices were tentative answers to this problem.

The question of modifications takes us nearer to the question of war-time tank design. After Dunkirk four tanks were in production, all of pre-war design: Matilda II, Valentine, Covenanter and Crusader. All needed modification either to improve their mechanical performance or to increase their tactical efficiency, and sometimes for both reasons. Much the same was to be true of Churchill tanks when they began to appear in 1941. To some extent the consequent repair and reworking programmes were essentially a manufacturing question: Crusader in particular was repeatedly criticised for its faulty assembly. But design confusions lay at the root of most of the trouble: the vehicles as planned were found on production and trial (which, as we have seen, occurred in that order in 'drawing-board orders') to be badly designed; and the early failure of the new tanks, Churchill and the Cromwell series, meant that every effort had to be made to fit existing machines with more armour and bigger armament than they had been originally intended to carry. Matilda and Valentine came off best in this struggle for improved mechanical and fighting efficiency, though the success of Matilda was mainly relative and mechanical: it proved impossible to increase its armour or armament. Valentine, on the other hand, was both mechanically

---

1 General Grant and General Sherman tanks when they arrived in the United Kingdom had to be transported by rail on specially designed well-wagons.

2 From the spring of 1943 tracked transport and recovery vehicles were required in view of operations in the close terrain of the European continent.

3 See p. 275.

reliable and (largely because the manufacturers resolutely resisted increases in weight) capable of several increases in armament: 2 pdr. and coaxial M.G. (Mks. I–V), 6 pdr. and M.G. (Mks.VIII and X), 75 mm. and M.G. (Mk. XI).[1] Real difficulties were experienced with Covenanter and Crusader. Covenanter, indeed, had the fatal disadvantage of a front radiator and many other more or less fundamental faults, needing very elaborate rectification. Crusader, with the highest power/weight ratio of the tanks here mentioned, was full of mechanical faults and it was not until the summer of 1943 that the vehicle was regarded as satisfactory though it had done much good service before that date. Parallel with the redesign made necessary on grounds of mechanical efficiency Crusader also underwent several functional changes—indeed the increasing weight of the machine was one reason for mechanical troubles. Designed originally for a 2 pdr., a version with a two-man turret mounting a 6 pdr. was prepared in 1941, and an additional 14 mm. of armour was added to the front: beyond that the tank could not go and attempts to mount the 95 mm. how. and to increase armour by another 6 mm. were failures. By 1943 it had joined Covenanter, Matilda and Valentine as an 'obsolete' vehicle.[2] The upheavals in production caused by modifications belong to the story of production rather than design. It was, however, in resisting the heavy and continuous pressure of the production departments that the design hierarchy enjoyed its first major success. True, during 1940 and 1941 the design department issued several directives intended to limit modifications[3] and to make the Director of Tank Design the arbiter and approving authority. But always an exception was made in favour of modifications designed to give greater mechanical efficiency or to meet urgent user requirements; and by the autumn of 1942 it was possible to insist that modifications must themselves be rigorously tested by 1,000 miles of running—in order to avoid modifying the modification. What was never satisfactorily resolved was the gap between the bulk issue of a vehicle and the arrival of dependable user comment on it, which came when production was well in hand and when modifications were most resented by the manufacturer. To equip a division with its basic A.F.V's 340 tanks were needed: by August 1941, when this number of Crusaders had been delivered, production was at a monthly rate of 65 machines; by February 1942, when user reports were arriving

[1] Marks III and V had a three-man turret; other marks a two-man turret.

[2] For further information on the complicated story of the adaptation of some of these vehicles to special roles see pp. 341–342 and 348.

[3] And also to canalise them. It was a great difficulty throughout that manufacturers tended to modify for ease of manufacture and troops in the field did so in order to secure a temporary mechanical or tactical advantage. It was essential to keep track of these *ad hoc* changes in design.

thick and fast, production was running at 130 machines a month, and by March, when field criticism was being translated into modifications, production was ranging between 170 and 200. It was by then possible to relax the production drive, as we have seen, and when one remembers that in the summer of 1941 one quarter of tanks in Britain issued to troops were in fact 'under repair' one can understand why the policy of more prototypes and no more 'orders off the drawing-board' was made to apply to new development at that time.

In turning to consider new war-time designs of tanks we must begin, however, with a tank which unhappily illustrates all the defects in the old system. This is A.22, later named Churchill or Infantry Mk. IV. The genesis of this vehicle was authoritatively explained by the Prime Minister in a statement in the House of Commons:[1]

> On 11th June 1940, I summoned a meeting . . . to consider our tank production programme. We had . . . in the United Kingdom less than 100 tanks. These and those under production at the time . . . had been proved in battle in France to be too weak to stand up to the German tank guns. Invasion of this country was expected. The problem, therefore, was to produce the maximum number of tanks of a sufficiently powerful kind for home defence. As a result of the meeting I called for a plan which would provide 500 or 600 tanks if possible by March 1941; these were to be over and above the existing programme and were not to interfere with it . . . On 20th July we met again . . . The Tank Board approved the specifications subject to certain modifications, and it was agreed to go forward with the utmost rapidity.

In fact production began to flow in the early summer of 1941, a very remarkable result of the 'utmost enthusiasm' which Mr. Churchill rightly ascribed to those responsible for the development. Vauxhall's, at first drawn in for consultation, took a major share in development, aided by a team from the Mechanization Board, appropriately enough as the specification called for the utilization of as many components as possible from the old A.20 model.[2] A crew of five was to be carried: two (Driver and Gunner) in the hull and three (Commander, Gunner, Loader) in the turret; armament was to consist of a 3″ mortar in the hull, a 2 pdr. and coaxial Besa with a 2″ smoke mortar in the turret; the armour was to be $3\frac{1}{2}$″ in hull front and turret (the latter cast) and 3″ on the sides; a circuit of 60–75 miles was called for and a speed of 18 m.p.h.; the estimated weight was 34 tons.[3] The novelties in the machine were considerable:

---

[1] H. of C. Deb., Vol. 385, Cols. 1772–4, 15th December 1942.
[2] See p. 314.
[3] It had also to be transportable by rail without special working; see pp. 335–336.

for the first time the Merritt-Brown system of regenerative steering was incorporated and the suspension consisted of a series of independently sprung bogies; the engine was a specially developed Bedford twin 6-cylinder. Development based on such innovations naturally led to unexpected difficulties: 'the performance of the engines in the tanks', Mr. Bartlett of Vauxhall's told the Tank Board in August 1941, 'had been vastly different from that which they had given on the bench'; at much the same time the suspension gave trouble—reasonable performance being obtained only at a speed of 8 or 9 m.p.h. By November 1941 the War Office reported that Churchills delivered up to October were unfit for the Middle East or for sustained operations even in the United Kingdom unless 16 modifications were incorporated, of which 10 were to the transmission and steering, and three to the suspension:[1] of the first 1,200 tanks produced, nearly 1,000 had to be 'reworked'. As late as July 1942, reworked and new vehicles were failing their acceptance test at very low mileages (about 150 miles) and it was not until early in 1943 that it was stated that 'substantial progress had been made in eliminating defects'. By this time, of course, Churchill had given a good account of itself in the raid on Dieppe and in North Africa. The 2 pdr. in the original tanks had been adopted since a design of tank mounting for the 6 pdr. was not available. When it was, the 6 pdr. was incorporated, and it later proved possible to alter a considerable number of 6 pdr. Churchills to accommodate a 75 mm. gun. More effective than these alterations was the design of a heavier machine, carrying 152 mm. of frontal armour and either a 75 mm. gun or 95 mm. how.; this development was inaugurated in 1943 and a considerable number of these tanks were manufactured.

Though A.22 thus emerged in the end as a fighting tank, the main requirement of the post-Dunkirk period was, as we have noted, for a heavy cruiser, not an infantry tank. Consequently, as soon as the immediate danger of invasion receded in the winter of 1940–41 designs of fast, heavily armoured cruiser machines were requested by the Ministry of Supply. The designs were to aim at 65 mm. of armour on the hull front, 75 mm. on the turret front, a diameter of 60″ for the turret ring; as powerful an engine as possible; maximum weight to be 24 tons and maximum speed to be 24 m.p.h.; the 6 pdr. was to be the main armament and a crew of five was to be carried. Three solutions were examined by the Tank Board in January 1941. Mechanizations and Aero and Birmingham Railway Carriage Co. both produced developments of Crusader, while Vauxhall's suggested a version of A.22 with less armour. 'The only hope to obtain production of a heavy cruiser in 1942 was to design the new model on lines

[1] Other essential modifications were to the hull; five other modifications were stated to be only slightly less urgent.

so near an existing type that it would not be necessary to manufacture a prototype', it was stated in January 1941; but this the Tank Board overruled, following their decision to avoid the drawing-board order,[1] though in fact the proposals which were given official support were both based on Crusader. The first of these was Mechanizations and Aero's proposal, developed under the serial A.24 and ultimately leading to Cavalier; the Vauxhall project did not get beyond the paper stage (A.23) and Birmingham Railway Carriage's proposal was not carried even as far as that. At the end of January Mechanizations and Aero were instructed to manufacture six pilots of A.24, one of which (it was hoped) would be ready for trials by the autumn. Meanwhile Leyland Motors in collaboration with Rolls-Royce had produced what was an even more promising development of the Crusader. This was a projected vehicle in some ways similar to A.24, but with a new power unit, an adaptation of the Rolls-Royce Merlin aero-engine (to be called the Meteor when employed in tanks) incorporating the Merritt-Brown gearbox. The Leyland Motors' proposal was given the number A.27 and its 'parentage' vested in the Birmingham Railway Carriage Co.[2] For reasons indicated below, the Meteor development solved several problems which had been encountered in Crusaders,[3] and, by providing an ample power/weight ratio, it offered a more extended field of subsequent development than did the Liberty engine. As it proved impossible at first to get enough Meteors, English Electric were made responsible for a revision of A.27 incorporating a Liberty engine, the two varieties being distinguished as A.27(M) and (L). These types were ultimately christened Cromwell and Centaur respectively and were also termed Cruisers Mk. VIII(M) or (L), Cavalier being Cruiser Mk. VII.[4] The main design problem was at first considered to be the suspension, for the original Christie suspension had been intended to carry less than ten tons, while the new projects were soon found to be more than thrice as heavy, the speed remaining considerable: prolonged work was therefore necessary before sufficiently robust coil-springs were evolved. But soon experience in North Africa showed the Liberty engine in Crusader to be fundamentally unreliable. A.24 (Cavalier) with the same engine could be shown to have a life only 80 per cent. of Crusader and correspondingly reduced reliability: this project was therefore clearly a dead-end. Similar doubts were felt about Centaur, although there an improved type of Liberty engine was to be installed. It was this confinement of hopes to the Meteor-powered

---

[1] See pp. 334–335.
[2] On design parenthood see pp. 349–350.
[3] See p. 344.
[4] An evanescent variety of this series arose in 1943 when it was found possible to fit a proportion of Centaurs with Meteor engines. Centaurs thus modified were called Cromwell X.

tanks which led the Tank Board in the winter of 1941–42 to pin their hopes on the development of 'tanks of this general type', i.e. Cromwell. Cromwell, in short, became the basic 'common-purpose tank' which was official policy by 1942, as we have seen.[1] Mounting a 75 mm. gun or a 95 mm. how., Cromwell was in action by the Normandy landings, and was better liked than its ancestors, though by then its armament was considered too light.[2] The advent of the 17 pdr. tank gun was met by the development, begun early in 1942, of a lengthened Cromwell, with lightened armour. A.30, as this development was named, was approved by February 1943, and was ultimately christened first Centurion and then Challenger. Another, and more reliable, development of Cromwell was the A.34 or Comet, which mounted a long 75 mm. (or 77 mm.) gun and was produced in time for the later stages of the 1944 campaign. We shall have to return later to the problem of the 17 pdr. gun in A.F.V's, since it produced considerable controversy and was effectively solved by mounting the weapon in General Sherman tanks.[3] Here it is appropriate to indicate that throughout 1942 and 1943 it was hoped to meet the General Staff requirement for an assault tank by up-armouring a Cromwell type of machine. Various solutions were investigated on paper and one, A.33, was taken to the pilot stage by English Electric; the total weight was 45 tons, a long 75 mm. gun was mounted and the frontal armour was 6″ thick. But this, and other designs of heavy cruiser, were not to reach production by the end of the war.

It is impossible to describe here the very large variety of special purpose machines which were developed during the later stages of the war—Assault Vehicles Royal Engineers, anti-aircraft tanks, amphibious tanks and wading devices.[4] But a brief indication must be given of three types of tracked vehicles—airborne light tanks, flame throwers and anti-mine tanks—and war-time development of wheeled A.F.V's must be touched on, before turning to A.F.V. component development, including armament, and the resources for tank design.

Light tanks, as already noticed, ceased to have much interest for the War Office after Dunkirk,[5] but Vickers continued to remedy defects in existing marks of light tank in a project (A17E1) known later as Mk. VII or Tetrarch. This had been offered to the Army in 1938 and the limited War Office requirement for the vehicle was met between the autumn of 1940 and the spring of 1942. Tetrarch

---

[1] See pp. 329–330.
[2] *The Times*, 11th May 1945, p. 2, and 5th January 1946, p. 5.
[3] See p. 346.
[4] For information on self-propelled guns, see p. 348.
[5] See p. 323.

had armour of 16 mm., a 2 pdr. and medium Besa, and weighed 7.6 tons. The novelty in the vehicles was in the steering which was achieved for gentle curves by bowing the track. In Mk. VIII or Harry Hopkins, developed under the number A.26, an attempt was made to give greater armoured protection. In fact, though much difficulty was experienced with the suspension, a reliable vehicle emerged by 1943; with 40 mm. frontal armour, the weight had only risen to 8.6 tons. Though Harry Hopkins had many features of current cruiser machines, its development proved too tardy for it to meet the General Staff requirement, which only crystallised during 1941, for an airborne A.F.V.: this was met by American vehicles, the Aero T9, mounting a 37 mm. gun; and Harry Hopkins became a mounting for the S.P. 95 mm. how. Two flame-throwing devices, one operated by cordite charges, the other by gas-pressure, were developed during 1941 and mounted on Valentines. The General Staff in March 1942 expressed a preference for the second type of flame-gun and required it to be mounted on Churchill tanks. As ultimately designed the flame-gun was mounted in the hull Besa position in heavy Churchill (Mk. VII) and had a range of 100–120 yards; under the name Crocodile it arrived in time for the French campaign of 1944. Anti-mine devices have a much longer history, the roller type, pushed in front of an A.F.V., being under development from 1937. During 1941 and succeeding years a very large number of devices were developed, but design was at first greatly circumscribed by a General Staff ruling that devices for detonating mines must not impair the fighting qualities of the tank. In September 1942 this restriction was removed and the most promising group of devices, employing flails which beat a path before the advancing tank, was developed. The most successful of this type, the Crab, which was finally accepted and incorporated in a proportion of General Shermans in British service, also did good work in France in the later stages of the war.[1]

Development of scout cars, armoured cars and carriers during the central years of the war was not spectacular. Little change was made in the scout car requirement, but, to supplement the limited quantities of Daimler vehicles, the Humber Scout Car was introduced: constructed on a commercial chassis, this hardly fulfilled General Staff demands. Similar trouble was experienced with the armoured car. A specially designed Daimler proved adequate at first, together with a somewhat unsatisfactory Humber. As General Staff demands for heavier armour and armament arose the Humber was modified,

[1] A noteworthy feature of anti-mine devices on A.F.V's is the variety of sources of inventions of this kind: a great many serving officers produced valuable ideas which were in some cases incorporated in the designs developed by the War Office Obstacle Assault Centre and by the Department of Tank Design.

but a more successful answer was provided by an A.E.C. armoured car. All these cars, however, had a performance which reached only the minimum acceptable: existing chassis were incapable of the extra loads involved. In September 1942 there was an important change in General Staff policy: armoured car requirements were in future for an essentially reconnaissance vehicle, thus reducing the need for armour and armament, but increasing the necessary accommodation and radius of action. The Coventry vehicle was being developed at the time and an attempt was made to modify it to fit the new specification—an attempt which ended in failure in 1944 when it was turned down by the General Staff. Here again, a large proportion of overseas types had to be employed by British Forces—notably the American T.17E1. As far as carriers were concerned the two basic types were the Vickers Bren Carrier (the Universal) and the Loyd, a private design provided during the early months of the war. The designer of the latter, Mr. Loyd, did much work towards a new carrier but in the upshot, though both carriers were recognised as having inadequate load-carrying capacity, the modifications which were introduced were all fairly small, and designed to fit the two vehicles for special roles—such as the Loyd slave battery. The place for a heavy duty carrier was partly filled by the American Ford. A requirement was expressed in September 1944 for a tracked reconnaissance vehicle.

It will have been evident from earlier pages that, although designs of completed vehicles were often disappointing, much successful development occurred in components for tanks. Here the most notable mechanical advance lay in the engine. The increasing weight of A.F.V's made it an essential condition for future progress that the power/weight ratio should remain high. In 1941 the desirable ratio was fixed at 15 b.h.p. per ton, possibly dropping as far as 12 b.h.p. In current vehicles this was achieved only in Covenanter (Meadows engine, 18 b.h.p./ton) and Crusader (Liberty, 19 b.h.p./ton).[1] Covenanter was useless on grounds of reliability, however, and the Liberty engine in Crusader, though mechanically undependable, remained the only hope, though this would have permitted increases in weight up to only 30 tons. The need was evident for a light, compact and reliable engine possessing reserves of power sufficient to allow of considerable subsequent development. Similar considerations had presumably led to the use of the Liberty in the Christie chassis before the war:[2] designers naturally turned to a more modern aero-engine. Early in 1941 Mr. Pilkington of Leyland Motors and Mr. Robotham of Rolls-Royce produced a suggestion for an adaptation of the Rolls-Royce Merlin as used in aircraft. Its 600 b.h.p.

---

[1] Cf. Valentine (A.E.C.) and Churchill (Bedford), both 9 b.h.p./ton.

[2] Another reason was the extreme cheapness of the engine in the interwar period.

offered the chance of progressive use with vehicles up to 40 tons; it was extremely reliable in aircraft; it would be easier to increase the already established production of Merlins than inaugurate production of a radically new engine; finally, the only two projects for new engines—diesels under development by Fowlers and by Mr. Ricardo—were in the embryo stage. The first order for Meteors was placed in August 1941. Meteor was not, of course, the ideal engine for tanks, having been designed for aeroplanes, but it was not only better than available United Kingdom engines and Liberty; it was also markedly better than various American Ford engines whose virtues were canvassed—mainly on production grounds—during the winter of 1942 to 1943. These Ford V.8's had been specially developed to meet the requirements of United States Ordnance, and hopes were held out of a 12-cylinder version which would have met British tank specification. In fact the 12-cylinder engine was slow in development, only the V.8, rated at about 500 b.h.p. was in fact available, and, though the War Office complained that the Ministry of Supply was not giving unanimous advice on the matter, the Chairman, Armoured Fighting Vehicles Division, succeeded in maintaining his contention that only a 600 b.h.p. engine was adequate. This decision to insist on quality rather than quantity (it was claimed that 3 Ford V.8's could be made for every 2 Meteors) could scarcely have been operative if it had occurred eighteen months, or even a year sooner.

Much work was also done in developing armour and welding of armour. Here perhaps the most significant result was a negative one—the decision to adhere to the employment of homogeneous plate in British A.F.V's. This turned in the last resort on a guess. Would the German Army continue to employ capped projectiles (against which homogeneous armour offered the best protection) or plain shot (against which face-hardened plate was better)? In the event the decision to retain homogeneous armour was justified by enemy practice; but a great amount of research was devoted to investigations of both the theoretical advantages involved and the overcoming of the many manufacturing difficulties which the large-scale production of hardened plate would have involved. The rapid increases in thickness of armour, in the weight of attack to which it was subjected and the need for stricter control over quality in an expanded production of plate, led to a new technique of specification being adopted after much research, based primarily on a ballistic limit, rather than the simple immunity which had previously been adopted. Further research was also involved in the attempt to reduce alloy content, also made necessary by the increased quantities used in more heavily armoured tanks. Here a very remarkable achievement was the reduction of the nickel content by four-fifths;

smaller but significant reductions were also made in the content of aluminium and molybdenum.[1] The price of this was a greater vigilance in the control of quality.[2] Welding had been used for armoured wheeled vehicles from 1939. Its extension to tracked A.F.V's was slow, since little was known of the performance given by bolted and riveted armour under attack. Though by 1941 the advantages of welding had been established (avoidance of machining to fine tolerances, reduced weight, greater ballistic strength), it was not possible suddenly to make drastic alterations in manufacturing methods. The widespread use of welding was thus only accomplished with the reduction in the tank programme in and after 1943. Manufacturing limitations were responsible also for the comparatively restricted use of armour quality castings, though they were widely employed for turrets and gun mountings.

The Meteor engine and the Merritt-Brown controlled differential together mainly solved power unit and transmission problems in the range of heavy cruisers of 1942 and later.[3] Two other components were severely taxed by the added weight and the steadily maintained speed: tracks and suspensions. Like armour, track design was to a great extent at the mercy of the shifts in raw materials and productive capacity. The superiority of cast manganese steel tracks over steel and cast iron was demonstrated by 1941, but the shipping position by then was critical and an urgent hunt for alternatives produced numerous solutions, the most promising being hylastic steel and rubber. In the event the manganese shortage did not last long, and rubber tracks were clearly inadvisable after Japan came into the war and cut off supplies of crude rubber. Rubber tyred wheels were, however, used in the suspension which finally replaced the old Christie type in the new heavy Cruisers. The development of the new suspension was facilitated by a good deal of United States experience, for the Americans (unlike the British and Russians) had not employed the Christie type in their A.F.V's.

The most important single component in the tank is the gun. The changes in policy with regard to tank armament have already been indicated.[4] We must now follow the design and development implications. Broadly three phases may be discerned: first—the '6 pdr. tank at all costs' of 1941–42; then the controversy over the 'dual-purpose gun' of 1942–43; finally the urgent problem of mounting the 17 pdr., the last armament problem of the war as far as A.F.V's are concerned.

---

[1] See p. 362.

[2] A branch under the Director of Tank Design dealt with armour, but much work was naturally done by the appropriate branches of the Iron and Steel Control.

[3] Improved versions of the Merritt-Brown gearbox were installed in the Churchill, Cromwell and Centaur.

[4] See pp. 325–327.

Parallel with these stages though, as we shall see, really independent of them, was the development of improved ammunition for existing guns and of super-velocity shot which was to improve the performance of British guns very remarkably. The problem of mounting the 6 pdr. (as later of incorporating the 17 pdr. and other larger pieces) was the size of existing turret rings: the pre-war tanks available in 1941 (Valentine and Crusader in particular) were only just capable of accommodating the gun, while the change severely interrupted the production programmes not only of the tanks, but also of the 2 pdr. and 6 pdr. A.T. equipments, needed with equal urgency. However in 1942 the first 6 pdr. tanks made their appearance, together with a number of 2 pdr. tanks converted to the new calibre. During 1941 the 17 pdr. was developed, like its predecessors envisaged from the start as a tank as well as an anti-tank gun. It was the high merits of the 17 pdr. which lent intensity to the controversy of 1942 over a dual-purpose gun; its size, which made it impossible for it to be mounted in any available 6 pdr. tank, led to the investigation of a number of alternatives. Vickers put up suggestions for an 11 pdr. and then a 12 pdr. both to be fitted in the 6 pdr. mounting, and both dual-purpose; in October 1942 an 8 pdr. was mooted, which was the 75 mm. American gun whose popularity has been described,[1] fitted to the 6 pdr. mounting; and later there was a proposal to use the United States H.V.75 mm. (or 76 mm.) gun. In the event, Churchill and Cromwell mounted the medium velocity 75 mm. gun, and Comet the Vickers H.V.75 mm. (the so-called 77 mm.). The really important step, however, was the successful installation of the 17 pdr. in General Sherman tanks. The conversion was at first rejected as impossible by the Tank Division of the Ministry of Supply, but its feasibility had been demonstrated by the summer of 1943 and the United States vehicles which were modified in the United Kingdom played a major part in the French campaign during 1944: the first attempt at a 17 pdr. British tank, Challenger, was a comparative failure and made the General Sherman conversion all the more vital.[2]

All this time steady improvements had been made in the performance of existing guns by increasing muzzle velocity, by providing piercing caps to increase penetration of face-hardened armour (usual on German tanks by 1942) and by adding ballistic caps which maintained projectile velocity to greater ranges. An A.P.C.B.C. shot (with both a piercing and a ballistic cap) was prepared for the 2 pdr. by September 1942. The 6 pdr. was improved to a greater

---

[1] See p. 329.

[2] The history of close support weapons in A.F.V's is less complicated. The pre-war 3" how. was gradually replaced in a proportion of new Infantry tanks from 1943 by the 95 mm. how.

extent: the length of the tank gun was increased to 50 calibres, equal to the length of the A.T. equipment; the muzzle velocity was increased in this way from 2,700 f.s. to 3,000 f.s., while a muzzle-brake was adopted, copied from captured German 5 cm. A.T. guns. This change was introduced during the summer of 1942 and ammunition design kept pace: the propellant charge was increased and the shot weight increased from 6 lbs. 4 oz. to 7 lbs. 2 oz. A design of A.P.C. shot was ready by October 1942 and of A.P.C.B.C. by January 1943. A.P. and A.P.C. shot were designed simultaneously for the 17 pdr.; A.P.C.B.C. shot was ready by 1943, and by 1944 an H.E. round had been developed, in line with the dual-purpose criterion already discussed.[1] A more original attempt to improve performance was made in an adaptation of the tapered bore or Gerlich gun put forward in 1940 by a Czech designer resident in Britain. The effect of the principle was, by reducing the bore of the barrel towards the muzzle, to increase the pressure of gas on the projectile and thus, for a given charge, to effect a much increased muzzle velocity. The Janecec 2 pdr. (or Littlejohn) was unfavourably viewed by the Director of Artillery and its investigation was carried on slowly under the Director General of Tanks and Transport, B.S.A. being given a development contract. In the winter of 1941–42, however, a German gun of parallel type was captured and, in February 1942, the Controller General of Research and Development transferred development to the Director of Artillery. By January 1943 the first mark of the super-velocity 2 pdr. was approved, a second mark being developed to deal with spaced armour. The Armaments Design Department had meanwhile evolved a composite-rigid shot (with tungsten core) which had better ballistics and did not involve a taper bore: this was adopted for the 6 pdr. in October 1943. Both these designs were ballistically unstable, though composite-rigid shot was better in this respect and further super-velocity ammunition was in active development during 1943 and 1944. The resulting shot was initially developed in the Research Department and was called Discarding Sabot; it consisted of a projectile of good ballistic shape encased in a duralumin body which was discarded during flight. Discarding Sabot shot was approved for both 6 pdr. and 17 pdr.

These advances in performance of 2 pdr., 6 pdr. and 17 pdr. were, of course, for the guns in their A.T. role, which, as we have observed, became a secondary function of tank armament after 1943. We must now briefly sketch the development of the 6 pdr. and 17 pdr. A.T. equipments. The introduction of the 6 pdr., designed before Dunkirk, was delayed for production and not design reasons: the carriage, a split trail type, was common to both the 6 pdr. and the 2 pdr. The

---

[1] See pp. 327–331.

17 pdr. was equally straightforward as far as design of gun and carriage was concerned: designs were approved in the summer of 1942. But the equipment weighed 3 tons (three times as much as the 6 pdr.) and its handling clearly raised tactical issues. As early as April 1941 the Commandant of the School of Artillery pointed out that 'it seems to relegate the piece to a purely static role owing to the size of the tractor which will be needed to haul the equipment, to the inevitable delays into and out of action, and to difficulties of concealment'. He added that 'the Germans have hit on a different solution, viz., a self-propelled and armoured mounting'. An obvious solution would have been to mount the gun in a tank in the orthodox way: the difficulties in the way of such a development have been outlined already.[1] Self-propelled mountings were in the air at the time; quite apart from German use of such equipments, it seemed essential to make use of the anti-tank potentialities of the 25 pdr. and the 3.7″ A.A. gun; the Field Artillery equipment had in any case been designed from the start to defend itself against tanks and was provided with solid shot; the 3.7″ gun was analagous to the 8.8 cm. German equipment which was for long the best anti-tank gun on either side. In the event only makeshift self-propelled artillery equipments were developed: a 25 pdr. on the Canadian Ram chassis being the first to appear, in 1943. The General Staff at the time had hopes of the United States 3″ A.T. gun mounted on either a T.1 or M.10 chassis, but by July 1942 it was clear that few of these would be available before 1943 and it was thus imperative to get a self-propelled mounting for the 17 pdr. Crusader was ruled out because investigations showed that little protection could be provided; Valentine was adopted (though the General Staff were not satisfied with it) as the best of two poor alternatives. At the same time work was started on an S.P. 17 pdr. mounted on one of the new cruisers (A. 30). In practice, the main self-propelled anti-tank equipment was the United States 3″ M.10, and a considerable number of these were converted to take the 17 pdr.

The preceding pages have traced in outline the policy behind A.F.V's and some of the main design and development projects adopted to meet that policy. It will be evident that the design resources which existed in the first months of war were inadequate to deal with the enormous volume of work entailed in the tank programme after Dunkirk. Many firms and official agencies have been named above which had no connection with A.F.V's in the rearmament period. We must turn therefore to a short account of the expanding resources of tank design before concluding this chapter.

---

[1] See pp. 345–346.

For a start, however, it should be stated how much more numerous the resources were even in 1940 than they had been at the start of rearmament. Instead of design being concentrated entirely in Vickers-Armstrongs, a number of other firms had considerable experience. Nuffield Mechanizations and Aero had been responsible for Cruiser Mk. IV and Crusader; L.M.S. Railway collaborated with the Mechanization Board to produce Matilda; Harland and Wolff had done much work on A.20. Moreover, by December 1940 tanks were being produced by nearly twice the number of assemblers who had been making deliveries a year earlier, while component manufacture was also on a broader basis. This diffusion in the knowledge of the problems of tank production could not but be favourable to an understanding of design problems. But this itself made it necessary to canalise the growing industrial (and operational) experience. It was consequently a wise step to create a Department of Tank Design, in place of the old Mechanization Board, on the recommendation of the original Tank Board.[1]

The change was, however, intended (like everything else in the hectic year after Dunkirk) to increase production and collaboration in design between the Mechanization Board and designing firms was not envisaged in the new arrangement. While responsibility for new designs lay ultimately in the Ministry of Supply, with the Director General of Mechanical Equipment (Design and Development) and his successors, the Department of Tank Design was a department for modifications in design rather than in design itself. While new projects were given to various firms, the Department of Tank Design rectified the faults in current production vehicles. This arrangement was formally laid down in January 1941 and subsequent alterations in headquarters nomenclature and responsibility did not alter it: design was, so to speak, split into two sections—one officer supervising activity in commercial design groups, the other being the Director of Tank Design. The point is worth stressing for it was very different from the normal arrangement in a government design department. It was not until the last months of the war that the Department of Tank Design designed a complete A.F.V.

The insistence on production in 1940 and 1941 made it proper to give even greater autonomy than in the past to the firms responsible for new development.[2] Production reasons are therefore behind the system of 'design parentage' which was characteristic of tank evolution during the war. It was assumed that a firm allocated to tank production would make a better job of its own designs, and could be expected to educate other members of the production group into the

---

[1] See p. 331.

[2] William Hornby, *Factories and Plant* (H.M.S.O. 1958), Ch. V.

new manufacturing problems involved.[1] That in the straitened circumstances of 1941 this was a wise attitude can hardly be disputed. Once quality considerations came to the fore again it was to be more questionable.

The first big accession of design resources came with Vauxhall's participation in Churchill. As noted already, design of this vehicle was intended to avoid any conflict with the existing tank programme.[2] Hence a firm not previously connected with A.F.V. production was selected. The choice justified itself: all the difficulties encountered in the bold development of a radically new machine were tackled by the firm with enthusiasm. Cruiser development naturally was undertaken by firms already connected with Cruiser production. Mechanizations and Aero (formerly Nuffield Mechanizations and Aero) were responsible for Cavalier and Leyland Motors (who delivered their first Covenanter in December 1940) produced the original design of what was to become Cromwell: the detailed design work of this tank was given to Birmingham Railway Carriage Co., where industrial capacity for production was to be found. The Liberty-powered version of this (Centaur) was undertaken by English Electric. Parentage was usually split up to cover the main sub-assemblies and the full degree of mutual aid within industry itself would be difficult to describe briefly. The following table of the 'Design Parent Organisation' as it stood in the autumn of 1942 may serve as an indication:

Description	*Cavalier*	*Centaur*	*Cromwell*
General	Mechanizations and Aero	Leyland Motors	Birmingham Railway Carriage Co.
Engine	Morris Engines	Morris Engines	Rolls-Royce
Transmission	Mechanizations and Aero	David Brown	David Brown
Suspension	Mechanizations and Aero	Leyland Motors	Birmingham Railway Carriage Co.
Tracks and Sprockets	Mechanizations and Aero	Leyland Motors	Leyland Motors
Turret and rotating platform	Mechanizations and Aero	Leyland Motors	Birmingham Railway Carriage Co.

The 17 pdr. tank (Challenger) was the work of Birmingham Railway Carriage Co. Leyland Motors were responsible for A.34 (Comet). Later projects were handled mainly by the firms already mentioned but valuable additional strength was given to development resources by the close association of Rolls-Royce with all new Cruisers. From

[1] Production 'parentage' was presumably the original concept: one firm leading a group making the same equipment. Design 'parentage', responsibility for a given project, was an extension of this.

[2] See p. 338.

November 1941 the experimental establishment of this firm at Belper worked full time on A.F.V's. Equally valuable help was provided, especially for tracks, armour and A.P. shot, by the metallurgical branches of the Armaments Research Department, by the technical branches of the Iron and Steel Control and by the principal steel firms.

The contribution of Vickers to war-time design was not as dramatic but should not be minimised. The firm was not only expert in producing tanks: it was also capable of gun design, a field which none of the other manufacturers of tanks could touch. Moreover Vickers was entirely self-supporting as far as design staff was concerned, while, at any rate in the early stages, technical staff had to be lent by the Ministry of Supply to the other firms engaged on tank design. In the long-run, though Valentine had proved a hardwearing and fairly adaptable A.F.V., it was outmoded and was never popular even in auxiliary roles, or as a self-propelled mounting. Harry Hopkins, the firm's light tank, was also in the end something of a side show. But in the H.V.77 mm. gun Vickers made a major contribution and could in any case feel satisfied that their pioneer work in armour, armament and suspensions should have proved capable of multifarious development in other hands.

Doubtless the tenacity with which Vickers modified Valentine in what proved in the long-run to be a vain attempt to keep the tank alive, was due to production considerations. Such preoccupations were felt by all tank designers who were also manufacturers. An irritation among the manufacturer-designers with the ups and downs of military requirements and with suddenly demanded modifications was particularly strong in 1940 and 1941. As one firm told the Ministry in July 1940, visits from 'these so-called experts' from the Mechanization Board 'give us a pain in the neck': the production department of the Ministry of Supply, largely staffed by industrialists, tried to obtain the final say in all changes to current production as late as August 1941. But more ambiguous than the relations of maker to designer, necessarily tense at the best of times, was the relationship of the parent firms to the Ministry of Supply and the Tank Board. Not unnaturally they resented being absent from policy making meetings at which their design work was considered and where their future programme of development might be upset. In September 1942 a group of heads of firms connected with tank design approached the Ministry of Supply with the suggestion that industrial representatives should attend Tank Board meetings.[1] The Minister of Supply had naturally to turn this suggestion down firmly; that it was made shows both the keenness of the firms

[1] Cf. remarks in Cmd. 6865, *War-time Tank Production* (1946), pp. 17 and 45.

involved and the somewhat confused thinking which derived from the 'parentage' approach to tank design.

The Minister in his letter to the tank manufacturers which has just been mentioned wrote that:

> It is the definite policy of this Ministry to use to the maximum extent possible the design facilities available in the various industrial establishments engaged on tank work and, as far as possible, to confine the Design Department to the role of consultant and as a source from which manufacturers can obtain advice and general information based on broad experience.

In fact the Department of Tank Design was growing steadily and, as the only body of technicians concerned with the whole of the tank programme, acquired by mere experience an ever more commanding voice in tank development. Apart from anything else the armament of the tank became the chief factor in design, and as all tank guns (except some of Vickers) were officially designed,[1] this naturally led to a greater official control of, and interest in, the turret and indeed the whole of the tank superstructure. 'Turretry'—like armour, stowage and a host of other 'factors in design'—became a matter of great expertise, and beyond the capacity of any single firm. Undoubtedly the Department of Tank Design was the main source of new design strength in the later years of the war. Its organisation and development is discussed elsewhere[2] and it is necessary in this context only to stress the point that any antithesis too sharply drawn between the Department of Tank Design and 'private' or 'industrial' sources of design is in some ways highly artificial. A considerable proportion of senior officers at the Department of Tank Design had been begged, borrowed or (so the firms themselves sometimes thought) stolen from commercial undertakings. Just as in earlier days the Mechanization Board had lent staff to design firms, so the reverse process strengthened the Department of Tank Design. Nevertheless, the connection between design and production remained when, towards the end of the war, the Department of Tank Design itself became the originator of a complete vehicle design, and it proved necessary to seek capacity for its manufacture, not in private industry, but in a state factory. This was, perhaps, a sign that in all but actual victory the war was over. The bulk manufacture of tanks of 40 tons or 50 tons or more was scarcely analagous with the peace-time pursuits of even heavy industry. We may conclude that in 1945, as in 1935, 'tanks were not a commercial proposition'.

---

[1] By the Superintendent of Design (later Chief Engineer Armaments Design), not the Director of Tank Design.

[2] J. D. Scott and Richard Hughes, *Administration of War Production* (H.M.S.O. 1955), Ch. XIII, Section (iii).

CHAPTER XIV

SPEED AND EFFICIENCY OF DESIGN

THE activity described in the previous pages had as its aim the evolution of equipment which would satisfy the quality requirements of the Army. The degree to which this was achieved is thus the proper test of the success of development, and calls for consideration here. So does the relationship between British equipment and German equipment, for it was the duty of the design agencies to advise on future development as well as to respond to expressed War Office demands. The validity of the resulting designs depends in great measure, however, on their being available in time to meet the tactical situation envisaged at the time of the original requirement; and, equally important, a design of virtuosity is useless unless it can be translated into the requisite quantities without serious strains on productive capacity and engineering technique. This chapter will therefore deal first with the speed of design and efforts to accelerate it; then with the efficiency of design (ease of manufacture, ease of maintenance and durability) of British equipments. Next the degree to which equipments corresponded with the original requirements of the Army will be considered and this will lead to a brief concluding section where the comparative merits of British and German weapons and the relative merits of the development organisations in the two countries will be discussed.

In the development of a new military store three major intervals can be distinguished:

(a) from original notion or need to formulation of General Staff specification;

(b) from General Staff specification to approval of pilot manufacture;

(c) from pilot manufacture to acceptance for bulk production.

The influences determining the duration of each phase vary enormously, and only the middle period of design work in the narrow sense —the production of mock-ups, pilots and production drawings— can to some extent be controlled by the degree of priority or urgency accorded to the project.

In peace-time the period of gestation preceding the issue of a General Staff specification was usually lengthy. This was due both to the uncertain nature of the war for which the equipment was intended and to severe financial limitations which made false starts extremely undesirable. The period of some ten years which preceded the specification of the 25 pdr. Field Artillery gun was a case in point, while hesitation over the re-equipment of medium artillery units was another illustration of War Office unwillingness to decide on a type in view of the dangers of asking for equipments which might not be satisfactory. Before the war the detailed processes of design in the second stage involved the preparation of a mock-up and detailed drawings for pilot manufacture: in artillery this was often done on a competitive basis, Vickers and the Superintendent of Design both submitting projects. In the case of an ordinary weapon this stage was comparatively uneventful; design was in the hands of one or other of two long established and competent agencies and, if need be, it could be fairly readily accelerated. With an A.F.V. on the other hand, it often happened that Staff requirements altered while drawing was in progress, or some component which was to be manufactured proved defective; then redesign was involved, more or less extensive as the case might be. Moreover, after 1930, design of A.F.V's was very often in the hands of firms new to the work and in any case less amenable to direction and less capable of being speeded up. The interval between manufacture of prototypes and approval for full scale production was occupied with trials and with design modifications undertaken as a result of user criticism. In peace-time, trials were very elaborate. The equipment was tested from every point of view, its performance in the narrow sense, its mechanical reliability, its hardiness and robustness in operation. Thus an artillery equipment would have firing trials to test its accuracy as a weapon and efficiency as a machine; gun and carriage would have travelling trials over all types of ground; and it might be subjected to prolonged exposure to damp and extremes of temperature; or tested for its ability to exclude sand, dust and water. A tank would be tested as a vehicle by extensive running; as a gun-platform by extensive firing; and in addition would be subjected to attack by artillery as a check on the strength of construction and behaviour of armour, as well as by small arms fire in order to check bullet splash; if intended for assault work it would also have to surmount an elaborate series of obstacles. Moreover during these trials expert field users collaborated to ensure that the equipment was suitable for normal regimental employment. In the case of competitive design both equipments were, of course, put through identical trials. The intention was to produce conditions as nearly as possible like the worst which the store might encounter in the field. Often faults were revealed which led to lengthy redesign or even outright rejection.

Some detailed notes on the development of particular stores will be found in earlier chapters. Some of this information must be briefly re-examined for the light it sheds on the time taken in development. The information for five important equipments of pre-war origin may be tabulated thus:[1]

Equipment	A First mooted	B General Staff Specification	C Pilots delivered	D Approved for production	E First produced	Total time Years A–D	B–D
25 pdr.	c. 1925	1936	1937	December 1938	February 1940	13	3
3.7″ A.A.	c. 1920	1933	1936	April 1937	January 1938	17	4
Boys A.T.	c. 1927	1934		May 1936	1937	9	2
Bren. L.M.G.	c. 1925	1931		June 1935	1937	10	4
No. 4 Rifle	c. 1920	1924		1935	1942	15	11
Infantry Tank Mk. II	?	1934		1938	September 1939		4
Cruiser Tank Mks. V and VI	?	1936		1939	November 1940		3

This table reveals very clearly the leisurely processes of pre-war design. In particular two points may be noted: the lengthy period between the first suggestion that a new equipment was needed and the issue of a concrete requirement by the General Staff; and the tendency for this formal requirement to coincide, in the cases quoted, with the start of rearmament. One may wonder, indeed, if the decisions on the 25 pdr. and the 3.7″ A.A. gun would have been arrived at so soon had not the re-equipment of the Army been a most urgent problem in the early 'thirties. It must be added, however, that the period which elapsed between approval and first bulk manufacture was in its way as important. The design of the No. 4 rifle was deliberately put on one side in 1935; but in the other equipments production was started as soon as possible and the interval thus to some extent reveals the suitability of design for production. This gap between approval and first production is, however, less significant in peace-time than in war-time, for most of the equipments mentioned were at first manufactured by firms who gave no special priority to war production, or by agencies (Vickers and Royal Small Arms Factory) which were specialists in such work. A further complication lies in the approval of Matilda, Covenanter and Crusader in 1938 and 1939 before design was in all ways completed: they were the start of the 'drawing-board orders'.

When we turn to the steps taken in war-time to reduce the intervals between the initiation of development and the completion of design we shall find it less useful (and in some cases impossible) to distinguish the completion of designs from first production, as a

[1] It is not always possible to say with exactness when a design was first considered.

result of the steps taken to accelerate the processes of design. Obviously the greater abbreviation was achieved in the first stage of all, the gap between the first notion of a new project and its formal requirement. In peace-time the situations for which new weapons were needed were hypothetical; in war-time they were actual. Hence the General Staff frequently formulated a requirement for a new store almost as soon as they were aware of the existence of a new tactical problem and, particularly with minor items of equipment, transferred the field demand to the Ministry of Supply with little hesitation. Even in the case of major assemblies, tanks, guns, ammunition, though there was (particularly in 1940 and 1941) a reluctance to upset the planned production of existing types, in all cases the time taken to express a quality requirement was very much shorter than it had been before the war. In practice what the War Office were doing was to take decisions on theoretical grounds in a way which they would not have done before the war, or at any rate before rearmament began. Nor during the war would the overloaded experimental facilities of the country have permitted the construction and physical comparison of all the guns considered from time to time for use in tanks, in the way that experiment and trial preceded pre-war decisions on types. 'Theoretical armament research' became indeed a recognised branch in the Armaments Research Department. Rather similar was the abandoning of 'competitive design': time and facilities did not permit of such extravagances. But this was for most stores the most that could be done to truncate the second stage in design, from General Staff specification to the ordering of pilots or prototypes. There was a physical limit on the speed with which even an expanded Armaments Design Department could work; 'priorities' got in each others' way and so did 'top priorities', while battle experience constantly flooded design directorates with small modifications of the very greatest urgency. Nevertheless, besides the ending of competitive design, there was one way in which economies could be effected: it proved possible to do a good deal of concurrent design on components which in peace-time would certainly have been designed successively; a gun in peace-time was usually designed before its carriage, while in war-time design of both went on together. This device of concurrent design was naturally most easily practised in the case of equipment consisting of major sub-assemblies, like tanks. The third stage, from production of prototypes to approval for production was cut short in two ways, which are closely related to one another. The number of prototypes ordered was considerably increased. At first this was done in the main to facilitate trials: instead of one equipment going from place to place while it underwent three or four different tests, several were ordered so that trials could all be conducted at the same time. Soon this was seen to have a further advantage in educating the producing firm in the details of the new store and in revealing at an early stage any aspects of the design which were not suitable for large-scale manufacture. These developments are found in the later stages of rearmament and in certain stores they naturally led to the 'drawing-board order', the most drastic step taken to expedite production of a new equipment. In its essence this consisted of approving an equipment for production before it was fully designed, let alone tested, so that the manufacturer would tool-up with the certainty that production would start. The 'drawing-board order' was only applied extensively to A.F.V's, and it is not clear whether it was regarded primarily as a means of expediting design as such or of introducing production at an earlier stage than would otherwise have been possible, or both. As already noted, with the passing of the quantity crisis in 1942 A.F.V's reverted to the system, never abandoned in other stores, of manufacture and testing of prototypes before production was authorised.

There can be no doubt of the saving of time which resulted from these steps, though the 'drawing-board order' failed to commend itself after the period of 'numbers at all costs' was over. Moreover, with the full industrial resources of the country available to the Ministry, the significant dates are not so much those which show the interval between specification and approval for bulk manufacture as those which show the whole process—from first mooting to first production. If we reconsider the above table exclusively from this viewpoint and add some significant items of war-time development, the full impact of the more urgent methods of war-time will be evident:

Equipment	*First mooted*	*First delivered*	*Interval in years*
3·7″ A.A.	c. 1920	January 1938	18
25 pdr. F.A.	1925	February 1940	15
6 pdr. A.T.	April 1938	September 1941	3½
17 pdr. A.T.	March 1941	August 1942	1½
No. 4 Rifle	1924	January 1942[1]	(say) 11
Boys A.T.	1927	1937	10
Bren	1925	1937	12
Sten	December 1940	December 1941	1
Polsten	June 1941	March 1944	2¾
4·2″ Mortar	1940	January 1942	2
Matilda II	April 1934	September 1939	5½
Covenanter, Crusader	October 1936	November 1940	4
Churchill	November 1939	November 1941[2]	2
Cromwell	July 1940	December 1942	2½

[1] See p. 331.
[2] See pp. 338–339.

For major artillery and small arms equipments the war-time development was thus five or six times speedier than peace-time development; although in the case of tanks the war-time pace was only double the pre-war, it should be noted that the pre-war examples quoted are all rearmament types, which were being produced far more rapidly than the light and medium designs under development prior to 1934.

Figures such as those quoted above are rough and ready and should not be pressed too far. When we turn to the question of efficiency of design the difficulties of establishing useful standards of comparison are even greater. Efficiency of design was defined above as including ease of manufacture, ease of maintenance and durability. All these qualities are closely connected and it was their close association which was to produce the criterion of 'reliability' in A.F.V. design which we have already had occasion to examine.[1]

If ease of manufacture was the main issue in weapon development armies would have advanced little beyond the sticks and stones of remoter times, and the German Army, always equipped with elaborate weapons, would have been penalised on that account in every campaign. In fact a study of the past reveals that military equipment becomes progressively more complicated; that each war sees a more determined effort to obtain victory by machinery; and that the lethal power at the disposal of a given number of soldiers grows greater as time goes on. This mechanization of warfare has, of course, been intensified in the last century in the wars fought between the principal industrial countries of the world and, the competition to enlist technology having begun, contemporary total war makes 'ease of manufacture' a very relative term. Even as early as the First World War the bulk of military equipment was commercially produced in the sense that the basic equipment of the armies prior to 1914 was already in regular peace-time production by the so-called 'armament firms' and others; but in the construction of tanks and gas warfare equipment there was a distinct trend towards weapons for the manufacture of which special facilities had to be developed. This tendency to 'uncommercial' military stores was greatly intensified during the 1939–45 war, while even the manufacture of weapons previously regarded as conventional—guns, gun carriages, ammunition of all types—presented grave production problems as a result of the decline in Britain of firms specialising in armament production and the consequent necessity of placing a great deal of production in the hands of non-specialist undertakings.[2] Nevertheless, it is obvious that a design should not

---

[1] See pp. 323–324.

[2] On the dispersion of British war production, see M. M. Postan, *British War Production* (H.M.S.O. 1952), Ch. VIII.

make demands on the technical resources available for its production greater than is absolutely necessary: other things being equal, a store should be readily manufacturable in proportion to the quantities in which it is required; the extreme care taken in the design of the No. 4 rifle in the pre-war period that it should be simple to produce in bulk shows how the principle was applied to a basic store. The essence of the ambiguity in ease of manufacture is, of course, that a design may present difficulties to one firm or in one country and yet be accommodated simply enough elsewhere: in such a case the design has to be altered or production resources have to be modified; for some varieties of the super-velocity anti-tank ammunition in service by the end of the war completely new and specially developed production facilities had to be provided. In most cases, however, equipment was produced by relatively small adjustments to either design or manufacturing resources. It may well be that in practice it was alterations in productive methods which were more influential in securing satisfactory output than alterations in design. The two factors are in any case closely connected.

The only available indexes for the comparison of weapons from the viewpoint of ease of manufacture are man-hours and costs. The use of man-hours as a guide can mislead since it obscures the relative efficiency of various firms, does not indicate raw material shortages or limitations due to plant, the supply of standard components (e.g. ball bearings) or specialised production capacity (e.g. drop forgings); moreover it cannot be applied to tanks. Cost, on the other hand, though available for tanks, is always only approximate and in any case reflects so many factors involved in manufacture that it reveals ease of production even less accurately than man-hours; while in the case of stores where the system of free issues prevailed, it can be computed only with difficulty if at all.[1] In what follows man-hours will be used as a basis for comparison, except for tanks where cost must be employed; and a separate note will deal with raw materials.

There are really two points for investigation. First, how far were existing designs modified to secure economies in production? Second, how far were new designs easier to produce than older designs? A rapid indication of the answer to the first question may be found in the following table:

	Man-hours Original Mark	*Man-hours* Later Mark	*Saving* %
40 mm. Bofors A.A.	2,420	1,500	38
Sten . . .	11	5½	50

[1] On free issues, see M. M. Postan, *op. cit.*, pp. 411–416.

It must be stressed that these simplifications were not obtainable in all similar equipments; and frequently a reverse process took place when Service demands for increased performance in special roles might involve a marked rise in the time of manufacture: Mk. V Sten, for instance, took twelve man-hours, or slightly more than Mk. I. But on the whole as the war progressed there were some remarkable savings in production due to modifications in design, particularly in small arms, where the great quantities required made it especially advantageous: a saving of 25 per cent. was achieved with the Bren and of about 14 per cent. with the Besa; while the most remarkable advance was secured with the Polsten, designed for the Army in place of the very elaborate Admiralty Oerlikon gun.[1] As for the second problem, the time of manufacture of certain basic artillery equipment is a useful guide:

Gun and carriage	*Man-hours*
25 pdr. F.A.[2]	3,085
2 pdr. A.T.	2,682
6 pdr. A.T.	1,293
17 pdr. A.T.	2,726

There are impressive figures: the 6 pdr. took about half the time needed to manufacture the pre-war 2 pdr.; and the 1942 17 pdr. was more economical in man-hours than the 25 pdr. with which it is strictly comparable. These figures are all the more revealing when it is remembered that, generally speaking, war-time manufacture tended to be in less specialised firms than was the case in the pre-war period, and the results indicate those advances in 'design for production' referred to above.[3] The cost figures which we must consult to obtain similar light on tank development, while defective as noted, are nevertheless worthy of study:

Basic Cost Price of Tanks[4]

Year of 1st order	*Type*	*Approximate weight (tons)*	*Basic cost price (Contracts) £s*
1937	Infantry Mk. I	11	6,000
1937	Cruiser Mk. I	13	12,710
1938	Matilda	25·75	18,000
1938	Cruiser Mk. II	14	12,950
1938	Cruiser Mk. III	14·25	12,000

1 Number of components—Polsten 119, Oerlikon 250; of machining operations—Polsten 900, Oerlikon 3,000; cost—Polsten £60–70, Oerlikon £320.

2 Not including the trailer.

3 See pp. 266–267.

4 To a considerable extent these are 'estimated' not real costs. Original prices are quoted but costs were later scaled down in cases where production went on for some years (Matilda, Valentine, Crusader and Covenanter).

Basic Cost Price of Tanks—continued

Year of 1st order	*Type*	*Approximate weight (tons)*	*Basic cost price (Contracts) £s*
1939	Cruiser Mk. IV	14·75	13,800
1939	Covenanter	15·85	12,000
1939	Crusader	17·53	13,700
1939	Valentine	15·6	14,900
1940	Churchill	38·5	11,150
1942	Cromwell	28	10,000

Bearing in mind the increasing complexity of tank design, the uncertainties in policy and the fall in the value of the pound between 1937 and 1942, the table indicates that Churchill and Cromwell were infinitely easier to produce than the A.F.V's of early rearmament days—even allowing for the higher costs of tanks produced (as the 'interim' Infantry Mk. I and Cruiser Mks. I–IV were) in small numbers. That this trend may reflect the types of industrial capacity involved is the essence of the point: it was often claimed that the designs of the older heavy-engineering firms were found difficult to manufacture by more up-to-date enterprises, and it is reasonable to suppose that Nuffield's or Vauxhall's designs were more closely related to modern production techniques than were Vickers'. The weight/cost ratio shows that the increases of material in tanks (mainly armour) were not reflected proportionately in costs; if, as seems likely, the weight of a tank is in direct proportion to the man-hours involved in its construction, the 'manufacturability' of tanks can also be shown to have progressed. There were, however, powerful forces pulling in the opposite direction; attempts to secure easy production led sometimes (as in the case of Churchill) to vehicles so defective that reworking (not allowed for in the table above in the case of either Covenanter or Churchill) had to be undertaken; while modifications to Crusader, equally not shown above, were legion, as we have seen.

Any design could be made impracticable by raw material shortages. How far did designs improve between the start of rearmament and the end of the war in respect of the demands they made on materials likely to be scarce? This was a problem not likely to be overlooked in pre-war planning and the Supply Board constantly reminded Service departments of the need to use materials readily available in war. Most General Staff specifications of the rearmament period stipulated that certain materials should not be used, and a very great deal of research was directed towards substitute materials, such as bakelite instead of wood in rifle 'furniture'. But the pre-war planners fortunately had limited prescience and did not impede the pneumatization of the army, for example, because of the possibility that

Malayan rubber might not be available. In the event, the greatest single problem of war-time was to be the conservation of alloying elements in steel. With the detailed steps in securing economies we cannot concern ourselves; nor is it possible to compute the savings involved. But the following figures are significant when one recalls the vast amounts of steel consumed in guns, tanks, ammunition.

Alloys in Certain Stores: Changes 1939–43

Alloy	Homogeneous Armour Formerly	Homogeneous Armour Later	A.P. Shot Formerly	A.P. Shot Later	Artillery Forgings Formerly	Artillery Forgings Later
C	·26	·27	·57	·75	·38	·40
Mn	·80	1·10	·80	1·50	·75	·90
Ni	3·50	·30	·25	—	1·85	1·45
Cr	1·50	·30	·98	1·00	·75	·65
Mo	·40	·26	·22	—	·25	·25
Si	—	—	—	·45	—	—
Va	—	—	—	—	·10	·03

Here again, it might be necessary to use considerable quantities of a difficult material if an operational demand made it essential, as tungsten had to be employed in the super-velocity projectiles.

The factors of ease of maintenance and durability are both essentially quantitative: one faulty gear box or gun mounting is neither here nor there; a 'chronic' weakness can imperil an army. Ease of maintenance was a feature for which full provision was made in the elaborate trials of pre-war development. At the mock-up stage and later with the prototypes, the user was able to consider equipment in order to locate difficulties in handling and maintenance. This rigorous control was kept up with weapons as a whole, but was abandoned for a time in A.F.V. development. The results of this were that ease of maintenance was often claimed to be totally absent from British A.F.V's: 'American tanks are easier to maintain'; 'the Grant engine could be replaced in a fraction of the time taken to replace a Crusader engine'; the German system of unit assembly was widely admired. The inaccessibility of the Crusader engines and joints in the engine lubricating system added to difficulties in the field, since it proved essential to run in all new Crusaders in the Middle East before issue to units; provision of spare parts was chaotic because in tanks ordered 'off the drawing-board' spares requirements had been calculated by analogy with other vehicles and not from trials. As far as durability is concerned (the degree to which equipments may be relied on to stand up to physical tests of their endurance), this again was more or less adequately assessed in the trials which preceded the approval of small arms and artillery weapons, and in these cases attempts to shorten the development process had no evil consequences. But in A.F.V's it was precisely the absence of such safeguards which produced the reliability crisis of 1941–42: components in practice were shown to have a short life or, as we have seen, to behave in battle conditions and in a vehicle very differently from their record on the factory bench. For example, nothing is more significant than the unexpected effects on A.F.V's of the desert in North Africa: the conditions which wrought havoc with engines proved favourable to tracks and steering mechanisms, since relatively little steering was needed, and these components had a much longer life than had at first been estimated. In both ease of maintenance and durability a further factor must be mentioned. As the war went on the mechanical aptitude and experience of tank crews tended to decline: the drivers and other members of tank crews trained before 1940 were far more expert in getting the best out of their vehicles; this undoubtedly accounts in part for the high reputation acquired by Matilda. More than once tank development firms complained that perfectly sound designs of vehicles were being condemned for what was, in the last resort, defects in the quality of the crew rather than the tank. But the War Office could rightly answer that it was their job to produce 'good soldiers not merely good mechanics' and point to the popularity of General Sherman with the troops.

Apart from tanks, however, it may be stated confidently that efforts to shorten the time of evolution of new equipments did not have any bad effects on the finished store. Even in the periods of greatest stringency designs were still marked by great finish and the 'Rolls-Royce' appearance of weapons was sometimes adversely criticised, though the troops preferred this and never ceased to refer to the very high grade turn-out of German equipment, where few manufacturing relaxations seem to have been tolerated. It is of course true that many of the less orthodox weapons, developed by unorthodox agencies, were at first both unkempt to look at and excessively difficult to manufacture (the S.T. grenade, for instance);[1] but these difficulties were put right and such stores were soon in fit state for manufacture and field supply. Even in the case of A.F.V's there was a marked improvement towards the end of the war, when the full rigour of development trials and tests had been re-imposed.

It is not possible to present a simple balance sheet of staff quality requirements and actual responses in terms of designs. Prior to 1942 there was no overall review of the quality requirements of the Army; and the review carried out in that year produced during 1943 a series of requirements the satisfaction of which falls only partly within the period of hostilities. Before 1940 the 'General Staff specification' was issued by the Chief of the Imperial General Staff's

---

[1] See pp. 267–269.

Specification Committee, which met to consider a draft specification prepared by the technical director concerned (Director of Artillery or Director of Mechanization). The draft as revised by the meeting was the 'General Staff specification'.

In small arms design we may take as examples the Bren gun and the Boys A.T. rifle. In the Bren the weight was slightly higher, the rate of fire and range slightly lower than the General Staff specification required; with the A.T. rifle an almost complete identity between specification and performance was accomplished. The Field Artillery specification was also met fully, except that the equipment was slightly heavier than the requirement—a result very largely of the greater range achieved during development to meet a subsequent request by the Staff. In medium artillery the Staff were undecided, as we have seen, but ultimately requested a '4.5″/60 pdr. with 55 lb. shell, range 20,000 yards and a 5″ gun/how., with 78 lb. shell, range 18,000 yards'. This policy was similar to the conversion of the 18 pdr. and provision of a new 25 pdr. pursued in Field Artillery and led, as we have noted above,[1] to a complicated development story. In the event the equipment produced was the 4.5″ gun and the 5.5″ gun/how. The 4.5″ gun exactly met requirements and the 5.5″ gun/how. ultimately tallied closely with the General Staff specification when in 1942 it was provided with an 82 lb. shell ranging up to 18,500 yards in place of the 100 lb. shell which ranged up to 16,000. Heavy artillery was considered by the Committee in 1938 and a gun and a howitzer were both specified. In the event the gun project was dropped, and the howitzer alone was developed:

General Staff Specification	*7.2″ How.*
1. Projectile—300 lbs.	1. 202 lbs.
2. Calibre—7.85″	2. 7.2″
3. Range—16,000 yards	3. 16,600 yards
4. Mounting—common to the new gun as far as possible.	4. Fitted existing 8″ how. carriage.

This was markedly different in projectile weight, but it is the main exception to a general success in meeting the specifications in the small arms and artillery equipment here considered. As we have seen A.A. guns were developed more hastily and the General Staff specification procedure was hardly appropriate;[2] the A.T. gun (2 pdr.) was of course the existing tank gun.

In A.F.V. specifications a notable success was the design of the Daimler Scout Car, which completely met General Staff requirements, but with tanks in the narrow sense the story is less cheerful.

---

[1] See Ch. XI for further details of artillery and small arms development.
[2] See Ch. XII.

We may perhaps omit from consideration the projects for light, medium and 'close support' tanks, discussion of which held the stage till 1934, and concentrate on the 'new tank for co-operation with infantry' which made its appearance in 1934. The infantry tank, debated at length between 1934 and 1936, finally culminated in a formal specification, and with this the resulting tank, Matilda (Infantry Mk. II) may briefly be compared:

General Staff Specification for A12E1	*Matilda*
1. Armament: 2 pdr. and 3.03″ M.G.	1. 2 pdr. and 7.92 mm. Besa.
2. Armour: 70 mm.	2. 70 mm. sides; up to 78 mm. front.
3. Speed: Minimum 15 m.p.h.	3. 15 m.p.h.
4. Weight: Maximum 20 tons	4. 26.5 tons
5. Circuit: Minimum 50 miles	5. 160 miles

Only in its weight did Matilda fail to correspond with the stipulated conditions. The close correspondence achieved is of considerable interest when the originality of the tank is remembered and its relative effectiveness as an A.F.V. The cruiser requirement of 1936 cannot be neatly matched with Covenanter and Crusader which purported to answer it. Throughout General Staff policy changed; and detailed examination would only reveal the hesitant attitude which in the end led the staff to demand more or less what they were told they could expect to get.

During the war such new basic artillery and small arms equipment as was developed in time to see action was, as already indicated, not developed against a General Staff specification in the proper sense of the term. That is to say that the process which gave the Army the 6 pdr. and 17 pdr. A.T. guns, the 6 pdr. A.A., the 4.2″ mortar and so forth, did not begin with the General Staff formally expressing a requirement for a weapon of given performance. What happened was that the tactical situation demanded fresh equipments: these were developed by technical directorates and approved by the General Staff. The 6 pdr. was offered to the War Office after it was designed; the 17 pdr. arose from an enquiry from the Tank Division of the Ministry of Supply and the 6 pdr. A.A. from a request from the General Officer-in-Charge, A.A. Command. Only with the formation under the Deputy Chief of the Imperial General Staff at the War Office of new weapon directorates did the Staff again revert to systematic statements of weapon policy. These were to lead to long-term investigations in both field artillery and small arms. In A.F.V. development they had more immediate repercussions.

War Office representatives on the Tank Board were, of course, fully responsible with the officials of the Ministry of Supply for tank policy from 1941 onwards. But for some two years this collaboration produced no general statement of requirements and only in September 1942, as a first fruit of the Deputy Chief of the Imperial General Staff's re-organisation, did a comprehensive tabulation of future policy emerge. Several aspects of this have already been discussed above[1] and here we must scrutinise only the War Office request that the standard type of future A.F.V. should be a medium cruiser, the common basic assembly from which special types of A.F.V's should be constructed. If the A.F.V's which saw action in the later stages of the war are surveyed it will be evident that this plan was far from being carried out. British troops were equipped with General Shermans (17 pdr. and 75 mm.), Cromwell (75 mm.), Challenger (17 pdr.), Comet (77 mm.) and Churchill (75 mm.). It is true that the Cromwell, Challenger and Comet tanks were all generally related, suspension, transmission and power unit were common and all 'reasonably hard and fast'. But a heavy version of Cromwell had proved impossible, an up-armoured Churchill having to be accepted instead; and in the self-propelled and other special roles modified 'obsolescent' tanks, Valentines and Crusaders, were employed, together with American vehicles. Thus the General Staff requirements of 1942–43 had not been met by the end of the war so far as tanks were concerned; and the same is true of armoured cars and carriers.

In short, both before and during the war the Army's quality requirements for weapons were met, broadly speaking, as far as artillery and small arms were concerned, but they were not met so far as tanks were concerned. That the coincidence of finished store with General Staff specification was so complete in artillery and small arms was doubtless due to the formulation of the draft specification by the Director of Artillery prior to the expression of the staff requirement: in a sense the Staff were asking for what they were likely to be given. This method of the technical director telling the General Staff what to specify was, no doubt, 'hay-wire', in the Director General of Artillery's phrase; but it seemed to work. With A.F.V's, on the other hand, the General Staff seemed to have stated their requirements—more correctly, perhaps, in theory—on *a priori* grounds and with a minimum of advice from the Director of Mechanization. In any case, after 1930 there was no official tank design organisation to collect and correlate basic technical information, while the Mechanization Board never had the resources, the experience or the status of the Ordnance Board. In the event, as noted above, the General Staff were compelled to take what they could get—as for instance they accepted Valentine, though it corresponded in no sense with their expressed requirements—which

---

[1] See Ch. XIII.

was a very different thing from asking for what they could expect to be given. In the first two years of the Second World War the specifications tended to dry up; when resumed in 1942 and later, they were often expressed in more general terms than before the war. So far as A.F.V's are concerned, the specifications then became a subject of debate by the Tank Board and gradually there evolved a more close harmony which produced an arrangement where War Office requirements for tanks were based, as of old their artillery requirements, on accurate and qualified advice. In this the Tank Board could and did attempt to look ahead, and in this too they resembled the Director of Artillery (later Director General of Artillery). This officer had been responsible in War Office days for not only meeting but also anticipating the trends of Staff policy: he had to have the 6 pdr. ready, for example, before the General Staff were ready to ask for it. Both the artillery and tank directorates were ready with the 17 pdr. T. and A.T. gun in advance of Army requirements, a significant point, for the gun was to be urgently needed at the front when it was finally in production.

At any rate until the recreation of weapon directorates in the War Office in and after 1942, it was the job of the technical directorates to be aware of trends in enemy design; even after this reinforcement of the weapon policy departments of the War Office the designer remained an essential source of new notions, not merely the executor of Staff policy; and throughout technical officers from technical directorates in the Ministry of Supply were appointed to armies in the field with the special task of reporting back on both enemy and British equipments. Thus the Ministry of Supply technical departments must share with the General Staff the responsibility for the success or failure of British equipments in the field.

The material for a summary comparison of certain basic British and German weapons has already been given in earlier chapters.[1] From this it may be stated that in artillery as a whole there was little to choose between British and German equipments, although the former were uniformally heavier than the latter. The same equality is roughly true of small arms, though the German 7.92 mm. M.G.42 was a versatile weapon—almost as light as the Bren, more effective in range and rate of fire than the British medium M.G.; of infantry weapons only the mortars were markedly inferior to comparable German equipment, though it may be added that the Germans had better infantry anti-tank weapons of the Bazooka type. In anti-aircraft artillery, which must be compared with contemporary enemy bombers, the British equipment must again be given a good

---

[1] See Ch. XI, Field Artillery and Small Arms, pp. 270–274 and Ch. XII, Anti-Aircraft, p. 298 (cf. note on mortars, pp. 298–301). The difficulties of weapon comparison in Chapter X should also be remembered, see p. 248.

report, though in the field the 3.7″ A.A. gun remained sensibly heavier than the German 8.8 cm. This German gun, also designed for the anti-tank role, proved one of the most successful and versatile of enemy weapons and was for long the main problem encountered by British armour. In the A.F.V. comparison there was, it must be admitted, far less success. Though the deficiencies revealed during the French campaign of 1940 were primarily quantitative rather than qualitative, there is no doubt that for the rest of the war Germany had the advantage: Pz.Kw.III and IV proved capable of advances in armour and armament which regularly embarrassed British commanders; the later tanks, Panther and Tiger, were proof against attack by all British A.T. guns at normal ranges, except the 17 pdr. which, as one observer wrote, 'arrived just in time'.[1] The 17 pdr. with super-velocity ammunition mounted in General Sherman tanks was the best British equipment in the last stages of the war and, of course, does not bear direct comparison with Panther (long 75 mm. gun, 80 mm. frontal armour sloped at 55°, front of turret 110 mm.) or with Royal Tiger (88 mm. gun, 150 mm. frontal armour sloped at 50°, 180 mm. turret front). But, in a sense, such direct comparisons are somewhat unreal. Panther was manoeuvrable enough, but Royal Tiger was not, and the speed and reliability of 17 pdr. General Sherman, with its effective if makeshift main armament, was perhaps more useful to the Allied advance than slower, more powerfully armed and armoured vehicles might have been. Certainly it was reported that 'if Rundstedt had been equipped with British armour when he attacked in the Ardennes on 16th December 1944 he would have reached the Meuse in thirty-six hours, which would have placed the Allies in a very awkward position'. The lack of effective British self-propelled equipments cannot, however, be denied.

The sustained competence of German design suggests some concluding reflections on the development organisations of Britain and Germany. Considerations of German weapon design still await the final verdict of historians,[2] but certain advantages she possessed seem clear enough. First, by depriving Germany of all overseas commitments the Allies limited the tasks which any recreated army had to face: no India or Africa complicated her strategy or put a brake on re-equipment policy. Second, as a defeated power she had every inducement carefully to consider the causes of her failure and to apportion blame to faulty weapons among other factors. Third, a sense of grievance and a traditional respect for large-scale enterprise facilitated the rapid reconstruction of a massive private armaments

---

[1] See *Royal United Service Institution Journal*, Vol. XCI, No. 561, February 1946, 'Tank and Anti-Tank', by Brigadier R. M. P. Carver, C.B.E., D.S.O., M.C.

[2] See, however, the well-informed article in the *Economist*, Vol. CLI, No. 5390, 14th December 1946, pp. 942–943, 'British and German Tanks'.

industry.[1] Fourth, as the aggressor she could plan with complete freedom of action for the sort of war which best suited her and development resources could be planned accordingly. Finally, with no official hesitation or compunction about 'rearmament' expenditure' a technique of ordering large numbers of prototypes was pursued which was to result in the stabilization of tried designs—particularly in the series of tanks (Pz.Kw.I–IV) in development before the war.

Even after the start of the war these general advantages stood Germany in good stead so long as she retained the initiative—that is to say, until the end of 1941 when her campaign in Russia failed in its objective. From then onwards German strategy became increasingly defensive, and this is reflected in weapon development. The initial start which Germany enjoyed prolonged its effects, especially in weapon development. In certain spheres (aircraft, radar) British design was markedly ahead, but this is not true, as we have seen, of purely military stores.

It was on the private armaments firms, larger, more numerous and better equipped than anything available in Britain, that the German Government relied in the main for armament development. The development agencies of the *Wehrmacht* itself were intended merely to co-ordinate staff requirements with industrial sources of design and to progress work undertaken by private firms. There were no German counterparts to the Armaments Research and Design Departments; there was no equivalent in Germany to the Department of Tank Design. It cannot be said that this reliance on commercial sources of design was misplaced. The heavy engineering industry of Germany was well able to cope with the weapons and A.F.V's developed for the Army. Effectively there were no labour or machine tool shortages, at any rate before the closing months of the war, and German equipment scarcely at all reflects any concessions to 'ease of manufacture': to the end much of it was highly elaborate and difficult to produce. As for speed of design, the above pages tell their own story—a parity in most artillery and small arms stores, a marked success by Germany in the race between mortars, A.T. guns and A.F.V's. It seems that the durability of some German equipment (notably tanks) may have been somewhat less than in comparable British types of equipment: this was offset by a far more extensive and efficient field repair and recovery organisation.

Nonetheless, as the military strain in Germany increased during 1942 and 1943, a start was made on a more rigorous organisation of development resources, for the system described above was full of

[1] The German Government was, of course, financially interested in a wide sector of the 'private' armaments industry.

wasteful reduplication of effort, overlapping of development projects and unused design and research facilities. When a tightening up accordingly became necessary it was accomplished laboriously and inefficiently. The harnessing of German academic scientists, for instance, was cumbersome and lethargic; later in time than the mobilisation of research workers achieved in Britain, it was far less happy and productive in its results. Moreover, in weapon development proper there was a marked tendency in Germany in the later years of the Second World War to create official design organisations rather than rely on private sources of design. Germany, too, was finding 'uncommercial' the complex and unorthodox machines called for by modern war.

PART III

RADAR

CHAPTER XV

THE DEVELOPMENT OF RADAR

(i)

The Origins of Radar

It was in 1934, a year in which British anxiety at the spectacle of Nazi Germany began to break out at many different points in practical measures, that the Secretary of State for Air, Lord Londonderry, set up a committee of scientists under the chairmanship of Sir Henry Tizard to investigate the possibilities of countering heavy air attacks.[1] The committee began its work by making a general survey of the problem of air defence in all its aspects. This measure, as it proved, was to be momentous and historic, but the committee's first step now seems almost fantastically unreal, and its second curiously accidental. Its first was to investigate a death ray; its second to act as accoucheur at the birth of radar. Methods of detecting the position of enemy aircraft were discussed at the first meeting, and among these methods was the use of radio waves, discussed in consequence of a memorandum on the possibilities of the so-called death ray, which had been prepared at the request of a member of the committee by Mr. (later Sir Robert) Watson-Watt, Superintendent of the Radio Department of the National Physical Laboratory. The committee was probably not deeply impressed by the possibilities of the death ray, but it was interested to have some figures of the amounts of electro-magnetic energy which might be involved. Mr. Watson-Watt had had no difficulty in producing figures which relegated the death ray itself once again to the realm of fantasy, but having done so he made the counter-suggestion that it might be possible to detect aircraft by radio waves. At the committee's invitation Mr. Watson-Watt pursued this idea in a second paper on the 'Detection and Location of aircraft by radio methods'. In this celebrated paper he set out the principles upon which the technique of radar is based.

For some ten years before 1934 scientists had been studying the properties of the ionosphere, that is the region of the atmosphere lying between 60 and 500 miles above the earth's surface. The peculiarity of this region is that the air in it is highly ionised, that

[1] Committee for the Scientific Survey of Air Defence.

is to say that many of the molecules have lost an electron and become positively charged. The result of this ionisation is that the highly rarefied air of these upper regions is partly conducting and accordingly will not allow a free passage to radio waves (electromagnetic waves whose wavelength is long compared with light or heat waves) such as is allowed by the non-conducting air in the lower layers of the atmosphere. The extent to which the free passage of radio waves is impeded by the ionosphere depends on their wavelength; broadly speaking all waves of length greater than ten metres are reflected by one or other of its ionised layers. The ionosphere concerns us because of the technique most commonly used for investigating its structure and properties. In this technique, very short pulses of radio frequency energy are transmitted upwards by a wireless transmitter; these pulses are reflected by the ionised layer, and the returned pulses, or echoes, are recorded by a receiver adjacent to the transmitter. The receiver also records the direct pulse from the transmitter and is equipped with devices for measuring the interval of time elapsing between the arrival of the direct and reflected pulse; since radio waves travel with a constant known speed, this time interval is proportional to the distance over which the echo has travelled and hence to the height of the ionised layer.

Mr. Watson-Watt had also developed cathode ray tube methods of studying the electrical effects of lightning discharge and hence of following the movement of thunderstorms. The possibility which now suggested itself was that of applying these techniques to the detection of aircraft. His second memorandum outlined broadly the general shape of radio-location development during the next two years. The basic calculations mentioned are given with the comment that they show that the echoes to be expected from aircraft at ranges of about 10 miles, flying at heights of about 20,000 feet, should be about 10,000 times stronger than the minimum required for measurement.[1] A radio wavelength of 50 metres was assumed in making these calculations, partly because it was expected that the average aircraft wing would resonate at about this wavelength and partly because the pulse technique for it was well established at the National Physical Laboratory. The memorandum proposed that the volume of sky to be kept under observation should be 'floodlit' with radio waves; it did however mention the alternative method, which later superseded floodlighting, of using a beam of radio illumination.[2] The floodlighting method was preferred because it would be simpler to

---

[1] This implied the probability of obtaining ranges of 100 miles or more.

[2] Certain terms more usually associated with the use of visible light are commonly used, with the same meaning, in radar practice, and will be so used here without further explanation unless there seems to be an ambiguity.

develop. Mr. Watson-Watt later stated that the choice of floodlighting was the essence of R.D.F.;[1] the British were the only one of the combatants to use this system. The memorandum pointed out that the position, in three dimensions, of an aircraft could be determined by the measurement of its range from three separated receiving aerials and that a line (or chain) of stations would permit this to be done over a long front. A rudimentary method by which friendly aircraft could be identified was proposed as an aid to controlling interceptions from the ground when both fighter and bomber were located by radio.

An historic experiment was made on 26th February 1935, when an aircraft, flying in the 50 metre beam from the B.B.C.'s station at Daventry, produced a detectable echo in the receiver when it was eight miles away. It was a rough demonstration of the distance at which an aircraft would produce an echo, the distance being determined from the known position of the aircraft. The fact that aircraft would reflect continuous radio waves was already known, but no measurements had ever been made of the range at which the reflections could be detected.

The demonstration was more than promising; it was epoch-making, and the Director of Scientific Research at the Air Ministry at once took steps to provide facilities at Orfordness for the intensive study of this means of locating aircraft.[2] The objects of the research were, first, the determination of the approximate positions of hostile aircraft at the maximum possible range, and later the more-or-less continuous determination of the three-dimensional positions and movements of hostile and defending aircraft under all conditions of visibility, and the control of A.A. guns. The Tizard Committee took the occasion of expressing its strong faith in R.D.F., and said that within five years at the most it would be able to set interceptor fighters on to all aircraft at about 60–100 miles from the coast; they thought it likely that radio-location would ultimately supersede sound location in A.A. gunnery.

Preparations for setting up a research station at Orfordness[3] were not completed until the middle of May, but the intervening period was fully occupied by the construction at Slough of a pulse transmitter, giving much higher power (20 kW.) and shorter pulses (10–50 microseconds) than had hitherto been used in ionospheric investigations. Modified ionosphere receivers were used to accommodate the shorter pulses. A demonstration given to the Secretary

---

[1] R.D.F. was a cover intended to delude the enemy, if they became aware of it, into believing that it stood for radio direction finding.

[2] See Chapter XVII.

[3] Treasury sanction for the expenditure on the scheme of £12,300 in the first year was obtained on 13th April 1935.

of the Committee, Mr. Rowe, a month later, showed a great advance, ranges up to 67 km. being obtained. The wavelength used in the demonstration was 26 metres.[1]

Activity at Orfordness covered the period from May to the end of July 1935. Mr. Watson-Watt summarised the position in a third paper in which he pointed out that increased ranges should be obtained by using higher aerials, as well as by improving the equipment in other directions; he suggested using 200 ft. masts, preferably on cliffs or hills. He touched on the strategical use of the system, proposing a chain of radio-location stations made up of transmitting stations at about 20 mile intervals with receivers at alternate stations. He also referred to the possibilities of beam illumination and of very short wavelengths (2–10 metres or even lower), the latter especially for detecting low-flying aircraft and ships; he urged that this work should not hinder the development of the longer wavelength flood-lighting system since that alone could be expected to be in operational use quickly.

The second phase of the Orfordness activities covered the development of means for measuring angles of elevation and bearing from a single station. This was important because up to then such measurements had required two stations, and a complex system of communication between them. In the autumn of 1935 Mr. Watson-Watt suggested that bearing should be determined from the receiver by using a stack of crossed dipoles and a radio-goniometer. This suggestion immediately bore fruit and Mr. Watson-Watt told the Tizard Committee in December that he was prepared to incorporate direction-finding in the first part of the chain, which it was now proposed to erect in 1936. Hitherto he had thought it to be two years away because of the insensitivity of previously existing direction-finding systems. The development of new methods of finding direction and height led to a complete modification of the view of what the chain should consist of, since by their use any station which consisted of a transmitter and receiver could determine completely the three-dimensional position of an aircraft, and the final chain was therefore made up of transmitter-receiver stations each passing complete plots to the Fighter Command interceptor organisation which was now being built up to take full advantage of R.D.F.

By the summer of 1935 the original R.D.F. early warning device had reached a fairly advanced stage of development. The idea that the stations should form a coastal chain was already accepted, and it was appreciated that the provision of cover for any stretch of coast

---

[1] On 25th July 1935, the Sub-Committee on Air Defence Research agreed that the experiments had already produced results to justify the initiation of executive action on the radio method of location and detection.

required the installation of one R.D.F. station for every twenty miles of its length. It was upon this basis that the Air Council decided to proceed. As cover was required from the Tyne to Southampton, twenty stations had to be built. This project, for twenty stations covering the East and South-East coasts, came to be known as the Home Chain, and the stations in it as C.H. (Chain Home) Stations; its construction dominated the development and production of R.D.F. equipment until almost the outbreak of war. The Home Chain was a strategical commitment of the first order; even as a financial commitment the estimated million pounds was a formidable one in pre-Scheme F days.

The Air Council therefore decided that construction should be undertaken in two stages, and that the first stage should comprise a chain covering the Thames Estuary, which should be used for large-scale tests of the system and would form the nucleus of the complete chain. This proposal involved the provision of five stations between Southwold and South Foreland. Only four sites were referred to because the fifth station was to be at Bawdsey, which it had now been decided was to be established as a research station and the headquarters of the chain, and for which separate Treasury approval was obtained.

Bawdsey was still the only complete station when, in June 1937, almost a year after the target date, the Deputy Chief of the Air Staff raised again as a matter of increasing urgency the question of the main Home Chain. Thus freshly alerted, the Government agreed that the Air Ministry should be authorised to proceed with the organisation of the whole chain as quickly as possible. Treasury approval for the annual operational costs of the complete chain, estimated at £174,000, was given on 12th August 1937.

A fairly large sum was required for completing the five original stations in accordance with the standards that had now been established, and this, and the greatly increased cost of works services and apparatus for the fifteen new stations, reflects the technical advances that had been made since 1935. In the first place, every station was now to have both transmitter and receiver so that full advantage could be taken of the newly developed equipment for finding direction and measuring height. Secondly the equipment was more powerful and sensitive. Thirdly, and this advance accounted for the greater part of the increase in the cost of works services, it had been decided that (in order to minimise the risk from deliberate jamming by the enemy) every station should be capable of operating on any one of four wavelengths in the band from 8 to 13 metres; this decision required the provision of eight towers at every station, four 240 ft. wooden and four 350 ft. steel, and accounted for £28,000 out of the £49,000 estimated for works services at each station.

Contracts were given to Metropolitan-Vickers for 20 sets of transmitting equipment and to Cossors for a like number of receiving equipments, the designs to be based on performance specifications prepared at Bawdsey.

Thus by the end of 1937, R.D.F. was regarded by the Air Staff as having proved itself, and the first stage in the development of radar was complete.

At the beginning of 1938 the Air Staff policy called for the completion of the chain of twenty stations by the last day of 1939, and in fact during the Munich crisis the Thames Estuary Chain went into continuous operation and some cover was given to the Forth-Clyde, Tyne and Humber areas by mobile sets hurriedly installed at three of the sites chosen for the final Chain. By the end of May, the whole chain was handed over to the Air Force.

In January 1939 the Air Staff decided that cover was needed north to Scapa Flow and west to Portland, and it was accordingly decided to erect four more stations; further extensions of the chain to cover Liverpool and Belfast were discussed in May. Finally in June the Air Staff ruled that the whole chain must be on a full war footing by the 7th August.

Thus when war came in September Britain was guarded by an R.D.F. chain of 19 stations stretching from Netherbutton in the Orkneys to Ventnor in the Isle of Wight, tested in the Home Defence Exercises of August 1939,[1] confident and ready. R.D.F. was an established, and was soon to prove itself a highly successful, weapon.

(ii)
The Centimetric Revolution

Effective and successful though it may have been, the radar weapon was already upon the eve of a development which was to increase its effectiveness and versatility many times, a development, comparable in importance with the original R.D.F. application itself, which Sir Robert Watson-Watt has described as the centimetric revolution. The supreme advantage of the floodlighting system had been that it could be developed speedily, since the constituent devices of which it was composed were not new; the secret was that they were assembled in such a way as to do a new thing. From the beginning however scientists had realised that there would be advantages in an alternative system in which the pulses were

[1] A.O.C.-in-C., Fighter Command, reported after these exercises that 'the R.D.F. system worked extremely well . . . although doubtless capable of improvement as the result of experience, [it] may now be said to have settled down to an acceptable standard'.

radiated in a single narrow beam, for if floodlighting had an overriding advantage, its limitations were nevertheless severe. It was not readily adapted to measuring angles of bearing with great accuracy, which was a serious disadvantage in controlling anti-aircraft fire; in airborne radar the lower edge of the rapidly widening beam touched the ground vertically below the aircraft from which it was being radiated and thus picked up random echoes which limited range to the flying height; the wide range of angles over which signals could be received made the system susceptible to jamming.

On the other hand the scientists had always appreciated that a narrow-beam radar, capable of sweeping the sky with a fan of radiation or of pointing like a long pencil of light through darkness, would be a fundamental advance. Such a radar would be endowed with a fine discrimination in the measurement of angles of bearing and would be able by its narrowness to avoid the clutter of random echoes and also the radiations of a jamming transmitter. The multiplicity of applications that would become possible was such that it was worth making a great effort to overcome the many difficulties that lay in the way of development.

The width of a radio beam depends primarily on the size of the aerial in relation to the wavelength used; the shorter the wavelength, the smaller the aerial needed to produce a beam of given width. For example at a wavelength of 1·5 metres it is possible to make an aerial capable of radiating a beam perhaps 20 degrees wide and yet small enough to be rotated fairly easily. This was in fact done in the CHL stations to which reference is made below[1]. Even these aerials however were still some 30 feet across. But if the wavelength were reduced to say 10 centimetres a beam of the same width could be obtained with an aerial only 2 feet in diameter and sharper beams with aerials not much larger. A really sharp beam from a really small aerial was the prize offered by operation at a wavelength of a few centimetres.

The great difficulty in getting down to shorter wavelengths lay in generating adequate power. The wavelength of 1·5 metres just mentioned was the shortest at which the valves then available would deliver reasonable amounts of power. To go to wavelengths as low as 10 centimetres seemed almost beyond practicability in 1939. Experimental oscillators had been built around special valves, notably the multi-segment magnetron and the newly-invented klystron, but they yielded at the most a few watts of power. For radar purposes peak pulse powers thousands of times as great were needed. It was in this direction that one of the most striking and dramatic leaps forward in the whole scientific history of the

---

[1] See pp. 388–389.

war was taken by a team at Birmingham University, led by Professor M. H. L. Oliphant.

This team had begun work in the autumn of 1939 on various aspects of the problem of centimetric radio. The new idea, which was contributed by Dr. J. T. Randall and Mr. H. A. H. Boot, was to combine resonant cavities with the multi-segment magnetron. The resultant device, the resonant cavity magnetron, produced hundreds of watts at the first trial early in 1940; by the summer a sealed-off version giving 10 kW at 10 centimetres had been developed in collaboration with the G.E.C. Research Laboratories. This valve, by making really short waves viable, lay at the heart of the centimetric revolution. With it the Telecommunications Research Establishment was able, in 1940, to embark on a programme to develop centimetric radar.

This programme was divided roughly between basic research, under Dr. H. W. B. Skinner, and the application of centimetric methods to airborne radar, under Mr. (later Professor) P. I. Dee. The basic research included, besides the further development of magnetron transmitters, work on receivers, aerials and reflectors and the waveguides to feed them, and various essential ancillaries. In these fields major contributions were made by university laboratories, especially at Birmingham and Oxford, and by industrial laboratories. By the late summer of 1940 all the basic elements of a centimetric radar had been established, by September the parallel development of a practical system had advanced so far that a range of 5 miles was obtained on a Blenheim and in November a motorboat and a submarine were seen at 7 miles.

In order to understand the sometimes complex history of the development of radar during the Second World War, it is necessary to bear in mind three fundamental factors. The first is that up to the outbreak of war development was concentrated upon the Home Chain, although it was well understood that a whole host of other devices could quickly be developed when attention could be spared for them. The second is that the development of these devices of the second stage of radar history was begun in the period 1939/40, and was carried some way on "floodlight" principles. The third is that this development was then overtaken by the Centimetric Revolution.

We shall have to follow these developments in a number of different fields of radar warfare. Among the devices under development when war broke out were A.I. (Air Interception) equipment, to be carried in night fighters to aid in the closing stages of an interception; A.S.V. (Air-to-Surface Vessels) equipment for locating ships and surfaced submarines; I.F.F. (Identification Friend or Foe) to be installed in all aircraft to enable C.H. and other stations to distinguish friend from foe; and the naval type 281, a high-power aircraft warning set for use in ships.

One or two devices, for example a mobile early-warning set, had gone even farther and were in the early stages of production. These were however essentially variants of the basic C.H. station and they thus show the beginning of what was to be the main pattern of radar development, the continuous adaptation and extension of the use of existing equipments. Space forbids us to pursue these adaptations here; it is rather upon the breaks in the pattern, the jumps into new fields, that attention must be concentrated. When war broke out the most novel radar device was one known as G.L., which was intended to help anti-aircraft guns to find their targets.

(iii)
Aiding the Guns

The idea of using radar in this way was conceived immediately after the famous Daventry experiment in February 1935.[1] The need for some improved method of controlling A.A. guns was very evident. The existing methods of control measured range, elevation and bearing visually by day, and by night used sound locators giving approximate elevation and bearing only. Sound locators were inaccurate at best and the comparatively low velocity of sound made for a time-lag which rendered them useless against fast aircraft. Although the accuracy of angular measurements by visual means was reasonably good, range-finding by the optical monostatic range-finder was not satisfactory, since the errors increased as the square of the range.

The gravest defect of the optical instruments lay, of course, in their comparative uselessness in conditions of bad visibility. At night they could be used only when the target was illuminated by searchlights, which were themselves restricted by cloud. In 1935, when the Tizard Committee reviewed air defence arrangements, they noted that there must be a very high proportion of the time during which aircraft could operate when they could escape observation by flying above cloud. The most that could then be said for the guns was: 'Nevertheless we incline to the view that whilst the direct effect of gun-fire can be over-estimated, guns will always remain necessary, certainly in the inner, and probably in the outer, zone'. The new technique offered possibilities of breaking through the restrictions of

---

[1] See p. 375.

visibility. The improvement of long-range early-warning in itself tended to add to the importance of A.A. gunfire, but it was not until the development of G.L. that this type of defence emerged fully from the comparative obscurity of 1935.

The history of G.L. began early in 1937, when a small group of War Office scientists was attached to Bawdsey Research Station. The project considered most quickly adaptable to Army needs was a short-range warning equipment, on the floodlighting principle, which was to be used for bringing guns and searchlight crews to the alert and enabling them to align their instruments in the general direction of the raiders. Air Ministry workers at Bawdsey had already built a first model of a set of this kind and it was proposed to adapt this to Army requirements. The wavelength adopted was six metres.

Meanwhile, some members of the War Office team began to study extremely difficult problems associated with obtaining positional data sufficiently accurate for gun-laying. For this purpose ranges had to be determined to within yards, and angles to within minutes of arc; thus permissible angular errors were one-sixtieth of those allowable in the older application. So stringent were the requirements that even the research workers felt that some years must elapse before a solution could be found. In May 1937 doubts were expressed in the Air Ministry 'whether it will be solved in our time'. Yet within weeks an accuracy of the order of 100 yards at ranges between 3,000 and 14,000 yards had been reported, and by November rapid and unexpected progress was such that it had become a matter of urgency to produce experimental apparatus for field trials. In December the Sub-Committee on Air Defence Research was informed that the probable error of a single range observation was now about 25 yards and of an azimuth bearing less than 1 degree. 'At the present stage of research therefore', the report continues, 'R.D.F. equipment for anti-aircraft work can at once provide a range-finder of high accuracy, which is independent of the conditions of visibility. It can also provide a direction-finder for leading visual instruments on to targets'.

In this development the first emphasis had been placed on the range-finding function, because it is in the measurement of range that radar has outstanding advantages over other systems, apart from its independence of conditions of visibility. In particular, the errors in range measurements do not increase with range. For gun-laying purposes it is highly desirable that the range of the target should be measured continuously if the predictor is to calculate accurately the rate of change of range. In this respect the radar method has a further advantage over the optical range-finder, with which it is possible only to make a series of spot measurements. The G.L. range-finder could be arranged so that continuous range-measurements were translated into the rotation of a spindle and fed direct to the predictor.

In the same way continuous measurement of angles of bearing and elevation (or 'angle of sight' in gunner's terminology) is desirable. No attempt was made to realise these desiderata in the first G.L., because it was believed that the accurate measurement of angles, especially of elevation, would be very difficult to achieve. The system used did not permit continuous measurement, but only the determination of a series of spot readings, and although results had been encouraging, no satisfactory system for measuring angle of elevation had been devised.

The development of a radio range-finder having been achieved, a production order for 500 sets was placed early in 1939. The transmitters were entrusted to Metropolitan-Vickers and the receivers to A. C. Cossor—the only firms who at that time knew the radar secret. By the end of 1940 the bulk of the contract had been completed. This equipment was known as G.L. Mark I and Mark I star.

Meanwhile, research had been proceeding to develop a G.L. capable of providing all the data necessary for the fire control of A.A. guns, thus eliminating all optical instruments. This involved arrangements not only for measuring elevation as well as azimuth, but for providing continuous measurements of these quantities, as well as of range, so that the data could be fed direct to the predictor. In the summer of 1940, the set was still under development when the beginning of the German night offensive made the provision of elevation-finding a matter of extreme urgency. Anti-Aircraft Command made direct contact with Mr. Bedford, Chief Designer of A. C. Cossor, who had proposed a scheme for adapting the elevation-finding principle used in the G.L. Mark II system, to G.L. Mark I, without interfering with its internal arrangements. This contact was a source of inspiration to Mr. Bedford and his staff, and imparted considerable impetus to the development of his device—known as the elevation-finding or E.F. attachment—and to the conversion of Mark I sets. During the autumn of 1940 about fifty sets of G.L. Mark I were fitted with this attachment.

The development of G.L. Mark II presented special difficulties, particularly in the mechanical arrangements for transmitting the information from the radar set to the predictor. Transmission was done by means of a train of gears, and production of sufficiently accurate gear wheels gave a great deal of trouble. The Gramophone Company, who were developing the receiver,[1] ultimately surmounted these difficulties, but for production reasons the gears were sub-contracted to specialist firms. 530 sets of G.L. Mark II were produced

---

[1] The transmitters were made by Metropolitan-Vickers. Part of the receiver production was undertaken by Ferranti and A. C. Cossor as daughter firms to the Gramophone Co.

in 1941: the next year the total output was 1,017 (the total order was for 1,679).

The addition of height-finding to G.L. gave rise to a number of difficulties in operation. For the device to work successfully it had to be sited on perfectly flat ground; it was necessary therefore to surround the equipment by mats of wire-netting some 100 yards in diameter. Such devices were difficult to instal, and their use prevented the equipment from being readily mobile. Next it was found that the aerial feeders exhibited unexpected variations from day to day which upset the calibration. Calibration of the many G.L. sets was complicated and slow, and calibrators were recruited from industry or seconded from other establishments, hastily trained at the A.A. Radio School at Petersham, and sent into the field.

Yet despite the difficulties, G.L. results, when analysed, were impressive, and showed a quick improvement. Expressed in terms of the number of rounds of unseen fire required to destroy an aircraft, the improvement was from 20,000 "rounds per bird" in 1940 to 4,000 in the spring of 1941.

Beyond this it was not possible to improve the performance of 6 metre G.L., and fundamental disabilities remained. Apart from questions of accuracy and limited cover in elevation and the difficulty about the level site, the equipment was liable to jamming; it was affected by ground echoes from the surrounding country; it could not be dug into the ground for protective purposes; and it could not be used for the dual-purpose 5.25″ Anti-Aircraft/Anti-Ship coastal guns. The scientists realised that these disadvantages could be largely overcome by the use of much shorter wavelengths. The Air Defence Experimental Establishment therefore began the development of a G.L. set working on a wavelength of 50 cm., and by October 1940 had produced an experimental equipment delivering a pulse power of some 20 kW.

This was the stage that had been reached when the fruits of the centimetric revolution became available, and it became possible to think realistically about wavelengths below 50 cm. In October the R.D.F. Applications Committee recommended that maximum effort should be concentrated on wavelengths below 10 cm; the 50 cm work was to continue only as an insurance against possible failure of the 10 cm.

This decision was the first of three which determined the form which G.L. Mark III should take; the second concerned the type of valve to be used. Professor Oliphant and others considered that the klystron offered advantages over the magnetron for a ground installation: however, development of the magnetron rapidly outpaced the klystron. In the spring of 1941 it was decided to use the magnetron for G.L. Mark III. By that time a power of 40 kW.

could be obtained from this valve, and it was confidently expected that this could be exceeded.

The G.L. Mark III development was undertaken by a small team from the Air Defence Experimental Establishment working at Birmingham University, but this arrangement proved to be unsatisfactory owing to the separation from the Establishment, and in January 1941 the main effort was concentrated at the Establishment.

The first experimental G.L. Mark III set was made up of two units, the first consisting of transmitting and receiving paraboloids, together with their associated radio equipment, mounted on a searchlight turntable. The presentation unit, which was converted from a G.L. Mark II receiver, and control equipment were mounted on another trailer. The equipment had a generic similarity to the earlier marks, in which there were also separate cabins for transmission and reception. A prototype of this double-unit equipment was tested in May 1941. These trials showed that bearing and elevation could be measured to within about 10 minutes of arc by good operators and that typical aircraft could be followed to ranges of about 18,000 yards. The set demonstrated, therefore, the great advantages of centimetre waves for G.L. It was not engineered for Service use, and the Air Defence Research and Development Establishment (formerly Air Defence Experimental Establishment) proposed a complete redesign for production purposes, in which the whole equipment would be housed in a single cabin.

The possibility of developing a single cabin model (later known as Model B) was discussed in January 1941, and design was undertaken by the British Thomson-Houston Co. in collaboration with the Air Defence Experimental Establishment. In July the General Staff decided to adopt this design.

The War Office urged early production, and to achieve it they were prepared to accept the simplest form of the equipment, but the Ministry of Supply considered that the advantages of the B model were so great as to outweigh the relatively small delay in production, and it was finally agreed that model B should be adopted. This was the third important decision in the history of G.L. Mark III. It was also decided that 25 handmade pre-production B models should be made, and that the War Office should raise a demand for 1,000 production equipments, later increased to 1,500[1] but reduced again in 1943.

By the middle of 1941 the design of model B was settled. The equipment consisted of a single large cabin, mounted on a trailer, carrying two four-foot paraboloids on the roof. The electrical

[1] The first contracts for 900 sets were placed in October. They were extended by a further 600 sets in January 1942.

equipment was contained in two main units inside the cabin, the first a vertical cylinder supporting, and rotating with, the paraboloids, which housed the transmitter and receiver, and the second a presentation unit embodying an improved display system. The British Thomson-Houston Co. developed the cylindrical rotor and the Gramophone Company the presentation unit.[1] The first equipment was tested in March 1942 and full production began in the spring of 1943.

Some three years elapsed between the first experimental work on G.L. Mk. III and large-scale production. In Professor Cockcroft's opinion, 'about six months were wasted due to the false start on the design and about six further months due to indecisions of policy and slow placing of orders'. G.L. Mark III was an excellent equipment when it finally went into service, but had been overtaken by the march of progress before it made its appearance. During the first half of 1942 the automatic-following method, proposed originally at the Telecommunications Research Establishment for A.I., had been developed to such a stage that American trials had shown its accuracy to be comparable with that of visual instruments, with a considerable saving in numbers of operators and complexity of operational procedure.[2] In a similar manner, by the time G.L. Mark II began to come off the production line, it had been rendered obsolete technically by the development of Mark III, although a year was to elapse before the latter went into service. This situation was by no means uncommon in the radar field generally.

This brief sketch of the history of G.L. may be ended by a quotation from a paper by Sir Robert Watson-Watt: 'In anti-aircraft gunnery ashore the number of "rounds per bird" in unseen fire in the United Kingdom, after the simplest radar aids had been in use for a short time, stood at 18,000. With improved radar this figure fell to 4,000 on the average of 1941 and to 2,750 in 1943. This last figure is almost as good as that (2,600) for the much smaller amount of visual fire on the average of 1941 to 1943. Thus radar made one radar-aided H.A.A. gun worth at least five not so aided. . . .'

(iv)

Aiding the Night Fighters

G.L., like the Home Chain itself, belonged essentially to the defensive phase of the war, the phase in which Britain's main effort in the air was devoted to beating off enemy attacks. It was one of a group of

[1] These were the parent companies in the production programme.
[2] An American equipment of this kind, the SCR.584, played an important part in the A.A. defences against flying bombs.

similar devices, the original idea of which had been conceived at a fairly early stage in the development of the Home Chain, at a time when no thought had been given to—when in fact no thought could be spared for—devices appertaining to offensive operations. Chronologically a little later than G.L., but logically linked to it, there began the serious development of A.I., the device for enabling night fighters to find enemy aircraft.

As early as 1936 Mr. Watson-Watt proposed that a radar equipment, later called A.I. for Air Interception, should be fitted in a fighter to increase the pilot's range of vision to some five miles or so. Owing to Home Chain priority, it was July 1939 before an A.I. set in a Battle aircraft was demonstrated to the Air Officer Commanding-in-Chief, Fighter Command, who recommended that he should be given three or four sets so that he could study appropriate tactics. Twenty-one A.I. sets were accordingly ordered to be made by hand and fitted in Blenheim aircraft on the highest priority. Trials of the equipment, which was called A.I. Mark I, were made, and after some modification it was considered satisfactory enough to justify placing an order for 300 sets.

One very serious difficulty, however, prevented this early A.I. from being a real success. Since its primary purpose was to give guidance to the pilot of a fighter up to the point at which he could see the enemy at night, it was very important that the minimum range should not exceed the maximum visual range. It was, however, this grave discrepancy which the early equipment displayed. This fault proved very stubborn, but eventually after increased effort was devoted to it, two solutions were proposed, one by the scientists at the Air Ministry Research Establishment, and one by Electric and Musical Industries Ltd.[1] The Air Ministry method reduced the minimum range to 800 feet by means of modifications to existing equipment and 100 Blenheim aircraft were to be fitted with the equipment (known as A.I. Mk. III). Owing to the success of the Electric and Musical Industries equipment, this programme was not completed, but the first operational success with A.I. was scored by Mark III fitted in a Blenheim fighter. The Electric and Musical Industries solution was, however, clearly superior: it involved discarding the existing method of pulsing the transmitter and using a new modulator and power pack with the same transmitter and receiver.[2] The minimum range obtained with this equipment was less than 500 feet, a very considerable improvement.

[1] The Air Ministry Research Establishment also suggested a third modification which gave a minimum range of 600 ft. This arrangement (known for a time as Mk. IIIB) was more complicated and was abandoned in favour of the better and simpler E.M.I. scheme.

[2] In both Mark III and Mark IV the transmitter was that manufactured by Messrs. E. K. Cole for A.S.V. using the new micropup valves.

Early A.I. work also showed ambiguities in the indications of direction and elevation, but this was finally cured in the summer of 1940 by changing the polarisation of the aerial system on the fighter from horizontal to vertical, and the equipment, known as Mark IV, remained the main A.I. set from November 1940 until the arrival of centimetric A.I. in the spring of 1942.

Meanwhile developments were taking place in the wider field of defence against enemy air attack. In November 1939 Air Force controllers were sent to selected Home Chain stations to make a trial of the so-called 'all-R.D.F.' interception method; and while the results obtained were not satisfactory, the experiments were important as marking the beginning of a long series of trials by the Service and scientists which culminated in the development of a comprehensive and efficient system of radar defence.

Some such system had been an ambition from early days, and the early development of A.I. both emphasised the need and suggested how it might be met. It emphasised the need because, while there was a difficulty about minimum range, there was also a difficulty about maximum range. This difficulty, already mentioned,[1] arose because random echoes were picked up from the ground as well as from other aircraft, with the result that the height of the A.I. aircraft above the ground was also the limit of its effective range of radar 'vision'.

A very short experience of this limitation of A.I. emphasised the need for close control from the ground. It was realised that the night fighter controller must be provided with accurate and immediate information about the positions of both bomber and fighter. These requirements were not satisfied by any of the existing systems, since the Home Chain was too slow and inaccurate for such rapid and precise indications, and also because it had become essential to convert range and bearing measurements into an actual plan position by some high-speed mechanical process.

The Home Chain however was supplemented by beam-type radar stations designated CHL (Chain Home Low). Conceived and developed for Army coastal defence purposes, these equipments had been adapted and used to fill the gap under the CH radar net through which low-flying aircraft were able to approach undetected. In this role the CHL stations were of great importance but they also made a major contribution to radar development generally in so far as they proved to be the genesis of a comprehensive system for controlling interceptions.

The aerials of the CHL stations, which worked on the comparatively short wavelength of 1·5 metres, were arranged to sweep a

---

[1] See p. 379.

vertical fan or beam of radiation to and fro across an arc of the sky seawards of the station. It was not difficult to adapt the aerials to make the beam sweep a complete circle around the station and to site these modified equipments inland. Because they worked on the principle of the rotating beam it was possible to arrange the cathode ray tube in these modified equipments to display a kind of map of the surrounding sky upon which the aircraft appeared as slow-moving spots of light as they were caught in the beam. The progress of the aircraft was shown without the need for an elaborate conversion procedure since the plan positions of all aircraft were indicated directly and on the same reference grid. This mode of presentation—a scientifically elegant solution of a difficult problem—was known as plan position indication and the device operating upon the principle as the P.P.I. (Plan Position Indicator).

The combination of a modified CHL station and the P.P.I. formed the basis of a comprehensive system. It was a basis only, because gaps still existed in the vertical coverage and the next stage in the control of night fighters was the development of a double aerial system which was capable of measuring height and filling the gaps. Encouraging tests with primitive apparatus embodying the P.P.I. had been made, and these tests led to an extended series of operational trials with a special mobile equipment which served to emphasise the vital necessity of height-finding and gap-filling. The new double aerial, capable of fulfilling these functions, was fitted at Durrington in November 1940. Thus Durrington was the prototype of the self-contained stations with P.P.I. which came to be known as G.C.I., for Ground Control of Interception, and which formed the primary method of night fighter control for the remainder of the war.

As a consequence of the encouraging results obtained with the experimental complete G.C.I., the Ministry of Aircraft Production initiated a programme for twelve hand-made transportable equipments, to be followed by the production of 120. These were to be improved versions of the Durrington equipment and would take some time to produce, but it was felt that an effort should be made to exploit the new technique at the earliest possible moment. It was therefore decided in November to undertake a crash programme to produce six mobile equipments, in spite of the fact that the new techniques were not fully proved.

The six sets were to have gap-filling and height-finding; split ten-foot aerials were used; and three of the sets were fitted with P.P.I. As a result of one of the almost fanatic yet effective bursts of activity which were so often called for in the early production of new radar equipments, the first equipment was sent to its site on Christmas Day; the last was despatched on 6th January 1941.

The success of these six stations was immediate, notwithstanding their imperfections. Victories by night fighters rose steadily from 2 enemy aircraft destroyed in December 1940 to 52 in April 1941 and 102 in May. In March 1941 equipments became available from the production programme for 12 sets; several more stations were therefore erected. During the first half of 1941 many technical improvements were introduced; and as a result of operational experience, G.C.I. was integrated with the Sector organisation and ancillary radio-telephone and radar systems into a general system for the close control of interceptions, which was at last truly comprehensive and complete. In this final form G.C.I. would undoubtedly have been of great importance had the Germans ever been able to resume their attacks on this country on a large scale. They did not do so, but in another sphere of warfare another kind of attack was being developed with equal ferocity and greater determination.

(v)
Against the U-boats

As the German submarine campaign grew steadily in intensity during 1940, the improvement of anti-submarine tactics became more urgent. The primary problem was that of location. Owing to their low under-water speed, the U-boats had to perform most of their manoeuvres on the surface. Even so, the visual target presented by a U-boat running awash was very small, and the difficulties of escort vessels were greatly increased by the U-boats' habit of attacking by night. A submarine's conning tower, at night in a mid-Atlantic swell, is to all intents and purposes invisible.

The idea of an airborne radar, to be carried in reconnaissance aircraft for the purpose of locating ships and surfaced submarines, was another among the many which had occurred very early in the pre-war phase. It had been carried further than some of the others; experimental equipment had been constructed and striking results had been obtained with it at the end of 1937 and early in 1938, and by the outbreak of war an Air-to-Surface Vessels (A.S.V.) equipment was in a fairly advanced state of development. This was the 1.5 metre A.S.V. Mark I, and it was followed by an improved version, Mark II, which was fitted in two forms, the short-range which was capable of searching forward of the aircraft only, and the long-range which was able to search abeam of the aircraft as well as ahead. The fitting of the short-range equipment began early in 1940, and the long-range followed about a year later. Very shortly before this, at the end of 1940, the Germans had begun to operate submarines from the French ports in the Bay of Biscay, and a new anti-U-boat strategy became possible: that of attacking U-boats as they crossed the Bay on the way to or from their patrol areas. Patrols were begun by Coastal Command in May 1940. At first they did not sink many U-boats, owing (amongst other reasons not connected with radar) to the comparatively short range of A.S.V. Mark II. And the U-boats fitted, as a counter-measure, a wireless receiver capable of picking up the A.S.V. transmission and so giving the commander warning of the approach of an aircraft. Obviously what was wanted next was an A.S.V. working on a wavelength which could not be picked up by this U-boat receiver. This need, combined with the limited range of the 1.5 metre A.S.V., led to A.S.V. becoming a major claimant to the fruits of the centimetric revolution. In March 1943 A.S.V. Mark III (British) and Mark V (American) centimetre equipments went into operation.[1] Their range on submarines was ten miles or more, and their affect was immediate and devastating. The next three months saw a great holocaust of U-boats, largely, though by no means entirely, in the Bay of Biscay; they were sunk at the rate of one a day.

Centimetric radar was also brought into the escort vessels. A demonstration was held in 1940 which convinced naval observers that centimetre apparatus, primitive as it still was, was capable of following a submarine out to 7½ nautical miles from the equipment on shore.[2] The naval representative showed great interest and it was decided that the Admiralty Signal School should develop a 10 cm. equipment for naval use.

By February 1941 a party of Signal School scientists had developed a set whose circuits were reasonably reliable and whose performance it was thought would be reproducible. The Captain of the Signal School made the bold decision to accept the risk that trials might show the set to be unsatisfactory and to order immediately components for 150 sets. He also decided to manufacture in the laboratory 24 copies of the experimental prototype, and ruled that no modifications were to be accepted unless they were essential or could be introduced without delaying production. The equipment was to be called type 271.

Because speed in development was necessary, the equipment was reduced to the simplest form possible, and could not be offered for universal application. The essential limitation was the need to mount the aerial vertically above the radar office and not more than 20 ft. from it, measured along the cable. It therefore appeared that the

---

1 See p. 393.

2 The equipment was on a site 250 ft. above sea-level. The range quoted is for the stern-on view; broadside-on the signals were about twice as strong.

equipment in the form proposed could not be fitted in destroyers but would be suitable for use in corvettes.[1] It was accordingly decided to fit the first set in the corvette *Orchis*, due to complete on 23rd March 1941.

As soon as an indication of the essential modifications had been obtained from preliminary trials of this installation, a second meeting was called to discuss the introduction of these modifications and the immediate manufacture of the first twenty-five sets. The Captain decided to make further use of the resources of the firm of Allen West—which throughout the war worked very closely with the Admiralty on such 'crash programmes'—and which made an important contribution to this one.

The 271 set consisted of a magnetron transmitter feeding a so-called 'cheese' aerial (i.e. a cylindrical paraboloid); a similar aerial was used for reception. This type of aerial was chosen because it produced a beam which, while sufficiently narrow in the azimuthal plane to give accurate indications of bearing, is broad enough in elevation not to move off the target when the ship rolls. As a means of saving development time, in a manner very characteristic of radar development generally, the indicator unit for A.S.V. Mark II was adapted to the 271.

During April comprehensive sea trials of the installation in H.M.S. *Orchis* were made. These demonstrated that, in spite of the low power,[2] a small submarine running on the surface could be seen to 4,000–5,000 yards, and a destroyer to 10,000–12,000 yards. Even so small an object as the submarine's periscope, when the boat was submerged, was picked up at 1,100–1,300 yards. Such a degree of sensitivity was quite new in naval radar and it was decided to increase the initial order to 350. By July, 25 corvettes had been fitted, and at the end of the year over 100 sets had been made and 50 ships fitted.

Type 271 quickly had its effect on operations. In its primary role as a U-boat spotter it was a great success and led to a considerable rise in the number of sightings and attacks. But it also had many other uses. The ranges obtained in the trials on small objects were shown by operational experience to be no freak performances, and type 271 was frequently the means of locating ships' boats and life rafts at night. The accurate indications of the presence of other ships and the clear discrimination between them was a tremendous help in station-keeping and shepherding the convoys. The Commanding Officer of H.M.S. *Orchis* wrote that 'after being in a ship

---

[1] By then the question of fitting in ships had been discussed with the Director of Naval Construction and the Director of Anti-Submarine Warfare.

[2] The power obtainable with the original E.1198 magnetron was about 7 kW.

fitted with type 271, night navigation in one without will seem a perilous business'.

A number of improved versions followed the original, including types 272, 273 Marks I to IV, and 277. These later equipments used much more powerful transmitters (70 kW. in the 273 Mark IV) and were provided with various refinements. All types of ships were equipped and the set was also adapted to other Services' requirements. In April 1941 the Admiralty agreed to the allocation to the War Office of one of the first 25 sets to be made. The Army used these sets, modified, for coast defence purposes, initially in the Dover area.[1] The Telecommunications Research Establishment also adapted the radio units of type 271 and its successors to various ground equipments for Air Force use. In fact the 271 was the progenitor of a series of 10 cm. ground transmitters and receivers which became almost standard inter-Service equipment.

The production of the type 271 set is one of the outstanding examples of a crash programme undertaken on the initiative of a research and development establishment. It is undoubtedly important that the original demonstration was made not only to the Admiralty Signal School scientists, but also to Naval Officers. Both were convinced of the utility of the new device and the latter needed no further persuasion about its value.

(vi)
Aiding the Bombers

The laying of anti-aircraft guns, the close control by ground stations of fighters, the ability of these fighters finally to 'home' on enemy bombers by the use of their own radar sets, and the helping of escort vessels to locate submarines—and incidentally to navigate in dark and dirty weather—were the most important new achievements of radar during the defensive phase of the war. The defensive phase of the war, however, does not admit of any very exact definition. Many devices, such as A.S.V., overlapped it. In any case the thought of strategical planners, not to say the combative spirit of large sections of the population, eagerly ranged into the future, and it was only natural that the thought and the enthusiasm of radar scientists should take part in this general movement. Indeed, although the urgent pressure to develop defensive radar prevented them from making experiments in other fields, the possibilities of applying

[1] These were the CD Mark IV sets.

the principles of their new art to offensive operations had been considered by the radar scientists long before the war. As early as 1938 a member of the staff of Bawdsey Research Station conceived a method of using pulse transmissions to aid aircraft in navigating back to their bases.

During the spring of 1940, Mr. Watson-Watt, who was then Scientific Adviser on Telecommunications to the Air Ministry, foreseeing that a navigational aid would shortly become a necessity to Bomber Command, returned to this idea and encouraged its originator, Mr. R. J. Dippy, to elaborate it.

In June 1940, the Assistant Chief of the Air Staff (Radio), Air Marshal Joubert, paid a visit to Swanage[1], gave a frank exposition of the severe navigational difficulties which beset Bomber Command at this period, and explained that a device was needed which would aid bombers to reach a point within five miles or so of their target. A secondary requirement was an aid to returning home. The Gee system was explained to the Air Marshal who, appreciating its possibilities, asked that experiments on it should be proceeded with urgently.

To appreciate the further history of the development of Gee it is necessary to understand how it works. The system in effect lays down in space a lattice formed by two sets of intersecting lines; the aircraft is provided with an instrument by means of which it can determine upon which of the lines in each set it is flying at any instant, and hence find its position from the point of intersection of the two lines. This result is achieved as follows: a ground transmitter (called the master or A station) transmits pulses which are received by the aircraft after a certain lapse of time. The same pulses are received by a second ground station, called the B slave station, which for each pulse that it receives (and after a time interval which is constant) transmits a pulse of its own. This second transmission is also received by the aircraft. The equipment carried by the aircraft enables the navigator to measure the duration of the time interval that elapses between the receipt of the A and B pulses. Suppose that a series of time interval measurements is made and that the aircraft is flown meanwhile on such a course that each interval is the same as all the others. It can be shown that the course necessary to achieve this is a hyperbola having as its foci the two ground stations. Similarly, if a different time interval is chosen another hyperbola will be traced, having the same foci. Thus the two stations provide a complete system of hyperbolic lines of constant time difference, and the aircraft, by measuring the time differences between the

[1] Bawdsey Research Station had been renamed the Air Ministry Research Establishment and in June 1940 was situated near Swanage.

arriving pulses, can determine upon which member of the system it is flying. This does not by itself fix its position, but only gives it a so-called position line, which could, however, be followed if the need arose. By introducing a second, or C slave station triggered by the same master station, a second system of hyperbolae can be set up which, by properly placing the C station, can be made to intersect the first. Thus by measuring the time interval for each of the two pairs of stations, the aircraft can find its position from the point of intersection of the two hyperbolae. The accurate measurement of small time differences was the essence of the system. And—an important point—no transmission was required from the aircraft.

Later a fourth ground station (the D slave) was added to the three mentioned above. The function of this station is to resolve the ambiguity which arises from the fact that, in general, any two hyperbolae from the two systems have two points of intersection. This ambiguity is of consequence only at comparatively short distances from the ground stations. Also, by proper siting, the D station can be made to improve the long-range accuracy in certain areas, by providing a more suitable angle of cut than is given by the other stations. In addition to these transmitting stations there is a ground receiving station whose function is to monitor the transmissions, in order to ensure that each is radiated at a constant required time interval after that from the Master station, this being an essential feature of the system. The complete assembly of four transmitters and monitor is known as a Gee Chain.

The first step was to build a scale model of the proposed system. Low-power transmitters were erected at Worth Matravers and Christchurch and an experimental aircraft equipment constructed. In the autumn of 1940 flight tests were made, using this arrangement, which demonstrated the practicability of the system for giving a position line, although since there were only two transmitters a complete fix could not be obtained. In November, Bomber Command officers flew with the equipment and were deeply impressed by its possibilities, with the result that the Command informed the Air Ministry that they regarded the provision of Gee as an urgent necessity and suggested that a small number of sets should be made by hand at once. The Telecommunications Research Establishment (formerly Air Ministry Research Establishment) was therefore instructed to make 12 sets of airborne equipment, shortly afterwards increased to 24, for trials in the following spring.

In July and August 1941, operational trials were carried out with the 24 hand-made equipments, and reported upon with enthusiasm. Gee, wrote the trials squadron, was 'undoubtedly far in advance of any other system now in operation in the R.A.F.'. This confirmed the Air Staff's opinion of the value of the device, and the Chief of the

Air Staff ruled that future production was to be planned on the scale of one Gee set in every bomber.

The security of Gee caused particular anxiety, not because the enemy might copy it and use it, but because, once he had appreciated its significance and method of working, he would be able to jam the system, at least over his own territory. Also when the system became operational it would be only a matter of time before a sufficient number of sets from crashed aircraft fell into the enemy's hand to reveal the secret to him. The Telecommunications Research Establishment strongly urged, even before the trials, that Gee should not be introduced piecemeal, but should be withheld from service until it could be used on a reasonably large scale, and at a conference presided over by Sir Henry Tizard, the Air Staff agreed that no operational flights should be made until 300 sets were ready.

The 300 sets were to be made by hand by Cossor's, with delivery in January 1942. In the meantime the idea of the surprise use of Gee on a large scale had been carried yet further in the Telecommunications Research Establishment, who proposed that 200 sets should be made by Dynatron Radio—a small firm often used for crash programmes—with help from them.

Many unusual steps were taken to press the matter on, this crash programme for the production of Gee by Dynatron Radio being in fact the first occasion on which the crash-programme concept was exploited consciously and to the full. It was not completely successful; deliveries did not keep pace with the ambitious schedule; nevertheless there was no doubt that the effort had been worthwhile.

On the agreed basis that the system should be used on the largest scale possible and not introduced piecemeal, the Deputy Chief of the Air Staff recommended 1st March 1942 as the target date. But the Prime Minister wished the device to be used as early as possible, so it was decided that the date should be 1st February, when it was estimated that 235 aircraft would be available. It was then discovered that this was a considerable over-estimate and that, owing to difficulties with the provision of aircraft and their accessories, barely half this number would be ready. There were further difficulties about devising a satisfactory means for destroying the equipment and its accompanying lattice charts (which would have been particularly revealing to the enemy) in the event of an aircraft being shot down. Ultimately, the Chief of the Air Staff informed the Prime Minister that 94 aircraft and crews would be ready by 15th February, and this date was agreed upon as the target date for beginning operations.

The first large-scale Gee raid was made on the night of 8th March 1942, when some 80 Gee-fitted aircraft, in a total force of about 350, were used as fire-raisers in a raid on the Ruhr. The operation was highly successful, as were others mounted on a similar scale on succeeding nights. Progress thereafter was rapid. By August the whole of the main bomber force was fitted with Gee, and a second chain of ground stations had been erected to cover Southern France.[1] From this time onwards the whole organisation of mass raids, involving very complicated problems associated with routeing both outgoing and returning bomber streams, was based on the use of the new device. It was found possible to operate under much worse weather conditions than hitherto, since Gee made it a comparatively simple matter to divert bombers to other airfields when the weather closed in at their own bases during the return flight, and it was generally agreed that this service alone justified all the effort and strain of its urgent development and early production. Another very gratifying feature of its early use was its extremely high serviceability, which rose to over 95 per cent. quite quickly, and remained there.

Other applications of Gee soon followed. In particular the Navy installed the equipment in their light coastal craft operating in the English Channel. Naval use of Gee was subsequently extended and in minesweepers especially it was found to be of the greatest assistance in the precise sweeping of channels. Gee was also used by Coastal Command and in light bombers.

Meanwhile, in anticipation of enemy jamming, the Telecommunications Research Establishment was at work on improving both ground and airborne equipment. The Mark I aircraft receiver had been designed to work on one wavelength only, and since it was a commonplace of radar development that one of the best anti-jamming measures was a sudden change of wavelength, the design of a Mark II receiver with variable tuning had been begun as early as September 1941;[2] other improvements including anti-jamming circuits, were also made, and by 1945 some 50,000 sets had been constructed. The accuracy of the ground sets was also improved and facilities for rapid change of wavelength were added.

Early in 1943 the British fears were justified; the Germans began to jam Gee. The Mark II set, introduced in February, afforded some relief, but the battle continued; the scale of jamming was steadily increased and ultimately was effective over practically the whole of the enemy's territory, to the coasts of France and Holland. Nevertheless Gee was still of great value; the bombers could plot an accurate course out to the enemy's coasts, and it continued to provide an invaluable homing system. Furthermore, by switching on a hitherto undisclosed wavelength at the time that the bombers were reaching

---

[1] The original chain covered Northern France and Western Germany.

[2] This principle of multiple wavelengths was early recommended by the Telecommunications Research Establishment and urged upon the Air Staff by Sir Henry Tizard.

the target, it was often possible to provide adequate Gee cover in the all-important target area. By these methods Gee retained its usefulness to Bomber Command throughout the war.

Valuable as Gee was in all phases of bomber operations, what was perhaps its most spectacular use occurred in the opening phases of the invasion of Europe. For this operation it was decided that the general navigation (as distinct from exact target location) of all bombing and troop-carrying aircraft, British and American, should be done by Gee and that the surface craft should also use it. Five wavelengths, some of which had never before been disclosed, were used as a precaution against jamming. Not the least important advantage conferred by the use of Gee in an operation involving so many thousands of aircraft and ships was that its traffic-handling capacity was unlimited. Moreover, at such comparatively short ranges from the ground stations the accuracy is particularly good. The success of the D-day operations undoubtedly owed a debt to the accuracy of navigation, and hence of timing, made possible by this aid.

It would be difficult to exaggerate the importance of Gee to the bomber offensive. It had its limitations, but as a general navigational aid it enabled navigators to pursue an unrestricted course, certain in the knowledge that they could at any moment determine their position to within a few miles, in a way never before known in aerial navigation.

Gee, then, did much to alleviate the difficulties of finding the target area, difficulties which had been alarmingly demonstrated to the Air Staff by an analysis of aerial photographs undertaken in the summer of 1941. But the alarm had been caused by the fact that only a proportion of aircraft even reached the *area*, and even when this alarm was allayed, and the Air Staff were assured that most aircraft would normally reach the area, there was still the anxious problem of hitting comparatively small targets *within* the area. Even before this, renewed and special interest in the problems of bombing very small targets at night had been aroused in the Wireless Investigation and Development Unit (later embodied in No. 109 Squadron), an operational unit whose duty it was to investigate the radio navigational beams used by the Germans to guide their bombers to targets in Britain. The Wireless Investigation and Development Unit wished to counter these aids by direct attack on the transmitting stations and did in fact try to bomb several of them, using the stations' own beam signals as an aid to a crude form of blind bombing. These were the first attempts at blind bombing by the Air Force.

The Telecommunications Research Establishment were aware of these experiments and of the anxieties which had given rise to them, and in November 1940 consideration was being given to the possibility of measuring range, with sufficient accuracy for the purpose of blind bombing, by radar methods. Interest in the ultimate accuracy of range measurement arose from the unexpected accuracy attained in the early development of G.L. during 1937 to 1938, when a figure of within 25 yards was obtained. Some experiments were made using C.H.L. (Chain Home Low) apparatus with a modified display system, the results of which indicated that an accuracy of 80 yards in the measurement of a single range could be achieved. The Telecommunications Research Establishment suggested that use might be made of this method of accurate range measurement in attacking the German beam-station on the Cherbourg Peninsula, which was within range of one of the South Coast C.H.L. stations. The bombers were to be guided in azimuth by flying along the German beam itself, their range being measured accurately by the C.H.L. The instant of bomb release was to be signalled on the ordinary communication channel. An important innovation in the arrangements proposed was that, in order to be certain of reliable pulse returns from the aircraft at maximum range, a pulse repeater (in this case a modified I.F.F. (Identification Friend or Foe) set) was to be carried in the bombers. This piece of apparatus is a combined transmitter-receiver which picks up the pulse from the ground station, amplifies it, and re-radiates it. In April 1941, No. 109 Squadron made several operational flights using this method, but they were not successful.

In January 1941 the Telecommunications Research Establishment suggested an elaboration of the scheme. In this it was proposed that for azimuthal control the aircraft should fly along a beam similar to the ordinary Blind Approach beam; deviations from its correct course were to be measured by a second C.H.L. and signalled to the pilot by modulating the beam itself. Range was determined by modified C.H.L. as in the simpler scheme. This new proposal had the advantage that no reliance was placed upon signals radiated by the enemy and so targets were not restricted to radio stations. The system was called 'Howler Chaser', but was dubbed Oboe because the note of the modulated beam was thought to resemble that of an oboe. The name stuck and was transferred to the very different system which followed.

In May 1941 a group was formed at the Telecommunications Research Establishment to pursue the study of radio aids to blind bombing. A new system was proposed in which the aircraft's position was fixed by cross-cutting accurate range measurements obtained from two ground stations. In this way the maximum advantage would be taken of the unique ability of radar to measure range accurately. Bomb release and other operating signals would be made by a pulse signalling system using the same radio channel as was employed for range measurement. This arrangement, combined with the use of centimetre wavelengths, would greatly reduce the vulnerability of the system to jamming. Finally it was suggested that the range of the system could be extended to 600 miles by using a repeater aircraft, i.e. an aircraft flying on a fixed course and carrying an apparatus which would repeat the signals from the ground station to the bomber and vice versa. This system (without the repeater) was essentially that ultimately used, which was called Oboe, and differed radically from the Howler Chaser to which the name was first applied.

In June 1941 these proposals were put before the Air Staff. Their reception was cautious, but in spite of some misgivings the Chief of the Air Staff decided that the scheme should be developed on the highest priority. This accorded with a ruling which he had recently given that, although the security of defence must be assured, priority should be given to the needs of Bomber Command.

The Air Staff's lack of enthusiasm was based upon two objections. The most serious was that the aircraft would be exposed to a very grave risk of damage from A.A. fire or fighters, because they would have to fly on a steady course at a constant height for several minutes whilst in the neighbourhood of the target, so that the mean course and ground speed could be measured accurately at the ground station. The other objection was that the traffic-handling capacity of the system would be too low. One pair of ground stations could handle only one aircraft every ten minutes, and the rate of bombing so obtained was considered inadequate.

The first operations which were undertaken indicated that the risk to bombers operating in these circumstances might not be so grave as was feared. These operations, which were known as Trinity Oboe, came about in the following way. It had been found that normal visual attacks on the German battleships in Brest harbour were being severely hampered by smoke screens. In October 1941 the Air Staff stated that some means were required for bombing these ships blind, and the choice fell on a modification of the Howler Chaser idea. The attacking aircraft were to determine their azimuth by flying along a special narrow beam,[1] whilst range and the instant of bomb release were to be found by the experimental Oboe station, which had been erected at West Prawle. The aid of the Telecommunications Research Establishment was enlisted in connection with the use of the Oboe equipment, and in December 1941 and January 1942 operations were conducted which had a considerable

[1] The so-called Baillie beam, a 6-metre dot-dash split radio beam similar in principle to the standard beam approach, developed by No. 80 Wing, R.A.F.

measure of success. From the Oboe point of view the striking fact was that more than thirty Stirling aircraft flew singly, for several minutes and on a straight path, over a heavily defended area without suffering a single loss. The result did much to overcome the most serious apprehensions which the Air Staff harboured about the Oboe project.

Impressed by this success, Bomber Command asked specifically for a blind bombing aid. In February 1942 the Air Staff asked for trials of an Oboe system, working on 1.5 metres, over a bombing range, by the end of April; the 1.5 metre repeater scheme was also to be developed urgently; so the Telecommunications Research Establishment pressed on vigorously.

It may be as well at this point to explain a little more clearly how Oboe, properly so-called, worked. The aircraft was controlled from range measurements made at two ground stations; these stations transmitted pulses on the same wavelength but at different rates, or pulse recurrence frequencies. One ground station, called the Tracking or Cat station, was used to direct the aircraft so that it flew at a constant and exactly known radius about the ground station. The resulting track of the aircraft was an arc of a circle, whose centre was the Cat station, passing exactly over the target. The position of the aircraft relative to the desired track was made known to the pilot by means of dot-dash signals in his telephone, similar to those used in standard beam approach systems. The second ground station, called the Releasing or Mouse station, was situated at some considerable distance from the Cat station. At the Mouse station the aircraft's range and ground speed were measured, and from these measurements, combined with a knowledge of the height of the aircraft and the ballistic characteristics of the bomb, the point at which the bomb was to be released was calculated, and a signal sent to the aircraft accordingly.

Information had to be signalled to the aircraft from both Cat and Mouse stations, and this was done on the same wavelength as was used for the range measurement by modulating the emitted pulses.[1] The aircraft pulse-repeater equipment was arranged to demodulate the pulses so as to extract the signals for the information of the pilot and observer. Further, in order to permit the control of more than one aircraft at a time on the same wavelength, a system of multiple pulse recurrence frequencies was evolved, the aircraft equipment being arranged to select the required pair of frequencies. Lastly there was the method of increasing the range by means of a repeater

---

[1] Two systems of modulation were used. In the earlier one the relative spacing of successive pulses was varied (space modulation). In the later system the width of the pulses was varied (width modulation).

aircraft, although as it happened this refinement was never used operationally.

In April and May 1942 bombing trials of the 1.5 metre prototype were made at Stormy Down range. The ground stations were situated at Worth Matravers (Cat) and West Prawle (Mouse), some 90 miles from the target. A Wellington aircraft was used and the trials were highly successful. The accuracy obtained was comparable with that given by visual means and was, of course, wholly independent of the visibility of the target.

These striking results, exceeding the expectations of the Air Ministry, at once brought up the question of using Oboe in this simple form against the enemy. What was the best use that could be made of it? The decision was that the ground stations should be sited to cover the Ruhr, as there was an urgent need to improve the accuracy of attack on the industrial cities which at night were doubly hidden owing to the industrial haze. Arrangements were accordingly made for the production of 20 airborne sets and a pair of duplicate ground stations as a matter of great urgency.

Meanwhile, Bomber Command proposed a method of using Oboe operationally which would in effect vastly increase the traffic-handling capacity of the system. It was the simple suggestion that Oboe should be used to control aircraft dropping, not bombs, but coloured target indicators, which would then be bombed by the main force aircraft. This was in line with the operational policy, which Bomber Command was then developing, of using a special force—soon to become famous as the Pathfinder Force—to mark targets with incendiary bombs. The Air Staff readily accepted the idea which then took its place as an associate or extension of the Oboe scheme.

The obvious aircraft for the Oboe role was the Mosquito, which had recently come into service. The bomb-carrying capacity of this type was small, but for a target-indicating aircraft large capacity was not necessary. In any case the Mosquito had the great advantage of being able to fly very fast as well as very high and so was considerably less vulnerable than other types to A.A. gunfire and to fighter attack.[1] In January 1943 it was decided to arm No. 109 Squadron with Mosquitos.

Oboe Mark I was first used operationally on 20th December 1942, when bombs were dropped by single aircraft on targets in the Ruhr. When experience had been gained, Oboe Mosquitos were used as target markers in a series of devastating attacks on the Ruhr, the first of which took place on 5th March 1943. For the first time Essen, and particularly the Krupps works, were hit by a really heavy

---

[1] See pp. 84–86.

weight of bombs. During the spring of 1943 Bomber Command proceeded virtually to destroy the Ruhr industrial area, and in this great battle the part played by Oboe was of incalculable importance.

With Oboe, as with so many other radar devices, enemy jamming had been feared, since it had been realised from the beginning that 1·5 metre Oboe Mark I could readily be jammed. Anti-jamming precautions were taken, however, and the Mark I system continued in use for a period of almost two years, for nearly a year of which there was no jamming at all. This astonishing fact has since been explained by German scientists. It appears that, as they had no information or apparatus to guide them,[1] it took them nearly seven months to associate Oboe signals with bombing raids, and some months more elapsed before satisfactory jammers were developed and deployed. For this and other reasons the loss of Oboe aircraft proved to be remarkably low.

The main subsequent development of Oboe was the introduction of a centimetre version. The complete centimetre system, known as Oboe Mark III, included the multiple-pulse-recurrence-frequency arrangement for permitting the operation of up to four aircraft on a single wavelength, but this system did not go into operation until April 1944. The multi-channel Mark III stations were designed as fixed stations situated in Britain, and they played an important part in the early stages of the invasion. A mobile centimetre equipment, known as Mark IIM, was also developed; units of this type were deployed on the Continent in the later stages of the invasion, advantage being taken of their mobility to keep pace with the rapidly advancing front.

With Gee and Oboe, Bomber Command had much of the aid it could be given by radar, but there was still one grand desideratum—a device or devices which would carry out the same task at ranges greater than either Gee or Oboe could command. This deficiency was supplied by a device called H2S, in which the operational features of Gee and Oboe were to some extent combined—fixes for general navigation could be obtained, and the accuracy of fix, though less than that of Oboe, was good enough for blind bombing. Although H2S had the disadvantage that the aircraft radiated a signal while the equipment was in use, it had the supreme advantage of being independent of ground stations and therefore not limited in its range of operation.

The history of H2S, like that of Oboe, begins with the investigations into bombing accuracy which were made in 1940–41. It was in 1941 that the installation of cameras in bombers provided

[1] Only one Mark I airborne equipment fell into the enemy's hands and that was almost completely destroyed in the crash of the aircraft which carried it.

for the first time, by means of photographs taken at the instant of bombing, really accurate information about release points: an analysis was made of some 650 air photographs taken, which established the magnitude of the errors. Something was required that would provide general aid to navigation without limitation in range and which would at the same time enable an aircraft to find a town or built-up area when it had reached the vicinity by other means.

Mr. Watson-Watt made the problem known to the Telecommunications Research Establishment at a Sunday Soviet[1] in October 1941; the ensuing discussion ranged over many new suggestions and many early experiments were recalled. Among resurrected ideas was one of enabling an aircraft to navigate by means of a radar device giving direct information about the ground over which it was flying. This idea was for a device which would be selfcontained and independent of ground stations, and would depend for its effectiveness on the possibility that the echoes obtained by a radar set in an aircraft from built-up areas could be distinguished from the echoes given by open country. The possibility that radar might be used in this way by bombers to aid their navigation had been discussed from time to time in the Air Ministry as well as in the Telecommunications Research Establishment,[2] and tests made early in 1939 to determine the optimum wavelength for discrimination between town and country echoes had indicated that 10 metres was likely to be best. In the meantime the remarkable development of the centimetre technique had taken place, in the course of which echoes from the ground had frequently been observed. In experiments at Leeson House, part of the Telecommunications Research Establishment premises overlooking Swanage, radar echoes from the town had frequently been used for the purposes of calibration.

At the Sunday Soviet of October 1941 it was suggested that earlier experiments should be associated with the new centimetre technique. The use of centimetre waves would enable a small aerial to be made, capable of giving the required accuracy of bearing. But would equipment working on these wavelengths give adequate differentiation between town and country echoes, when operated in an aircraft, where the angle of view was necessarily much steeper than from Leeson House? This was the vital question, to which an answer was quickly found. On 1st November 1941 a Blenheim aircraft fitted with an experimental 9 cm. A.I. system was flown from Christchurch with the centimetre beam tilted downwards, rotating at 300 r.p.m.

---

1 See pp. 482–483.

2 For example, at the meeting of the Committee for the Scientific Survey of Air Defence on 15th February 1940, Professor Blackett suggested the use of A.S.V. or a radio altimeter for the identification of rivers, coastlines and mountains, as an aid to navigation; the Assistant Chief of the Air Staff expressed a wish for a trial, but none appears to have been made.

and isolated responses were immediately observed on the range/azimuth presentation. On approaching Southampton a response was seen on the screen which appeared almost certainly to represent the town. Further experiments[1] were made and photographs taken of the cathode ray tube in the aeroplane provided striking evidence of the success of the tests.

On 20th November the Chief of the Air Staff informed the Prime Minister of these promising results. The Secretary of State for Air then ordered six flights to be made to 'determine whether the signals obtained in separate flights could be definitely associated with specific ground objects'.

We are now concerned with the nature of the echo which was established in the course of the H2S experiments. These experiments established beyond doubt that a built-up area invariably contains at least a small number of surfaces placed at such an angle that they will give a powerful direct return without scatter, and that such an area thus gives a characteristic response, readily distinguishable from ordinary ground responses. Moreover, if three reflecting surfaces are mutually at right angles (for instance, a corner of a courtyard) it can be shown that the incident radiation reflected from each of the three surfaces in turn always returns along its own path, no matter what its direction of incidence. Such a system of surfaces is often called a 'corner reflector' and in the combination of its reflections with the direct reflection given by any built-up area will always return strong echoes.

A Telecommunications Research Establishment Report dated 23rd April 1942, published the results of a more exhaustive series of flights, and its first conclusion was 'the H2S scanning system affords the likelihood of successful target selection and accurate location with some possibility of selective bombing within the target area'. The report also pointed out that the system could be converted, with comparatively little difficulty, for use in spotting surfaced submarines and vessels at sea, that is to say as an A.S.V. (Air-to-Surface Vessels). Some time before this, however, in December 1941, there had arisen in connection with the new device the question which invariably harasses all who are responsible for the development and use of new devices in time of war, the question of whether to wait and gain the advantage of advanced development or strike at once and gain the advantage of time. In no field was this question more harassing than in that of radar, and in no radar development did it present itself more acutely than in that of H2S; and, as frequently happened, this problem was associated with the problem

---

[1] Mr. Watson-Watt participated in one of these flights just before his departure for the United States on 9th December 1941.

of the amount of risk that should be accepted of disclosing information to the enemy; this problem also was acute.

At a meeting on 23rd December 1941, Lord Cherwell, the Prime Minister's scientific adviser, said that it was necessary to consider which of the two centimetre transmitting valves, the magnetron and the klystron, was to be used. His second point was whether it would not be desirable to use a simplified form of H2S as a device to ensure hitting a built-up area as such, rather than as a general navigational aid. These questions involved fundamental strategical issues. Taking the second one first, the Telecommunications Research Establishment had in mind an equipment using the P.P.I. (Plan Position Indicator) to give a map display of the ground beneath the aircraft. Lord Cherwell was inclined to the view that a simpler form of display—a split aerial with left-right display for homing to a target echo—would be adequate and could be developed with less delay. His idea was that the device in this form would be of use for blind bombing once the neighbourhood of the target was reached; as regards navigation he believed that the Air Force could, and should, greatly improve its astro-navigation.

The issue of map versus left-right display was linked with the other major question, the use of the magnetron over enemy-held territory. The magnetron was Britain's most recent and advanced centimetre-wave valve, and was capable of producing far higher powers than any other valve. On it depended A.I. Mark VIII; centimetric A.S.V. and G.L.; and a host of other devices. Its development was known only to the Allies. The klystron on the other hand, though capable only of lower power, had been described in the scientific press. The magnetron, a particularly robust piece of equipment, was mechanically almost indestructible; flying it over Germany therefore involved the risk of presenting the enemy with a sample of this device—the key to our latest centimetric technique. To the map display form of H2S the magnetron was practically essential; it seemed probable, however, that the simpler left-right display could be achieved with the less novel, less efficient, but more easily destructible klystron. It was agreed that both the left-right display and the klystron transmitter should be developed in parallel with the map display and the magnetron transmitter.

Development work pressed forward, and on 21st January the Chief of the Air Staff reported progress to the Prime Minister, saying that contracts had already been placed with the Electric and Musical Industries for electrical units, Metropolitan-Vickers for an electrical scanner, and Nash and Thompson for a hydraulic scanner. Development at Electric and Musical Industries was at this time based on the klystron; the firm was to make 200 pre-production units by semi-tooled methods to provide supplies before the bulk production of

1,500 sets began. The Air Staff had decided to begin operational use when production reached 100 units a month, which the Electric and Musical Industries expected by the end of October 1942. One of the problems involved in the H2S development was that of housing scanners in a heavy bomber, and about this little was known. The Halifax was chosen as the first aircraft to have the new equipment because it appeared to offer the greatest number of alternative positions. On 27th March 1942 the first Halifax fitted with the experimental scanner housing—a perspex cupola in the under-turret position—landed at Hurn. In it the Telecommunications Research Establishment installed an experimental equipment built on the laboratory bench and using a magnetron transmitter-receiver box of A.I. Mark VII design. The Halifax flew in April, and ranges of 4 to 5 miles were obtained on towns from 8,000 feet altitudes—a result which, although not unsatisfactory, hardly realised the hopes based on the performance of the equipment in the Blenheim.

Even before the klystron-magnetron and presentation problems were solved, another problem, even more specifically characteristic of radar development, arose. This was the problem of combining H2S with A.S.V. Centimetric A.S.V. was then under development by a different group at the Telecommunications Research Establishment and by a different contractor, and it appeared that this might involve unnecessary duplication. A minute by the Telecommunications Research Establishment dated 16th March pointed out that the scanner and its perspex cupola could be common to H2S and A.S.V. and so also could the electrical units, if the magnetron were used. The Telecommunications Research Establishment thought this the most desirable arrangement, but the magnetron was essential for A.S.V. in order to obtain adequate ranges on U-boats.[1] If the ban on the use of the magnetron for H2S could not be withdrawn, then it was suggested that as many units as possible, including the scanner and cupola, should be made common to the two systems, but that separate transmitter-receiver units should be prepared, a klystron unit for H2S and a magnetron unit for A.S.V. To speed production, it was also suggested that an A.S.V. magnetron transmitter-receiver unit should be developed from A.I. Mark VIII by Electric and Musical Industries. This combined H2S and A.S.V. plan was approved by the Secretary of State, and Electric and Musical Industries were asked to undertake the work on the basis of using modified A.I. Mark VIII Units for A.S.V.

The reference to the use of the same scanner for A.S.V. and H2S is important. It implies that the simplified left-right system for H2S

[1] There was no security objection to the use of the magnetron for A.S.V. since, if it were lost, it would almost certainly be lost in the sea and consequently there would be no risk of the Germans finding it.

had in fact been abandoned in favour of a scanning system, with a P.P.I., although no formal decision appears to have been recorded. The Telecommunications Research Establishment had, however, reported that the left-right system was unlikely to be successful even when used with a magnetron.

On 6th May the Prime Minister wrote to the Secretary of State for Air: 'I hope that a really large order for H2S has been placed and that nothing will be allowed to stand in the way of getting this apparatus punctually. If it fulfils expectations it should make a big difference in the coming winter.' This expression of faith tempered by caution did not quieten scepticism in other quarters. Successful British experience on town detection was not being confirmed in the United States: this, added to doubt expressed in Service circles and the unfavourable progress of the Halifax installation, was mainly responsible for a meeting called by the Assistant Chief of the Air Staff in May 1942, at which important decisions were taken, and the following instructions issued:

> 2. (a) That the system should be accurate enough to guarantee that bombs would fall within an industrial or other area selected as a target.
>
> (b) That the Air Staff would be satisfied in the first instance if the range of the device enabled the aircraft to home on a built-up area from 15 miles at 15,000 feet.
>
> 3. Subject to there being no delay or interference with the development of the equipment and its introduction into the Service in a form which will fulfil this aim, it was agreed that details in design to enable it to be used as a navigational aid to determine a specific area or target could be incorporated during the later stages of development and operational trial.

This was an encouraging document, but encouragement was to be very badly needed during the next month. On 7th June there occurred one of those disasters inseparable from experimental work carried out in the air—the Halifax aircraft fitted with the prototype H2S, and carrying five of the scientists working on the device, crashed on a test flight and all the occupants were killed. The loss of the equipment and of so great a proportion of the total of knowledge and experience was a catastrophic setback in the scientific development of H2S.

In the summer of 1942 development had in fact still a long way to go. The prototype equipment in the Halifax was elementary, and even with the forbidden magnetron results were not good; scepticism continued to flourish in both the Service and the Telecommunications Research Establishment. Unexampled efforts were being made, and planned, to get a number of adequate equipments into the air.

Electric and Musical Industries were to produce the first sets entirely by hand, using every device possible, but the Gramophone Company (manufacturing associates of Electric and Musical Industries) were expressing caution about the time required and thought that only fifteen equipments could be completed by Christmas, while bulk production could not begin before June 1943. Enthusiasm for the device, and in fact a reasoned belief in its potentialities, was now sustained in high quarters—the enthusiasm being frequently fanned and the belief renewed and confirmed by the Telecommunications Research Establishment—and meetings were held, initiated by one over which the Prime Minister presided, to consider ways and means of overcoming this production difficulty. The result of these meetings was a decision that H2S 'should be given the highest priority of any R.D.F. development' and that 'the set to be made should be the Electric and Musical Industries and not the Telecommunications Research Establishment one, as the former is well-engineered and some 75 per cent. of the drawings are in existence'. A bold crash programme was framed: Electric and Musical Industries and the Research Prototype Unit—a Telecommunications Research Establishment offshoot—were to make 200 sets by Christmas, the Research Prototype Unit being turned over exclusively to this all-important task. On 15th July the Secretary of State for Air called a meeting to discuss the magnetron versus the klystron: it was decided to produce magnetron units only.

In the second half of 1942 the firms pressed forward under the guidance of the Telecommunications Research Establishment who were simultaneously engaged in training navigators in the use of the equipment. By the end of September the first Halifax to be fitted with H2S underwent Service trials with encouraging results. The Bombing Development Unit, which carried out the trials, reported that with skilful handling and good navigation, H2S 'will be valuable to a high extent both as a navigational aid and as an aid to locating targets'; serviceability, however, was poor. After further trials, it was reported that 'the accuracy of bombing with H2S under blind conditions will produce a concentration of bombs about the aiming point comparable to the best results that can be achieved . . . in perfect visibility'. Bomber Command asked permission for Pathfinder Force to use H2S operationally as soon as two squadrons were ready and equipment improved.

The time had, in fact, come to fix a starting date for H2S operations. After a period of intensive training, the first operation took place against Hamburg on the night of 31st January 1943, and the Air Officer Commanding Pathfinder Force said 'the operation was, in the light of the prevailing weather conditions, a brilliant success'; this raid was quickly followed by others, and on 9th February H.Q.

Bomber Command issued a report saying that the exceptional value of H2S for identification and bombing of the target and its great navigational value has been proved beyond all doubt. In February, Bomber Command asked that all their heavies (except Lancasters with 8,000 lb. bomb doors) should be fitted with H2S as standard equipment and that the main production should be increased, so further contracts were placed in the following months. During this period the Telecommunications Research Establishment made various improvements to the equipment, including the addition of waveguide feed to the scanner.

But the use of H2S in bombers was not the whole story. It will be remembered that it was agreed in 1942 that the device should be designed, as far as possible, as a common H2S/A.S.V. system, a course which had been urged by the Telecommunications Research Establishment.[1] Centimetre A.S.V. would remove the disability of U-boats 'overhearing' 1.5 metric A.S.V. signals—at least until the Germans could determine the new wavelength and design and fit suitable warning receivers. The Air Staff was faced with a painful choice.

In September 1942, the Vice Chief of the Air Staff settled the matter by deciding that 40 H2S/A.S.V. equipments being made on the crash programme should be diverted to Coastal Command for use in Wellingtons fitted with another, non-radar, device which was already proving valuable—the searchlight for spotting surfaced submarines known as the Leigh Light. Further production of H2S/A.S.V. was discussed at meetings in the same month and it was agreed that 1,000 combined equipments should be made to the Gramophone Company's design. Altogether 3,000 equipments were expected to be available by December 1943.

In December 1942 a number of Leigh Light Wellingtons were made available to be fitted with H2S/A.S.V., or A.S.V. Mark III as it was finally called. The Wellington installation differed from that in the heavy bombers, especially in that the scanner had to be mounted under the front turret—the so-called 'chin' position—instead of midway along the underside of the fuselage. Twelve aircraft of No. 172 Squadron were fitted by the beginning of March and two flew for the first time with A.S.V. Mark III on night patrol over the Bay of Biscay on 1st March 1943. The success of the great campaign that followed has already been described.[2] It does not seem too much to say that the single squadron of A.S.V. Mark III aircraft contributed significantly towards it.

In 1943 major advances in H2S technique were made at the Telecommunications Research Establishment, notably in improving

---

[1] See p. 407.

[2] See p. 390 and S. W. Roskill, *The War at Sea*, Vol. II, (H.M.S.O. 1956), Ch. XIV.

the 'picture' at short ranges and in stabilising the scanner so that the picture remained steady when the aircraft rolled. The most important advance, however, was the introduction of an equipment working upon an even shorter wavelength than the existing 10 cm. A fault of the 10 cm. equipment was that it was unsatisfactory for bombing a large town such as Berlin. If the discrimination of the equipment could be improved, a more clearly defined picture of the detailed internal structure of the town would result, upon which it should be possible to identify such objects as the lakes in and near Berlin. Such improved discrimination could be obtained by reducing the wavelength to 3 cm. thus, so to speak, sharpening the point of the radar pencil.[1] Development of 3 cm. radar equipment had been going forward at the Telecommunications Research Establishment during 1942, and production of the necessary radio units had been arranged. Early in 1943 a 10 cm. H2S in a Stirling was converted to 3 cm. and subjected to preliminary trials which suggested that the expected improvement in definition would be obtained. Telecommunications Research Establishment therefore asked for sanction for the addition of 3 cm. H2S work to their research programme: this was given in May 1943.

It was evident that no commercially produced 3 cm. equipment would be ready before Christmas. Much depended, however, upon heavy attacks upon Berlin which ought to be carried out before that date. Could the aircraft taking part not, in some way, be given the advantage of the new high-discrimination equipment? Telecommunications Research Establishment considered that the answer to this question was to modify a few sets so that some of the target-marking aircraft could carry the new equipment. The Air Officer Commanding Pathfinder Force (Air Vice-Marshal Bennett) strongly supported the suggestion and with the approval of the Ministry of Aircraft Production the Establishment undertook in September 1943 to equip six Lancasters (twelve sets of equipment) with H2S converted to 3 cm. In November these went on operations, showing results which fully justified the effort and faith which had been placed in them. Not only were the lakes at the approaches to Berlin clearly visible in the picture but even the Templehof aerodrome was readily discerned. By Christmas seven major attacks on Berlin and one on Leipzig had had the advantage of being led by aircraft using 3 cm. H2S.

More 3 cm. H2S Mark III were made available to the Pathfinder Force, and more aircraft of the main bomber force were fitted with an improved version of the 10 cm. equipment, but effectiveness of

---

[1] H2S Marks I and II worked on a wavelength of 10 cm.

the raids did not now increase in proportion to the improvement in the equipment of the force. In the Telecommunications Research Establishment the suspicion grew that Bomber Command were not making the best of the equipment. Thus in raids in which the Pathfinder Force marked the target blind, the marking was done by both H2S Mark II and the more accurate Mark III indiscriminately, instead of making blind marking the exclusive business of the best equipped squadrons. Moreover, no specially coloured target indicator bombs were dropped by Mark III-equipped aircraft, to enable aiming points marked by them to be distinguished from those marked by the less accurate Mark II aircraft. Telecommunications Research Establishment suggested that it was desirable to investigate, on operations, the results that could be obtained if H2S were used for blind bombing instead of blind marking—in short, for the purpose for which it was originally intended.

An important combined meeting of the Air Staff, Telecommunications Research Establishment and Bomber Command was held on 22nd April 1944 to discuss the future use of H2S. The Air Staff representatives were not far from agreeing with the Establishment's views; Bomber Command's difficulties were explained and agreement was reached upon a number of policy matters. Bomber Command also agreed to review the employment of H2S Mark III to ensure that it was in fact the most effective possible: subsequent operational results showed a decided improvement.

This conference also decided that Bomber Command should organise an experimental attack on a suitable target in which all bombs should be dropped blind using H2S only. The only form of marking was to be the use of flares to ensure that all crews bombed the same target, thus showing the use of H2S as a blind bombsight under operational conditions. This experiment was not a success, a result which Bomber Command construed to mean that 'H2S Mark II is not sufficiently easy to interpret by the average crew to enable blind bombing to be carried out with any degree of accuracy. . . .' But in the Air Ministry it was pointed out that, contrary to the agreement at the conference, flares were not used to ensure that all aircraft attacked the right target, and that many of the crews had had no recent experience of H2S bombing; 'with crews more in H2S practice and with better briefing and planning, considerably better results could be achieved'.

During mid-1943 work on H2S and centimetre A.S.V. tended to separate. The two projects were, however, inter-related on the production side, and the Telecommunications Research Establishment developed H2S in such a form that it could be used for A.S.V. with slight changes. A.S.V. Mark III would retain its superiority in performance over Mark II, but once the Germans determined its wavelength they would be able to warn their U-boats of the approach of A.S.V. Mark III aircraft. Plans were made to nullify this, and two courses of action were proposed. One was to fit Coastal Command aircraft with 3 cm. A.S.V. so that the enemy would need to discover a new wavelength and then to fit new search receivers. The second plan was to develop a 10 cm. A.S.V. of much higher power, fitted with a means of controlling the power output used.

The Telecommunications Research Establishment developed work along these lines in April 1943. The 3 cm. A.S.V. was to be similar to H2S Mark III, and 50 of the first production of 200 sets were to be diverted to Coastal Command, the remainder going to Bomber Command. The high-power 10 cm. set (A.S.V. Mark VI) was being developed and production of 200 was expected by the end of 1943. But by October an event which had been anticipated from the beginning had occurred; the Germans had countered the blow struck by centimetric A.S.V., and were 'listening' to it—that is to say, using A.S.V. radiations as warnings of attack. The development of A.S.V. Mark VI was now urgent, but the Telecommunications Research Establishment had been unable to obtain the appropriate aircraft—a Wellington Mark XIV—for a trial installation: there were also manufacturing delays. At a Telecommunications Research Establishment Sunday Soviet these facts were brought to the notice of the Air Officer Commanding-in-Chief, Coastal Command (Air Marshal Slessor) who, greatly disturbed at this state of affairs, expressed his astonishment to the Air Ministry, asking for the immediate allocation of 10 of the 50 3 cm. A.S.V. equipments to his Command. The Air Staff, however, finally decided that Bomber Command's need was the greater and, with Admiralty concurrence, a delay in the re-equipment of Coastal Command was accepted.

(vii)

Friend or Foe?

High-discrimination H2S, stabilised to counteract the rolling of the aircraft, may be regarded as the most advanced, as in fact the ultimate, radar weapon of the Second World War. To sit in an aircraft travelling over an abyss of impenetrable darkness and fog, and watch an accurate and detailed map of the ground below unfolding on a radar screen, was an experience which already belonged to a different world of warfare from the Daventry experiment of 1935. The sequence of devices with which we have dealt, G.L., A.I./G.C.I., the Naval 271 set, Gee and Oboe and H2S, have clearly reflected the progress of the war from the defensive to the offensive. Their story, however, is not the full story of radar development, nor would this be told even if space allowed us to give some account of many other devices, once of vital importance or promise, whose esoteric names—Grocer, Airborne Cigar and Rugger Scrum, Speckled Band and Mandrel, Boozer, Bagful, Blonde and Coal Scuttle—are in many cases already almost forgotten. Such an account would be incomplete in two respects. It would omit a part of the total, and it would look at the total from only one angle. The part of the total is a very important one, consisting of the radar recognition devices known as I.F.F.—Identification, Friend or Foe—which were basic to the whole concept of radar.

The first I.F.F. equipment, as we have already seen, dated from Bawdsey days, experiments having been begun in 1937; these resulted in the development of an equipment which, in 1939, the Air Ministry decided to produce in numbers related to the total aircraft production rates. This first equipment was designed to respond only to the Home Chain stations, and was in consequence out of date by the time it was ready for production, since it was now necessary for friendly aircraft to identify themselves to G.L. as well, and also to the standby early-warning stations which were now in use. The need for such an extension of facilities had already been recognised, and work upon a more advanced I.F.F. had been begun in the spring of 1939. Telecommunications Research Establishment, the Radio Department of R.A.E., and Ferranti all took part in this. The I.F.F. Mark II was a 'universal' requirement, fitted not only in all aircraft both Air Force and Naval, but also in naval vessels. The concept of universality—the need to fit all British aircraft and ships, and all allied aircraft and ships, with I.F.F. responding to an ever-growing range of devices, had already begun to dominate all thinking on the subject, and from now on it gave a special shape to the I.F.F. problem. I.F.F. Mark II itself quickly became out of date, and was succeeded by a new system—for it was really more than a new Mark—known as Mark III. It was based on a proposal first discussed at Bawdsey in 1939, the development of which had not then been considered practical by the Air Ministry. It was conceived from the outset as being comprehensive and universal, and was based on the principle of complete separation between the function of location—the true radar function—and that of identification, at the detecting station. A special band of wavelengths was to be set aside exclusively for identification purposes, and all aircraft, ships and vehicles which might have to identify themselves were to be fitted with equipment which responded automatically to interrogation on this band. All radar stations on the ground or in ships, as well as many in aircraft, were to be fitted with equipment for interrogating this equipment.

This universal system involved a programme of great complexity and magnitude, although rather from the large number of equipments involved than from special difficulties in designing the equipments. Yet design and development had its own problems, since the display equipments had to fit in with the various methods of displaying echoes used in different radar sets. Already by the early summer of 1940 the technical soundness of the scheme had been confirmed by the work which had been done at the Telecommunications Research Establishment, and in September the Air Ministry decided that the scheme should proceed. It was still however necessary to get the agreement of the other Services to the launching of a scheme which affected them so intimately, and which—since anything done on such a scale would acquire an immense momentum—would affect them far into the future.

There was another factor to be taken into account. This factor was the possibility of the United States entering the war, in which event it would be necessary to have an I.F.F. system common to both British and American forces. The Americans had in fact developed a system of their own, which was for convenience called Mark IV in the British, and subsequently in the combined, discussions. In the opinion of the British authorities, this American system contained features which were undesirable for either operational or technical reasons. But if the British were to argue about it, they must have some definite project of their own to put forward. It was therefore agreed that there should be no defection from the development of I.F.F. Mark III, and that nothing should be allowed to hold up outstanding work. In September there was a meeting between representatives of the two countries at which the new British system was described, and following this a British equipment was flown to America for further examination.

It had already been decided that a large-scale trial of the Mark III system was necessary, mainly to test its facilities for responding to various kinds of radar station, and generally to demonstrate its suitability for use by all three British Services. This test was made the more urgent by the need to show a working system to the Americans.

This test, which was held at Pembroke in December 1941, was perhaps the most elaborate system of trials in the history of radar. Eight ground installations then in use by the Army and the Air Force were set up,[1] and seven aircraft of all types, including those carrying

---

[1] The following equipments were fitted with interrogators, responsers and displays: Warren C.H. and a mobile unit (R.M.3B), St. Twynnels C.H.L., Ripperstone G.C.I., and 3 G.L's and an S.L.C. at the Manorbier A.A. School.

A.S.V. and A.I., were fitted with the Mark III transponder.[1] In addition a sloop fitted with a transponder was used to test identification of ships from shore stations. There were of course some difficulties, but on the whole the results were favourable. Not only the British, but the American observers as well, were in favour of universal adoption, and recommended it in their reports. These recommendations duly passed through a series of committees with higher and wider authority until they were accepted by the Combined Chiefs of Staff.

The Pembroke trials may be said to mark the end of the development stage of I.F.F. Mark III, and the beginning of the stage of mass production. There had been however, and there continued to be, purely technical development difficulties. Some arose over valves. Twice the transponder was redesigned to use a different type of valve, the change being necessitated by the enormous scale of production which was contemplated. A more serious trouble was encountered in the summer of 1941. This was a mutual interference effect known as 'ringing round' which occurred when several aircraft carrying the new equipment were operating simultaneously fairly near one another. In such circumstances it was possible for the transponders to interrogate one another independently of the ground stations, thus causing accumulated interference which ceased only when the aircraft moved out of range of each other. This was potentially a very grave defect, enough, as one of the principal scientists concerned said 'to condemn the whole of Mark III system as at present contemplated'. Fortunately it was found possible to eliminate the trouble by reducing the sensitivity of the transponder without seriously affecting the general performance of the system.

Closely associated with I.F.F. was another branch of radar which depended upon the principle of interrogating a transponder by a pulse transmitter. This branch was generally called 'beaconry', since the equipment with which it was concerned was the radar beacon. The beacon was in a sense the inverse of the I.F.F. set, in that it provided a means by which an aircraft carrying a radar set might identify a point, normally a point on the ground, by means of a transponder placed at that point, instead of the I.F.F. procedure of a station on the ground identifying an aircraft.

The idea was, as radar ideas go, an old one; it was mentioned in Mr. Watson-Watt's I.F.F. patent of September 1936.[2] In December 1939, an experimental transponder was made at the Telecommunications Research Establishment, primarily for aircraft I.F.F.

---

[1] Aircraft fitted with I.F.F. Mark III were: Spitfire, Blenheim and Wellington bombers together with a Coastal Wellington and Sunderland, which also carried long-range A.S.V. A Beaufighter was fitted with Mark IIIG.

[2] Patent Specification No. 25133/36.

use, and in February 1940 some 'beaconry' experiments were carried out with this. The first experimental beacon was followed by two or three with improved design which were installed at Coastal Command stations for the use of aircraft fitted with A.S.V. Later, improved models were put into production and a version suitable for use by night fighters fitted with A.I. was developed in the autumn of 1940. The beacons, used in two different ways, proved to be a great help to navigation. Homing beacons were installed at aerodromes to assist aircraft to home to their bases when visibility was bad. Marker beacons were installed either on the coast, to guide aircraft at sea, or at suitable points inland to assist night fighters to maintain their patrol lines while awaiting direction from the G.C.I. system.

The introduction of radar beacons to Fighter and Coastal Commands was followed by a rapid increase in their use, until, ultimately, a comprehensive network was established. Their application to the operations of Bomber Command was less straightforward. In the early stages of the war, the suggestion had been made that in addition to using beacons for homing to airfields, they might be used either to guide bombers to their targets if planted there by agents, or to give them a fix off the enemy coast if dropped with buoys into the sea. Such methods of operation were inherently difficult; but in any case bomber aircraft did not then carry radar of any kind, so it would have been necessary to provide special airborne interrogators for them unless indeed they had used the interrogators which were being developed in connection with I.F.F. When the first experiments on the proposed I.F.F. Mark III were made in 1940, it was realised that night fighters with A.I. would require some means of interrogating the new device. Accordingly, an experimental airborne interrogator-responser, low in power and of light weight, was made for the purpose, together with a directional aerial system suitable for homing. It was suggested that this equipment, which was called Rebecca, could also be used in bomber aircraft not fitted with other forms of radar, to interrogate special beacons.

As it happened, the Rebecca project was dropped for a time, but not permanently. In June 1941, some radar scientists began to consider possible applications of radar to the problems of Army Co-operation Command. One of these problems was the accurate location of dropping zones by aircraft carrying paratroops or towing gliders. It was suggested that this might be done with the aid of radar beacons. The proposal was that a very light beacon should first be parachuted into the dropping zone or be placed there by agents and that the aircraft should home to this. For this purpose Rebecca was revived, and developed in an improved form. A special beacon called Eureka, very light and easily portable, was also developed to

28

work with Rebecca. This development was not done very urgently at first, but the results were used to assist in airborne operations, first on a small scale in Sicily in July 1943, then on a very large scale in Normandy in June 1944 for the initial airborne assault in the invasion of Europe.

(viii)
The Radar Chess Game

So much for I.F.F. and 'beaconry'. The various marks of I.F.F. and the various beacons were all an obvious and natural extension of the radar principle. But, as has already been said, the story of radar development would be incomplete if it were told only in terms of developing devices to be used directly against the enemy. For the enemy himself used radar, and in this fact lies the key to one of the most interesting parts of the story of the development of radar in Britain. Between the British scientists and their Allies on the one hand, and the Germans on the other, there developed a radar war, prolonged and bitter, but also partaking of some of the excitement, and some of the elegance, of a chess game between masters.

By radio countermeasures, or R.C.M. as they came to be called, are meant devices, systems, or operational signals techniques designed to hinder or prevent the use by an enemy of his radio or radar signals. The most obvious countermeasure is jamming, that is to say, the radiation of suitably modulated signals on the same wavelength as that used by the enemy, the jamming signals being much stronger at the enemy's receiver than those that he wishes to receive. Other countermeasures include the radiation of signals so as to cause the enemy's direction-finding equipments to give false indications, the emission of 'spoof' signals intended to divert his attention from one's own operational system, and the discharge of reflecting objects capable of producing misleading echoes in his radar sets.

Although even before the war British scientists feared that the Home Chain might be jammed, it does not appear that any move was made to carry the war into the enemy's camp by jamming his radio systems. The effort could not in fact have been spared, and the conception of a radio war did not emerge until some considerable time after hostilities began. Up to the Fall of France, such R.C.M. work as was done followed two main lines. The first was the development by the Engineering Department of the General Post Office of means for confusing the indications of the so-called M.F. beacons used by the German Air Force to aid navigation.[1] The second was the organisation of means for jamming German Army High Frequency radio communications in the event of an invasion.

Meanwhile, however, evidence was accumulating from intelligence and other sources that the Germans had available a system of long-range radio beams which could be used to aid their bombers to find targets in Britain. By June 1940, it seemed reasonable to expect that these beams could be detected, direct observations of the signals being necessary to supplement the intelligence information and enable countermeasures to be devised. Accordingly, a ground listening organisation was formed and aircraft were equipped to investigate the signals from the air, while scientists from the Telecommunications Research Establishment were sent with suitable receivers to Home Chain stations where they made observations from the tops of the 240 ft. towers. At the same time an Air Force unit was re-formed at Boscombe Down to undertake investigations from the air.

The beam system on which the Germans operated was known to them as *Knickebein*, and although the British had an appropriate code-name—Headache—for it, it became familiar under its German original. The target was indicated by the intersection of two beams similar to the standard blind approach beams of the Lorenz system used by both the British and the German Air Force. The aircraft flew along the centre path of one beam until it found the centre path of the intersecting beam. The system was accurate enough to mark out an area of about one square mile over any target in south-eastern England, and it had the advantage to the Germans that it could be used by all aircraft in the *Luftwaffe*, since they were all fitted with the standard blind approach receiver. On the other hand, the receivers were simple and the choice of wavelength restricted, so that jamming was not difficult.

Immediate steps were taken to jam the beams. There were considerable difficulties owing to the lack of suitable jammers, and as a temporary measure medical diathermy sets were installed at a number of police stations for the purpose. Later more powerful transmitters were modified to act as jammers and an attempt was made to deviate the beams by using standard blind approach transmitters keyed in synchronism with the German beams so as to cause them to give false indications. The control of this rudimentary jamming organisation was placed in the hands of H.Q. Fighter Command. Very soon, however, jamming became so important an

---

[1] Medium Frequency beacons worked on long wavelengths in the region of 1,000 to 2,000 metres. A network of these beacons existed in Germany before the war and was extended into occupied territory after the Fall of France. The countermeasure referred to, called meaconing, was put into use in 1940.

activity that it merited its own organisation, and a special Air Force unit was set up for the purpose. This was No. 80 (Signals) Wing which, tackling its problems with great energy, had, by November 1940, supplied sufficient jammers to render the *Knickebein* system unreliable for target indication.[1]

The Germans however were ready with a successor to *Knickebein*, another beam system known to the British as Ruffian, and to the Germans as the *X-Gerät*. The Ruffian system employed the same principle as the *Knickebein*, but in a considerably refined and complicated form. It was undoubtedly very accurate, but it was more difficult to use than *Knickebein* and was therefore restricted to pathfinders. Its existence was first reported in the Air Ministry in September 1940.[2] Just as the system was more refined and complicated, so were the countermeasures, but by the beginning of 1941 they were sufficiently effective to cause the Germans to bring into operation a third system, to which they gave the code name of *Wotan* and which the British called Benito. This was the most advanced and complicated system used by the enemy. In some ways it was similar to Oboe, but like all the early German navigational aids it made use of continuous wave transmissions instead of pulses.[3] Later it was discovered that by one of those dramatic strokes—sometimes accidental—which characterised the radar war, the countermeasures were applied on the same night that the enemy first used the system on the full operational scale. The countermeasures used against Benito differed from those used against the earlier systems and in fact comprised the first use of what came to be known as 'subtle countermeasures'. The earlier systems aimed quite simply at blotting out the enemy's transmission. In jamming Benito, however, advantage was taken of the existence of transmissions from the aircraft on a different wavelength from that of the ground station to interpolate a similar signal in such a way as to upset the ground station's measurement of range. The interference however—and this was the crucial point—was not obvious, with the result that the ground station gave wrong information to the aircraft and the resulting bombing errors were attributed by the pilots to the stupidity of the ground operators and by the ground operators to the incompetence of the pilots. It was some time before the true situation was fully appreciated by the enemy.

---

[1] The *Knickebein* system was kept in being as a partial aid to navigation and to engage our jamming effort. The number of wavelengths available for it was greatly increased later in the war.

[2] The Ruffians worked on wavelengths between 3.5 and 4.5 metres.

[3] Benito worked on a wavelength of about 7.1 metres with modulation frequencies of 300, 3,000 and later 16,000 cycles/sec. It was not until 1944 that the Germans used the pulse technique for controlling bombers.

The defeat of Benito marked the end of the first phase of radio countermeasures and was followed by a lull, during which the position was consolidated and a good deal of thought given to the whole question. The jammers used against the enemy's navigational aids had necessarily been developed on an *ad hoc* basic; and many assumptions had to be made, the validity of which there was not time to confirm. Such matters as the most economic deployment of jammers, and the relative merits of subtle and crude jamming, were the subject of controversy. On the whole the result of this rather more leisurely consideration seemed to indicate that few mistakes had been made and that the principles and methods of beam jamming could be regarded as established. It now became possible to consider the broader aspects of countermeasures and to work out what may be called a philosophy of countermeasures.

An organisation was now brought into being to deal with this special part of the radar field. In the Air Ministry a branch was formed to collect information about enemy methods, while at the Telecommunications Research Establishment a radio countermeasures group was set up. The individuals who had been hastily assembled in August 1940 to aid in countering the *Knickebein*, had been welded into a team whose sole concern was to deny the enemy the use of his radio systems. In October 1940, the first of a long and important series of informal meetings to discuss countermeasures and decide a policy were held under the Chairmanship of the Director of Signals at the Air Ministry. Later, the Chiefs of Staff Committee approved the formation of a permanent interservice radio countermeasures committee, and decided that the Lywood Committee—as it had become known from the name of its chairman—should form the basis of this.[1]

As long as the Germans maintained a heavy air offensive against Britain it was necessary to give first priority to countermeasures against their radio navigational aids. Consequently, until the spring of 1941, little effort could be spared for studying their radar system. That they possessed a radar system or systems was, to say the least of it, strongly suspected—for instance when scientists inspected the wreck of the *Graf Spee* they found what they believed to be radar aerials, and in October 1940 what appeared to be radar transmissions on a wavelength of 80 centimetres were picked up. These came from an equipment which the Germans called *Seetakt*, used by their shore stations for ship watching and gunnery control. A few months later British radar scientists identified as enemy pulse transmissions certain signals which had hitherto been confused with British radio signals. From the study of radio observations and

---

[1] R.C.M. Board.

intelligence information it was established that these signals emanated from the Germans early-warning stations, a beam type equipment not unlike the British C.H.L., operating on a wavelength of 2·4 metres and known to the Germans as *Freya*. The next step was for a detailed survey of the *Freya* chain to be made by the Air Ministry scientific intelligence branch. Another German radar signal discovered came from the *Würzburg*, a beam type equipment operating on a wavelength of 53 centimetres and used to direct anti-aircraft searchlights and guns, and for height-finding at *Freya* stations.

These three systems, *Seetakt*, *Freya*, and *Würzburg*, formed the backbone of German radar for the remainder of the war. They were modified to increase their range and coverage; they were given much greater flexibility in their choice of wavelengths, but until the last few months of the war no radically different ground equipments or wavelengths were used.

As the nature of the German radar system was revealed, the R.C.M. Group at the Telecommunications Research Establishment turned its attention to the question of jamming radar transmissions. It found this new field very largely untilled. Some thought had been given to jamming before the war, not for the purpose of attacking the enemy, but to clarify the steps that would have to be taken to reduce the vulnerability of the British systems. The new group took these old conceptions, pressed them to their logical conclusions, and added new ones.

The period of quiescence and consolidation, which began when the activity of the enemy's beam systems declined, was abruptly ended when, under the cover of heavy jamming of the British radar systems, the *Scharnhorst* and *Gneisenau* escaped from Brest through the English Channel on 12th February 1942. This was a crucial incident in the early history of radio countermeasures. It was the first occasion on which they were applied deliberately for offensive purposes[1]—the British jamming of the German beams had been done in self-defence. The jamming was effective largely because it was unexpected; subsequent analysis showed it was technically not as severe as it could have been, and that the newly installed 10 centimetre coastal defence sets at Dover were unaffected. But perhaps the most important consequence was the impetus which it gave to R.C.M. development, and the clarification of the aims and potentialities of R.C.M. to which it led.

The implications of the incident, as may be imagined, were immediately and fully examined in the Air Ministry and at the

---

[1] The Germans had been attempting spasmodically to jam our radar since August 1940. The first attack was on C.H. using a very ineffective technique. The first sustained jamming of C.H.L. was done on 12th February 1942, and there had been little previous indication that suitable jammers existed.

Telecommunications Research Establishment. It is characteristic of the outlook and workings of the Establishment that their report by no means confined itself to technical questions. It suggested that a fluid radar war was developing and that either side could obtain only short-term advantages; the side with the greater commitments was the more vulnerable and the side with the greater mobility and the greater reserves was likely to have a decisive advantage. The existing British radar system was criticized[1] and the recommendation made that high priority should be given to the development of equipments, the wavelength of which could readily be changed over a wide band. The report made a number of recommendations, but its chief value lay in the fact that it was the first classical statement of the conception of radio countermeasures as an essential requirement of modern war.

From 1942 to 1944, the end of nearly all allied R.C.M. activity, whether development at Establishments or use by the Services, was the reduction of bomber losses, both night and day. New countermeasures were usually prepared in response to, or anticipation of, a change in enemy tactics. But that was not all; the scientists on both sides always tried to see two or, if possible, three moves ahead, and to prevent the other side from doing the same. The ideal was to deceive the enemy even about the current move. Thus the Germans delayed jamming Gee for some months because they were misled by the British use of a type of Lorenz beam, called the J beam, into supposing that it was upon this that Bomber Command relied for navigation. These J beams were put into operation just before the introduction of Gee with the deliberate intention of misleading the Germans in this way.

Up to the beginning of the Gee phase the greater part of the bomber losses was caused by flak. Had the British tactics remained unchanged, however, there is little doubt that the G.C.I. system which the Germans had developed (on different lines from the British system) would have enabled them to inflict greatly increased losses by night fighters. But Gee, by enabling the bombers to concentrate in high densities both along chosen routes and over the targets, robbed the Germans of the advantages their G.C.I. would have given them against a more random and spreadout kind of attack, and kept British losses at a low level. It was apparent by the end of 1942 that the main cause of these losses was no longer flak but night fighters, and from this point onwards the story of radio countermeasures is largely the story of the war against the night fighters.

---

[1] The main criticisms were that far too high a proportion of our equipment was concentrated in the 1.5 metre band and that in all bands the equipments were too inflexible with respect to wavelength change, owing to the use of phased aerial arrays.

If the concentration of bombers restricted the Germans' use of their G.C.I., it did not wholly destroy its value. They began to work out a new method in which G.C.I. was used to plot the general course of the stream of bombers instead of the positions of individual bombers. Once in the stream fighters were left to patrol free-lance, with the aid of A.I. Thus the whole operation still depended on radar—G.C.I. to locate the stream and fix the fighters, and A.I. to enable them to search effectively in the dark. If countermeasures could destroy these links then the enemy would be forced to resort to others.

In the many and lengthy discussions which took place in Britain, it was pointed out that the greatest effect on the German radio defences would be achieved by attacking the *Würzburg*. As well as its use for flak and searchlight control this equipment was the backbone of the G.C.I. system. The G.C.I. version was known as the *Giant Würzburg* because it had a much larger aerial mirror than that used in the anti-aircraft version. This large mirror gave the equipment not only a greater range, but a very much higher angular discrimination. This in turn meant that it could be jammed only by jammers located in the direction in which it was looking. Consequently a very widespread deployment of jammers carried in aircraft would have been needed to ensure that all the *Giant Würzburgs* were jammed.

The best countermeasure that could be employed against the *Giant Würzburgs* was undoubtedly that known by the code name of Window. This method, or variants of it, had been discussed from time to time since before the war. During 1941–42 a long series of experiments with it was made, in co-operation with Fighter Command, in the course of which its potentialities and the best operational technique were established. In principle Window was perfectly simple. It consisted merely in jettisoning from the aircraft a large number of narrow strips of metal or metallised paper, called dipoles, cut to such a length that they would resonate at the wavelength of the radar to be jammed, so producing in that radar a large number of spurious echoes. It was proposed that these dipoles should be dropped from all aircraft in a raid, in such numbers and at such a rate that the *Würzburgs* would be filled with a clutter of extraneous echoes so that raiding aircraft could not be distinguished.

The difficulty with Window was that it was a double-edged weapon. Indeed, had the Germans used it against the British, the British radar at that time—1942—would have been even more vulnerable to it than the German *Würzburgs*. It was therefore decided that, in view of this temporary inferiority in the British position, no immediate use of Window should be permitted lest the Germans should retaliate in kind. The next stage was to attempt to plan two moves ahead—to create an answer to their retaliation. It was therefore decided that, as the first step towards reducing the British vulnerability to Window interference, a crash programme should be initiated for the construction of C.H.L./G.C.I. sets working on 50 centimeters—instead of 1.5 metres—and capable of comparatively high resolution.

During the period when Window was forbidden, it was necessary to consider other means of defeating the *Giant Würzburgs*. Electronic noise jamming, that is jamming generated by a special wireless transmitter[1] was regarded as impracticable because, owing to the high discrimination of the *Würzburgs*, it would have been necessary to fit the jammers on the scale of at least one per bomber. Not only would such a programme have placed very heavy demands on productive resources and taken a long time, but it would have been robbed of a large part of its effectiveness by comparatively small changes of wavelength on the part of the enemy. Of the other proposals which were made, the most interesting was that for jamming night fighter communications.

In the control of night fighters the radio telephone communications channel between the ground control station and the aircraft was as important as the G.C.I. radar. It was this link which it was proposed to jam. At this time the bulk of German night fighter radio telephone was on the so-called high frequency band of wavelengths between 50 and 100 metres. The Royal Aircraft Establishment Radio Department proposed a simple procedure by which all bombers could radiate jamming signals at various wavelengths in this band. The procedure, which was called operation Tinsel, was introduced in December 1942. It proved effective and forced the Germans to use higher powers in their ground transmitters in an effort to counteract it. This step was in its turn countered by concentrating a number of Tinsel transmitters on each high-power station. Later, in 1944, high-power jammers known by the code name of Jostle were used, operating in special jamming aircraft flying in company with the raiders.

These measures filled the gap; by the summer of 1943 sufficient ground radars of high discrimination had been supplied in this country to make the threat of retaliatory Window raids of less consequence. There was nevertheless still a school of thought that opposed the immediate use of Window. The matter was referred to the Prime Minister and, on his instructions, the Air Staff authorised

---

[1] The distinction is between electronic jamming and passive jamming—that is the use of confusing reflectors as in Window.

its use by Bomber Command in the summer of 1943.[1] Window was dropped for the first time on the night of 24th/25th July, in the course of a very heavy raid on Hamburg. It had the immediate effect of not only reducing our loss rate[2] but of destroying the whole elaborate system of G.C.I. and G.L. by its resulting neutralisation of the *Würzburg* system. So serious was the interference with G.L. *Würzburgs* that for a time the flak reverted to sound locators—a resource which by the standards of 1943 was antediluvian. Moreover the decision to withhold the use of Window had allowed improved methods of production to develop and large stocks of material were built up, while at the same time the Air Force had sufficient time to become familiar with the technique. As a result the device, while still a complete surprise, was employed with overwhelming effect. The German radar system was, as it proved, not merely reduced to impotence but irretrievably shattered.

By this time—mid-1943—radio countermeasures had become a most important element in the whole field of radio and radar development. The various countermeasures which were in use had however been introduced as contingencies arose and operational control was in consequence in a number of different hands. The multiplication of users of radio countermeasures became a matter of concern in several quarters. At the Telecommunications Research Establishment it resulted in a series of unrelated demands from various users which led in turn to a duplication of effort. Later in the year therefore, it was decided that a new centralised organisation[3] should be set up to cover technical and intelligence, as well as operational, aspects of countermeasures work.

For the remainder of the war radio countermeasures played a steadily increasing part in the defence of the allied bombers. The enemy's methods of attack were varied and improved in many respects. Thus in the summer of 1944 he introduced a new type of A.I. called S.N.2, similar in principle to the British A.I. Mark IV and much better suited to free-lance operations than his existing equipment. To counter this, airborne electronic jammers, based on American equipment, were used. In his efforts to overcome our jamming the enemy tried many different methods, some very crude, of communicating with his fighters.

---

[1] It is interesting to note that the Germans revealed after their defeat that they had developed a form of Window as early as 1942, had had discussions very similar to our own, and had suppressed the scheme because they feared immediate retaliation. They pursued their ostrich policy even farther, by prohibiting any research on anti-Window devices for their own radar.

[2] Bomber Command estimated that Window probably saved 200 aircraft in the first two months of its use.

[3] No. 100 (Bomber) Group, R.A.F.

The success of our countermeasures and the persistence with which they were applied ultimately caused the Germans to try to supplement their location equipments by making use of the various transmissions radiated by Bomber Command aircraft.

By mid-1944 these included pulse transmissions on 3 and 10 centimetres and 1.5 metres, as well as a variety of jamming transmissions on 3.7 and 50 to 100 metres. The Germans established an elaborate network of ground direction-finding stations by means of which they could locate approximately the source of these transmissions and thus supplement their badly jammed early-warning radars. This step was a serious matter, but more serious still was the fitting of some of their night fighter aircraft with apparatus which enabled them to home to bombers radiating H2S pulses, and also pulses from Monica, a device which warned the bomber of fighter approach from the rear. The advantage of such a method was that it permitted the fighters to locate their targets from great distances and to operate more or less independently of ground control. Moreover, the fighters needed their A.I. only for the last half mile or so of an interception, at which range the British jamming was comparatively ineffective. The effect, had these tactics been applied on a large scale, would have therefore neutralised to a large extent the value of the allied countermeasures. The threat was grave, but fortunately the Germans did not adopt these tactics until after the Allies had recaptured a considerable area of occupied territory. As a consequence the distance which the allied bombers had to fly above enemy territory was greatly reduced and the Allies were able to adopt the only effective countermeasure without materially decreasing the efficiency of their raids. This countermeasure was that of restricting transmissions from our aircraft. The use of H2S was forbidden until the aircraft were actually approaching the boundaries of Germany; I.F.F. discipline over enemy territory was also tightened up. At the same time the enemy's picture of the situation was confused as much as possible by the use of spoof raids and diversions.

At the end of the war the Germans were developing a centimetric ground equipment of a very high discrimination, against which no economic method of jamming could be foreseen. With this development the radio defence had caught up with the radio attack and the tactics of night bombing would, if the war had continued, have required drastic revision. This particular phase of the chess game thus saw the enemy forced into a very inferior position but one from which, when the game was abandoned, he was emerging.

The other great phase of the war in which radio countermeasures played a major part was the invasion of Normandy. In this they had two broad tasks to perform. The first was to prevent the enemy from locating by radar the invading forces, sea and airborne. The direct

R.C.M. method was jamming, although radar of course played an important part in the destruction of the German radar stations by air attacks. The second was to mislead the enemy as to the point on his coast at which the invaders would land. This was done by, amongst other things, decoy invasions made up of small forces of aircraft and light naval craft using Window[1] and another device, Moonshine, which was specially developed to simulate large invasion fleets. The naval diversion consisted of a small number of light naval craft, each carrying balloons in order to increase their range of detection by coastal radar, and designed to produce the impression of a large fleet on the German radars. As it happened, only four of the Moonshine fitted craft were available on D-day, three being allotted to the Cap d'Antifer diversion and one to the Boulogne diversion. Both operations were observed by the enemy radars and were found to have the predicted characteristics. The most essential component of the deception was the application of Window to simulate, rather than as normally to conceal, the movements of radar targets. A technique was worked out to fake the appearance of a mass of shipping covering a front of 16 miles to a depth of 16 miles, and because of the very great difference in speed between ships and aircraft very exact navigation was required which was undertaken by the use of Gee or G.H.[2] systems. No attention to detail was spared to heighten the effect of this elaborate deception, and the little fleets concerned carried, for example, loud speakers relaying appropriate noises intended to confuse and alarm the listening German ears.

(ix)
The Universities and Industry

Whilst the bulk of radar development work was done in Government Establishments, a considerable amount was done in Universities and the research laboratories of some industrial concerns. In considering this aspect of radio development certain general statements can be made. The first is that not only were the Government Establishments responsible for the conception and initiation of most of the radar projects; to a large extent they also guided the work of the non-Government research laboratories. The second generalization is that

---

[1] It will be realised that since Window produced its jamming effect by causing a great number of echoes to appear in the enemy's radar, it could also be used to simulate the appearance of a large force of aircraft or ships.

[2] A blind bombing system using range measurements from pairs of ground stations.

university laboratories concentrated almost exclusively on fundamental research, whilst the industrial laboratories, with few exceptions, undertook the kind of work which is best described as 'development for production'. Thirdly, one of the most important contributions, especially by the Universities, took the form of transferring experienced research workers to Government Establishments. Finally, it may be said that most of the projects initiated in industrial laboratories were for communications rather than radar purposes.

The transfer of a large number of their best scientists to the Government service was the Universities' first, and perhaps most important, contribution to radar development. In some Universities however it was found more convenient to retain organised teams of scientists, who undertook research on specific problems on extramural Government contracts. Frequently the whole of the research laboratories of the appropriate department were turned over to Government work. Among the outstanding instances of this type of co-operation was the work on centimetric valves done throughout the war in the Universities of Birmingham and Oxford. The importance of Birmingham's contribution—the cavity magnetron—need not be stressed again here. Other important work was done on theoretical questions. Thus at Manchester and at Leeds mathematical studies were undertaken to determine the mode of operation of the magnetron. At Manchester work was done on cables and wave guides. At Sheffield an investigation was made into the stability of the permanent magnet used with the magnetron.

A third contribution which was made by some Universities took the form of the loan of laboratory space for use by teams of Government workers. An outstanding example of this is furnished by the University of Bristol, where accommodation was provided for Admiralty scientists working on centimetre valves. Whether they used them themselves or lent them, the Universities possessed both the facilities and the men required for radar work.

Considered as a whole, the radio industry was not well equipped with research facilities. Indeed, this was one of the reasons why radio development for the armed forces was so closely restricted to Government Establishments. The principal exception to this rule was the research laboratories of the General Electric Co. which were capable of tackling a large range of problems, including some of a fundamental nature, and were particularly skilled in valve research. The British Thomson-Houston Co., Metropolitan-Vickers, and the Standard Telephone & Cable Co. also had large research laboratories capable of a variety of investigations. Electric and Musical Industries was essentially a research organisation, feeding information to the Gramophone Co. and to other allied concerns. These were the principal firms capable of research work. There were also a number of, so to speak, intermediate firms with small though skilful research teams. Examples of these firms are A. C. Cossor, Pye Radio, Murphy Radio and E. K. Cole, to name four only.

We may look first at the contribution made by this intermediate class of firms. It took two forms: first, development for production of equipment designed by Government Establishments; and second, the development of equipment initiated by the firms themselves. The first kind of development formed by far the greater part of their work; in the radar field it formed the whole of it, for the only projects initiated by these firms were for communications equipment. During the first two years of the war development for production of radar equipment designed by Establishments was nearly always done from prototype models supplied by the Establishments. Gradually, as the pace of the radio war quickened and as these firms became more experienced in the new art, it became customary to bring the firms in at an earlier stage in the development. The Establishments however continued to exercise supervision of the work and were always responsible for the initiation of projects.[1]

The major industrial research laboratories contributed to radar and radio work in two ways. The first was the development for production of equipment for which the Establishments were the design authorities. The second was research on techniques, especially on valves, for which, as a rule, the Establishments had no facilities. The bulk of their work was in the first of these classes. In essentials it resembled the work done by the intermediate class of firms, but it was more common for the bigger concerns to be brought in early in the development and to be given a comparatively free hand in working out technical details. For example, Electric and Musical Industries were introduced to H2S shortly after the first experimental flights in the Blenheim, when the general form of the final installation was in a most fluid state and the firm made many important contributions to the circuit technique used.[2]

[1] A noteworthy exception to this rule was the proposal, made in 1940 by Messrs. A. C. Cossor, to make an elevation-finding attachment for G.L. Mark I, to which reference has already been made, see p. 383.

[2] See pp. 407–409.

PART IV

Scientific Establishments

CHAPTER XVI

THE RESEARCH ESTABLISHMENTS: INTRODUCTORY

In all the activity which has been described throughout this account of the development of weapons, constant reference has been made to the part played by one or another of the Government-controlled research and development establishments. As a body, the scientists, engineers, technicians and industrial staff who manned these establishments constituted the front line in the battle for supremacy in the quality of weapons.

To the public, and even to the general body of the Service for which they worked, very little was known about the Establishments, even when they possessed a world-wide reputation in their own branch of science or technology. Probably the only one to be known to the nation at large was the Royal Aircraft Establishment at Farnborough. At the beginning of the rearmament period there were however some score or so of establishments devoted to the improvement of weapons, together with a considerable number of semi-independent units of a similar nature. On the air side the picture was dominated by the Royal Aircraft Establishment, the other major establishment being the Aeroplane and Armament Experimental Establishment, which was in part a user establishment for testing new types of aircraft and in part a centre for research into aircraft behaviour. On the naval side responsibility was more widely dispersed among the Admiralty Research Laboratory, the centre for basic research, and a number of establishments devoted to particular lines such as radio, metallurgy, and so on. The War Office administered two establishments which undertook research and the design of weapons for all three Services, as well as another half dozen devoted to its own particular problems of mechanization, signals, bridging, and so on.

The government establishments as a whole were in every respect exceedingly diverse. As regards their staff, it varied in numbers from half a dozen or fewer to several thousand. In function also they varied widely, some undertaking research only, some development only, some designing equipment for manufacture by industrial firms and some advising industry about design which the industry itself undertook. They were diverse also in historical origin. New establishments were founded during the rearmament period and the Second World War, but the oldest was a hundred years old before rearmament began. The senior government-controlled establishment for undertaking the scientific improvement of weapons of war was H.M.S. *Excellent*. During the period with which we are concerned H.M.S. *Excellent* was a shore establishment—what the Navy calls a 'stone frigate'—and devoted mainly to gunnery training. It did, however, maintain an Experimental Department, the work of which may be traced directly to trials of gunnery equipment carried out by H.M.S. *Excellent* as early as 1832, in its days as a sea-going vessel. These trials were tests of the operational efficiency of existing weapons (presumably new types) but they were also experimental and could directly affect future development. They directly foreshadow the modern position of the Experimental Department as a civilian establishment, responsible, in conjunction with the inter-service Ordnance Board and the Armament Design and Research Departments, for research and development in Naval gunnery. The same addition of experimental to testing functions is characteristic of other Naval establishments of early origin such as H.M.S. *Vernon*, which historically has been responsible for representing the interests of the users in the development of undersea weapons, but which in modern times also carries out design work. The Admiralty Compass Observatory, another establishment of comparative antiquity, has a similar history. It was in 1842 that the Admiralty Compass Department was formed, including among its functions the examination and testing of commercial compasses. The Compass Observatory, which was responsible during the Second World War for the design and testing of all Naval compasses, owes its origins to this body.

During the present century the origins of establishments display more of the characteristics of systematic provision. Most of them were set up to fill what was recognised to be a gap in the knowledge of defence planners, or even to find out what gaps there were. The Admiralty Research Laboratory is perhaps the clearest example of this process. After the First World War the inadequacy of the existing arrangements for extending the scope of scientific research was recognised, and in 1920 the first Director of Scientific Research in the Admiralty, Sir Frank Smith, was appointed with a laboratory directly under his control. This was the Admiralty Research Laboratory, and its task was that of carrying out scientific research of a fundamental and pioneer character which might bear on Naval interests and for the prosecution of which no outside agency existed. The origin of the interdepartmental Armament Research

Establishment is not dissimilar, although the gap in existing knowledge was perhaps more obvious in this case. It owed its being to the recommendations of the Explosives Committee, a body which was set up under the chairmanship of Lord Rayleigh to examine the reasons for defects in armaments which had been revealed during the Boer War. That body recommended the setting up of an establishment with the function of applying scientific method to the improvement of armaments, a function which has not altered to this day.

One of the most modern establishments, the Naval Construction Research Establishment,[1] was founded in the same way, as a deliberate attempt to fill a gap. The Director of Naval Construction had been urging ever since the First World War the need for an establishment to conduct enquiries into the phenomena of underwater explosions, and particularly their effect upon ships' structures, a highly complex and unknown field. Experimental work on underwater explosions was limited to occasional trials at Portsmouth and Chatham and to work which was carried out by H.M.S. *Vernon* and which, valuable as the results might sometimes be to the Director of Naval Construction, was done primarily in the interests of the Director of Torpedoes and Mines. The sinking of the *Prince of Wales*, *Repulse*, and *Ark Royal* provided the final impetus and in 1943 the Naval Construction Research Establishment came into being.

By no means all establishments however owed their position at the outbreak of rearmament either to a slow and as it were logical development over a long period of time or to a specific act of creation to meet a specific need. In many cases their evolution had followed a path much less smooth and straight. An apparent haphazardness in the way in which the establishments started, grew, acquired and shed functions is in fact a very marked feature of their history. Thus many establishments owed the form which they took on in the rearmament period to the grafting-on of functions involving original research or design to an older body originally carrying out other activities. The Armaments Design Department (formerly Design Department) is an example. It was originally no more than the drawing office of Woolwich Arsenal, under the supervision of an officer known as the Superintendent of Design. The staff consisted only of a small number of serving officers and a large number of draughtsmen. The 'primary duty' of the drawing office was officially described as: 'The preparation of original designs for the Army, Navy and Air Force, of guns, gun carriages and mountings, ammunition and allied stores, bombs, pyrotechnics and certain torpedo stores, small arms and their mountings'. Briefly the procedure was for the Services to put their requirements for armaments to the Ordnance

[1] See also Ch. XVII, pp. 457–458 and Ch. XIX, pp. 484–485.

Board in the form of a general idea or rough specification, and for the Ordnance Board to translate this into a firm specification. The function of the Superintendent of Design's staff was to produce detailed design drawings in accordance with this specification. Despite the responsibility, knowledge, and experience which this function involved, it was something less than is ordinarily understood by design. The Ordnance Board specification, in the case of guns and carriages, was given in considerable detail and might even be accompanied by sketch drawings, so that at least the outlines of design had already been done when the Design Department entered the field. The Department was not expected to give any critical consideration to the Ordnance Board specification or to attempt to improve upon it; indeed since it had no experimental facilities and no finance except from the Ordnance Board it had no basis on which to evolve criticism or improvement. It will be clear from what has already been said that the Design Department had no responsibility whatever for long-term development of armaments. Such matters as the trend towards higher velocities or rates of fire, and consideration of the development effort which it was worth expending upon advances of this kind—all these were questions for discussion and settlement by the Ordnance Board. The interpretation of Staff requirements was also an Ordnance Board function. It was the Ordnance Board which discussed and determined the armaments which (for example) would be appropriate for a new type of Naval vessel, and the Design Department never enjoyed as a matter of course direct knowledge of Staff planning, or the strategical concepts against which requirements were envisaged. Yet this body, through a variety of changes, the most notable of which will be discussed later,[1] was eventually to be entrusted with full responsibility for the design and development of all armaments.

Particular significance attaches to the origins of two establishments which have little but this significance in common, that they owe their foundation peculiarly to the ability, foresight and vigour of a particular individual. The first of these is the Admiralty Experiment Works. This exists to carry out the model tests of ships' hulls, tests which have been one of the most important aids to the designing of ships. William Froude, one of the most distinguished figures in the history of Naval architecture, obtained Admiralty authority in 1870 for a proposal to conduct tests of model ships, and from then on devoted himself to investigations in accordance with a technique which he evolved and which has since been adopted throughout the world. The principle of all such tests is outlined in a manner which could hardly be improved in the article upon Froude in the *Dictionary*

---

[1] See pp. 474–478.

of National Biography:

> The Admiralty Establishment at Torquay erected for carrying out these experiments contained a covered tank 250 ft. long, 33 ft. wide and 10 ft. deep. Above the tank was suspended a railway, on which ran a truck drawn at any given speed and beneath this truck the model was drawn through the water, and its resistance was measured by a self-acting dynamometer on the truck.

Before long it became standard practice to subject all new Naval ship designs to such model tests, which came to constitute one of the most notable applications of scientific method to ship design.

The work of Air Commodore Whittle, the pioneer of what is now known as the jet engine, is another, if less direct, instance of what amounted to the creation of an establishment as a result of the initiative of one individual. The story of Air Commodore Whittle's work is told elsewhere in this volume,[1] and we have seen that in 1936 a company called Power Jets Ltd. was formed to develop his project, financed entirely by private backers who saw in Air Commodore Whittle's invention important commercial possibilities. Thus the development of what is now so widely known as the 'jet engine' became the private business of a private company and was carried on within the framework of private research, and may therefore be considered as outside our subject. Nevertheless the organisations which were the forerunners of the National Gas Turbine Establishment, the private firm of Power Jets Ltd., and the Government-owned firm Power Jets (Research and Development) Ltd., corresponded in many respects to a research establishment.

Improvisation to take account of brilliant scientific advances in the case of particular establishments was complemented by improvisation to take account of what were essentially political difficulties in the case of another. This was the Royal Aircraft Establishment, which originated in the Royal Aircraft Factory, itself a product of the School of Ballooning formed in 1892. After 1910 the Factory vigorously prosecuted studies of heavier-than-air aircraft and by 1914 had a considerable list of achievements to its credit. These were not only achievements in the development of aircraft generally—although they included such important steps as establishing the utility and strength of the biplane compared with the monoplane; they were achievements in the actual design and the construction of aircraft. To design and construct aircraft was in fact the principal *raison d'être* of the Factory. Aircraft manufacture, however, was in course of becoming an enticing commercial proposition, and a disapproval of government participation in it soon began to be expressed.

[1] See Ch. IX.

Many rods were used wherewith to beat the Factory. Among its functions, for instance, it included the testing of all aircraft submitted to it. The Factory standards, though low enough by modern standards, were considered too high by some manufacturers whose aircraft had consistently been failed. The fact that the testing authority was itself designing and manufacturing aircraft led to suggestions that private manufacturers of aircraft were deliberately failed because of jealousy. In 1916 the administration of the Royal Flying Corps was itself under criticism, and a judicial enquiry held in 1916 covered both the Royal Flying Corps and the Factory. A leading critic, Captain Bennett-Goldney, stated in evidence before this committee that: 'The Royal Aircraft Factory is no longer a school of research and experiment but a large main factory competing unfairly with private enterprise, with which an attempt was made to create a virtual monopoly'. Another enquiry, devoted exclusively to the Factory, was now put on foot, but this—the Burbridge Committee[1]—came to conclusions which offered little positive guidance to the authorities responsible for the Factory. They did however suggest on the whole that the War Office intended the Factory to be 'devoted to experimental rather than manufacturing purposes'.

The Government finally took the view that even if the charges made against the Factory of usurping the role of industry were not justified, the atmosphere of hostility would have a deleterious effect and must be dissipated. Very shortly afterwards the decision was taken to discontinue both the design and manufacture of aircraft by the Factory. Since this was the main function—as has already been said the *raison d'être*—of the Factory, it might have been asked what there was left for it to do. Would it not die of inanition? The answer is part of aeronautical history, although it is doubtful whether the exact role of the Royal Aircraft Establishment, as it soon after became, its double role of technical adviser to the commercial designers of aircraft and as actual designer of aircraft equipment, is well understood outside a limited circle. More will be said about it in the following chapters.

The government research and development establishments devoted to the improvement of weapons were not, then, at the onset of rearmament, a neatly constructed piece of machinery. They embodied no general theory of how to carry out such work; they were untroubled even by the anxious speculation of later years about the optimum size of research establishments. They were the product of a process of evolution entirely empirical and exposed to many political hazards. This did not prevent them however from being more closely

---

[1] Cd. 8191, Report of the Committee on Royal Aircraft Factory, and Report to the War Committee by the Air Board on the subject of the Royal Aircraft Factory, 1916.

bound together than an examination of their formal constitution would suggest. Only three departments of state were involved, and control of the establishments was in the hands of a small number of directors of research and development who maintained close touch with one another in framing their programmes. Problems were divided up, and overlapping was avoided or (since it is not always undesirable) rationalised. The heads and senior members of the establishments were personally acquainted and met frequently; there was a good deal of semi-official exchange of information or suggestion, and even mutual aid. But this, like other things, including enthusiasm and ability, was unevenly distributed.

The difficulties involved in nursing enthusiasm and ability in the interwar years were very great. How could the head of an establishment encourage his technicians to press on the development of a new device when high authority evinced so obvious a lack of interest in re-equipping the forces? The head of the establishment, and his technicians as well, were in any case often engaged in elaborate, long-drawn-out, and rather humiliating struggles to have a partition erected in the laboratory, recruit an assistant, or obtain some trivial piece of equipment. Here, the position improved with rearmament. Another problem, fundamentally associated with making the most of limited resources, was more intractable; it was indeed the central and fundamental problem of attempting to reconcile irreconcilables —the disinterested pursuit of knowledge for its own sake on the one hand, and the improvement of weapons of war on the other. The Directors of Scientific Research at headquarters were perpetually on the horns of a dilemma. Research into fundamental physical or chemical problems might, at any time, and particularly to people who were looking for them, produce a means of improving a particular weapon beyond the hopes of its military users. To effect such improvements was their true *raison d'être*. But concentration upon such basic work was a great risk, since it might produce no useful result at all. A less fundamental approach, a 'development' approach, was sure to produce *some* result, although it would not be spectacular. Scientists, however, were trained to make the fundamental approach, and were at their most contented and effective when allowed to make it. When they were diverted into development their enthusiasm and ability fell off. On one side lay the Scylla of small safe advances (while perhaps a potential enemy was producing a master-weapon), on the other the Charybdis of a search which might have no result, and might leave one in the end with no answer to the small safe advances made by the enemy. To steer a course between the two was the aim of all establishments which had any interest at all in basic research; how this course was steered is a subject which deserves consideration.

CHAPTER XVII

BASIC RESEARCH

As soon as an attempt is made to trace the history of basic scientific research as a Government-controlled activity (and this chapter is such an attempt) the question of defining basic research arises. While it is unlikely that any very elaborate or exclusive definition will be universally acceptable, certain essentials are not likely to be contested. The object of basic research is to find out how, in particular respects, nature works, and although the principles which a researcher elucidates may lend themselves to practical application, such an application is not his specific concern. There is no Government establishment with a clear charter for basic research in this purest sense of the term—basic research unallied to any Service interest. If we take the case of the Admiralty Research Laboratory, the establishment which by charter comes nearest to having basic research as its object, we find that it exists to carry out pioneer research that may bear on Naval interests. But this phrase 'may bear on Naval interests' is a vague one. On a liberal interpretation it admits so wide a field as almost to be co-extensive with that of the University scientists, for it is difficult to envisage any sphere of research which might not yield fruitful results with a bearing on warfare, and Government establishment activities during the period with which we are concerned in fact embraced such diverse subjects as the study of microbiological activity, and the formation and decay of waves. Has the Government scientist normally been afforded this latitude? What in fact was research bearing upon Naval interests taken to mean? More generally—how 'basic' was research as carried on in the research establishments?

In the development of weapons for the Navy, as we have already seen, it lay with the Admiralty Research Laboratory to make the contribution of 'basic' research.[1] At its foundation in 1920 it was placed under the direct control of the newly appointed Director of Research, a distinguished 'pure' scientist, and from the outset the intention to direct thought and effort upon the fundamental problems was emphasised. The Laboratory was sufficiently an innovation to arouse some feeling on the part of the Naval staff, not perhaps of

[1] See Ch. XVI, p. 434.

suspicion, but of watchful tolerance. They did not exactly welcome the idea of scientists telling them how things should be done, but the functions of the new Laboratory appeared sufficiently nebulous and harmless not to raise the idea in any extreme form. The Staff contented themselves by asking what the new Laboratory could do that the various Departments employing Service officers did not already do. This was a question which could not be answered in its own terms. It was implicit in the nature of the Laboratory's work that prophesy about its results was impossible. It is the essence of a discovery that it is a discovery, and it could not be given as a justification of the Laboratory that revolutionary and fruitful discoveries might be made there. The argument for its existence could only be that given favourable conditions of time and money the probabilities of such discoveries being made were greatly strengthened.

As the Laboratory took up its tasks it became clear that scientific thought could most usefully be applied to certain fields, and by the opening of the rearmament period the staff was divided into five groups, one covering each of the principal fields. The striking characteristic which these fields have in common when viewed as a whole is practicality. Their titles are indicative—Remote Power Control and Electrical Transmission; Acoustics; Electro-magnetic; Stabilisation; Optical and Range-finding. All were devoted to the improvement of warships as machines for fighting at sea, and not to warships as ships or—directly—to their weapons. How 'fundamental' was the work which they did?

Remote control of gun mountings certainly involved some radically new approaches to engineering problems. During the 'twenties the Laboratory was at work upon the stabilisation of searchlights, and by 1927 it had constructed a unit incorporating a hydraulic drive, a device known as a 'sensitive oil relay', a magslip hunter and resetter. This was an elaborate and original piece of engineering, and in its sea trials in 1928 it was successful, during a full gale, in illuminating the target for 90 per cent. of the time. Further elaborate developments followed. The Laboratory designed a new hydraulic stabiliser in which the gyroscope operated directly on one of the sensitive oil relays, the gyroscope itself being of a new—the rigid spindle—type. From 1931 this system, known as the Mark V Searchlight Control System, became standard for all new construction. And it was by this avenue that the Laboratory was led into its work upon the remote power control of gun mountings.

The general problem facing the group was to cause a heavy mounting weighing anything from a few tons up to a thousand tons or more, to copy, automatically, continuously, and with very great precision, the motion calculated by the associated fire control computer or predictor. To tackle a problem of such magnitude it was necessary to build a special heavy engineering laboratory, but when this was done progress was rapid. By 1935 remote power control was practical politics. Its later development involved widespread ramifications. Two—the Type P Predictor Sight and the remote control of the Bofors 40 mm. gun—were of particular interest.

The Type P Sight was widely used in the Fleet. It was primarily a low angle sight, gyro-stabilised only against that component of the ship's roll which occurs in the vertical plane of sight. Hitherto, the optical equipment of gyro-stabilised sights had consisted of monocular telescopes, the line of sight being stabilised by gyro control of the erecting prisms. Moreover, the light efficiency of this system was low. In the Type P Sight, however, the new feature of binocular telescopes was introduced, the optical system employed being on the lines of the high-efficiency systems incorporated in modern night glasses. A further innovation was the optical projection into the field of view of the indications of the director setting scale.

The remote control of the Bofors 40 mm. gun was undertaken for the Army in 1938, to form a close-range fire control system for the Army. For the experimental outfit, standard searchlight units were used, and although their power was inadequate they enabled an early demonstration of the whole system—predictor and gun—to be given. The Admiralty decided that the results were good enough for the equipment to go into production immediately, accepting the fact that the standard Naval type of oil unit was overloaded. Production developed on a great scale when war came and, later on, the Establishment's designs were sent to the United States, where manufacture started on a still greater scale, magslips and oil gears running into tens of thousands. This fire control system, the whole of which—apart from the gun itself which was of Swedish origin—was designed at the Laboratory, saw service in many theatres of war, including the Battle of Britain.

In optics the Laboratory passed from comparatively simple development of the elementary equipment in use in the Navy in the early 'twenties to a more fundamental kind of research which was begun in 1937–38. At this date both the Navy and the Army had run into trouble with height-finders, which, at high angles of sight, were under-estimating range. The scientists believed that the error was associated with a stratification of the temperature of the air within the tube. The problem posed by this was one of building testing equipment of a new order of sensitivity. It was desired to check, to within half a second at any angle of sight, the infinity adjustment of range-finders of eighteen feet base-length, and this under the weather conditions which would be met in service. The Laboratory, in collaboration with Metropolitan-Vickers, designed and constructed equipment which successfully carried out such tests.

Steps to cure the serious defects which were revealed—they took the form of stirring up the air inside the tube—had been taken when the advent of radar rendered optical height-finders obsolete.

The Laboratory had a special—almost it might be said a traditional—interest in electro-magnetic research, partly because in its early years one of the leaders of the Laboratory specialised in this field as well as possessing a talent for theoretical work. (He undertook, for example, a mathematical investigation into the theory of shock waves.) In the rearmament and war years work was, of course, concentrated upon the battle against the magnetic mine, which first appeared towards the end of 1939. The Director of Torpedoes and Mines, who also consulted his own establishments on this problem (H.M.S. *Vernon*, in particular), approached the Superintendent of the Admiralty Research Laboratory, who considered the problem appropriate to the Electro-magnetics Group since they had already spent some time devising methods to defeat the magnetic torpedo, which was expected to be a major danger in war-time. Two methods had been considered. First, there was the cancellation of the magnetic field of the ship so that the torpedo would not work, which, however, was found to be impracticable. A second method was the use of various coil arrangements for protecting ships against non-contact torpedoes by inducing premature firing, and to demonstrate the practicability of this a model was built of H.M.S. *Curaçao*, complete with coils, as early as 1938. Much later on, when the problem of the magnetic mine came up at the beginning of the war, the model technique provided an easy laboratory method of testing whether a proposed system of degaussing coils would be adequate to make a ship safe in passing over a mine. This was really the solution to the problem, but degaussing could not be carried out immediately on all vessels owing to the shortage of cable. H.M.S. *Vernon* also was interested in the problem, and a member of their staff invented 'wiping' as an emergency measure, to be used until enough cable could be made for all ships to be coiled in the manner described above. 'Wiping' involved the dragging of an enormous magnet up the sides of the ship, thus rendering her immune for about a week.

As, throughout the rearmament period, war came nearer, and still more after its outbreak, such urgent practical development crowded out other work in the Laboratory. This was considered to be not only inevitable, but actually desirable. It happened in many ways, direct and indirect. Thus during the rearmament period the Laboratory embarked upon projects, or parts of projects, which entered into spheres of research which were more or less unexplored, and where the instruments necessary to carry out certain necessary operations had never even been devised. The Laboratory was then, in common with other institutions carrying out work in such new fields, compelled to design and construct its own instruments. In 1936, for example, the Acoustics Group was entrusted with the task of reducing audio-frequency noises in water caused by submarine auxiliary machinery. By the end of 1939, the Group had come to the conclusion that practical results would not be obtained in the reduction of noise transmitted to water by submarines without some direct method of measurement in the water, and for this task the existing equipment was not suitable. The Group accordingly got in touch with British Thomson-Houston Co. of Rugby for the supply of one of their discrete frequency analysers. Very extensive tests of the properties of all kinds of resilient materials were made with a view to finding that most suitable for use as anti-vibration mountings in submarines. Finally a non-resonant audio-frequency quartz hydrophone was designed, which soon began to provide useful information. The consequence of this kind of activity in the design and construction of instruments was that in many cases the groups paid the penalty for the richness of their equipment and the special skill they had acquired in its construction, by being given still more application work because of the facilities which they had acquired for undertaking it.

The strictly war-time work of the Laboratory was in the main an extension—in some cases a resurrection—of projects already mentioned, or of allied or similar projects. In 1941 it was involved in noise trials of submarines and, as a result, after experiments to determine the variation of propeller noise and depth, and to correlate background noise pressures with sea state, a 'silent operating' routine was evolved. The obverse side of the same work (so to speak) was upon the detection of enemy submarines, especially of their X-craft. Later, again, work was undertaken upon a magnetically operated underwater fuze for use in a rocket-propelled weapon. Infra-red research, though many of its objects came to be attained by radar, continued, and in 1941 work was done on ship location using thermocouples as detectors. On the chemical side much work was done upon means for making dyed plastic infra-red transmitting filters for use in connection with infra-red applications.[1]

It is perhaps surprising that, in the circumstances of war, any research of a genuinely fundamental character was done at all. Yet such surprising efforts were in fact made. The most striking characteristic of the Oceanographical Group, for example, was that direct possibilities of application were never crucial factors in the Group's activities. Although the findings of the Group were obviously highly relevant to such operations as the Normandy beach

---

[1] *Journal of the Royal Naval Scientific Service*, Vol. 2, No. 2, pp. 55 et seq.

landings, it was the Americans who did most of the practical work, and it was never regarded as a duty of the Group to co-operate with them, although in fact they did so. It may not, when the original charter of the Admiralty Research Laboratory is considered, seem surprising that a group of six men should at a comparatively late stage in the war devote the whole of their time to pure scientific research without any thought of immediate practical gains, but such freedom was nevertheless a phenomenon rare in peace and unique in time of war.

Such, in the main, was the work undertaken by the Admiralty Research Laboratory. It is fair to describe it as being, characteristically, the most forward-looking kind of engineering development work rather than, in fact, the 'basic research' which would be considered as such in an academic laboratory. And if this was the characteristic of research for the Navy in the Admiralty Research Laboratory, it is unlikely that similar work in other Admiralty establishments was less practical. It was indeed 'development', and as such falls to be dealt with later.

In aeronautics the organisation of basic research has always been complicated. Some of the reasons have already been indicated in the preceding chapter in relation to the early history of the Royal Aircraft Establishment.[1] But in order to understand the complications more fully it is necessary to know something of the controlling body, the Aeronautical Research Committee.

The Aeronautical Research Committee, which began its history in 1909 as the 'Advisory Committee for Aeronautics', has from the outset had the same kind of composition, a combination of the most eminent aeronautical scientists with representatives of the government departments concerned with aeronautics. It was an advisory and not an executive committee, but the scientific reputation of its individual members, and its prestige as a body, ensured that the advice which it gave was treated with respect, while its own activity ensured that it was always able to provide a lead. It controlled the activities of one of the two principal laboratories devoted to aeronautical work—the Aerodynamics Department of the National Physical Laboratory—and had a considerable influence over the aerodynamic and engine research undertaken at the other, the Royal Aircraft Establishment. Its sphere of interest lay entirely in the basic science of aeronautics, and the success with which it discharged its responsibilities was reflected in the high international reputation of the British work in this field.

---

[1] See pp. 437–438.

With basic research in the hands of the Aeronautical Research Committee, the Air Ministry felt themselves free to a considerable extent to concentrate on their own main interest, that is to say, on the development of military aircraft, as opposed to purely scientific research in aeronautics. In the last chapter we discussed the confusion and difficulties and disputes that arose about the research and other functions of the Royal Aircraft Establishment. That issue was not finally decided until 1924, and the decision even then was forced by outside political pressure rather than based upon deliberate policy. It was not even left clear at that time—partly because of the role of the Aeronautical Research Committee and of the National Physical Laboratory—that the Royal Aircraft Establishment's functions were, strictly speaking, those of basic research at all. The Halahan Committee,[1] set up in 1924 to report on the organisation of the Royal Aircraft Establishment, considered that its primary function should be the provision of a 'full-scale aeronautical laboratory for the Air Ministry', its tasks being development work on experimental aeroplanes and engines, the testing of experimental instruments and accessories, the development of special flying instruments for which there was little commercial demand, and investigations of failures. Certain other subsidiary functions were added, but on the whole the view appeared to be that basic research in aeronautics was the province rather of the National Physical Laboratory than of the Royal Aircraft Establishment, although it was considered right that they should continue for the time being with some more 'basic' work upon which they were already launched.

To carry out the functions which were laid down for it by the Halahan Report, functions intended to be largely those of development as distinct from research, the Royal Aircraft Establishment was divided into fourteen departments, four of these being development departments,[2] and the remaining ten, which included the Aerodynamics, Physics and Instruments, Wireless and Photographic and Metallurgical Experimental Departments, carrying out both scientific research and technical development.

There were, however, dissenting views. The Air Member for Scientific Research, Air Vice-Marshal W. G. Salmond, had at the beginning of the year expressed the view that the reduction of staff at the Royal Aircraft Establishment had damaged the research side of its work. On the development side, he pointed out, there was continuous pressure from the Air Staff, but on the research side there was no one to exercise comparable pressure. The Air Member for

---

[1] Committee on the Organisation of the Royal Aircraft Establishment, Farnborough.
[2] Airworthiness Department, Technical Publications, Contracts Technical Supervision Department and Main Drawing Office.

Scientific Research was sure that the only way to right the balance was to appoint a Director of Scientific Research in the Air Ministry.

The suggestion raised some difficult issues, issues mainly of the higher control. It meant splitting control of the Royal Aircraft Establishment between the existing Director of Technical Development and the new Director, and in the Establishment itself, if it meant giving more weight to basic research, it did not solve the difficulties about the line of split between such basic research and technical development. The Air Member favoured a system of joint control by the Director of Technical Development and the Director of Scientific Research and a method of combining work for both in the Establishment. It may have sounded confusing; it was not administratively attractive; and it was dubiously regarded. Nevertheless the appointment of a Director of Scientific Research—the chief aim of the Air Member for Scientific Research's proposals as regards Headquarters—was approved in March 1924.

The number of Royal Aircraft Establishment departments involved in the research issue was small, but their functions were of cardinal importance. Those of the Aerodynamics Department—according to an official statement—were to provide the aerodynamic information needed for current problems and projects in aircraft, to exploit advances in theory and to co-ordinate them with actual experience in flight, to indicate the most profitable lines of advance in aircraft design, to employ the experimental resources of the department in solving urgent problems arising in the use of aircraft in service and in tests of prototypes, and to assist industry in the design of aircraft. This statement, which actually follows very closely the lines of a report made to the Aircraft Supply Council of the Ministry of Aircraft Production in 1943, would have been equally applicable nineteen years earlier in 1924. Wind-tunnel work, including tests of contractors' models, had always been handled by the Aerodynamics Department. Examples of the work of the department were quoted both in 1924 and in the 1943 report. In 1924 the department was concerning itself, amongst other things, with the control of aeroplanes in flight beyond the stalling angle and the combination of slot and aileron control for this purpose, and the development of a sleeve target. In 1943 its recent achievements included the investigation and introduction of spring tab controls and of a night towing scheme for gliders. Each of these two characteristic tasks of 1943 stands in the clearest succession to its forerunner of 1924.

This same continuity can also be discerned in the work of the Engine Department. Since the period immediately after the First World War when it gave to the industry the original designs and experience on which the modern air-cooled radial engine is based, the Department's work had been mainly restricted to the services and auxiliaries of the power plant rather than to the basic engine design itself. Both in 1924 and in 1943 the Engine Department was reported to be at work on, for instance, carburettor problems. At both dates too there are references to the research into fuels which has always been an important part of its work.

Other departments which undertook some amount of basic research were the Metallurgical, Instruments and Oxygen, Ignition and Electrical, Chemical, Wireless, and Photographic. These were the pre-rearmament names; by 1943 Ignition and Electrical had become Electrical Engineering, without however any significant alteration in its role, and an Instrument and Photographic Department represented an amalgamation of two of the departments as they had been earlier. Chemistry and Metallurgy had been amalgamated in the Materials Department, which also included the functions of non-metallic and materials testing. An Armament Department was added in 1937. The main concern of each of these departments was the design and development of items falling within its sphere. All however undertook some research work, varying considerably from time to time and from department to department in the degree of its applicability, but being in some cases at least carried forward with no immediate application in mind at all. A long and impressive list of the achievements of each department could easily be cited. In the case of the Electrical, Instrument and Photographic, and Radio Departments, the reader will readily comprehend at least the type of material contained in such a list. The work of the Materials Department is perhaps less readily imaginable by the layman. Among the war-time research problems were those connected with fire-resistant paint, anti-misting preparations for windscreens, new light alloys, and many experimental determinations of the qualities of materials of all kinds.

Another department of the Royal Aircraft Establishment, the function of which is perhaps not immediately clear from its name, is the Structural and Mechanical Engineering Department, formed in 1941 by amalgamating the Airworthiness and Mechanical Testing Departments. The preoccupations of this department were strength and rigidity, and the development of these was pursued in many ways, one of the most important of which was by investigation of flutter and vibration. Investigations into strength were not limited to the main members of the aircraft but were carried out upon undercarriages, propellers, fuel tanks, and other similar elements.

From 1939 onwards the Airworthiness Department, and its successor the Structural and Mechanical Engineering Department, was, like the Aerodynamics or Materials Departments, an institution devoted to research and to advising the industry.

The same process which occurred generally in the Royal Aircraft Establishment—the sacrifice of fundamental research to 'applications'—may be observed in the other old-established major research agency, the Armaments Research Department.[1] As has been explained already, the Armaments Research Department, as it existed during the recent war, had its origins in the Experimental Establishment which was formed in 1902, following upon the recommendations of the Explosives Committee.[2] The Explosives Committee was composed of distinguished civilian scientists, and the Experimental Establishment which it brought into being was intended to be a means of applying scientific methods to the improvement of armaments. The Research Department was from its origins a servant of the Navy as well as of the Army and later of the Air Force.

The administrative position was further complicated by the fact that not only the three Service Departments, but also the Home Office and the Department of Scientific and Industrial Research contributed to the finance, the Admiralty, War Office and Air Ministry contributing 40 per cent., 45 per cent. and 15 per cent. respectively of the total cost of the work done on Service account, while the other two departments paid for work which was actually carried out on their behalf. All the departments which were concerned sent representatives to an annual meeting at which the programme was discussed. Financial authority was invested exclusively in the Ordnance Board, who naturally authorised expenditure only upon projects which they had examined and approved. This not only limited the more expensive type of experiment (for example, it was not until 1939 that investigations were carried out upon the effect of bombs bursting inside buildings) but also to some extent curtailed that free play of scientific curiosity which so often arrives at valuable conclusions by means of a digression from the 'quickest way'. It is not surprising that in this important matter, where the balance is always difficult and delicate, the natural anxiety of the Service authorities to effect speedy improvements in weapons often prevailed over the equally natural disposition of scientists to seek a more radical and generally less speedy solution. That the Service authorities were justified in their anxiety about the speed of work by the research and development departments (whether or not their ideas about calculating the pace were sound) was shown in the memoranda which led up to the Guy Report.[3]

---

[1] See Ch. XI.
[2] See pp. 434–435.
[3] Report of the Committee on Armament Development. See Chapter XIX.

There is however a good deal of evidence that even before the opening of the rearmament period, when pressure of work was not so great, research had tended to be pushed aside by development. As early as 1926, before the pressure of severe financial stringency had begun to operate, the Duckham Committee[1] had noted that: 'The volume of day-to-day experimental work in the Research Department is fast relegating many important questions of fundamental research to a comparatively subsidiary place in the general programme'. The position in this respect however varied a good deal from branch to branch. In the Metallurgical Branch for example an element of basic work was kept going on Department of Scientific and Industrial Research account, and on the Service side also this branch carried out work on subjects such as the overstrain of steel and temper brittleness which was of a research nature, and of wider theoretical as well as practical interest. Investigations carried out under the auspices of the Department of Scientific and Industrial Research included the casting of brass ingots, structure of steel ingots, crystallisation of metals from liquid and the structure and properties of electro-deposited metals. Work such as this, which attracted the attention of metallurgists engaged upon academic and industrial investigations, gave the Department wide contacts and a high reputation, which stood it in good stead during the war.

For a large part of the Establishment however the observation of the Duckham Committee held good, and no major change in this situation occurred for a number of years after the date (about 1935) at which this account of the organisation of the Research Department has been opened. Minor changes in organisation took place, and the staff was expanded to meet the rearmament programmes of the three Services, particularly that of the Navy, which involved many new designs of guns and associated research. The tendency was actually towards an increase in the small ad hoc items. In his report for 1937, the Director of Explosives Research noted that 'while the number of requirements specified in the Priority List remains substantially the same, approximately 200, the number of questions requiring technical opinions or research has exceeded 4,000, a 35½ per cent. increase over 1936–37'.

And if this tendency towards 'problem-solving' was already marked in 1937, it is not surprising that it grew markedly in the years that followed. At the Research Department there were special reasons for this, organisational reasons associated with user control; and it was this user control which, in 1943, led to a crisis and to a new kind of organisation.[2] All this is dealt with below,[3] as is—from the

[1] Committee on Research, Experiment and Design of Guns, Ammunition and Projectiles.

[2] Under the change of name to Armaments Research Department.

[3] See Ch. XIX, pp. 474 et seq.

point of view of organisation—the new administration of the Department. This new administration was eminently 'research-minded'. The new Chief Superintendent,[1] having come direct from Cambridge, was in close touch with the academic world, and was able to obtain, for the branches which had been brought into being, a number of distinguished academic scientists. These included four Fellows of the Royal Society (Professors Sugden, Garner, Curtis and Mott) who formed the character of the direction of the Department at this period so that it soon became known as the 'F.R.S. regime'. To some extent the new academic influence in the Department consisted in the control by newcomers of existing functions. Thus Professor Sugden became Superintendent of Explosives Research, originally covering the same field as the old directorate of this name, but later, when this field of work was split into three branches (Chemical Research, Applied Explosives Research and a smaller Explosive Research Branch), Professors Curtis and Garner took over the Applied Explosives and Chemical Research Branches respectively.

In the way of functional innovations in the field with which we are most concerned the most noteworthy was the setting up, under Professor Mott, of the Theoretical Research in Armaments Branch, in September 1943. This branch consisted very largely of mathematicians drawn from Cambridge and the Ordnance Board. It was formed in the belief that a close study of fundamental principles would often suggest the most profitable line of experimental work, and further that a systematic analysis of the results of experiments would lead to discoveries or new methods of attack which would otherwise be missed. The functions of the Branch were both to carry out such fundamental research and also to provide (so far as possible) answers to such short-term problems of a theoretical or mathematical nature as were submitted to it by other branches of the Department. Among the subjects upon which the Branch worked were external and internal ballistics, the detonation and blast of explosives, plasticity and fracture of materials, calculation of trajectories and the mechanical solution of mathematical problems.

The creation of Professor Mott's Theoretical Research Branch in 1943 may be considered as a fresh injection of basic research intended to tone up the system of armaments development. Such injections were not uncommon over the whole field of munitions development in the wider sense. But it is probable that in no field of research were they as common as in radar. The story of radar has already been told in this volume,[2] and it has been told very largely as a series of

[1] Professor J. E. Lennard-Jones, F.R.S.
[2] Ch. XV.

steps in development—of steps from the original Home Chain type of station to A.I. and A.S.V.; of the evolution of the long series of centimetric bombing aids; of the moves and counter moves in the field of radio countermeasures. Yet if the story was one of development, it was development carried out by men eminently and obstinately research-minded, for it was with such men that the radar establishments were staffed.

Nothing illustrates better than the history of radar establishments the theme of diversity of origin, of adaptability, the practical, spontaneous, ad hoc quality of British research establishments generally. Counting radio establishments as well, there were in the period with which we are concerned, six in all. The oldest were the Admiralty Signal Establishment, which grew out of the Experimental Department of H.M. Signal School, and the Radio Department of the Royal Aircraft Establishment. Both of these were concerned with radio communications and with radar, although in the Royal Aircraft Establishment radar was of lesser importance. Not much younger were the two Army establishments, the Radar Research and Development Establishment (R.R.D.E.) and the Signals Research and Development Establishment (S.R.D.E.). The Radar Research and Development Establishment grew out of the Air Defence Experimental Establishment and dealt primarily with radar; the Signals Research and Development Establishment (formerly the Signals Experimental Establishment) concentrated on radio and line communications. Youngest of all was the Telecommunications Research Establishment (T.R.E.) which was the radar establishment for the R.A.F. and the chief centre of radar research in the country. The Telecommunications Research Establishment grew out of the pre-war Bawdsey Research Station (B.R.S.), at which radar was born.

It was Bawdsey Research Station, and later the Telecommunications Research Establishment, which more than any other determined the approach and the attitude.[1] As has already been indicated, the most urgent task confronting Bawdsey Research Station was the development of the early-warning chain.[2] The danger was so great that it was tacitly agreed by all the Services that any development likely to increase the defensive strength of the R.A.F. should have first priority.[3] It was considerations of this nature, allied to the difficulty of recruiting suitable scientific staff, that made it imperative to

---

[1] See pp. 480–482.

[2] Ch. XV, Section (i).

[3] For example, when in 1939 it was shown that the War Office Coast Defence (CD) R.D.F. set was capable of detecting aircraft at much lower altitudes than the C.H. stations, the first sixty production models of this equipment were at once taken for R.A.F. use, as so-called C.H.L. stations to supplement the C.H. stations, and none was available to the Army until the end of 1940.

restrict work at Bawdsey to developments likely to yield important results in a comparatively short time.

But if one factor was working against the fundamental approach, another was now put into operation in its favour. In the autumn of 1938 an important and successful move was made to strengthen the scientific effort devoted to R.D.F. At the instigation of Sir Henry Tizard and Mr. (later Sir Robert) Watson-Watt, Professors R. H. Fowler and J. D. Cockcroft of the Cavendish Laboratory, Cambridge, were invited to Bawdsey, where they were initiated into the R.D.F. secret and asked to consider how the resources of their laboratory might best be used to further the work.[1] In the spring of 1939 Professor Cockcroft again visited Bawdsey with Messrs. P. I. Dee, J. A. Ratcliffe and W. B. Lewis, the leaders of the Cavendish team. There followed other meetings and discussions and it was agreed that Dr. Lewis should go to Bawdsey to take charge of a wide field of research. It was also agreed that there should be a wholesale introduction of physicists to the R.D.F. problem, some eighty to be invited from various universities to visit C.H. stations in parties. To carry through this scheme plans were made during the summer for eight parties to go to C.H. stations on 1st September. The arrangement proved to be successful and most of the parties remained at their stations for several weeks. Thus when the university scientists were ultimately brought in, they came in considerable strength and with a high standard of ability, bringing with them a preponderantly theoretical outlook, the outlook of the physicist rather than the engineer. The impact of the university men upon the government service was considerable, but because Bawdsey already had a quasi-academic atmosphere its effect was one of degree rather than kind.

It is at about this point—the outbreak of war—that the history of Bawdsey Research Station, and more particularly that of its achievements in basic research, became linked with that of the Radio Department of the Royal Aircraft Establishment. This Establishment dated from 1924, when a separate Wireless and Photographic Section, known as No. 10 Department, had been set up; later photography was separated from wireless. Up to 1940 the Radio Department was concerned only with communications and not with radar. Broadly, the difference between the two was the difference between a known and a new art. The development of communication equipments did not, generally speaking, involve any very novel circuit problems, except in the case of certain aspects of the V.H.F. work. On the other hand, the conditions under which aircraft sets

[1] Earlier in the year Sir Henry Tizard had told Professor Cockcroft that important radio developments were in hand and that there was a need for high powers at short wavelengths.

operated were such as to call for a very high degree of engineering skill and ingenuity on the part of the designers. Such skill was amply provided by the Royal Aircraft Establishment design staff, who had moreover to be familiar with the conditions peculiar to the operation of wireless sets in aircraft.

The general background of the Royal Aircraft Establishment Radio Department, then, was this: it was staffed with skilled and ingenious engineers; it was not wanting in research workers; it had a comprehensive view of the qualities needed in radio equipments and components for Service use; it had an intimate and continuous knowledge of the peculiarities of aircraft and of those who flew in them; and it was acquainted with the abilities and limitations of industry. This was a very different background from the research-minded 'string-and-sealing wax' background of Bawdsey. Bawdsey was engaged in the study of an entirely new art under conditions of great urgency. It was not well acquainted with industry. Its lack of engineering experience became especially noticeable as the work on airborne R.D.F. grew. These considerations led to a decision that the Telecommunications Research Establishment should be the research establishment for all R.A.F. radio and radar work whilst the Royal Aircraft Establishment should do the development.

This arrangement did not work satisfactorily in the long run. Indeed it is difficult to see how it could have done, in spite of the precedents for such a division in Government scientific work. Research and development are essentially continuous activities, especially when the aim is the rapid production of an item of military equipment, and they require the closest collaboration at all stages. Moreover personal considerations supervened. The research scientists who devised a new piece of equipment were unwilling to hand it over to someone else for development. They not unnaturally wished to see it into service themselves and they did not altogether trust the ability of the development engineers to produce a satisfactory equipment. On the other hand, an able engineer would in the course of development work, inevitably have ideas of his own, which he would wish to develop himself but which, on a division of responsibility of the kind under discussion, would have to be handed back to the Research Establishment. The Telecommunications Research Establishment moreover considered that the Royal Aircraft Establishment was unimaginative in its approach and excessively slow in getting equipment into service, whilst the Royal Aircraft Establishment regarded the Telecommunications Research Establishment's engineering as slipshod and totally unsuited to Service conditions.

The division of research and development between the two establishments was in fact obscured as time went on. In the event, no communications research was done at the Telecommunications Research Establishment owing to the greater urgency of radar. In some cases the Telecommunications Research Establishment continued with the development of equipments after the research stage had been completed,[1] in others they took back projects after they had gone to the Royal Aircraft Establishment, as in the further development of 1.5 metre airborne radar. Above all, the Telecommunications Research Establishment had been made the inter-service centimetre research establishment and was firm in its refusal to part with any aspect of the work, which was growing rapidly in amount and extent. Ultimately the position was accepted and, at the beginning of 1943, a directive was issued to the effect that the Radio Department of the Royal Aircraft Establishment and the Telecommunications Research Establishment were one department and that each should carry through work entrusted to it in both the research and the development stages. Unfortunately, the Royal Aircraft Establishment felt that the radar work entrusted to it on these terms was the less interesting part of the programme and was only that which the Telecommunications Research Establishment did not want to do.

Still more unfortunate, although the two establishments were to be regarded as one, they were not in fact one, but were separated by a considerable distance and an awkward journey. The obvious and right thing to do was to unite the two establishments in the same place, probably in Malvern. The situation would have been changed completely had this been done. But such a step was physically impossible, mainly owing to lack of accommodation. Unhappily it would appear that the higher authorities were content to accept the union as impossible without taking satisfactory steps to minimise the difficulties arising from the situation.

A move to improve the co-ordination of the work of the two establishments was made by the Ministry of Aircraft Production in 1943. The Ministry was acutely conscious of the desirability of amalgamating the two establishments; in April 1943 this step had been urged upon the Minister. But the difficulties were insurmountable. The Ministry of Aircraft Production therefore proposed as a compromise arrangement that senior officers in the establishments should be selected to act as co-ordinators, responsible to headquarters, of all the work on various groups of projects in the combined programme of work. For example, in the initial arrangements, Dr. Barlow of the Royal Aircraft Establishment was made co-ordinator of all ground radar, including airfield control and fighter

---

[1] For example, the 50 cm. stand-by C.H.L./G.C.I. A.M.E.S. Type 11.

direction, whilst to Mr. (later Professor) Dee of the Telecommunications Research Establishment was assigned all airborne radar. The programme was divided into eight sections, four co-ordinators being appointed from each of the establishments. The scheme went into operation in the middle of 1943.

In spite of sincere attempts the scheme was not a success. The reasons for its failure are not far to seek. In the first place, it was asking too much of human nature, in the possession of which quality scientists differ little from other people, to expect an individual in one establishment to assess impartially the work of another establishment. Too often co-ordination was interpreted to mean transfer of work, and of staff, and generally the transfer was away from the Royal Aircraft Establishment. In the second place it was felt that co-ordination of this kind was properly the duty of Headquarters, and that the institution of the scheme was tantamount to an admission that the headquarters staff was failing to fulfil its duties. Such a feeling was not conducive to the most desirable relationship between Headquarters and the establishments. The scheme was not formally abandoned during the course of the war but it did become less and less effective as time went on.

The radar work done by the Royal Aircraft Establishment was mainly concerned with the engineering development of ground stations, C.H., C.H.L. and G.C.I. Although most of it was done in collaboration with the Telecommunications Research Establishment and was based on Telecommunications Research Establishment ideas, a small research team was built up which was capable of undertaking problems on its own initiative. For example the centimetric air-transportable G.C.I. (A.M.E.S. Type 27) and the centimetre aerial for the latest fighter-direction ships (project Knobbly) were both developed by the Royal Aircraft Establishment on their own. A considerable programme of work on the examination and reconstruction of German radar equipments was also carried through, including important tests to determine the effectiveness of our radio countermeasures against these equipments. The work of the Department in radar was however coloured by its relations with the Telecommunications Research Establishment which unhappily were not always of the best. How this arose has been indicated in the preceding paragraphs. Broadly, the Department felt that it was given an impossible task, that of interpreting in practical form someone else's ideas, without any compensations, such as the opportunity to exploit its own ideas, and without its just share of the high level interest and encouragement which was given to the Telecommunications Research Establishment. How far these feelings were justified it is difficult to say. What is obvious enough however is that in time of war it was not really practicable for the authorities to say to one establishment: 'You will do research', and to another: 'You will do development'. What was done in each depended upon tradition and atmosphere as well as upon orders from above.

Yet it would be a wholly false antithesis to present the Telecommunications Research Establishment as being occupied with any activity that could be described as basic research while the Radio Department of the Royal Aircraft Establishment and other establishments were occupied with development. The principal achievement of the 'basic research' approach adopted by the Telecommunications Research Establishment was undoubtedly the devising and the development of centimetric radar. The story has been told;[1] it was a brilliant development carried through with great foresight, speed and determination. It was undoubtedly the forward-looking and ambitious attitude of academic scientists which provided the drive needed for this remarkable development. Yet once the development had been achieved—and the essential fundamental work was carried out as early as 1940—its adaptation in one field after another of the radar work was essentially a development problem, or rather a series of development problems. In radar as elsewhere, in the Telecommunications Establishment as in other establishments, the tendency was to concentrate upon the practicable and upon the immediate.

The same tendency may be finally illustrated in the field of naval warfare. The Naval Construction Research Establishment[2] was founded as late in the war as June 1943. For very many years before this date the Director of Naval Construction had been urging the need for more thorough and widespread investigation into all matters pertaining to the strength of warships. But it was not until profound anxiety—and indeed alarm—had been caused by the serious warship losses of the years 1939 to 1943 that a decisive step was taken to meet this requirement. The decision was to set up an establishment, including a structures laboratory, to deal with the problems of the strength and protection of warships, and to carry this work forward by studying what has since been described as the 'fundamental characteristics of the shock and forces to which ships are subjected'. Although the establishment was founded primarily for structural research many of its problems were fundamentally physical in nature. The new establishment, therefore, recruited physicists and mathematicians as well as engineers and approached its task in a 'research' frame of mind. Yet it was not long before the

---

[1] Ch. XV, Section (ii).

[2] See also pp. 484–485.

Establishment found itself abandoning theoretical work on ships' propellers and difficult long-term questions such as brittle fractures in welded steel, and spending about half of its total time on ad hoc problems such as providing quick information about damaging enemy ships, since explosives and tactics can be developed much more quickly than elements in the designs of ships.

The pressure, in fact, was irresistible. The pattern of development of all those Government scientific establishments which were intended (or parts of which were intended) to throw practicality out of the door, was one in which practicality was smuggled back through the window. It is perfectly obvious that everyone very largely wanted this to happen. On the whole the Service Chiefs wanted it openly and strongly; on the whole the scientists acquiesced. But they acquiesced readily, and often willingly, and it was the highest Service and 'Headquarters' authorities which, in many instances, took steps to prevent research and development from becoming uninspired and over-practical. It was the pressure of war itself which was irresistible.

CHAPTER XVIII

DESIGN AND DEVELOPMENT

THE tendency, then, of 'basic' research was to degenerate through the pressure of war into ad hoc and applications work immediately essential to winning the war. Naturally those establishments which were formally devoted, not to research but to design and development, were free from this particular problem. If they had an analogous problem it was that design work was occasionally swamped by urgent production jobs and the routine work of testing came to take up much more time. Just as research establishments tended to be drawn into the sphere of their colleagues in development establishments, so these colleagues in their turn tended to be drawn ever closer to production. The tendency was—not of course for the men but for their work—to be assimilated into industry, since in many cases the establishments in question were set up to supplement and correct the work of industry. The theme of this chapter becomes indeed the distribution of design and development between establishments and industry and the historical reasons why they were done in some cases by the one and in others by the other.

At the opening of the rearmament period the Admiralty, which had the longest record in this field, was supplied with a number—it would perhaps be hardly accurate to say a system—of establishments for developing the principal components of naval armaments. In 1920 the Admiralty Engineering Laboratory was transferred under its Superintendent to a site at West Drayton where it was joined by a small experimental section of the Director of Electrical Engineering's Department which had previously occupied two rooms in Great George Street, London. From this small beginning there had grown up an Admiralty Engineering Laboratory consisting of the approximately equal-sized Mechanical Engineering and Electrical Engineering Departments. Each of these Departments was autonomous in purely technical matters, the Superintendent of the Mechanical Engineering Department exercising a general administrative control over the whole establishment. The work of the Laboratory lay in improving the mechanical and electrical equipment of ships, a large part of it being associated with immediate problems. The nature of these problems on each of the two sides of the Laboratory was, of course, quite distinct.

The Mechanical Engineering Department traces its origin to the resolution passed in 1915 by a joint meeting of the Marine Engineering and Internal Combustion Engineering Sub-Committee of the Board of Invention and Research, that it was essential in the national interest to establish an experimental station for research in Naval engineering under the direction of the Admiralty. The main concern of the meeting was internal combustion engines for submarines. It was widely feared that Britain was falling behind Germany in this field, and that the British system of relying entirely on the efforts of private firms had not proved successful. It was not proposed to replace altogether the work of private firms, but was intended to supplement it.

The only submarine engine in use in 1915 was the airless injection engine. It had many disadvantages, but because the design was a Vickers monopoly and since no alternative was available in this country, it had perforce to be accepted. Admiralty policy was in particular to procure a better engine and in general to break the Vickers monopoly. It was from this situation that the Mechanical Engineering Department of the Admiralty Engineering Laboratory was born.

From its origins, therefore, all through the 'twenties and into the rearmament period the Mechanical Engineering Department was mainly concerned with the design and development of internal combustion engines for submarine propulsion and the investigation of associated problems. In the 'thirties it took on also Admiralty type tests and special tests of proprietary makes of British and foreign engines. This involved the establishment of safe-service ratings for such engines, recommendations for improvements, and the investigation of problems presented by failure or unsatisfactory performance.

All activities of all naval establishments are of course governed by Admiralty policy, but the length of time involved in developing major mechanical items such as a diesel engine meant that the results produced by the Mechanical Engineering Department were to a peculiar extent at the mercy of changes of policy. It was hardly possible, as it sometimes was in other establishments, to present headquarters with a *fait accompli* in the way of design in a short period. This often meant that laboratory experiments were out of date before the last stages of development had been reached. It also flowed naturally enough from this state of affairs that the Laboratory, not called upon by its charter to undertake 'research', had not felt greatly tempted to go beyond the bounds of its character. Its aim has been the application of pure physical knowledge to engineering problems. Some long-term jobs, for example, the thermal and gas load stresses in pistons, were undertaken, but such work was dropped during the war when much effort was devoted to gas, oil and material analysis; to measurement by electronic equipment of strain, pressure, speed, vibration and noise; and to an incursion into gas turbine work, including tests of the use of heavy fuels.[1]

The main function of the other Department of the Laboratory, the Electrical Engineering Department, has already been described as the investigation of electrical engineering problems with a view to their immediate practical interest. The scope of the work included all items of electrical engineering as applied to H.M. ships. It was divided into sections dealing with accumulator research and experiment, cable research and experiment, electrical machinery, illumination, switch-gear and delicate instrument work. Later, sections dealing with remote power control, fire control and telecommunications were formed. Emphasis on these items was of course unequal. Up to 1935 improvements in searchlight optical arrangements and light sources had played a more prominent part than they did thereafter. The characteristic war-time activities included switch-gear development work on fuses and shock and vibration testing.[2]

Other Admiralty establishments devoted to the same kind of work in different fields at the onset of rearmament included the Torpedo Experimental Establishment (originally the Royal Naval Torpedo Factory). This was a civilian establishment, with a Naval Captain as Superintendent and a small Naval Staff to advise on the tactical aspects of torpedo warfare and on the application of new designs and new ideas to Service requirements.

Apart from these Admiralty establishments concerned with design and development there were others concerned mainly with testing and with the provision of user experience. The concept of user experience is one for which the Admiralty has always had great regard, but it is an elastic one. If user experience is ill-informed it is worthless. If it is well-informed there is a persistent temptation that user experts will influence design and that their opinion on the final weapon will not be independent in the strictest sense of the word. It is a traditional part of Naval policy to accept the latter evil, if evil it is, and consequently Naval user establishments, though never in a position to dictate design requirements, have influenced them to a considerable degree. H.M.S. *Vernon*'s[3] general duty was the representing of the interests of the users at all stages in the development, production and use of undersea weapons. This involved an extensive system of trials—sea trials on prototype underwater weapons and equipment, acceptance trials, theoretical and practical investigations for the Director of Armament Supply, and the provision of facilities for trials to those departments concerned with weapons in which

[1] *Journal of the Royal Naval Scientific Service*, Vol. 5, No. 2, p. 42.
[2] Ibid., Vol. 8, No. 4, pp. 97 et seq.
[3] See Ch. XVI.

H.M.S. *Vernon* was interested. H.M.S. *Vernon* was able to exert a considerable influence on design through various channels. The control side of the design of torpedoes was in fact very largely in their hands and they were also officially responsible for the design of torpedo impulse gear. Some design work was also carried out purely on personal initiative. Thus a member of H.M.S. *Vernon*'s Diving Section who also happened to be Secretary of the Admiralty Diving Committee initiated most of the improvements in submarine intake apparatus, making his own drawings and arranging for the construction of prototypes.

But it is true to say that the functions of H.M.S. *Vernon* were pared down according to a logical and consistent pattern, namely the representation of the user interest to the exclusion of all design work (though influence on design remained unimpaired). This was because it was felt to be an illogical arrangement that the designer of equipment and its layout should also be the critic as to its suitability for use at sea. Consequently in the course of the war H.M.S. *Vernon* had relinquished both the design and layout of torpedo impulse gear. Its sole design responsibility was then for mines. But the Mine Design Department was in a somewhat curious position inasmuch as it was technically independent of H.M.S. *Vernon*, owing responsibility directly to the Superintendent of Mine Design, and through him to the Director of Torpedoes and Mines. The Captain of H.M.S. *Vernon* had no access to the Mine Design Department's confidential reports and the control he exercised was purely administrative. The relationship between H.M.S. *Vernon* and the Mine Design Department was nevertheless very close. H.M.S. *Vernon* was consulted at the earliest possible stage of development, and at various stages meetings were held which were attended by all interested departments and every opportunity given for H.M.S. *Vernon* and others to state their points of view.

The origins of H.M.S. *Excellent* have been described.[1] During the war its functions crystallised into the watching of all development projects from the user aspect and carrying out trials on gunnery equipment much as H.M.S. *Vernon* did. These aims were pungently expressed in a paper designed for circulation within H.M.S. *Excellent*:

> To ensure that the development of naval gunnery proceeds on lines dictated by sea experience rather than office expediency, and to ensure that the gunnery equipment of H.M. ships be fitted to the satisfaction of the user rather than the manufacturer.

---

[1] See Ch. XVI.

The war-time work of the Department was foreshadowed as early as 1933. The *Centurion* bombing trials for which the Department was responsible were not merely a continuation of the trials of bombers against ships which had been conducted for a number of years before that date. For one thing they were on a larger scale, and they were designed to test not only the technical efficiency of the Air Force but also the staff work of the Navy. In these very important trials the target ship, H.M.S. *Centurion*, had full tactical freedom and a degree of realism befitting the opening of rearmament was attained. The Experimental Department of H.M.S. *Excellent* was drawn in in order to undertake an analysis of the trial, and the results showed the need for a further intensive trial programme to establish the best means of defence against close-range attack. Since this in its turn clearly involved a heavy programme of work for the Department it may be stated that from this time forward it was working upon the rearmament programme.

Apart from the new 'rearmament' trials programme which was then put in hand, the Department was engaged during this same period upon a number of major tasks which included trials of the prototype 4″ Mark XIX mounting; mock-up trials of the 4.7″ gun for carriers; gun trials of Leander Class cruisers; and rough weather trials of cross level arrangements.

H.M.S. *Excellent* by 1935 was provided with two departments undertaking trials and experimental work associated with trials. The Experimental Department was divided into three groups, dealing respectively with fire control development and ship fitting; gun-mounting development and ship fitting; and ammunition supply, flash venting and blast. The Anti-Aircraft Department was divided into two groups, one concerned with training development and the other with the development of synthetic training devices. That a staff of a small size was adequate during the period 1935–37 was largely due to the comparative simplicity of gunnery equipment trials at the time. Complete trials of a destroyer required two days in harbour and one day at sea; by 1943 they required three days in harbour and two days at sea with an inspection staff much larger than had been required in 1935.

The gun trial programme during 1935–37 was in fact not a heavy one, and was overshadowed by the combination of development projects which it was the task of the Experimental Department to watch from the user angle. These included the 14″ turret, 4.7″ twin mountings, a proposed new ammunition supply system, trials to improve the flashlight qualities of ammunition containers, and preliminary trials of the 20 mm. Oerlikon gun. It was in 1937, when the 'Southampton' Class cruisers, and 'Tribal', J. and K. Class destroyers began to come forward, that the emphasis began to shift from development to ship fitting.

During the year 1939 the amount of work in hand, including the carrying out of trials of guns and equipment in armed merchant ships, was so great that additions to the staff became an urgent requirement, but although some changes were made as a result of the outbreak of war, they did not result in any real strengthening. Nevertheless during 1940 and 1941 additions did at last begin to be made to the staff on a considerable scale, and these additions reached their peak in 1943.

The internal re-organisation which took place in H.M.S. *Excellent* during the war was the result mainly of evacuation measures. At the time of the fall of France it was evident that Portsmouth was liable to heavy bombing and possibly to German landings, and it was planned to evacuate H.M.S. *Excellent* in two stages. Although only the first stage was actually put into effect, the amount of travelling which was involved between the dispersed location and Portsmouth, added to that involved in carrying out trials of gunnery equipment, was such that by the autumn of 1940 the situation was getting out of hand and heavy arrears of work were piling up. The Experimental Department was no longer able to carry out properly its function of giving new projects full attention from the user aspect, and was in any case getting out of touch with the Anti-Aircraft Department at a time when it was becoming clear that all future equipment would have to be dual purpose with the accent on the A.A. role.

The situation was reviewed in January 1942 and new arrangements were made. The Anti-Aircraft Department ceased to exist; its training commitments were taken over by the instructional side of H.M.S. *Excellent* and its development projects were taken over by the Experimental Department. Secondly, the system whereby Devonport and Chatham Gunnery Schools undertook the gunnery trials of certain ships came to an end in favour of a system which concentrated all ship trials in H.M.S. *Excellent.* Broadly speaking the organisation of the new combined Department which came into being consisted of a vertical division into development and ship fitting and a horizontal division into gun mountings and fire control. No further re-organisation of any importance occurred after this date until the end of the war.

The most important Army establishment was the Armaments Design Department (formerly Design Department). Before the war the full cycle of development, from origin to finished article, might take as long as seven years. The validity of the specification on the other hand might not exceed four years, inasmuch as appreciations of potential enemy armament would come along during that period which would modify the requirement. There was thus a margin of time in which the Design Department was able to move with a certain amount of freedom in deciding about what should be done in the way of modification in the work carried out in accordance with the specification.

The Department achieved some very important successes in the design of weapons. As we have seen, the normal process was for the Ordnance Board to prepare a specification of a new weapon in considerable detail.[1] The next step was for this specification to be sent, not only to the Design Department, but also to a commercial firm for the production of a competitive design. In the case of guns a 'commercial firm' almost invariably meant Vickers, and competition between the Department and Vickers might almost be said to have been the cornerstone of policy in armaments design, fully approved of by the Ordnance Board and the higher authorities, during the pre-war years. Examples of guns which were the subject of such competition were the 4.5″ for both the Navy and the Army; the 4.7″ Marks IX–XII; the 5.25″; the 6″ Mark XXIII; the 14″ and the 8″. In all these cases the Department was the successful competitor. Army equipments included the 5.5″ and the 4.5″; the 25 pdr.; the 2 pdr. Mark X tank gun, and the 4.5″ A.A. gun. There were, however, some spheres in which one or other had a monopoly. Thus the Department had always been responsible for the design of guns and ammunition for all three Services, and of carriages and mountings for the Army, and Vickers had always been responsible for the mountings of naval guns.

The relationship between the Department and Vickers was not confined to competition. Competition was sometimes dispensed with even before the war, and during the war it became quite usual to allocate a project to one or the other; the Naval 4.5″ Mark V gun, the 2 pdr. Mark VIII, and the 75 mm. Mark V were among the Vickers designs undertaken without competition. In other cases the firm collaborated with the Department; cases of collaboration tended to increase during the war with the growing complication of design.

The Air Ministry design and testing departments were the Aeroplane and Armament Experimental Establishment, the Airborne Forces Experimental Establishment, the Royal Aircraft Establishment and the National Gas Turbine Establishment. The Aeroplane

[1] See pp. 435–436.

and Armament Experimental Establishment was located, until the outbreak of war, at the Air Force station at Martlesham Heath in Suffolk. The Establishment had always been under the administrative control of an Air Force Command, and in 1934, at the beginning of the expansion period, the Commanding Officer was a serving officer of Group Captain rank. In addition to the small group of test pilots, sufficient to operate two squadrons, the technical staff dealing with armament testing, and the administrative and maintenance staff were all Service personnel. The only civilians in the Establishment were a small number of scientists and technicians led by a Chief Technical Officer. The Chief Technical Officer controlled the technical side of the flight test work, determining the nature of the tests to be carried out and analysing their results. Up to 1934 there was an aircraft research flight but even after this ceased research continued into methods of testing and also, to a limited extent, into actual aerodynamic problems. The flying organisation consisted in 1935 of two squadrons, first the Performance Test Squadron, with three flights: and secondly the Armament Squadron of two flights, one dealing with gunnery and one with bombing tests. Armament flying was controlled by the squadron commander of the Armament Squadron. There was no Fleet Air Arm pilot or rating in the Establishment up to 1935, although prototype Fleet Air Arm aircraft were tested at Martlesham. At the outbreak of war Aircraft and later Armament Research Sections consisting of civilian scientists were formed, but these were almost entirely concerned in developing new testing techniques, particularly in the design of recording instruments for obtaining more accurate results than were obtainable by visual methods.

It was in the field of aircraft armament that the most important developments occurred at the Aeroplane and Armament Experimental Establishment between 1935 and 1939. The Armament Section dealt with weapons and installations in new types and variants of aircraft and in each case addressed itself to three important questions. First, can the weapon be safely and efficiently carried to within striking distance of the target in the prescribed aircraft? Secondly, having been carried to within striking distance can it, or its projectiles, be made to hit the target with the required accuracy? Thirdly, will the weapon destroy, or effect the required degree of damage upon its target? It was with questions such as these, in connection with a wide variety of devices, that the Aeroplane and Armament Experimental Establishment were engaged in the armament side of their work.

But there were also important developments in the central field of the testing of new designs of aircraft. The tests to which the Aeroplane and Armament Experimental Establishment subjected aircraft were always numerous, complicated, and exacting, and they have always tended to become more so as the complications of modern aircraft have increased. During the expansion period and up to 1940 and 1941 one particular and definite advance was made from an older world in which pilots' experience had been the supreme criterion in such testing into a more modern world in which quantitative tests provided the norm. Early in the expansion period the civilian scientists began to feel that more could be done to introduce scientific techniques into the assessment of performance. They were naturally anxious to make the most scientific approach to this problem and in particular to replace fallible human judgment by impersonal measurements wherever this was possible. A great deal of work was done to devise means of making such measurements, and from about 1937 onwards pilots' opinions about manoeuvrability, longitudinal stability, lateral and directional trim and general performance were increasingly supplemented in this way. There were however two views about the value of such measurement; or to be accurate, about the value of the results produced in relation to the time and effort required to produce them. At the time of the outbreak of war there was an important element of Service opinion within the Establishment which favoured a return to the earlier methods as one means of meeting the heavier demands of war. This policy was favoured by the Commanding Officer, but the Chief Technical Officer, supported by his staff, was opposed to it. He considered that the strain of war upon the Air Force would best be met by an extension rather than a reduction of quantitative testing.

So radical a disagreement could be solved only by an appeal to higher authority, and the question was in fact referred to the Director General of Research and Development who decided in favour of the quantitative approach. This was a highly important decision and did much to determine the future character of the Establishment as a whole. It confirmed that the testing of aircraft to determine their aerodynamic and handling qualities was a proper field for scientific method and so gave to the Aeroplane and Armament Experimental Establishment an official blessing for its war-time expansion into an establishment which depended upon close collaboration between civilian scientists and the original Service personnel.

The movement here, then, although perhaps less obviously, again illustrates the larger theme. The Service pilots of the Aeroplane and Armament Experimental Establishment increasingly shared their special responsibilities as flying—and fighting—personnel with scientists and engineers who by training were closer to industry, to 'production', than they were to the Air Force. The pilots indeed, with the acquisition of scientific and engineering techniques, themselves moved closer to 'production' in understanding and sympathy.

We may observe the same pattern elsewhere as the war advanced. In the case of the Admiralty Compass Observatory its work, both on the testing of the compasses and new design work arising out of the correction of faulty compasses, also grew to great proportions with interesting effects on its relations with industry. H.M.S. *Vernon* was compelled to decentralise many of its duties as the burden of ensuring that all ships left for sea with their equipment fully efficient became increasingly onerous. Again the Admiralty Experiment Works found itself concentrating on the urgent problems of the German pressure-mine and investigations of underwater noise and detection. These activities lay outside the pre-war scope of the Establishment's work and were undertaken because of the special facilities of the Admiralty Experiment Works. The Admiralty Gunnery Establishment found that its workship was sometimes diverted to production purposes. The Armaments Design Department found itself very overworked, particularly with the correction of design faults in the work of certain firms who were comparatively new entrants into the armaments field. The amount of time spent in correcting or attempting to correct faults in such outside designs became a serious drag upon the work of the Department. An officer in the Gun Group calculated that during the winter of 1944–45, by which time the number of firms involved in armament work was of course very large, some 18 per cent. of the total time of the Group was spent in this way.

Yet the pattern of division between industry and the establishments cannot be understood merely by reference to the war-time tendency for urgent day-to-day needs to draw closer to production the work of establishments which in time of peace were concerned with less immediate—less 'practical'—developments. A general determining factor, influencing the establishments at their births and throughout their lives, was that of commercial profit.

The history of the Royal Aircraft Establishments makes the importance of this factor very clear. We have already seen[1] in its early history the effect of industrial jealousy of Government participation in a profitable field, namely the decision to discontinue the design and manufacture of aircraft. As late as 1924 the Halahan Committee[2] toyed with the idea of including a certain amount of production work among the functions of the Establishment but the fear of trespassing on the sphere of industry or even of appearing to do so was always potent, and the idea was dropped. Some of the departments—the design departments—did carry out the design work of certain items of equipment such as radio sets, instruments,

---

[1] See pp. 437–438.

[2] Committee on the Organisation of the Royal Aircraft Establishment, Farnborough. See p. 446.

cameras, and electrical equipment. But the irksomeness of not being able to build an engine remained. During the war those scientists and designers of the Royal Aircraft Establishment who were concerned with jet development recorded their dissatisfaction at not being able to build an aircraft with a jet engine for test purposes. This restriction was bound to have effects on the actual advice given by the Royal Aircraft Establishment to industry during the war.

The idea of a 'pattern' in the relationship of the development establishments and industry must not however be carried too far. Relations varied greatly at different times and in different sectors. At their points of greatest contrast they ran from direct competition to close collaboration. We have seen that competition was the official policy at the Admiralty Engineering Laboratory, that the establishment was set up to break the Vickers monopoly of the submarine engine (and also as submarine specialists).[1] In 1934 the Admiralty, in accordance with its policy of competition, ordered engines from four sources. The best two engines were produced by the Admiralty Engineering Laboratory and Vickers respectively. The Laboratory was attempting to make big advances in power output (not necessarily for submarines) on a limited size and weight. Unit engines were built, but none was really successful and none went into service. These failures were not peculiar to the specialised type of engine essential to meet space and weight, and particularly height requirements for the Naval Service, but were general throughout the world. Many firms, in fact, produced failures without having the limitations of space and weight imposed upon their designs. During the war a Committee under Sir Roy Fedden examined the possibility of the production of a high-power light-weight compression ignition engine. From the considerable number of engines and proposals examined, including designs put forward by several British firms and the Admiralty Engineering Laboratory, the Committee finally selected a design by Ricardo.[2] Competition was also generally favoured as a policy for the Armaments Design Department and also for the Fighting Vehicles Design Establishment.

At the opposite extreme was the relationship of simple co-operation in which the establishments and industry carried out certain tasks for each other. Normally, of course, the firms served the establishments. But occasionally the reverse took place. The shortage of precision gear led the Admiralty Gunnery Establishment to offer to undertake certain production commitments, though date promises which might interfere with development work were never given. A batch of torque amplifiers, for example, which were initiated

---

[1] See p. 460.

[2] Sir Harry Ricardo, Ricardo & Co., Engineers (1927) Ltd.

and developed at this same Establishment were hastily produced by them, though normally they would have gone out to be manufactured.

The extreme of abnormality was provided by the case of the National Gas Turbine Establishment,[1] which, in its later war-time stages, raised echoes both of the early troubles of the Royal Aircraft Establishment and of the contemporary problem of the Admiralty Engineering Laboratory in the field of turbine development. From the date of the nationalisation of Power Jets Ltd., in 1944, the Board of Directors became the main policy-making body for administering the development of the gas turbine engine. In the course of their early meetings the directors discussed such questions as the formation of a patents pool, the possibility (and propriety) of the firm, as a Government-owned concern, becoming a member of the Society of British Aircraft Constructors, and the possibility of developing collaboration with Short Bros. because of that firm's similar status in being Government-owned. The firm's functions were discussed in relation to a letter from Sir Stafford Cripps[2] in which he said that they should not confine themselves solely to aircraft gas turbines, but should contemplate a wider field such as marine engines, power stations, and locomotive gas turbines. Another important and delicate question which was discussed was that of the design of complete engines, and the manufacture of pre-production batches of such engines. There was some opposition to this on the grounds that industry would regard even so limited an amount of manufacture as unfair competition. The Minister himself, however, who was present at this meeting, said that while the Company were not designers in the usual sense, part of their function must necessarily be design for experimental purposes; this involved the manufacture of pre-production batches. The Company's Charter was then amended to include the right to design, construct and develop prototype engines, components and accessories, and to develop materials for their construction; and to devise methods of manufacture appropriate to such engines and to manufacture small batches of such engines so as to carry development up to the production stage. It is interesting as we said earlier to note the recurrence of the problem that faced the Royal Aircraft Establishment—the fears of arousing the hostility of the aircraft industry.[3]

It will be seen from this brief summary that it is not easy to pick out a simple pattern from the complicated relationships between establishments and industry. Where the industry had a long tradition of autonomy and success—or even autonomy alone—the establishments never found it easy to extend their influence on design. On

---

1 See also Ch. IX.
2 Then Minister of Aircraft Production.
3 See pp. 437–438 and 468.

the other hand, rivalry between old-established firms and establishments could be friendly as is shown by the Armaments Design Department and Vickers and the successful collaboration between the Central Metallurgical Laboratory and I.C.I. For the rest, the relationships seem to have been determined by special factors in each particular instance.

Yet, after all, it was not the relationship of the development establishments, and still less of the research establishments to industry which was their most important one. It was another relationship which above all determined what work they should do and the conditions under which they should do it. Both to the research worker and the engineer by far the most important relationship, and one which in fact determined almost every single aspect of his work, was that with Headquarters. It is this that we must now consider.

CHAPTER XIX

THE STATUS OF THE ESTABLISHMENT AND THE STATUS OF THE SCIENTIST

JUST as the best-designed weapon will be of restricted value if it is not properly used, so the best scientists and engineers can only do their best work if, first, they are called upon to do it and, secondly, if they are given conditions in which they can do it. It might seem at first glance safe to assume at least that scientists from the time they were brought into the design and development of weapons were called upon to do their best; but consideration will show that this is not in fact safer than assuming that such weapons as tanks were or will be used to maximum advantage in the early days of their employment. As for the provision of conditions in which scientists and engineers can do their best work, it is easy to see that ideal conditions are—to put it at its lowest—no easier to provide than is ideal maintenance of elaborate and delicate weapons. In some cases the nature of the problems with which the scientists are concerned is such that there is little scope for initiative; in others, where the scope is larger, the establishment is content to rely very largely on headquarters instruction or guidance. In other cases again the staff of the establishment may be less content to do so but is discouraged from assuming greater responsibility. More rarely, matters have gone to the opposite extreme, and an establishment has been at a certain period, or in a certain field of work, almost autonomous in determining what work it should do and how it should be done.

It was the Air Ministry which first attempted to enlist the aid of the research scientist as an intrinsic part of its non-organisational structure. Even so it may well seem curious that until 1924 there was no special machinery in the Air Ministry devoted exclusively to watching the interests of scientific research. The main responsibility for the advancement of aeronautical science in Great Britain lay in the hands of the Aeronautical Research Committee, a brief history of which is given elsewhere in this volume. It is sufficient to record here that the status and opportunities of aeronautical scientists greatly improved after the formation of the Aeronautical Research Committee.

The first development after the appointment of the Director of Scientific Research in the Air Ministry in 1924 occurred in 1929, when the Treasury appointed the Carpenter Committee[1] 'to examine the functions and organisation' of the most important scientific organisations under Government control, including the scientific organisation of the Air Ministry, and 'to report on the method of recruitment and conditions of service of the civilian scientific and technical officers employed therein'. The Chairman of the Committee was Professor H. C. H. Carpenter, F.R.S., and the members, who were predominantly drawn from the senior scientific personnel of the Government service, included the Director of Scientific Research at the Air Ministry.

The Air Ministry salary scheme, which was a principal object of the Carpenter Committee's study, had been based on the organisation of the National Physical Laboratory, especially in regard to recruitment and conditions of service. The Committee's general conclusion was that 'the present salaries and financial prospects of the scientific staffs in the Government service are shown to be generally inadequate by the difficulty of recruiting and retaining officers of the high standard required by the work to be performed'. The Committee's evidence was based on an examination of the terms and conditions of work offered by competing employers, such as universities and private industry.

The Committee touched upon a vital point in suggesting that men of the Scientific Officer class with high academic qualifications should be employed on work which definitely required these qualifications and not waste their time on work of an 'ancillary character'. In general, it was the Carpenter Committee's intention to offer a more attractive career to the scientist who possessed above-average talent, and that advancement and promotion for the man possessing scientific ability should be more rapid.

Owing to severe financial stringency, it was January 1933 before the Treasury were prepared to adopt the Committee's suggestions; even then they would not agree to any changes above the level of £500 basic salaries, and it was October 1934 before the Treasury considered applying the Report in its entirety. The second stage of the Carpenter Report became effective on 1st January 1935 and extended the new scales to the higher ranks.

If then the Carpenter Report had comparatively little effect of a dramatic or even immediate kind, it was nevertheless something of a landmark in the history of Government science, and did something towards creating a new attitude towards scientific research. The Report insisted that scientists should be treated as scientists, emphasising the extremely high qualifications required in the Scientific Officer class, thus exalting the role of the scientist and creating an

---

[1] Committee on the Staffs of Government Scientific Establishments.

atmosphere congenial to research. The Committee's findings may therefore be considered as the initial stepping stone to the reform of the Scientific Civil Service proposed in the White Paper of 1945.[1]

The next step forward after the Carpenter Report and its final implementation in 1935—at least the next formal step forward which can be identified with a particular moment of time—was the Guy Report of 1942.[2] This concerned the Armaments Design Department,[3] which, as we have seen, was the servant of the Ordnance Board, which kept to itself all responsibility for long-term development of armaments. There is ample evidence that for some time both within and without the Department its situation was anomalous and unsatisfactory. Despite their title of 'Design Officers' the military officers who composed its directing personnel and were the vicars of the Ordnance Board, were not and did not pretend to be qualified designers of armaments. Yet it was the Design Officers who controlled and administered the work of the Department and took responsibility for it; the draughtsmen, i.e. the men who actually undertook the concrete responsibilities of the design of new weapons, were, in 1935, little more than 'Other Ranks'.

An organisational change occurred in 1937 which was followed by developments of some importance in the role of the Design Officer. The title of Superintendent of Design was changed to Chief Superintendent of Design and from that time on he reported no longer to the Chief Superintendent of Ordnance Factories but direct to the War Office. And there for years matters rested.

It was in 1941, when the post of Controller General of Research and Development was created in the Ministry of Supply to be responsible for 'the initiation, conduct, and progress of all Ministry of Supply research carried out in Ministry of Supply Establishments and extramurally',[4] that the study which the new Controller General (Mr. Oliver Lucas) made of the establishments led him to believe that there was room for a good deal of improvement in this field. Mr. Lucas was anxious that the Research and Design Departments should have a full sense of the importance and responsibility of the work which they were carrying out, and he was also concerned about the extent of overlapping between them. He did what he could by visits to the two Departments to improve matters in these two respects, but by the beginning of 1942 he had reached the conclusion that no more could be done along these lines and that what was

---

[1] Cmd. 6679, *The Scientific Civil Service, Re-organisation and Recruitment during the Reconstruction Period*, September 1945 (H.M.S.O.).

[2] Report of the Committee on Armaments Development, 12th August 1942.

[3] See pp. 436 and 464–465. Also J. D. Scott and Richard Hughes, *Administration of War Production* (H.M.S.O. 1955), Ch. XIII.

[4] See also Ch. X.

needed was a thorough investigation of the Ordnance Board and the two Departments.

Meanwhile the Scientific Advisory Council had become interested in these matters and had carried out, through a committee under the chairmanship of Lord Hankey,[1] an examination of the way in which the Departments were working. The committee made a number of recommendations tending to increase the prestige and independence of the scientists in the establishments, but the Controller General was apparently not satisfied that even if these recommendations were put into effect the defects in the existing organisation would be cured. Anxiety about these defects had already reached such a height that the President of the Ordnance Board declared that 'development is an unwanted foster child and has been, I fear, treated as such', and it seemed clear that what was needed was a very complete investigation with the possibility of re-organisation of a really radical nature.

It was to carry out such an investigation that the Guy Committee was set up in May 1942.[2] In proposing to the Minister of Supply that such a Committee should be set up, the Controller General expressed his 'serious concern' on the subject of the Research Department and the Armaments Design Department. 'It has become increasingly evident to me', Mr. Lucas wrote, 'that very considerable criticism of the efficiency and speed of work of this group has been and is being expressed by departments of this and other Ministries . . .'

The Guy Committee was composed of the Director of Naval Ordnance, the Director of Artillery, the Director of Armament Development, Staff representatives of the three Services, the Deputy Controller General of Research and Development of the War Office, Sir Edward Appleton, and a member of the Ministry of Supply's secretariat. Seven independent assessors were available representing academic and industrial interests. The Committee heard evidence from a very large number of sources. The evidence given by the President of the Ordnance Board was of particular importance, and Vice-Admiral Pridham had already set out before this date the criticisms which he made to the Committee. In a memorandum addressed to the Controller of the Navy, Vice-Admiral Pridham had stated that 'a Ministry whose principal concern is production (the antithesis of development) stands between the Board and the initiators of requirements in the field of battle'. He believed that contact between the Ordnance Board and the Staff was inadequate, and suggested that, in order to save time and effort it was essential

---

[1] Joint Panel of the Scientific Advisory Committee (Defence Services Panel) and Engineering Advisory Committee.

[2] Committee on Armaments Development.

that the Ordnance Board should be called in at the initial stage of all investigations, that is to say before requirements were framed.

Much of Vice-Admiral Pridham's criticism was backed up by Mr. C. D. Gibb, Director General of Weapon and Instrument Production, who said in some notes submitted to the Committee on Armaments Development on 17th June 1942:

> If the Ordnance Board is to remain the arbiter of what is or is not a good weapon or the lines on which development is required, it must be composed of younger and more flexibly minded officers. . . . As I see it the Ordnance Board must either cease to exist, or become a body of consultants, or the testing branch of the design and research departments.

On the aspect of organisation with which we are here most concerned, Vice-Admiral Pridham in the evidence which he gave to the Guy Committee dealt in strong terms with what has already been touched upon in this chapter as the fundamental anomaly in the organisation of the Armaments Design Department. He declared that the three fighting Services relied for the design of new ordnance equipment on a department which included no designers:

> One-time Naval and Army officers who saw small prospects of rising in their profession, now direct and conduct design detail, to the best of their ability no doubt, but as amateurs with no basic education of the nature necessary to this work. They are assisted by draughtsmen. A man with engineering qualifications and experience is conspicuous by his absence and experimental workshop facilities are inadequate. The fighting Services cannot produce through any system of special training the man best fitted to direct and supervise the work of designers. The careful selection of a Production Engineer for this post seems to afford the only fully satisfactory solution.

The evidence of Mr. C. D. Gibb, the Director General of Weapon and Instrument Production, suggested that the fault lay not merely with the designers. He accused the General Staff of not providing a stable weapon policy so that the Armaments Design Department was compelled to rush out new designs, production having to start before pilot models and other trials could be made. The inevitable consequence was that design constantly changed as production advanced and more experience became available. This of course was inimical to efficient and rapid production. The reason for this was partly Government stringency before the war in not allotting sufficient money for research and development, but he was not satisfied that this policy had been completely abandoned. Nevertheless, Mr. Gibb considered that the staffing of the Armaments Design Department was unsatisfactory. Not merely were the staff overworked and underpaid, but their training and experience was not suitable for the work they were doing.

The recommendations of the Guy Committee went a long way to meet the criticisms which had been made. In the first place the formal status of the Armaments Design Department was raised considerably. It was affirmed that subject to the requirements of the programmes of the Director of Naval Ordnance, the Director of Artillery and the Director of Armament Development, whose position and authority were to be maintained, the head of the Armaments Design Department should be established as the authority on armament design and responsible for the conduct of the work in his department.

As was to be expected, however, the main recommendations were concerned with the staffing of the Armaments Design Department. There was to be a change in leadership. A highly qualified and experienced mechanical engineer was to be appointed by the Ministry of Supply in consultation with the Admiralty and the Ministry of Aircraft Production with status and emoluments identical with those of the post of Director of Naval Construction. There was thus to be a bold departure from the cheeseparing methods of the past.

The staff was to be strengthened by the establishment of an engineering section of highly-trained and experienced mechanical engineers headed by four to six Principal Design Engineers, with supplementary lower categories of design engineers to provide a team of about forty in all. They were to be recruited from the best men available whether inside or outside the Establishment. This staff was to be additional to and superimposed on the existing organisation, and would first concentrate on new work or special investigations then needed, and later would be infiltrated into the section. The new engineering section was to draw on existing staff for particular projects, thus assisting infiltration. In due time the Chief Engineer Armaments Design was either to introduce new highly qualified designers into executive posts in existing sections or confirm in or promote to such posts from existing Service or civilian staff, the choice being made on grounds of suitability alone. The number of Senior Design Officers was to be increased. The principle of promotion primarily by seniority was to be abolished and in addition further means were to be found for rewarding merit apart from promotion. Finally, the authority of the Controller General of Research and Development over the Design and Research Departments was confirmed.

Such were the principal findings and recommendations of the Guy Committee. Almost all were implemented. A distinguished production engineer, Mr. F. E. Smith of I.C.I., was brought into the position of Chief Engineer Armaments Design, and just as Professor Lennard-Jones inaugurated the 'professorial regime' at the Armaments Research Department, using his wide University contacts to introduce distinguished academic scientists into the establishment, similarly Mr. Smith brought to the Armaments Design Department a number of highly qualified engineers and designers.

After Mr. F. E. Smith's appointment more civilian Design Officers were appointed to each section, most of them being draughtsmen who had been promoted on grounds of merit. The changes in personnel as a result of the Guy Report did away with the system whereby the Armaments Design Department was controlled by a Service Superintendent with Service Officers as executives for each section, and few civilians in any administrative posts or any design posts higher than that of a draughtsman. The Report had, in brief, fundamentally changed the status of the civil professional personnel in one of the great central establishments. It had effected a great reform. At one step it had done more to improve the position of the government scientist and engineer than any organisational or administrative reform, or any combination of organisational and administrative reforms, between 1924 and 1945.

Such reforms may be called 'imposed' reforms. A person in authority—in the case of the Guy Committee it was Mr. Oliver Lucas—investigates a field in which he believes there is a weakness, and institutes measures to remove it. In the case of the research and development establishments there is evidence that the discontent expressed in various ways by the establishment personnel themselves was a factor of importance in attracting headquarters attention to their problems. In another sector of the establishments, however, was a group of scientists who were so placed as to be able not merely to seek, but demand attention. These were the radar scientists, and their position and their demands were a very powerful factor in the transformation of the status of the scientist and the status of the establishment which took place between 1939 and 1945.[1] It is hardly too strong to distinguish the reform which they brought about as a 'revolutionary' reform.

Something has already been said in these pages of the various radar research establishments, their relationship with particular services, and their organisational structure. But what has been said gives only a restricted and formal picture of the work of the research establishments. Such a picture fails to show the extent to which these establishments anticipated tactical and strategical requirements by devising radar equipments appropriate to them, and in fact contributed to the development of tactical ideas as well as to the progress

---

[1] See Ch. XVII, pp. 452–457.

of technical methods. This interplay of technical and tactical ideas, and the unexpected role played by the scientists in it, was one of the outstanding features of the history of radar, particularly in the R.A.F.

The production of a new equipment at the time when it was needed by the Service was only the successful culmination of activity which had almost invariably gone beyond the sphere of scientific research and development. This unusual extension of the activities of a scientific establishment was especially characteristic of the Telecommunications Research Establishment; that this was so was as much to the credit of the R.A.F.'s willingness to accept ideas from civilians as to the scientists' ability to contribute to the solution of problems not ordinarily within their sphere of interests. The basic reason for this state of affairs was no doubt that radar was a new applied science, and whereas in the development of aircraft or armament the R.A.F. was well aware of what it might reasonably expect, or at least hope for, this was not so in the development of radar. The only people who could form a clear idea of the potentialities of radar when applied to any particular tactical or strategical problem were the scientists in the Establishments. The scientists had therefore seen that it was of the greatest importance that their knowledge of such problems should be full, accurate and up-to-date. The pace of the radar war was such that this could hardly be achieved by a formal exchange of scientific memoranda and tactical appreciations. The aim of the scientists was to maintain such close and friendly contact with the Service that they would be aware of a problem at least as soon as the Service realised its existence; their ideal was that any problem for which radar might be useful should be formulated in discussion with themselves. We must consider the attitude of the Service to these aims and ideals.

The interpretation of the strategical air policy of the War Cabinet, its translation into action, and the devising of appropriate tactics was the most responsible task of the Royal Air Force. This task was entrusted to senior officers, who applied to it the professional skill acquired by special study and many years of experience. It would hardly be surprising if the claims of scientists to be admitted to this sphere were regarded with impatience. The general absence of such impatience, and the willingness to discuss, to co-operate, and to be advised, were among the most striking features of the development of radar.

To what were they due? The acceptability of radar scientists in Service circles was, in the first place, a function of the acceptability of radar. Even when this is allowed for however, something must be said of the tradition of close and sympathetic contact which, in the years before the war, was established on the scientific side by Sir Henry Tizard, Sir Robert Watson-Watt, and Mr. Rowe, the Chief

Superintendent of the Telecommunications Research Establishment, and on the Air Force side by Sir Philip Joubert, by a succession of Deputy Chiefs of the Air Staff, and many other Air Force officers of all ranks. In meetings and informal discussions, at Bawdsey Research Station and in the Air Ministry, in Command Headquarters and at Operational Stations, the problems of each side were fully, continually and frankly discussed. This tradition of close co-operation was maintained at all levels, and was referred to by Lord Justice du Parcq in his report to the Prime Minister on radio matters in 1942: 'In the actual working out of the problems on which research workers are engaged, there seems to be full and enthusiastic co-operation between Service representatives and the scientists, The former suggest in oral discussion what they would like done. and the latter suggest what might be done, and there is fruitful exchange of ideas across the table.' While the greatest strength of the liaison was informal and personal contacts, there were nevertheless certain institutions of a more-or-less formal nature which have played an important part; they have to do with the origins and traditions of Bawdsey Research Station.

It has already been told how work on radar began at Orfordness in 1935 with a staff of eight or nine scientists of the Department of Scientific and Industrial Research working under the auspices of the Air Ministry.[1] It quickly became clear that, for technical reasons, more accommodation was needed; and Bawdsey Manor was in due course chosen as the most suitable site from all points of view. The characteristics which later distinguished the Telecommunications Research Establishment from its contemporaries grew out of Bawdsey and Orfordness. Since in their developed form these characteristics were so important to the war effort, as well as being unique in the history of Government Establishments, it is necessary to consider here the influences that caused them to grow as they did. There were four major factors—the geographical situation of the Manor, the type of men who went there, the kind of work that was done, and the vital importance of the work to the operations of the R.A.F. We shall discuss these separately.

First, the geographical situation of the Manor. It was a large, late nineteenth-century eccentricity, built of stone-faced red brick and dominated by two cupola-topped towers rising from adjacent corners. It was however beautifully situated in some 160 acres of park within a few yards of the sea and facing a private cricket pitch which was later to become well-known in R.D.F. circles. It was a selfcontained world, its remoteness enhanced by the River Deben which cut it off from the main road, the railways, and Felixstowe.

---

[1] See Ch. XV, Section (i).

So much for the place; what of the people who came there? These were the scientists who for nearly a year had been working in the even greater seclusion of Orfordness. Generally speaking they were young men who had gone to the National Physical Laboratory from their universities and had consequently spent the whole of their professional lives in an academic or quasi-academic atmosphere. Physicists rather than engineers, they were soaked in the technical tricks peculiar to the pulse method of ionospheric research. This last qualification was unusual but was considered necessary for the work at Bawdsey; the difficulty that Sir Robert Watson-Watt subsequently encountered in recruiting new members to his staff was probably more closely related to his insistence on it than to any demand for an abnormally high standard of ability. Able as the pre-war R.D.F. workers were, it cannot fairly be claimed for them, nor would they claim for themselves, that they were as a body outstandingly brilliant or the cream of the country's scientists; such men came later.

In enumerating above the factors that caused Bawdsey Research Station to acquire its distinguishing characteristics, it was said that two of these were the kind of work that was done there and the vital importance of the work to the operations of the R.A.F. The second of these two is really a part of the first, but the distinction is worth making. The essential point about the nature of the work is that it involved a completely new art with infinite technical possibilities; hence there was engendered among the scientists a single-minded enthusiasm from which sprang a torrent of new ideas, so much so that it was often more important to restrain than to stimulate invention. Bound up with its technical possibilities were the tactical and strategical applications of the new art. It was clear to the initiated that these could bring about revolutionary changes in R.A.F. tactics; hence to follow closely the progress of the experiments was the concern of the highest R.A.F. officers as well, of course, as of those scientific and political leaders who, as members of the Committee for the Scientific Survey of Air Defence and the Sub-Committee on Air Defence Research, had fathered the work. Moreover, because the technique was so new it could not be divorced from the tactics of its use; it followed therefore that tacticians had to work with, and even be guided by, technicians. The newness of the work, its operational importance, and the necessity for the closest co-operation between technical and operational personnel had been realised by the small group of people, at the Air Ministry and at the Research Station, who had been in R.D.F. from the beginning; this realisation had led to the establishment at Orfordness of the habit of informal discussion between senior visiting officers and the scientists[1] (it goes without

[1] It led also, later on, to the detachment of a section from Bawdsey to H.Q. Fighter Command, to watch and advise on the operational use of C.H. From this section was developed operational research at R.A.F. Commands.

saying that discussions among the scientists themselves were never-ending). This habit went with the staff to Bawdsey where it grew into a tradition.

Reference has already been made to the shortage of staff for radar work before the war[1] and to the comparatively large scale initiation of university scientists that followed from contact with the Cavendish Laboratory. Thus when the University scientists were ultimately brought in, they came in considerable strength and with a high standard of ability, bringing with them a preponderantly theoretical outlook. This consorted with the policy which Mr. Watson-Watt had always followed in recruiting staff to Bawdsey, although it began to appear later that a greater proportion of engineers would have been an advantage. The impact of the university men upon the government service was considerable but, because Bawdsey already had, as we have seen, a quasi-academic atmosphere, its effect was one of degree rather than of kind.

In the course of the war Bawdsey Research Station became successively the Air Ministry Research Establishment and the Telecommunications Research Establishment, and moved from Bawdsey to Dundee, Dundee to Swanage and Swanage to Malvern. But despite these many changes, and a vast increase of members, it remained in some vital sense the same place. Liaison between the Establishment and Headquarters, and between both and the Service, was given a tone at Bawdsey which it never lost.

We have already seen that the greatest strength of this liaison was, and continued to be, in informal and personal contacts. There were nevertheless certain institutions of a more or less formal nature which played an important part. Most of these began in Swanage, but, with the rest of the Establishment, they grew to their full stature in Malvern. First we must refer to an institution which stood, so to speak, halfway between the official and the informal. This was the Telecommunications Research Establishment 'Sunday Soviet.'

The Sunday Soviets perhaps owed their immediate inception to the circumstance that in the days when the Air Ministry Research Establishment first moved to Swanage, Air Marshal Sir Philip Joubert had a house at Bournemouth situated conveniently for visits to the Establishment. The Air Marshal had been appointed in June 1940 to the newly-created post of Assistant Chief of the Air Staff (Radio), A.C.A.S.(R), with the responsibility of co-ordinating radio and radar matters from the Service point of view. He found himself frequently at the Telecommunications Research Establishment on a Sunday, involved in discussion of all aspects of radar policy. As Sunday was not then officially a working day, the atmosphere was

---

[1] See p. 452.

informal, and the discussion unburdened by an agenda. The London blitz enhanced the value of a week-end resort at which official business could be carried on in a more peaceful atmosphere, and brought many other distinguished visitors. In due course it became a regular thing to find, congregated in the Superintendent's room, every Sunday, as well as a number of Telecommunications Research Establishment scientists, an A.O.C.-in-C. or his deputy, supported by staff officers of various ranks; a senior member of the Air Staff; a high Air Ministry or Ministry of Aircraft Production civil servant and perhaps a scientist from a University or another Government Establishment. Rank and seniority were obscured, if not forgotten, and everyone devoted himself to mastering someone else's business and informing others about his own. Sunday Soviets quickly proved their use and became an institution; Sunday had in fact to be made an official working day in order that any scientist whose opinion might be wanted would be available. By retaining throughout their history a good deal of the early atmosphere of informality and frankness, the Sunday Soviets remained a most important instrument in creating good relations between scientists and serving officers. They were perhaps chiefly remarkable as a vehicle for informing the scientists about the Air Force.

There is no doubt that the informal relationship, the free discussion of the strategical and scientific development, which the Telecommunications Research Establishment scientists were able to establish as the norm between the Establishment and Headquarters (including, in an extended sense, the highest Service officers) had powerful effects on the relationships between other establishments and headquarters. It was not everywhere revolutionary; the tone of the relationship remained that of the Civil Service or of the particular fighting service for which a particular establishment mainly worked. But it was modified. The permanent scientists in the Admiralty Research Laboratory, in H.M.S. *Excellent* or the Royal Aircraft Establishment could not, as could the temporary, university people in the Telecommunications Research Establishment, go about 'with their resignations in their pockets'; nevertheless because some government scientists had inserted themselves into the higher counsels of the Ministry of Aircraft Production and of the Air Force (and even, on occasion, of Downing Street), *all* government scientists tended to be more fully consulted, to be supplied with more headquarters information, to have their advice asked earlier.

Generally speaking this change in atmosphere was not (except as has already been described) formalised in organisational changes. Some may perhaps be discussed. In 1944 the Controller of Research and Development approved changes at the Aeroplane and Armament Experimental Establishment at Boscombe Down which had, amongst other effects, that of raising the principal scientist in title from Chief Technical Officer to Chief Superintendent, and in capacity to a rather higher position vis-a-vis the Air Commodore commanding the station. But such measures were exceptional; formal steps to change the status—perhaps it would be more accurate to speak of steps to recognise the change which had occurred—had to await the post-war reforms. Nor can we see dramatic, or even very clear, cases of scientists seizing in the later years of war an initiative which had formerly been denied to them. When such cases appear, complicating factors are generally present. In 1944 the Admiralty Research Laboratory boldly permitted some of the effort which had been directed towards combating the German pressure mine to be extended to the more general investigation, both from a theoretical and practical point of view, of the factors which influence wave generation and decay. This extension—or diversion, as it may well have appeared to some naval officers—could be represented in the light of an assertion of a new attitude of scientific independence. In fact there is no evidence that it was so intended or so regarded. Yet it was made, and is not without significance. Again in 1943, the Experimental Department of H.M.S. *Excellent* was able, for the first time, so far to depart from its testing functions as to initiate and carry through the design of a device known as the simple electronic deflection calculator. Again, it would be possible to suggest a picture of scientists newly asserting a right to undertake the tasks for which they thought themselves best fitted. It would not be an accurate picture, because it would not allow for the fact that it was the dissolution of the Anti-Aircraft Department of H.M.S. *Excellent* and the distribution of its members among other departments which made the departure possible. Yet again the departure is not without significance.

Perhaps, outside of radar, the clearest example of the new atmosphere, of the progress of the government scientist towards independence and the full status of a colleague, lay not in any existing establishment, but in the setting up in 1943 of the new Naval Construction Research Establishment. The sinking of the *Prince of Wales*, *Repulse* and *Ark Royal* in 1941 caused very grave anxiety about the vulnerability of our capital ships to enemy attack, and led to the Government's setting up a committee of investigation under Mr. Justice Bucknill. The terms of reference of the committee were:

> To review the circumstances attending the loss by enemy action of capital and other heavy ships since the beginning of the war and to consider whether there are any specific material measures or line of investigation which might profitably be adopted or pursued with intent to improve the defence of British warships against existing or anticipated enemy weapons.

There was proved to be a very clear need for the establishment which came into being in June 1943 with the title of Admiralty Undex Works. It was to be an establishment responsible to the Director of Naval Construction and its first task was to conduct an enquiry into all aspects of the phenomena of underwater explosions and particularly their effect upon ships' structures. This was a highly complex and almost unknown field. The establishment, in beginning operations, had the great benefit of the interest and advice of Sir Geoffrey Taylor, who made a number of very valuable suggestions. There were two techniques of investigation of underwater explosions, first the use of piezo-electric gauges for measuring the initial and subsequent pulses, and secondly, the use of high-speed underwater photography. Much experimental work was done using these techniques. But the interest of this establishment was not of course limited to a study of explosions; they were concerned with the effects of the explosions upon ships' structures. Elaborate studies were accordingly made of the results of underwater explosions upon targets built of ships plates simulating the outer and inner layers of plates.

The setting up of this Establishment, the kind of work which it undertook, and the conditions in which it undertook it, illustrate great changes in the status of the scientist and the status of the establishment. It shows an atmosphere in which Government departments and Service chiefs not only turned naturally to scientists for help, but permitted a good deal of latitude to the scientists in determining *how* they should help. It shows an extension—an extension by no means final but nevertheless important—of the liberalising tendencies which had been at work in the appointments of Directors of Scientific Research, in the Carpenter[1] and Guy[2] Reports, at Bawdsey and in the Telecommunications Research Establishment. It foreshadowed the post-war reform towards which these steps were leading.

[1] Report of the Committee on the Staffs of Government Scientific Establishments, 25th September 1940.

[2] Report of the Committee on Armaments Development, 12th August 1942.

APPENDICES

APPENDIX I

Stop-Gap Orders

Note 1

Summary of Stop-gap orders for the Fairey Battle

At the time when Scheme C was being discussed by the Ministerial Sub-Committee on Air Parity the Fairey Battle single-engined medium bomber had seemed, when compared with existing bombers, a substantial improvement. From the very beginning, however, there had been something wrong with the P.27/32 requirements for a Hart replacement. The requirement for speed had been expressly drawn up to be comparable with the twin-engined bomber (B.9/32), so that the relative value of the two classes could be assessed. By 1933 the Deputy Chief of the Air Staff pronounced that the specification was not likely to produce a light day bomber of high performance. It was too late to cancel the specification—it was already out to tender—but the Air Staff agreed to alter certain requirements to bring it into line in all respects with the Sidestrand replacement (B.9/32).

During the latter part of 1934 the firm partially redesigned their aeroplane, but even this action was not sufficient to enable the single-engined type to compete on equal terms with the twin-engined types which had by now leapt far ahead in performance. The position in relation to the new Programme F was that, although unsatisfactory, the Battle was the only light medium bomber developed from an Air Ministry specification at all ready to go into quantity production. Consequently in common with the Bristol Blenheim a very considerable number were ordered during 1936 both from Fairey's, the parent firm, and Austin's new airframe shadow factory. Fairey's received an order for 655 on 23rd May 1936. Austin's were prepared to manufacture as many towards a total of 900 as possible, but the Air Ministry actually ordered only 400 with materials for another 100.

The P.13/36 substitution scheme, approved by the Treasury and the Air Council in spring 1937, showed how anxious everyone was not to have any more Battles than was absolutely necessary; all those (189) not expected to be delivered from Fairey's by 31st March 1939 were to be cancelled.

In the early spring of 1938 (when Scheme K was receiving hard knocks from the Chancellor of the Exchequer) the Air Council found it necessary to place a certain number of stop-gap orders (the first since Scheme C in 1935) to maintain the level of production during 1938 and 1939, i.e. the date of completion of the existing programme. Both Fairey's and Austin's Battle orders came up for review. It was agreed to restore

Fairey's cancelled 189, but no-one wanted to give Austin's the order for the remaining 386 Battles that had been planned over and above the 500 to which the Air Ministry were committed. The Chief of the Air Staff wanted Austin's to produce Wellingtons because of their greater bomb-carrying capacity, but there were objections on production grounds to this. Finally the matter was left open for a while, but before a decision had been taken Scheme L, with its need for accelerated output changed the position. Austin's, in a frenzy of enthusiasm, offered to make no less than 676 more Battles before 31st March 1940, the date of completion of Scheme L. Fortunately, however, no-one in the Air Ministry believed that they could do it and Austin's had to be content with their originally allocated number of an extra 363. No extra Battles were required from Fairey's in spite of the programme being extended by twelve months.

Austin's were soon in trouble over their enlarged order. Mr., later Sir, Ernest Lemon's review of the prospects of the industry in September 1938 found that Austin's were heading for a serious deficiency in deliveries by March 1940. The position at Fairey's was better; so much better that Mr. Lemon considered that extra Battles could be obtained from that source to compensate for Austin's failure. Accordingly he recommended that 200 more Battles should be ordered which made a total of 855 on order. The firm received the order in 2 instalments, 150 on 1st November 1938 and 50 on 15th December 1938.

Another order with Fairey's for 200 Battles was recommended in December 1938, and placed on 11th February 1939, to maintain the production organisation and labour force until the Manchester programme began. As this presumably could not be until some time after the completion of Scheme L, Battles were perpetuated even beyond the extra twelve months of life they gained from the exigencies of Scheme L.

A yet further series of stop-gap orders was thought necessary in April 1939 because of purely industrial problems. 100 Battles without engines were recommended from both Austin's and Fairey's 'on condition that the labour force be increased by 5 per cent. per month in the next few months'.[1] The form that these last two took shows that the Battle was considered redundant for operational use and no effort seems to have been made to lengthen its operational life by means of modifications, probably because by 1938 there was a prospect of a sufficiency of other suitable types for first-line purposes. The usual fate of obsolete aircraft is to be turned over to Training Command and the Battle finished its career in this way. At the outbreak of war it was decided to order 400 as target towers, 300 from Austin's and 100 from Fairey's.[2]

Although judged by Air Staff standards the Battle was obsolescent from about 1938 onwards and definitely obsolete by 1939, production continued at both Fairey's and Austin's until November and December 1940 respectively.[3] How many of these were produced as trainers it is not possible to say, but Battles saw active service in France in the spring

---

[1] The contract was placed with Austin's on 27th June 1939, but that with Fairey's not till 29th September 1939.

[2] The 100 from Fairey's were in fact not ordered.

[3] Austin's had their contract reduced by 334 on 7th November 1940.

offensive of 1940, and losses owing to their slow speed and light defensive armament were very heavy. Altogether Fairey's produced a total of 1,164 Battles during the 43 months between May 1937 and December 1940; and Austin's produced a total of 1,032[1] in the 27 months between September 1938 and December 1940.

Note 2

Summary of Stop-gap orders for the Whitley

The Air Ministry Specification B.3/34 for a heavy bomber dates from the summer of 1934 when the disarmament restriction on weight of bombers was abandoned. Mr. Lloyd of Armstrong-Whitworth had prepared some drawings for a bomber for the Czech Air Force in the spring and the Air Ministry asked him to adapt the design to their requirements. The contract for two prototypes was given to Armstrong-Whitworth on 14th September 1934 under special conditions to enable the requirements to be met as quickly as possible. There was no competitive tender and responsibility for the design was vested in the firm instead of the Air Ministry for the first time so that unnecessary changes should not be allowed to hold up construction. When Scheme C was being discussed in May 1935 the B.3/34 prototype had not flown; the lack of a suitable heavy bomber for immediate production was felt very keenly and the Air Ministry obtained Cabinet approval in principle to order types off the drawing board. An order for 80 Whitleys on 23rd August 1935 was the first example of the new procedure. Under Scheme F the order was increased by 240.

In the same year (1936) bombers with greatly increased range and weight-carrying capacity were specified (P.13/36 and B.12/36), which of course immediately made the Whitley obsolescent as a heavy bomber and virtually relegated it to the class of medium bombers.

Although the Whitley according to the theoretical standards of the Air Staff became obsolescent, orders for the type continued to be given regularly under every programme, partly because the production of the replacement bombers was constantly postponed, partly because numerical demands were increased and partly because Armstrong-Whitworth's industrial organisation was so weak that they were not considered fit to undertake a change in type.

320 were on order from Armstrong-Whitworth's in 1936 to be completed by 31st March 1939 under Schemes C and F; further orders for this type were not expected to be necessary as the plans for introducing the P.13/36 heavy bombers envisaged that these bombers should commence production in early 1939 and should replace all medium bombers not delivered by that date. It was thought that 120 Whitleys would be undelivered by 31st March 1939 and the Air Council agreed to cancel them.

---

[1] Total number on order from Austin's was 1,263. The number was reduced by 334 to 929, but an extra 100 were produced by Austin's to carry them over their changeover to Stirlings.

A year later in February 1938 it was evident that production plans for the P.13/36 were slipping back and that it would be necessary to order an additional 140, to be completed by October 1939, although delivery was still to be dependent on P.13/36 prospects.

The position was reviewed when types for Programme L were being discussed. The Air Council were most anxious not to accept any more Whitleys than were already ordered, and insisted on Armstrong-Whitworth keeping to the original date for completion of all aircraft on order. The firm very much wished to continue Whitley production, but the Air Council had by now decided that, as a stop-gap for the larger bombers, Wellington production should follow on as soon as possible and they gave a small initial order for 64.

In the generally unsatisfactory position of the delivery prospects under Scheme L revealed by Mr. Lemon in the late summer of 1938, Armstrong-Whitworth's case was considered one of the worst in the industry. The Air Council were forced to relieve the firm of the small Wellington order and replace it by a similar number of Whitley IV's in order to maintain numerical output, in spite of the unfavourable comparison of range and bomb-load. The position at the end of September 1938, after taking account of the reshuffle of orders due to the investigation by Mr. Lemon, was that 412 Whitleys were on order, of which 100 had been delivered, and the remainder would be delivered by December 1939. No changeover to another type had yet been planned.

Under the extension of Scheme L in October 1938 however when orders for 5,500 aircraft of existing types were given, it was decided to order a further 100 Whitleys on condition that Armstrong-Whitworth took measures to build up their labour force.[1] This was in accordance with the Secretary of State's desire for further expansion within the next 6 to 12 months to bring forward the 1940 Whitley programme.

At the outbreak of war it was proposed by the Air Ministry that Armstrong-Whitworth should change over from Whitley to Manchester under the Group Scheme, but the Consultative Committee set up by the Society of British Aircraft Constructors Ltd. advised that the firm should continue with the Whitley. Accordingly early in September an order was recommended by the Air Council for 150 more Whitleys. The eventual plan for the changeover in January 1941 was not abandoned, although in October it was stated at a meeting with the Director General of Production that the new type would be the Halifax, as 'little work has been done on the Manchester . . . being designed by the Hawker Siddeley Group, to which Armstrong-Whitworth belong'.

This number, which brought up the total ordered from Armstrong-Whitworth to approximately 650, was thought, when the new programme was drawn up in January 1940, to be sufficient to last until the firm changed over sometime early in 1941. The controversy about which heavy bomber it should be, had resolved itself in favour of the Manchester and 300 were on order by March 1940. Armstrong-Whitworth,

---

[1] A contract for 164 aircraft was placed on 29th November 1938.

by the way, were the last firm in the Manchester Group to go into production.

In May 1940, just before Lord Beaverbrook became Minister, a new programme to obtain more of the existing types of medium bombers by postponing the introduction of new and heavy bombers was approved. The programme, as such, never went into operation but the principle of extra bombers of existing types was perpetuated in the concentration on the five priority types. The 300 more Whitleys recommended by the Air Council in mid-May were ordered in June together with a further 300 approved by Lord Beaverbrook.

During the discussions about Lord Beaverbrook's first programme, that of 11th July 1940, the position of the Manchester and the likelihood of a change to 4 Merlin engines taking place came up. Probably because of its uncertain prospects, it was recommended that the 300 Manchesters on order at Armstrong-Whitworth's should be cancelled. Since the Whitley was to continue there, in the following month (August 1940), when a large quantity of additional orders were approved by the Supply Board to secure continuity of production, the Whitley was included and a contract was placed on 16th October 1940 for 300. Existing orders were to last until September 1941 and the new order, raising the total to 1,562, was to maintain output for a further six months, i.e. March 1942.

This date, March 1942, fixed for the supersession of the Whitley at Armstrong-Whitworth, was adhered to throughout the winter, and the short life of the 2nd October programme; the scaled-down programme of March 1941 also left it untouched, but the Manchester versus Halifax controversy broke out again in a new form—the Lancaster versus Halifax. Strong arguments were advanced in favour of the Halifax, but the Lancaster was finally adopted to replace the Whitley V in March 1942.

In the event, the changeover did not take place so soon as planned: the first Lancaster was not delivered until August 1942 and Whitleys continued in production until June 1943. This setback meant that two further orders of Whitleys had to be given. The first for 100 in August 1941 and the second for 150.[1] This last was made necessary by the delay in delivery of the spar milling plant for the Lancasters; the Air Ministry agreed that the gap should be filled by Whitleys and the order was released by the Aircraft Supply Council on 19th March 1942.

Performance of the Whitley had naturally not been allowed to remain static since the early days of its production. The Whitley V fitted with Merlin X engines achieved a substantial improvement over the early Whitleys fitted with Tiger engines. Maximum speed had been increased from 215 m.p.h. to 222 m.p.h. and maximum bomb-load from 3,080 lbs. to 8,000 lbs. As well as its function of medium bomber the Whitley was used for glider towing, paratroop dropping, and Coastal Command work. For the latter job a considerable amount of radio location gear was installed. In addition provision for 2 × 2,000 lb. bombs was made in 1937; armour protection for the crew in 1938; rubber covered fuel tanks in 1940 and power operated turrets in 1938 and 1939.

---

[1] Contracts placed on 5th August 1941 and 19th March 1942 respectively.

Altogether Armstrong-Whitworth delivered 1,812 Whitleys during the seventy-seven months between March 1937 and June 1943 that the type was in production. Of this number 1,466 were Whitley V's and 146 Whitley VII's for Coastal Command.

Summary of Orders for Whitley

Date	*Order*	*Reduction*
23. 8.35	80	
13. 5.36	240	
30. 4.37		120
4. 5.38	148	
29.11.38	164	
17.11.39	150	
18. 6.40	600	
16.10.40	300	
5. 8.41	100	
19. 3.42	150	
	1,932	120=1,812

Note 3

Summary of Stop-gap orders for the Blenheim

The Bristol type 142, given to the Air Force by Lord Rothermere, was the first aeroplane of the new monoplane-monocoque vintage to be ordered under an expansion programme. On 22nd August 1935 Bristol's were given an order for 150.

Under Scheme F the number of medium bombers required was very large; the heavier Hampden and Wellington had not yet flown and were not thought sufficiently safe bets for large-scale production. Consequently the numbers were to be made up with small single and twin engine types—the Battle and Blenheim. Scheme F also saw the inauguration of the shadow scheme and the two firms managing airframe shadow factories, Austin's and Rootes, were brought in, the former on Battles and the latter on Blenheims.

In April 1936, soon after the approval of Scheme F, the Air Ministry stated that they wanted 1,320 airframes of Bristol types and that 620 would have to be obtained outside the parent firm. It was not thought that Rootes could make more than 500 of these, but no decision as to who could make the remaining 150 was made at the time. By the end of the year most of the orders for Scheme F had been placed, and contracts had been given as follows: a further 568 to Bristol's making a total of 718; 600 to Rootes shadow factory and 250 to A. V. Roe. The total Blenheims on order was thus 1,568.

In April 1938 plans for accelerating production under Scheme L were discussed and the Air Council, while anxious to obtain extra aircraft from the industry within the appointed time (March 1940), did not wish to continue with the Blenheim any longer than had been planned, for they were doubtful of the suitability of the type; the arrangements made for extra Blenheims under Scheme L therefore cannot legitimately be classed either as 'continuation' or 'stop-gap' orders. Bristol's were asked to make 100 extra Blenheims before 31st March 1940, but only on condition that

Beaufort production was hurried up.[1] A. V. Roe's also were to make an extra 100 before December 1939 (presumably their original date for completing their programme).[2] Rootes were not to receive another order, but were to put forward completion of their programme by 9 months, i.e. March 1940 instead of December 1940. (It will be remembered that these decisions of the Air Council were based entirely on the manufacturer's own promises.)

The new position of Blenheim orders in May 1938, then, was as follows:

Bristol's	818
Rootes	600
A. V. Roe	350
Total	1,768

This was not much larger than before, but it was all to be achieved *within* the period of the new programme, whilst the 1,568 under Scheme F allowed a substantial carry-over beyond March 1939.

The assessment of the industry's prospects made by officials of the Air Ministry was summarised in Mr. Ernest Lemon's memorandum of September 1938. The revised delivery estimates[3] based on the findings and recommendations of this report gave the Blenheim position as follows:

On order at Bristol's	888
Rootes	600
A. V. Roe	600
Total	2,088

Bristol's figure included an extra order for 70 aircraft to compensate for an expected failure of Blackburn Botha G.R.s. The whole of the 888 were to be completed by August 1939, when Beaufort production would be in full swing.[4] Rootes programme showed that 320 of the total number were to be delivered after the 31st March 1940 which indicated that the firm were not expected to keep up to their promise of April 1938. 148 of A. V. Roe's total were to be carried over for delivery beyond the 31st March 1940. The figure 600 included the Air Council's very recent authorisation to put in hand materials for a further 250 Blenheims.[5]

It is surprising to find that both Rootes and A. V. Roe's should have received orders which entailed continuance of this type well on into 1940. Particularly is this so of A. V. Roe's, who already had a substantial

[1] Contract placed on 12th May 1938.
[2] Contract placed on 12th May 1938.
[3] Dated 30th September 1938.
[4] Contract placed 23rd November 1938.
[5] This 250 was not definitely recommended as an order until June 1939, although engines and sets of equipment had been ordered the previous winter. The contract was placed on 18th August 1939.

programme of Ansons in hand as well as the introduction of the Manchester heavy bomber in January 1940, and whose industrial position had not seemed to Mr. Lemon's investigators any too robust two or three months previously. The explanation is that these two orders formed part of the 5,500 aircraft for delivery after 31st March 1940 that were approved by the Treasury. Most of these, including the Blenheims, were stop-gap orders in the proper sense of the word, i.e. to help build up capacity and labour.

After the first plunge into ordering further quantities of the all-but-obsolescent type, other orders followed piecemeal during 1939 accordingly as the position in each firm varied. On 24th January 1939 the Air Council recommended ordering a further 62 from Bristol's 'to fill the gap . . . before the Beaufort comes into production'.[1] In April 1939 stop-gap orders for 800 aircraft were authorised by the Air Council and 250 were to be Blenheims from Rootes.[2]

On the outbreak of war Bristol's were just winding up their Blenheim production; they were already well into Beaufort production and Beaufighters were expected within a few months. Altogether 950 Blenheims had been ordered from the parent firm and only 50 of this number remained to be delivered after war broke out. Actually, however, Blenheims lingered on until March 1940, probably because of the delays occurring in both Beaufort and Beaufighter production. 1,000 Blenheims were made by Bristol's, of which 300 were Blenheim IV's of the improved 'long nose' variety.

Although extra orders had been given to A. V. Roe's, their main objective had always been the Manchester and on the outbreak of war it was agreed that Blenheims should be cleared out as soon as possible. 453 of the 600 ordered still remained outstanding, and it was hoped that these would be completed sometime in the late summer of 1940. Early in 1940, 220 Blenheims on A. V. Roe's order book were transferred to Rootes.[3]

Rootes, on the other hand, had orders totalling 850 by the time war broke out, of which 610 were outstanding. They were to carry production of this type on for at least another 18 months: an order for 400 more was placed immediately[4] and during the winter another 800 were added,[5] within the total of 23,000 aircraft approved on the outbreak of war. This number, together with the 220 transferred from A. V. Roe (2,270 altogether), was expected to last until May 1941, but under the Harrogate programme of January 1940, Blenheims were to continue until September 1942, for which a further 1,917 would be required; towards this an order for 600 to be placed in June was contemplated.

These and many other orders under the new programme were being considered when the whole situation was altered by the events which brought Lord Beaverbrook into office as Minister of Aircraft Production

---

[1] Contract placed on 25th February 1939.
[2] Contract placed on 6th June 1939.
[3] Contract for 220 with A. V. Roe cancelled 12th March 1940; given to Rootes 22nd March 1940.
[4] Contract placed 21st October 1939. This 400 included 100 recommended on 18th July 1939.
[5] Contract placed 30th January 1940.

in May 1940. The Harrogate and all other programmes were abandoned and the priority types became the centre of production. The Blenheim was one of these priority bombers. The effect on Rootes was no different from what had been planned in April: an order for 600 was placed in June 1940 although reduced temporarily by 220 in July. But A. V. Roe's whole production programme was altered; instead of fading gently out as Manchester production came in, Blenheim production had to continue at full pressure. In June 1940 no less than 820 were ordered.[1] As to how far this affected Manchester production soon to come in, there is no evidence.

Both Rootes and A. V. Roe's received further orders in August. (This was shortly after the first attempts at a new programme.) The principle was formulated that orders for bombers must be placed 12 months ahead and be sufficient to last for a further six months.

A. V. Roe's existing Blenheim orders were to be finished by September 1941, and 375 more were ordered, presumably to last the firm until March 1942.[2] The rather doubtful technical prospects of the Manchester at that time may have been partly responsible for this order which brought the total up to 1,575: indeed after the Lancaster was accepted for production from the summer of 1941, the quantity on order was reduced by 622.[3] In fact the firm did not continue Blenheim production beyond November 1941, the monthly rate gradually diminishing from May 1941 onwards as Lancaster production proceeded. In August 1941, 47 Blenheims were ordered to fill up the gap until actual deliveries started. Altogether A. V. Roe's manufactured 1,000 Blenheims during the 39 months between September 1938 and November 1941 that the type was in production: 750 of these were Blenheim Mk. IV's.

Rootes received an order for 780 further Blenheims in August 1940. This brought the total on order up to 3,430 and was intended to carry the firm on to February 1942. We have seen above that production of Blenheims at A. V. Roe's was maintained as intended in August 1940, and the reason is not far to seek. Frankly, the Air Ministry did not want Blenheims in such overwhelming numbers as the M.A.P. were preparing to give them. On 16th January 1941 the Air Member for Supply and Organisation gave the Air Staff's opinion, 'the Blenheim is an obsolescent type whose performance and armament are inadequate for operational conditions today'. Because of this and because American bombers could be obtained in increasing numbers the Air Ministry asked that Blenheim production should be reduced so that capacity could be turned over to Lancasters and Halifaxes.[4] They were agreeable however to one line (about 30 or 40 a month) being retained on Blenheim V's (the close support bomber version) and M.A.P. promised to do this. The Blenheim V did not however come in at Rootes (Speke)—the factory chosen for the Blenheim to continue—until September 1941, and during the first 9 months of 1941 Blenheims continued at an average of just over 100 a month.

---

[1] 420 on 6th June 1940 and 400 on 18th June 1940.
[2] Contract for 375 placed on 17th October 1940.
[3] Contract cancelled for 622 on 31st March 1941.
[4] Rootes' order was reduced by 171 on 3rd April 1941.

In addition in August 1941, 415 more were restored to the order book. This was presumably the result of a reversal of the previous Air Staff decision, for the Air Member for Supply and Organisation complained of the deficiencies in the Blenheim programme in February 1942 which had resulted in substantial arrears in overseas despatches. Incidentally, in April 1942 soon after this complaint, Blenheim orders at Rootes were finally reduced by 255. Eventually production of Blenheim V's was removed from Speke to Stoke and there it continued during the whole of 1942 at an average monthly rate of 57, gradually declining right up till June 1943.

During the 57 months between October 1938 and June 1943, when Blenheims were being manufactured by Rootes, a total of 3,421 were delivered, of which 253 were Blenheim I's, 2,231 Blenheim IV's and 940 Blenheim V's.

Summary of Orders

	Date	*Ordered*	*Reduced*
Bristol	2. 8.35	150	
	11. 6.36	568	
	12. 5.38	100	
	23.11.38	70	
	25. 2.39	62	
	29. 8.39		12
		950	12
A. V. Roe	22.12.36	250	
	12. 5.38	100	
	18. 8.39	250	
	12. 3.40		220
	6. 6.40	420	
	18. 6.40	400	
	17.10.40	375	
	31. 3.41		622
	17. 8.41	47	
		1,842	842

APPENDIX II

The Procedure of Aircraft Design and Development

1 *Introduction*

The provision of new aircraft for the R.A.F. is a lengthy procedure. The chain of events by which the original conception for the tactical use of an aircraft is gradually converted into the engineering reality of a prototype aircraft and later a production aircraft, is a long one. The risks of failure are so high that in 'normal' times, that is to say in pre-expansion days, for financial reasons, one stage in the chain could not be undertaken until the last one had been successfully completed. The normal procedure, therefore, occupied anything from five to seven years. The circumstances of the expansion period and, later, of the first four years of war, required that new aircraft should appear in service with less than this delay. The pressure of events—changing tactical needs and improved technique—forced the Air Ministry and later M.A.P. to modify the normal procedure very considerably, with the result that by the end of the fourth year of war new aircraft were obtained within a much shorter space of time. The 'normal' procedure, and the steps by which it was gradually transformed into the 'accelerated' procedure, will be the subject of this appendix: in the main the accelerated procedure is based on the telescoping of the prototype stage and the elimination of the competitive tender. The latter radical change affected very deeply the traditional methods of obtaining new designs from the industry. Accordingly a section of this appendix will explain the changes that occurred in the form of the specification and in the part that it played.

2 *The 'Normal' Procedure*

(a) OPERATIONAL REQUIREMENTS

The story of a new aircraft begins with the outlines of its main tactical functions. How these tactical ideas emerged from the theory and experience of the R.A.F. belongs to another story, but the way in which these new ideas were given shape and form must briefly be mentioned.

Every year when the Air Estimates were prepared a list of the new aircraft envisaged by the Air Staff was included. A specific sum was allotted to each aircraft in this 'Experimental Programme' and during the course of the following year the Air Staff instructed the Director of Operational Requirements to take one aircraft after another and to prepare a detailed statement of its main operational features. This statement usually opened with a brief outline of the main strategic and tactical function of the aircraft, which nearly always embodied some technical advance. A good example is an experimental fighter introduced in 1935. This was to carry a battery of four 20 mm. guns, which the Air Staff hoped would be a sufficient advance over the continental experiments of one such gun firing through the airscrew hub.[1] The detailed definition followed: the speed, range, rate of climb, service ceiling, bomb-load, armament, ammunition, armour, number of engines, number of crew, accommodation etc., would be specified according to the class of aircraft, such as day or night fighter, medium or heavy bomber, torpedo, reconnaissance, Army Co-operation etc. The main responsibility of the Director of Operational Requirements was then completed. He handed the Operational Requirements over to the Director of Technical Development whose business it was to see that the aircraft was built to meet those requirements.

(b) PREPARATION OF THE SPECIFICATION

The first pre-occupation that the Director of Technical Development had was to prepare a technical specification. This document had to cover the engineering aspect of the aircraft without which Operational Requirements would remain on paper. To ensure that the Operational Requirements were not entirely impracticable a member of the staff of the Director of Technical Development always advised the Director of Operational Requirements on the sort of aeroplane that their requirements would produce,[2] but at this stage the aeroplane had to be defined in engineering terms. What materials should be used; what mechanical and wind tunnel tests should be done to ensure that the structural strength and aerodynamics were correct; what all-up weight should be allowed; where should the centre of gravity be; what fuel and oil systems should be used; by what system should the undercarriage and control surfaces work; what provision should be made for maintenance and repair, and many other vitally important points were covered by the specification. The Operational Requirements and a list of equipment to be carried were added as appendices.[3] Before, however, this document was approved by the Director of Technical Development,[4] it had to be commented upon in detail by the many specialists who were concerned with the various aspects of the aircraft's use and equipment: engines, armament, instruments, maintenance and others. For this reason the preparation of the specification often took five to six months or more. When complete, the specification, which had now been allotted a serial number to distinguish it,[5] was ready to be issued to the firms.

---

[1] Origin of the F.37/35 Westland Whirlwind.

[2] Very often the Director of Operational Requirements had to sacrifice a requirement if the penalty in engineering terms were unduly heavy.

[3] Appendix B and Appendix A respectively.

[4] This Appendix does not attempt to distinguish between the part played by the Director of Technical Development Headquarters and the R.A.E. Administratively the two can be considered as one for this purpose.

[5] The specifications are allotted serial numbers. This number is combined with the year of issue and with a prefix signifying the class of aircraft, i.e. F.9/35 was a fighter specification, the 9th to be allotted in the year 1935. Similarly 'B' signified heavy medium and heavy bombers, 'A' Army co-operation, 'N' Naval fighters, 'S' Naval torpedo reconnaissance etc.

Besides being the vehicle for technical and operational requirements the specification had another function: when orders were given for the construction of a prototype or prototypes it formed part of the contract and provided the standard to which the contractor's product had to conform, as well as setting out his liabilities and obligations.

(c) COMPETITIVE TENDER

This stage followed the preparation of the specification. Between the two wars competitive tender was a cornerstone of the Air Ministry's relations with the firms, but its administrative processes added very considerably to the time taken to produce designs and order prototypes.

Briefly the procedure followed was this. The specification was given to the Director of Contracts to issue to certain named firms with an invitation to tender designs at a given date, usually three months ahead. The number of 'family' firms was large enough for there to be a certain degree of specialisation. For instance, firms such as Vickers-Armstrongs and Handley Page specialised in large bombers, while Short Brothers and Supermarine concentrated on flying boats and seaplanes; again Gloster's and Hawker's were essentially designers and builders of fighters. Tender designs therefore were usually only invited from those firms who were expected to be interested in the particular type required.[1] It was, however, accepted as a definite principle that *all* firms on the Air Ministry's list should receive a copy of every specification issued. They could in this way keep abreast of current service needs and if they liked they could send in a design which would compete on equal terms with firms who had been invited. Conversely, a firm who had been invited was under no obligation to send in a design. But before 1934 firms were competing fiercely for orders and the Director of Contracts was always able to pass back to the Director of Technical Development a good number of entries. Often as many as eleven firms would submit designs.

The analysis of tender designs was the task of the staff of the Director of Technical Development with the aid of the various specialists who had commented on the specification. A conference presided over by the Director of Technical Development and attended, amongst others, by the Director of Operational Requirements was then convened. This Tender Design Conference considered the analysis, weighed up the disadvantages and advantages of each design, and finally placed them in order of merit and recommended which were worth ordering. It was usual to choose two designs and to recommend that one prototype of each should be ordered. The Air Member for Supply and Research and the Air Staff then gave their views and the final approval of the Chief of the Air Staff was obtained. The Air Staff was chiefly concerned with the technical excellence of the designs; in spite of the financial stringency, they were not noticeably influenced by the money cost. They were however anxious to maintain the position of the 'family' firms and they were therefore

[1] Note 1 below gives the list of firms officially recognised as specialising in the various classes of aircraft.

influenced by the desire to 'spread' the available work as evenly as possible. But their strongest motive was undoubtedly to improve the technical standards of the R.A.F. The amazing number of new aircraft designed and ordered every year bears testimony to this. Thus in 1930 when the bomber squadrons of the Metropolitan Air Force numbered 24, there were no less than 11 different types of aircraft in service, of which only one type contributed more than three squadrons and five types contributed only one squadron each.

After the Air Staff's decision, the Director of Contracts was instructed to place the contracts. This process often occupied several weeks if there were many points to be cleared up with the firm.

Thus it will be seen that while the competitive tender took sometimes as much as nine months to organise, its object was to stimulate the drawing offices and to obtain the best possible designs, and it was considered by the Air Ministry to be well worth the trouble.

(d) CONSTRUCTION OF THE PROTOTYPE

The next stage was the building of the prototype aircraft. This was long and arduous and the scrap heaps of aircraft factories bear frequent witness to the sad beginnings, and sometimes to the equally sad ends of many prototypes. It is quite understandable why all designs did not survive the test of building, if it is remembered that what was submitted to the Air Ministry was only the barest sketches and that they nearly always included new ideas. Even the most promising design was likely to undergo substantial modification in the light of practical knowledge.

The first step was for the staff of the Director of Technical Development to call an Advisory Design Conference for each design. At this meeting representatives of the designing firm were brought together round a table with representatives of the Director of Operational Requirements. Each requirement was worked through in detail, and the firm which was responsible for the design[1] was given an opportunity to raise any points upon which for legitimate design reasons they wished to have concessions or a more detailed statement of requirements. Naturally a concession allowed to one firm would be communicated to the other firm engaged. Thus the projects were set on the way towards the detailed design.

The firm's next step was to erect the mock-up, i.e. a full-scale model of the fuselage and as much of the wing and tail as was necessary to demonstrate the pilot's view from the cockpit. It also had to show the cockpit layout and arrangement of the innumerable items of equipment and the controls which could not be satisfactorily worked out on the drawing-board. The mock-up was supposed to be ready in about two or three months, and would then be inspected by a horde of experts representing those specialist and 'user' interests which have been mentioned before. The criticisms and suggestions which were made at the Mock-up Conference could be sufficiently numerous or large to mean a considerable amount of redesigning. For this reason they were usually disliked by the firms, although their purpose was to decide, as far as was possible, the

[1] The responsibility was placed upon the shoulders of the firm in 1934.

final details of the operational and control equipment. Changes after the mock-up had been approved were made only for very pressing reasons.

After the Mock-up Conference the drawing office would concentrate on the detail design. They would continue to be so engaged for several months, but manufacture of detailed parts could start as soon as individual drawings were issued. When the detailed parts began to accumulate, assembly commenced and fuselage, wings and tail unit would take shape, first in skeleton and then with a covering of fabric or metal. It might, however, be necessary for specimens of, say, a wing section, to be tested in a wind tunnel and until satisfactory results were obtained work might be held up. After the main assembly had been completed, installation of equipment would begin. Some items were supplied by the Air Ministry on Embodiment Loan, i.e. engines, airscrews, undercarriage, turret, etc., but there were also other items such as radiators, fuel and oil systems and electrical equipment which the contractor had to obtain for himself. Installation of equipment was a complicated business and took a long time so it was often found simpler for the prototype to be fitted with the minimum necessary for it to fly. Operational equipment such as guns and turrets were installed at a later stage.

Finally the great day for the first flight of the prototype arrived. It was a milestone reached but not a milestone passed. Once the prototype was in the air unexpected troubles inevitably cropped up and their cure might take days or even weeks, whilst redesigned parts might have to be made and fitted. The firm, too, was responsible for a series of very stiff handling trials before they could guarantee that the aircraft met the safety requirements of the specification.

There were so many unexpected difficulties which might be encountered during the building of a prototype that the delivery date promised by a firm in the contract was nearly always exceeded; sufficient allowance was never made for such contingencies as equipment not being delivered on time or contractors' flight tests taking longer than was expected. It was quite usual for a prototype to take two years up to the time of delivery. But firms continued to make optimistic promises, partly through genuine enthusiasm and partly through anxiety to get orders.

(e) TESTS AND TRIALS

Next came the official trials. When the prototype was ready to be delivered, the Director of Technical Development received it at one of the Air Ministry's Aeroplane and Armament Experimental Establishments. There the prototype was put through its paces by the expert Service pilots attached to the Station. First they did handling trials to see whether the ailerons, flaps, elevators, rudders and other controls worked quickly and easily and whether the aircraft had good stability and flying qualities. Then during the next few months—a prototype might stay six months or more at the Experimental Establishment—came performance trials to determine the top speed, rate of climb, service ceiling, length of take-off and landing runs, fuel consumption, engine cooling and many other things. These completed, trials of operational suitability would follow.

Exhaustive reports of all these trials had to be rendered to the Director of Technical Development and they were carefully studied by all the experts who represented technical and Service points of view. Upon their recommendations, the Air Staff would decide if the type should undergo further development. If the prototype had survived the trials without crashing, there might be a choice between similar machines from different firms. Alternatively, both might be considered good enough for development.

(f) DEVELOPMENT AND PRODUCTION ORDERS

After the Air Staff decision had been taken to develop a type further, a small 'development' order would be given for sufficient aircraft to equip one squadron. It was sometimes found necessary to amend the specification, for by this time the many teething troubles which had emerged on the prototype would have made modifications inevitable. Also, during the considerable interval that had elapsed since the design was drawn up, technical and operational knowledge would have progressed and some of the new ideas would be quite easy to include in the development machines. While these machines were being built and delivered to the Service for further development trials and modifications, anything up to two years would pass. If, by a rare chance, the Air Ministry had sufficient money to afford a more general re-equipment with the new type, a production order would follow and again the specification would be altered to take into account further modifications. The first production deliveries would commence in about six months.

3 *The 'Accelerated' Procedure*

Considering the leisurely progress of new aircraft through the seven stages of design it is no wonder that new types took so long to mature. The duration of design and development of standard R.A.F. types in normal peace-time conditions is shown in the following table:

Stages of Design and Development

Stage	*Time allowed (months)* *Small aircraft*	*Medium aircraft*	*Large aircraft**
1. Air Staff notify Director of Technical Development of requirements for new type	Zero	Zero	Zero
2. Director of Technical Development prepares specification	5	5	6
3. Competitive tender (tender invitation; tender analysis and placing of prototype orders)	8	9	10
4. Construction of prototype	12	16	24
5. Tests and trials	9	14	16
6. Development orders	13	13	17
Development trials	12	12	12
7. Production orders	6	8	10
Approximate total time	5½ years	6½ years	8 years

* Excluding large flying boats.

Observance of this routine took anything up to eight years. The period was too long, even for the leisurely conditions of the late 'twenties and early 'thirties: it was bound to appear impossibly long in the conditions of expansion which prevailed after 1935. In addition, the many rapid changes at that time in the science and technique of aeronautics meant that a completely new race of aircraft had to be introduced. As a result, a movement began to reduce the interval between requirements and production;[1] this movement was to continue until well after the outbreak of war before it was felt that every possible time-saving device had been used.

The abridgments in the development procedure were focused at two points, the prototype stage and the competitive tender stage; in the process the specification stage also was considerably modified. Of the two, the prototype stage came in for revision first. The years 1935, 1936 and 1937 saw a formidable array of specifications for new operational types. In order that no new idea should be overlooked it was essential that designs should be obtained from as wide a circle of designers as possible. Therefore, the competitive tender was in its hey-day, and it was the prototype stage which fell first under the axe; luckily there was an orchard full of dead trees waiting to be cut down.

(a) ABRIDGMENT OF THE PROTOTYPE STAGE

Economising on the prototype meant the cutting out of some stages and the compression of others. The later stages had been unnecessarily protracted so that the 'development order' quickly disappeared. In future, the first order for a type was always to be large enough to warrant the firm planning for full scale quantity production immediately. As a compensation the Air Staff and other specialists were given a last chance to say what modifications and alterations they wanted fitted to the production machines. The prototype, fully equipped for operations and flying, was inspected at a Final Conference.

More prototypes and designs of each specification were ordered in an effort to hasten matters. By 1935 it had become a principle, endorsed by the Secretary of State, that prototypes should always be duplicated, regardless of financial limitations. Two of everything was made, thereby minimising extra design work and having both machines ready at the same time, with the added advantage that with two prototypes flying, tests could be divided and thus completed much quicker.[2] Also, if an accident should happen to one prototype, the future of the type would not be prejudiced, as the second machine would still be in existence. The wisdom of ordering more than one prototype was well demonstrated in 1937, when the solitary Wellington prototype was totally destroyed in a

---

[1] In May 1935, the Ministerial Committee on Defence Requirements instructed the Sub-Committee on Air Parity 'to examine in detail the proposals in the programme for the production of heavy and medium bombers (i.e. Scheme C) with a view to the acceleration, if possible, of the most modern types'.

[2] Although two prototypes to one design were ordered the second often lagged seriously behind the first which tended to reduce its value as a time saver.

crash, caused by a faulty tail plane. The rapid increase in the number of prototypes and designs ordered during the first years of expansion is best illustrated by the case of the Specification F.9/35 for a turret fighter. The Air Staff attached great importance to the type, but all the power operated turret designs submitted were completely untried. To ensure against failure, the Air Staff wanted as many alternatives to choose from as possible. Four different designs were chosen and seven prototypes ordered; two each of three of the designs and one of the fourth. As the financial allocation was exceeded, special sanction was sought and obtained from the Treasury Inter-Services Committee. All but one of these four designs proved unsuccessful, but because seven prototypes were ordered, no time was wasted in discovering which was worth putting into production.[1]

Even more important still were orders in anticipation of trials. The specific recommendation as to how to shorten the development period put forward by the Sub-Committee on Air Parity in May 1935 was that orders for new types should be placed in bulk before the prototype had been tested. In May 1935 the Cabinet, accepting the risk of financial loss, approved the recommendation.

In the following year, 1936, four new types were ordered in quantity before handling and performance tests had been completed by the pilots of the Air Ministry Experimental Establishment. They were the Battle light bomber, the Hampden and Wellington medium bombers and the Spitfire 8-gun interceptor fighter. Together with one or two others, they formed the backbone of the new Programme F and they were also the vanguard of the new ideas of Air Staff and designers. Thus there was a very considerable risk, which the Air Staff knowingly took. The Spitfire prototype was delivered on the 26th May 1936, and the first order for 300 machines was given a week later on the 3rd June. The Fairey Battle prototype underwent quick trials in July 1936, but a large production order had been given on the 23rd May. The Wellington and Hampden prototypes were both delivered in November 1936 whilst orders for 180 of each had been placed two months previously on the 15th August. It should however be remembered that all these prototypes had flown at their contractors' aerodromes several months before they were delivered or orders were given.

This system of giving orders before anyone knew how the prototype was going to behave was very risky, but the dangers were as nothing compared to those encountered under the Air Ministry's next step. Ordering before the tests had only saved a few months and a more drastic saving of time was wanted. In order to achieve it the Air Ministry began to place orders before the prototype had been in the air at all. Their first attempt was with the Armstrong-Whitworth Whitley twin-engined bomber. In August 1935, seven months before the prototype first flew and a whole year before it was delivered, the Air Ministry gave a quantity production order. They did not repeat the experiment until 1937, when

[1] The Boulton Paul Defiant was the type eventually chosen for production.

in April they ordered 187 Boulton Paul Defiant turret fighters four months before the prototype flew and eight months before it was delivered.

But the most important case was that of the heavy bomber. Always at the back of the Air Staff's plans for the Air Force had been the project for a really heavy bomber which could carry as many bombs as a whole squadron of smaller bombers about twice as far. In those days, when expansion was by no means unlimited, it was an attractive idea—for one thing it was so economical. Without increasing the numbers of the bomber squadrons, it was possible to re-equip them to do many times the amount of work. The difficulty was, of course, to translate this idea into reality quickly enough. The specification for these heavy bombers was only agreed upon in the autumn of 1936 and in early 1937, when the designs were still being selected, the Air Council Committee on Supply announced that they wished production to begin in two years' time to replace all medium bombers not then delivered. Contracts for prototypes of what afterwards became the Halifax and the Manchester bombers were quickly placed and were followed within a very few months by production orders. Another even heavier 4-engined bomber, subsequently known as the Short Stirling, had a similar history; the first production order was given eight months after the contract for the prototypes.

In each of these three cases the decision to place a quantity order with all its attendant and preliminary arrangements, such as jigging, tooling-up, material acquisition etc., was taken upon the strength of the designers' drawings alone. This was the policy which came to be known as 'ordering off the drawing-board'. As war drew nearer and the urgency of getting new types into operation increased, the practice of giving a separate contract for prototype and production machines was soon given up altogether. Instead, the firm would receive a production order and would plan for quantity production, and the first two hand-built machines would be rushed forward as prototypes. These machines were then subjected to intensive tests to reveal vital modifications which could be incorporated in the remainder without too much delay. Very nearly the first example of such an order was the Bristol Beaufort for which a production order 'off the drawing-board' for 78 machines was given in August 1936.

After that date many other types were ordered in this way and the results obtained from these shots in the dark were, in the main, justified. Of the types designed just before or just after the outbreak of war, three at least were ordered 'off the drawing-board'. They were the Bristol Beaufighter (designed late in 1938 and ordered in quantity in February 1939), the de Havilland Mosquito (designed in December 1939 and ordered in quantity in January 1940) and the Avro Lancaster (designed and ordered in the latter half of 1940). Several Fleet Air Arm types were also ordered 'off the drawing-board'. In the later stages of the war orders 'off the drawing-board' became even more common.

A sidelight on this is provided by the very important and interesting specification for a cannon fighter—the Westland Whirlwind. This type was generally acknowledged as a failure in its primary role of an interceptor fighter armed with 20 mm. guns. There were several reasons for this, but one reason which must have contributed to its failure was the fact that at a time, i.e. 1938, when nearly all types were being ordered 'off the drawing-board', the Air Staff required the Whirlwind prototype to complete brief handling trials before the production order was given to the firm. Its development period was thereby considerably retarded with the result that when it did come into service it had missed its operational opportunity and was never able to catch up the time it had lost.

(b) ELIMINATION OF THE COMPETITIVE TENDER

The changes just described—

(i) The disappearance of the development order,
(ii) Ordering more prototypes and designs to each specification,
(iii) Placing quantity orders in anticipation of trials and
(iv) Placing orders 'off the drawing-board',

did a great deal to shorten the period between the submission of the design and the placing of the orders. But the economies of time which were, or could have been, achieved by the compression of the different stages of prototype development were not enough. Sooner or later the second of the stages on which reform was focused had to be tackled and the competitive tender, the lynch pin of the pre-war system, was also sacrificed. That sacrifice was carried out either by allowing full play to private initiative in the initial stages (the so-called 'private venture') or by the policy of 'special orders' to earmarked firms. Let us consider these two developments separately.

(i) *Private Ventures*

We have seen how important was the part played by the competitive tender in the pre-expansion policy of the Air Ministry.[1] The Air Ministry depended upon it to stimulate the firms to produce a maximum number of technical ideas; the firms depended upon it to obtain a sporting chance of securing an order. Only one 'family' firm—de Havilland's—voluntarily denied themselves the assistance offered in this way by the Air Ministry. They felt that the specifications were all compromises between the engineering and the 'user' points of view and that they would best be able to follow their own particular lodestar of aerodynamics unrestricted by official requirements. Other firms probably felt the same, but could not afford to do likewise except in isolated cases. But these isolated cases gradually established a tradition of what were called 'private ventures'. If a firm had had a design rejected, or on their own initiative had produced a new design which they thought the Air Staff ought to have, they sometimes used to build a prototype themselves in the hope that the Air Staff would later change its mind and decide that it was interested after all. If this happened the Air Ministry would buy the prototype and pay for its future development; if not, the firm would be heavy losers.

Before 1934 it was recognised that good ideas were sometimes born in this way, but it was not a very common phenomenon. The Fairey Fox was an outstanding example of a successful private venture during the

---

[1] See pp. 501–502.

'twenties. For the rest the ordinary specifications and competitive tenders sufficed. But in 1935 it proved lucky for the Air Ministry that there was this tradition that aircraft designers might sometimes usurp the Air Staff's prerogative of divining what the R.A.F. ought to have.

In this year, in spite of several Air Ministry specifications, there was not a single new medium bomber ready to be put into production to fulfil Programme C. For several years previously the Bristol Aeroplane Company had been spending much time in research into a light yet robust metal structure for military machines. The result was a structure with very good weight/strength ratio and the particular advantage of having a skin and construction in which large apertures such as bomb doors, undercarriage doors and maintenance panels could be made. It had never been fully tried out in any machine until the opportunity was provided by Lord Rothermere who commissioned the company to build a fast commercial plane to rival the American Douglas machine bought by Lord Beaverbrook. The machine—called 'Britain First'—was completed in 1935 and was a bad commercial proposition, but it caught the roving eye of the Chief of the Air Staff for it had many points which made it an excellent medium bomber. Bristol's were prompt with a scheme for its conversion and the scheme was so simple that there is little doubt that the aircraft must have been from the very beginning designed as a military aeroplane. The Air Ministry lost no time in placing an order for the Bristol private venture machine, which was renamed the Blenheim.

A similar case happened a few months earlier in fighter development. Hawker Aircraft Ltd. had submitted a fighter design of their own, completely different from, but certainly instigated by, their design to Specification F.7/30, which had been rejected by the Air Ministry a couple of years previously. The Air Ministry were in need of a fast fighter in 1935 and paid for the prototype to be built: this was the Hurricane.

But probably the most extreme form of private venture is represented by the Mosquito. Although designers often tinkered with official requirements and offered suggestions for improving them, it was seldom that they were able to induce the Air Staff to adopt a design for a new tactical purpose. This happened however in the case of the de Havilland Mosquito. The firm's project was for a fast unarmed bomber. If it could outpace enemy fighters it need not be defended; conversely, if it did not carry a gun turret it could be made to go very fast. One or two members of the Air Staff were convinced by this argument, but in general it was not accepted for some months. Even after a small order 'off the drawing-board' had been given to the firm the controversy continued and the Air Staff changed their minds several times before the type finally came into production.[1]

(ii) *Special Orders*

But, important and even spectacular as some of the private ventures have been, it was not in the private venture that the true alternative to the competitive tender was found. The peculiar relation which existed between private designs and official requirements made it possible in the

---

[1] The private venture is more fully discussed in Ch. IV, pp. 83–95.

end to develop a system of 'special orders', which in principle is half way between the competitive tender and the private venture. It was with this compromise rather than with the private venture in its pure form that M.A.P. replaced the older and slower system.

Under the system of special orders M.A.P. entrusted the design and production of a new type to a firm which in the Ministry's view was at the moment best able to create a new type of the necessary kind. Isolated instances of this can be found very early. In 1934, the Air Ministry took the unprecedented step of commissioning Armstrong-Whitworth to build a heavy bomber to the B.3/34 specification without issuing a general invitation to tender.[1] Although Armstrong-Whitworth's design was partially sketched out before the Air Ministry issued their specification, it cannot be described as a true private venture. But this design, together with the Hurricane and the Blenheim prototypes, saved the Air Ministry valuable months during the difficult year of 1935 when at last there was the opportunity of expanding the Air Force, but when the aircraft they wanted to equip the Air Force with, were still on the drawing-board.

For the time being this remained an isolated instance. We have seen how the next few years passed—many new specifications and many more new designs all competing against each other. There was little need during this period for private ventures or for aircraft ordered without competition. Gradually, however, circumstances combined to alter the emphasis on the competitive tender. By the law of averages some of the types which were coming in in 1936 to 1938 were bound to be failures; unfortunately it was often the most important types that failed. At the same time, as a result of operational experience, urgent requirements for quite new types suddenly began to emerge. These two factors meant that replacements and new types had to be provided even more quickly than ever before. But the number of designing firms had not increased, neither had their senior drawing office staffs, with the result that the existing drawing offices and experimental shops were filled to capacity. It was clearly uneconomical and even impossible to expect the already overworked designers to spend time sketching out designs for a competitive tender if only one or two were going to be taken any further. Also, competitive tenders took an unnecessarily long time to organise. There was one example in 1936 of a 'special order'—that of the Fairey Albacore,[2] and in 1938 there was another one—the bomber of composite wood and steel construction ordered from Armstrong-Whitworth known as the Albemarle.[3]

Taken altogether, the new circumstances prevailing from about 1938 onwards made the system of competitive tender out of date. Fortunately, relations between the Air Ministry and the individual designers had always been close; therefore the Air Ministry knew the particular line of country that each designer was good at, whilst the designers themselves had always made it their business to be thoroughly conversant with Service needs. This subtle and unwritten understanding enabled designers sometimes to

---

[1] Whitley.
[2] See p. 134.
[3] See p. 94.

produce designs more or less out of the hat just when they were needed by the Air Ministry and led to the further refinement of the special order system. It is at this point that 'new' aircraft merge into 'developed' aircraft. The designs for the latter were little more than radical redesigns of existing types and were as a matter of course committed to the firm responsible for the original type. Many examples could be quoted from 1938 onwards. Perhaps the earliest was the Fulmar fleet fighter conversion of the Fairey P.4/34 light bomber; this was rapidly followed by the cannon fighter version of the Bristol Beaufort torpedo-bomber—known as the Beaufighter. Once the precedent was established the exigencies of war made it the most popular method of obtaining new designs and examples are almost too numerous to mention. The Lancaster, the Lincoln, the Tempest, the Brigand and the Spiteful may be quoted as the more important war-time examples.

In these several ways—by abridging the prototype stage and by eliminating the competitive tender and substituting the special orders and, more rarely, the private venture—the Air Ministry and M.A.P. endeavoured to cut down the development period of aircraft. In chapter VII the development period of all the most important war-time types is tabulated.[1] There the reader may judge how difficult the task was, and in how few cases the results were commensurate with the need.

4 *Changes in the form and function of the Specification*

The preceding paragraphs have dealt with the modifications of the 'normal' procedure of development prompted by the desire to reduce delays. Considerable changes also took place in the specification stage, which were only partially due to the time factor. The changes in the specification stage were of two kinds—changes in its form and changes in its function.

(a) CHANGES IN THE FORM OF THE SPECIFICATION

It will be remembered[2] that the Director of Technical Development's technical and engineering requirements were crystallised in the specification. As the responsibility for the design of the aircraft rested solely with the contractor, 'methods' of design in the text book sense were not officially laid down in the specification,[3] for the M.A.P. was satisfied that the 'approved' firms were capable of implementing requirements. The requirements of the specification were therefore limited to general statements of strength, safety and other design aspects. In the latter would be included special features implied in the Operational Requirements. Examples of these special features might be airbrakes for high-speed fighters, dinghy stowage for a heavy bomber, a pressure cabin for high-altitude aircraft, etc.

---

[1] See p. 146.
[2] Section (ii), Subsection (b) above.
[3] The technical branches of the M.A.P. and the R.A.E. were able to suggest methods of achieving requirements by means of a series of advisory publications. See pp. 512 et seq.

In the early days when aircraft were, relatively speaking, simple in construction and equipment, each specification was complete in itself. Requirements which were generally applicable could be repeated in new specifications without making the document unduly bulky or lengthy. The new aircraft designed and built during the expansion period brought in totally different engineering problems and methods to those of the wood and steel, fabric-covered structures of earlier days. In addition, production and supply considerations affecting the raw materials, component parts, and equipment of aircraft grew in importance, whilst the requirements of the R.A.F., in the widest sense of maintenance, safety and comfort considerations, also changed and multiplied with the increasing complexity of aircraft and equipment. As the experience of the technical branches grew, all these miscellaneous requirements and considerations were amplified and amended for the benefit of the designer. Their very number and universal application made it both impossible and unnecessary to reproduce them every time a new specification was issued. From 1940 onwards, therefore, the section of the Director of Technical Development's staff responsible for compiling specifications of particular requirements also undertook to codify and rationalise this body of general engineering requirements.

The new form which the instructions took was that of an Air Publication issued as a printed handbook. This handbook, known as A.P.970, was issued to all designers and was regularly amended to keep its provisions up to date. It was made to form part of the contract by the reference in the particular specification to the current issue of the handbook.[1]

So quickly did the body of M.A.P's mandatory requirements grow, that their notification to the designers was not confined to A.P.970: greater flexibility was needed—specialist branches were particularly anxious to notify their own obligatory general requirements—and the habit grew up of by-passing the A.P.970 procedure, by which means alone the requirement could become automatically a contract obligation. This was undesirable for two reasons: first, it made the task of the firms in keeping track of M.A.P's obligatory requirements very difficult, and secondly the fundamental definition of requirements in the limited sense of standards to be achieved was often extended to cover also methods of achieving those requirements.

In July 1941 therefore, the Controller of Research and Development instructed all technical branches that no general requirements could be issued to firms except by means of A.P.970 or of Aircraft Design Memoranda. The A.D.M. series was an old-established one and had been the means of issuing instructions to firms on many subjects other than design.

---

[1] A typical wording was as follows:
'The specification is issued to cover the design and construction of three 4-engined bomber aircraft . . . and gives only the particular requirements for the type as in amplification of the general requirements stated in (a) A.P.970 with amendments, (b) A.D.M's current at 1st March 1943, (c) S.I.S's current at 1st March 1943, and these requirements shall be completely fulfilled except where varied by this specification or where the prior concurrence of the Director of Technical Development has been obtained.' (S.I.S's are Standard Instruction Sheets covering the installation of items of equipment included in the Appendix A.)

During the next few months it therefore tended to become overloaded, and in any case it was not a suitable channel for aircraft design requirements. The issue of aircraft design requirements by this means was therefore limited to the following special cases:

(i) Requirements of a secret nature,[1]

(ii) Requirements of an experimental nature. After a period of approval these were incorporated in A.P.970,

(iii) A series of memoranda covering the standardisation of equipment,[2]

(iv) A similar series covering standardisation of materials.[3]

These limited A.D.M's were made contractually binding in the same way as A.P.970 by special mention in the particular specification.[4] This gradual tightening up of the methods and form of notifying firms of M.A.P's obligatory design requirements by no means interfered with the existing channels by which specialist branches issued advisory and explanatory notes on methods of fulfilling requirements to the firms. But none of these documents were mandatory or had any contractual force.[5]

The gradual change in the form of the specification thus began in 1940 when A.P.970 was made to cover general requirements, leaving individual specifications to cover particular requirements. By 1944 the form in which mandatory instructions were issued to the firms was largely stabilised. The A.P.970 provided the accepted general aircraft engineering practice and aimed (for ease of administration and use) at 'collecting together all technical instructions in one properly indexed publication'. This procedure was, through the Joint Airworthiness Committee,[6] approved by the firms themselves. Such instructions and requirements as had not yet been incorporated in A.P.970, or were for other reasons excluded from it, were issued to the firms in the form of Aircraft Design Memoranda. Particular specifications were thus confined to amplifying and modifying the A.P.970 and A.D.M. requirements to suit individual aircraft.[7]

Thus the specification issued for contract purposes and as a guide to designers, which in the old procedure took the form of a single document, different for each aircraft, now took the form of a series of documents—

---

[1] A.P.970 is a 'confidential' document.

[2] Aircraft Design Memoranda Series 500.

[3] These were the responsibility of the Research and Development (Materials) Section of the Directorate of Technical Development.

[4] In addition there was another very limited series of general requirements which were treated in the same way as Aircraft Design Memoranda. This was a set of three specifications dealing with aircraft in the series 'D.T.D. 1000 specifications'. Except for these three, the 1000 series dealt with other than aircraft items.

[5] The most important series of advisory notes were as follows: (i) M.A.P. Scientific and Technical Memoranda; (ii) Airworthiness Technical Notes; (iii) R.A.E. Technical Notes and Reports; (iv) D.T.D. Technical Circulars. (i) and (iv) were issued by M.A.P., (ii) and (iii) by R.A.E.

[6] On which the Society of British Aircraft Constructors Ltd. and the M.A.P. were equally represented.

[7] Under the procedure current in 1941 the specification itself was largely an amplification and modification of A.P.970 and A.D.M. requirements of a general engineering nature.

a large handbook—well indexed and classified, supplemented by a series of temporary memoranda, and a small particular specification qualifying and modifying the provisions of the general instructions.[1]

(b) CHANGES IN THE FUNCTION OF THE SPECIFICATION

The changes in the part played by the specification, which gradually came about in the first years of the war, were directly the result of the abandoning of the competitive tender. They are discussed in the main memorandum.[2] In the years before the war the specification, with the Appendix B, was the routine vehicle by which official ideas and requirements were inaugurated. It was often the vehicle of new and daring ideas about the tactical use of aircraft, although it was more usually a crystallisation of ideas that were already in the minds of many designers as well as the Air Staff's. In the realm of technical advances it would be less of a pioneer. It might encourage the designers to use new technical devices, but it would not specify them unless they were specially called for by the operational use of the aircraft. But whatever its particular requirements might be, the function of the specification was invariably the official inauguration of design work. In this is was aided by the existence of the competitive tender. Without a clear and precise specification, firms would have wasted their time in preparing designs which did not meet the Air Ministry's wishes, and would have thereby lessened their chances of success.

When the first special orders were given without competitive tender, the specification still played the same part. The Air Ministry made its particular wishes known to the firm chosen to design the aircraft through a specification and Appendices A and B. But, as we have seen,[3] the tendency was for new tactical functions to be met by more or less radical redesign of existing aircraft. The initiative to redesign an aircraft sometimes came from the M.A.P. and sometimes from the firm, and in both cases the aim would be to retain as much of the existing engineering structure and equipment as possible in order to save time.[4] The extreme case would be that of a new mark of an existing aircraft in which the changes could be incorporated in the production line by modification action. The specification would then be a very brief document for contract purposes, merely listing the modifications to be incorporated. But with the general requirements in A.P.970 permanently in the hands of the firms, the need for an individual specification as a guide to engineering and technical requirements was not so urgent.[5]

---

[1] It should be noted that the changes to the form of the technical sections of the specification left the form of the Appendix A (List of Equipment) and Appendix B (Air Staff Operational Requirements) unchanged. See pp. 17–718.

[2] See Ch. IV, Sections (iv) and (v).

[3] See pp. 510–511.

[4] Really new prototypes are few and far between and most of our specifications are for aircraft derived by alterations to existing designs in production.

[5] As an M.A.P. official pointed out: 'It will be noted that so far as preliminary work design goes, and most of the detailed design work, firms will in future have the necessary information once we have defined to them design weight, design speed and military load.'

Most important of all however was the fact that design work did not have to start at the beginning, but cut into the development process as it were in mid-stream. This meant that the designer and his staff had to be more closely concerned with the formulation of those particular technical and engineering requirements of which the individual specification was composed than if the design was *de novo*. We have seen how the Advisory Design Conference was an occasion, even in the 'normal' procedure, for the designer and his staff to be able to discuss the requirements of the specification with the staff of the Director of Technical Development in detail, and, if need be, to obtain their modification.[1] The Advisory Design Conference increased in importance during the war as an opportunity for the firms to state their views. If a specification for a redesigned type had been issued to the firm before the Advisory Design Conference had taken place (and this was by no means always the case), it was strictly in 'draft' form and could be changed without formality. It was only *after* the Conference that the final version of the specification was drawn up, approved and issued to the firms.

It is clear therefore that by the introduction of special orders as the usual war-time practice for obtaining new designs, the function of the individual technical specification itself was very considerably changed. Instead of acting as a fairly rigid standard laid down by M.A.P. which most firms endeavoured to aim at fulfilling as closely as possible, it became an agreed standard of requirements in the formulation of which the firms had had considerable influence in their own interests.

During war-time the Air Staff Operational Requirements which were issued as Appendix B to the particular specification also came to occupy a slightly different function. The unorthodox ways in which new designs were obtained sometimes meant that Operational Requirements were drawn up after the firm had submitted the project. In the case of the abortive Hawker high-speed bomber design, in 1941, which was largely a private venture, for instance, the draft specification to cover the design was sent to the firm without an Appendix B 'because it would be quite uneconomic in time if we took no action until the receipt of a final Appendix B'. Even where the initiative for the new design came more definitely from the M.A.P., the Appendix B would either not be issued at all[2] or would not be forthcoming at as early a stage as the draft specification.[3] The Appendix B was thus of less importance in inaugurating new projects than before the war, when it was quite common for Operational Requirements to be circulated to firms some time before the specification was issued.[4] The power of the Director of Operational Requirements to formulate requirements and to insist on their being fulfilled was not however in any sense impaired but the finalising of the detailed Operational Requirements, as for instance the decisions as to the number and calibre of guns which a fighter was to carry, was often postponed until a

---

[1] See Section (i), Subsection (d).

[2] Spitfire Mk. VII.

[3] See for example, F.4/40 (Welkin), B.3/42 (Windsor), and F.9/43 (Welkin development).

[4] Halifax and Manchester (P.13/36) and Warwick (B.1/35).

comparatively late stage,[1] whilst the broad tactical function of the new aircraft, such as for an interceptor fighter with increased speed and manoeuvrability,[2] had been well known to the firm since the beginning of the project. But the firms had greater opportunity to discuss the engineering and operational requirements at the Air Design Conference and on other less formal occasions before the specification and Appendix B were finalised.

Their bargaining powers were enhanced by the fact that most of the designs they were discussing were already in an advanced state of construction, so that it would often have been difficult to modify them. The Director of Technical Development and his staff, as well as the Director of Operational Requirements, indeed complained many times of the difficulty they had in overcoming the firm's resistance to the introduction of many features which were considered officially as vitally important. This state of affairs by which firms were sometimes able to evade requirements was at least one of the reasons why both the Director of Technical Development and the Director of Operational Requirements were anxious to re-instate the competitive tender.

The place and function of the specification and the Appendix B as the official vehicle for the inauguration of new designs accordingly became considerably modified,[3] and the firms came to be given a much larger opportunity to influence decisions on the requirements.

---

[1] Tempest I (F.10/41).

[2] Spitfire Mk. F.21.

[3] The second function of the specification—its part in the contract—was of course untouched.

NOTE 1

List of firms to whom aircraft specifications were to be issued for 'information'

1 *Bombers (Class letter B)*
Military Transport (Class letter C)
Sir W. G. Armstrong-Whitworth Aircraft Ltd.
Bristol Aeroplane Co. Ltd.
de Havilland Aircraft Co. Ltd.
Handley Page Ltd.
A. V. Roe & Co. Ltd.
Short Bros. Ltd.
Vickers-Armstrongs Ltd. (Weybridge)

2 *Fighters (Class letter F)*
Naval Fighters (Class letter N)
Blackburn Aircraft Co. Ltd.
Boulton Paul Aircraft Ltd.
Bristol Aeroplane Co. Ltd.
de Havilland Aircraft Co. Ltd.
Fairey Aviation Co. Ltd.
Gloster Aircraft Co. Ltd.
Hawker Aircraft Ltd.
Vickers-Armstrongs Ltd. (Supermarine)
Vickers-Armstrongs Ltd. (Weybridge)
Westland Aircraft Ltd.

3 *Flying Boats (Class letter R)*
Blackburn Aircraft Co. Ltd.
Saunders-Roe Ltd.
Short Bros. Ltd.
Vickers-Armstrongs Ltd. (Supermarine)

4 *Trainers (Class letter T)*
Target and Target Towing Aircraft (Class letter Q)
Airspeed (1934) Ltd.
Boulton Paul Aircraft Ltd.
de Havilland Aircraft Co. Ltd.
Heston Aircraft Co. Ltd.
Miles Aircraft Ltd.
Percival Aircraft Ltd.
A. V. Roe & Co. Ltd.

5 *Dive-Bombers (Class letter O)*
Torpedo-Bomber/Spotter-Reconnaissance (Class letter S)
Torpedo-Fighter/Dive-Bomber (Class letter H)
Sir W. G. Armstrong-Whitworth Aircraft Ltd.
Blackburn Aircraft Co. Ltd.
Bristol Aeroplane Co. Ltd.
de Havilland Aircraft Co. Ltd.
Fairey Aviation Co. Ltd.
Vickers-Armstrongs Ltd. (Supermarine)
Westland Aircraft Ltd.

6 *Gliders (Class letter X)*
Airspeed (1934) Ltd.
General Aircraft Ltd.

7 *Army Co-operation (Class letter A)*
de Havilland Aircraft Co. Ltd.
Westland Aircraft Ltd.

8 *Civil Transport*
Airspeed (1934) Ltd.
Sir W. G. Armstrong-Whitworth Aircraft Ltd.
Bristol Aeroplane Co. Ltd.
de Havilland Aircraft Co. Ltd.
Handley Page Ltd.
A. V. Roe & Co. Ltd.
Saunders-Roe Ltd.
Short Bros. Ltd.
Vickers-Armstrongs Ltd. (Weybridge)

APPENDIX III

Administration of Airframe Modifications

1 *The Purpose and Definition of a Modification*

The policy of maintaining the quality of the R.A.F's machines at the highest possible level has been discussed in the main memorandum;[1] one of the most important ways by which this standard was achieved was that of installing more powerful engines, greater defensive or offensive fire power or more efficient radio or other equipment. Some of these changes were large enough to warrant a new mark number to distinguish the aircraft so fitted from others not so fitted. There were, however, countless smaller changes which in the aggregate, and sometimes individually, were equally necessary if each type of aircraft was to be able to perform its appointed role as efficiently as possible and with the minimum risk and discomfort to the crew. These small changes were known under the omnibus term of modifications.

A more precise definition of a modification is a change in the drawings for an aeroplane which would involve one of the following:

(a) cost;
(b) date of delivery;
(c) operational characteristics;
(d) airworthiness;
(e) any other point specifically laid down in the specification.

It may be pointed out that (c) and (d) provide most, but not all, of the reasons for introducing modifications and that (a) and (b) might provide reasons why modifications should not be introduced.

Although the definition of a modification stated 'a change in the drawings', in fact a modification applied only to production aircraft. Prototype drawings were constantly changed during construction, either on instructions from M.A.P. or by the firm itself, and no great harm was done. But once the drawings were in the production shops any change would mean alterations to many processes already laid out. To check the necessity of a change and to minimise interference with production a certain procedure had to be observed.

Any change not covered by the definition stated above was termed an amendment and had always been dealt with by the firm and the Resident Technical Officer. Although many were no more than corrections to drawings, they involved a considerable amount of work, especially for

---

1 See Chs. IV, V and VI.

shadow or daughter firms.[1] This was aggravated by the habits of designing firms, acquired in the old hand-building days, of leaving the workshops to discover and correct for themselves small inconsistencies without notifying the drawing office. The result was a spate of queries from daughter firms whose labour was less skilled. Designing firms hindered by a shortage of checkers, could not be persuaded to check drawings, and many petty amendments which arose might easily have been avoided.

A change in drawings was only a modification when this procedure was set in train and the invariable rule was established that as soon as production drawings were in the workshop they must not be changed except by means of the accepted procedure. The position would have been much simplified if production had never commenced until prototypes were completed, as in the pre-expansion days, for then all the multitude of changes on the prototype, which became more numerous as it neared completion and underwent tests, could be automatically included in production. But the separate stages of prototype and production were impossible to distinguish and production preparations began before the prototype was in definitive form: the inevitable consequence was the large number of modifications which had to be incorporated before production began, and also for some time after production had begun.

2 *The sources of requests for modifications and channels of communication for notifying requirements*

During the period that an aircraft type was in production and on active service it was never free from modifications. Requests for modifications were likely to come from several sources and for the following reasons:

(i) From the firm. A modification under this heading might originate with the design staff of the parent firm as an improvement in design, or with the shops of the parent or daughter firm or even the sub-contractor who might press for an improvement in productability. There were quite a number of such modifications.

(ii) From M.A.P. An official modification of this nature might be put forward for production reasons, because of the shortage of materials (such as rubber), or other facilities (such as plant or skilled labour of a particular kind), or because certain types of equipment (such as engines, armament, instruments or radio) were being replaced in production by new types. Other modifications for production reasons might be put forward by the Deputy Directorate of Standardisation of Aircraft Equipment. The production 'easement', however, was not always felt by the individual firms who might be forced into extensive modification by the standardisation or replacement of instruments and equipment.

---

[1] Designing firms were usually known as 'parent' firms, and other firms who undertook production of aircraft under the aegis of 'parent' firms were usually known as 'daughter' firms. There were several cases of designing firms undertaking production of aircraft in a 'daughter' firm capacity, i.e. Westland's production of Spitfires; Fairey's of Beaufighters and Halifaxes, and Armstrong-Whitworth's of Lancasters, to mention only a few.

(iii) From the Service. These modifications could be attributed to operational requirements in the widest sense and were of two kinds:
- (a) those that were directed towards producing a better fighting machine and
- (b) those that aimed at easier repair[1] or maintenance, or prevention of accidents, or incidence of defects.

The percentage of the total number of modifications that could be laid to the account of each of the sources of requests for modification is difficult to assess, but the majority were without doubt of Service origin. Again the majority of modifications of Service origin were of the class that was directly aimed at providing a better fighting aircraft.[2]

The modifications under (i), (ii) and (iii) above show that any of the three main parties interested in aircraft production and performance might wish to change the aircraft in some respect to suit their own interests, and this fact, combined with the multiplicity of individual modifications, was a serious disadvantage. Modifications for operational reasons under (iii) (a) and (b) above mostly came from the Commands, although some originated in the department of the Assistant Chief of the Air Staff (Operational Requirements and Tactics) in the Air Ministry, which was the official filter for all requests for modification from the Services. A request bearing the authority of the Assistant Chief of the Air Staff (Operational Requirements and Tactics) was taken by the Directorate of Technical Development in M.A.P. to indicate that such a modification was genuinely necessary. There were two exceptions to this rule: firstly, those modifications intended to improve servicing and maintenance. These usually came from the engineering staffs of the Commands and filtered through the Director of Servicing and Maintenance, a member of the department of the Air Member for Supply and Organisation in the Air Ministry; secondly, modifications necessitated by the installation of new radio equipment. These reached the Directorate of Technical Development via the Director of Communications Development.[3] There was, of course, a tacitly accepted unofficial channel of communication between the user and the firm, and the user and the Directorate of Technical Development, whereby both were aware of Service needs in advance of the official request for action.

Requests from the different production directorates within M.A.P. were not sifted by one authority and their merits, therefore, were assessed in a somewhat haphazard way.[4] The officers in the Assistant Directorate of Research and Development (Landplanes) or the Deputy Directorate of Research and Development (Equipment Installation) concerned with the

---

[1] Repair was of course, strictly speaking, an M.A.P. responsibility under the Director of Repair and Maintenance; D.S.M. (Director of Servicing and Maintenance) was however an Air Ministry post.

[2] See Note 2 on p. 531 for an analysis of a typical set of modifications according to origin.

[3] The Assistant Chief of the Air Staff (Operational Requirements and Tactics) also gave his sanction to the radio modifications but was not likely to disagree with the recommendations of the Director General of Signals (the Director of Communications Development's opposite number in the Air Ministry).

[4] In some cases the Aircraft Equipment Committee acted as a central filter.

individual aircraft were responsible for passing these requests to the firm through the Resident Technical Officer.

There was, in addition, the special case of the 'omnibus requirement'. This was any requirement which was intended to be incorporated in several aircraft. In a case of this kind the Aircraft Equipment Committee would act as a filter, as the question of providing and buying equipment in large quantities arose. If this body approved of the modification it would pass it to the Airframes Modifications Committee, who were responsible from then onwards. This mention of the Airframes Modifications Committee leads to a discussion in detail of the modifications procedure which was mentioned in Section 1 as being essential before any change in aircraft drawings could be incorporated in the new production line.

3 *Central and local machinery for handling modifications*

The purpose of modifications procedure as is existed, then, was to control the whole passage of a modification from the point at which it was expressed as a definite requirement until the point when it was actually introduced into the airframe. Owing to the vast number of modifications on each type and the fact that most of them were comparatively simple, the system of control was predominantly local, headquarters control being limited to the formulation of policy, certain urgent or otherwise 'difficult' classes and the 'omnibus requirements' referred to above.

The chief organ of headquarters control was the Airframes Modifications Committee under the chairmanship of an Assistant Director (A.D./R.D.A.), Mr. F. E. Cowlin, who devoted the whole of his time to this work. The permanent members were selected to represent those same parties mentioned above as being responsible for putting forward requests for modifications. With the exception of one member (Director of Operational Requirements) they might also be concerned in putting the modification into effect. At the time of writing in May 1944 the Committee was constituted as follows:

Chairman	Assistant Director of Research and Development (Aircraft) (A.D./R.D.A.)	M.A.P.
and representatives of	Director of Operational Requirements (D.O.R.)	Air Ministry
,,	Director of Repair and Maintenance (D.R.M.)	M.A.P.
,,	Director of Servicing and Maintenance (D.S.M.)	Air Ministry
,,	Director General of Equipment (D.G.E.)	Air Ministry
,,	Director General of Aircraft Production (D.G.A.P.)	M.A.P.
,,	F.6	Air Ministry
Secretary	P.S.15(a)	M.A.P.

Local control was also vested in a committee—the Local Technical Committee—although the Director of Technical Development's own special representative, the Resident Technical Officer, played an important part with individual responsibilities of his own. The Local Technical Committees, which existed at every parent firm where airframes were designed and also at certain firms who undertook design responsibility for specialised equipment,[1] were under the chairmanship of the M.A.P. Overseer.[2] Official M.A.P. branches in charge of development and production interests were represented by the Resident Technical Officer and the Inspector-in-charge, Aeronautical Inspection Department; representatives from both the drawing office and works spoke on behalf of the firm. 'Daughter' firms were also represented.

It was mentioned above that a request for a modification was passed by an officer in the Assistant Directorate of Research and Development (Landplanes) or the Deputy Directorate of Research and Development (Equipment Installation) at M.A.P. through the Resident Technical Officer to the firm to work out the details.[3] When this had been done and the modification taken shape, it came before the Local Technical Committee together with any modifications proposed by the firm. The local committees had very wide powers which were given them purposely to enable them to make as many decisions as possible, as well as to prepare briefs on difficult cases for final judgment by headquarters. They were responsible for general approval for application of a modification to an aircraft, after taking into consideration the need for it and its cost in terms of extra work and delay on production.[4] Before the modification was released it had to receive *technical* approval as affecting something which was to be supplied to the R.A.F. This was solely a matter for the Resident Technical Officer as the Director of Technical Development's direct representative, and although it was his duty to consult M.A.P. on special points, it was his signature alone that rendered a modification technically effective.

4 *Evolution of Modifications Machinery*

At this stage it is relevant briefly to recount the evolution of this highly decentralised machinery for dealing with modifications.

During the First World War there was some control over modifications, but after the cessation of hostilities it lapsed and remained in abeyance until the mid-thirties. With the advent of the first expansion programmes it was realised that modifications would again present a problem and it

---

[1] Such as Dowty Equipment Ltd. (undercarriages). For full list of Local Technical Committees see Note 1 on p. 531.

[2] 'Daughter' firms were controlled by the Local Technical Committee at the parent designing firms, even if they were also parent firms in their own right, i.e. Spitfire production at Westland's was controlled by the Vickers-Armstrongs' Local Technical Committee, although for Whirlwind and Welkin production Westland's had their own Local Technical Committee.

[3] See p. 521.

[4] The terms of reference of a Local Technical Committee were set out in the letters of authority to the firm and the Resident Technical Officer to act, signed by the Director of Aircraft Contracts and the Director of Technical Development.

was thought a good idea to revive the old Modifications Committee. Mr. Grinsted of the Directorate of Technical Development was made responsible for the small committee and, besides technical development, the Air Staff, the Directorate of Repair and Maintenance (since divided into Directorate of Repair and Maintenance and Directorate of Servicing and Maintenance), provisioning branches (later the Directorate General of Equipment) and the Finance Branch were represented. The committee met once a fortnight for two or three hours and dealt in detail with every request for modification.

After the Munich crisis the work of the directorate increased and Mr. Grinsted, then Deputy Director of Research and Development (Technical Investigation), handed over the Chairmanship to Mr. F. E. Cowlin. It was evident that a single committee could not continue to investigate every individual case and it was thought that much of this work could be done locally. As an experiment, local modification committees were formed at certain of the busier designing firms and these grew into the Local Technical Committees. In the first place they were committees of local investigation and presented their case to headquarters to adjudicate. It became necessary to grant them financial powers and to begin with they were given permission to go up to £10 per aeroplane. When war was declared their financial powers were immediately raised to the ceiling and they were recommended to settle whatever they could for themselves; even if the decision was reversed later, the local committees were not to be blamed and any expense incurred prior to the reversal would be covered. Local committees were also established at every firm making airframes.

5 *An Illustration of the Machinery at Work*

A description of a typical incident that might occur in real life will serve to emphasise the real problems with which the Resident Technical Officer and the Local Technical Committee were called upon to deal, as well as to illustrate how the machinery worked.

We may suppose that a piece of the fin of a heavy bomber had dropped off. The Unit would inform the Director of Servicing and Maintenance of this by means of a defect report. The firm might also receive a verbal report of the incident—one of their mechanics perhaps heard about it privately—and the design staff may have given some thought to the matter. Perhaps, however, four or five similar incidents had happened within a few weeks and the Director of Servicing and Maintenance considered it serious. He would communicate with M.A.P. who would pass the matter to the Resident Technical Officer. The latter, having received all the details reported by the Units, would ask the design staff to devise a way of remedying the defect. The Resident Technical Officer and the firm's design staff would also have to assess what would happen if nothing were done. If it were true that the result of leaving the aircraft as it was would be serious or even disastrous, a technical requirement was established. In this connection it may be pointed out that the firm and the Resident Technical Officer were competent to assess the importance of a technical requirement, and no filter, such as the department of the Assistant Chief of the Air Staff (Technical Requirements), was needed as in the case of operational requirements, which might be merely refinements of equipment or local opinions expressed by Groups within the Commands.

But there was another assessment—one on which the firm would feel equally strongly. If this modification to the fin had been established as necessary for safety reasons what effect would it have on production and had it to be fitted retrospectively to machines already in existence? Could a practical programme for its application be planned? This was obviously the Local Technical Committee's field of work, and indeed the accurate balance of safety or operational urgency against disturbance of production due to various reasons was often a matter of extreme delicacy. Did the advantage to be derived from the modification outweigh the disadvantages which must inevitably flow from its introduction? Different views on this question might be taken by the production side and the design side of a firm and the Resident Technical Officer had to be prepared to cast his influence on one side or the other according to this own judgment. Some firms had a reputation for accepting modifications with less protest than others, although not all of these were equally quick at planning their introduction.

6 *Division of local and H.Q. responsibilities*

Obviously no modification could be introduced without causing some extra work somewhere, even though, in the aggregate, work might be saved, and the Local Technical Committees were licensed to make up their minds on production grounds, with certain exceptions, without reference to the Airframes Modifications Committee. About 60 to 70 per cent. of the total number of modifications were dealt with locally by the Local Technical Committees and were intended to be introduced into the production line without disturbance.[1] The cases which lay outside the competence of the Local Technical Committees were—

(i) Modifications which interfered with production deliveries.
(ii) Modifications involving a great deal of scrap.
(iii) Modifications which needed retrospective incorporation.
(iv) Modifications which affected embodiment loan supplies of equipment.

These exceptions all had wider implications than could be appreciated from a local viewpoint. The extreme case of interference with production would mean cessation of all deliveries until the modification was incorporated. Fortunately this was unlikely to happen, but the Airframes Modifications Committee at M.A.P. was called upon to exercise its judgment in many lesser cases. Their task, and that of the Local Technical Committees too, would have been easier if firms could have estimated more exactly the nuisance value of an intended modification. The planning office plotted production rates, but appears to have been unable to produce, at the early date when a decision was required, a

[1] Of the 1,085 modifications quoted as the net figure for Spitfire modifications up to the beginning of 1945 (see p. 241, fn. 2), 667 (or 61 per cent.) were non-retrospective.

quantitative assessment of the effect which a modification would have on production. Some firms admitted that they were not in a position to give the information until several weeks after they were committed to the modification. One of the most frequent excuses put forward was that firms were dependent on deliveries from sub-contractors, materials suppliers and others outside their disciplinary control. The reason why modifications resulting in scrap had to be referred to headquarters was that they affected supplies of raw materials for the industry as a whole. Similarly, retrospective modifications were nearly always undertaken at some place outside the firm's works.[1] Since the latter were, from the user's angle, so important, they occupied the lion's share of attention, though whether this was entirely in the best interests of the R.A.F. is not certain.

7 *Handling of Retrospective Modifications*

Because retrospective modifications were not fitted at contractor's works, this by no means implied that the contractor could wash his hands of the matter. To begin with, nearly all sets of spare parts had to be manufactured[2] and, if the job of fitting was a long or difficult one, the firms were bound to supply the skilled labour in the form of 'contractor's working parties'.

Retrospective modifications could be incorporated in existing machines in three ways:

(i) When an aeroplane went to Maintenance Command or the Civilian Repair Organisation for repair, major overhaul or role conversion.

(ii) When it was a simple job, it could be fitted by the Commands themselves, or when it was a specialised class of work (i.e. radio etc.) by R.A.F. working party.

(iii) When it was of such size or importance that it could not be done by Command personnel, a contractor's working party was sent to modify all aircraft on site.

It may be said here, in parenthesis, that the size of the job that could be done by Commands themselves varied with the size of aircraft and with the outlook of the individual Command. As a rule Home Commands were more inclined to ask for help than Overseas Commands. The latter were more willing to count the cost by estimating how long it would take how many men, and, if the modification was not obligatory, to deny themselves the luxury.

Considerable easement could result from such an action by a Command, for in most cases a contractor's working party meant taking men off production. Some firms foresaw this problem and two in particular provided the solution on their own initiative. The firms were Vickers Aviation and Bristol's: both of them built up special gangs of men over and above their works establishment, who were not only skilled, but able

---

[1] On rare occasions retrospective modifications were fitted at the maker's works, but this was apt to interfere with production and it also involved difficulties in the ferrying of aircraft and in releasing them from duty.

[2] Some modifications were designed to use stock spares and/or parts made up locally by the Services.

to be sent away to work on their own. This contributed in a marked way to the maintenance of those two very much modified aircraft, the Wellington and the Blenheim. In contrast, two other firms, Handley Page and Supermarine, had to make up their working parties from men taken off production whom they could ill spare. As a direct consequence, retrospective modifications either seriously harmed production at these two firms' factories, or were not attended to with anything like the degree of urgency which was necessary.

8 *Official Classification*

Modifications were officially classified into four divisions:

Class 1

Modifications dictated by extreme safety precautions. Until such a modification was incorporated no more new or repaired aircraft were delivered, and existing aircraft were grounded or kept off operations. This class was only permissible by the Controller of Research and Development after consultation with the Chief Executive and the Vice-Chief of the Air Staff and there were only half a dozen cases amongst all types.

Class 2

Modifications of operational or safety urgency to be incorporated in the production line as soon as practicable, and any delay in production to be notified and specially authorised; retrospective modification was compulsory as soon as the parts were available. If fitting the parts took more than 15 hours per aircraft on a small machine, such as the Spitfire, or 30 hours per aircraft on a large machine, such as the Sunderland, it was carried out by contractor's working party. The retrospective provisioning of parts, and possibly equipment, by the Director General of Equipment for such modifications was usually given high priority.

The initial recommendation by the Local Technical Committee for a modification of this class was thoroughly discussed by the Airframes Modifications Committee and was then submitted for approval to the Controller of Research and Development, through the Director General of Aircraft Production who could object on production grounds; the Director of Operational Requirements, who could confirm or deny that it was an operational requirement; and the Director General of Equipment, who could confirm or deny that the equipment was a supply possibility.

Altogether about 10 or 12 per cent. of the total number of modifications were Class 2; the weekly number was irregular but the average was about 14. Class 2 modifications were usually confined to the 'live' types of aircraft and the proportion which was of Air Staff origin was high. Some examples may be quoted:

Introduction of armour.
Introduction of under defence guns.
Introduction of self-sealing fuel tanks.
Many of the radio changes.

Certain important safety modifications not of Class 1 character.

Modifications aimed at suppressing an epidemic of unserviceability, such as those to the undercarriage of the Stirling.

A good example of Class 2 modification in detail was the case of the structural failure of spars in the wings of the Wellington. A certain amount of evidence was built up in Service units that Wellingtons were not returning from operations because wings fell off: when one day a member of the crew escaped by dinghy to tell the tale, the firm were able to concentrate on the cure. The cure was to make the spars of different material, but although the case for modification for safety reasons was a good one, there were two obstacles. The material was in short supply; and retrospective modification was technically very difficult. The firm prepared an alternative scheme by which, by means of a plug, the wings could be strengthened without changing the spar. It was not however so satisfactory as the alternative material. The latter was brought into new production as soon as possible and the plug confined to retrospective action on aircraft coming in for repair. As the supply position improved spare wings with new spars were fitted to the repaired aircraft and the interim scheme was extended to Wellingtons being repaired on site.

This is an example of an important modification which was prevented by physical reasons from being incorporated retrospectively in all machines as soon as safety considerations warranted. Such modifications were termed 'limited Class 2'. A number of other Class 2 modifications were limited for other reasons—for instance Halifaxes operating in the Middle East needed a certain modification, which did not affect home-based Halifaxes; the modification was then classified as Class 2 Special Order Only. Another example is the two kinds of Lancaster bomb doors—one for 4,000 lb. bombs and one for 8,000 lb. bombs. These were classed Special Order Only and the difference in their size necessitated the carriage of different wireless equipment.[1]

Class 3

Modifications in this category, as well as going into new production, were at the outbreak of war optional retrospectively. That is to say, it was open to Commands to have or not to have them fitted as they pleased. The optional conditions applied to Maintenance Command (No. 41 Group) and to Civilian Repair Organisation, as well as to Operational Commands. Maintenance Groups were given the option of refusing to incorporate the modification even if the Command being supplied wished for it, if this interfered with the schedule of deliveries of repaired and overhauled aircraft.

During the first year of the war, Class 3 modifications carried a heavy load. The quantities of parts and equipment required for retrospective modifications were determined as a percentage of the cumulative number of aircraft in operation, reserve and stock, and were therefore very high. Nevertheless as their use was optional, considerable quantities were never

[1] See Note 3 on p. 532 for analysis of modifications in Class 1 and 2 approved by the Airframes Modifications Committee up to 12th June 1944.

needed. In order to avoid this waste of materials and productive effort and the pressure on storage accommodation the terms of this class had to be revised. Discretionary modifications were drastically cut down, limiting them to such sets of parts as did not require manufacture of contractors' supply parts. As a compensation the so-called 'Command modification' was introduced and gained considerable popularity and success. Commands were allowed to devise, and were encouraged to make up the parts for, their own modifications dictated by their own operational experience. The Director of Technical Development was kept informed in case the modification provoked objection in principle, or could be more widely applied. An excellent example of a Command modification is the Hurribomber which originated with Air Marshal Sir Arthur Tedder's Desert Air Force.

Class 4

This class consisted of production-line-only modifications. Unless otherwise recommended, a Class 4 modification went into the production line without interference or scrap. In such a case the Airframes Modifications Committee at M.A.P. was merely notified of its advent. There were of course instances where scrapping of spare parts and some interference with production were justified and these had to be referred. There was in this class also a considerable number of Special Order Only items and these, by their very nature, had a certain nuisance value.

Although not retrospective in the strict sense implying operational aircraft, there were degrees of retrospection which enabled Class 4 modifications to be incorporated during repair and maintenance without the usual elaborate arrangements and inevitable disturbance. These were designated by the qualification—

'Class 4 and on repair'
'Class 4 and on replacement'.

The former applied to category B repair only and the latter meant that any stocks held by the Directorate General of Equipment were scrapped and replaced by modified parts as and when those parts became available.

9 *Conclusion*

This concludes the outline of the British system of administering and controlling the incorporation of modifications into aircraft. The description is limited to the system which applied to modifications to aircraft for the R.A.F. designed in the United Kingdom. The procedure for dealing with modifications to aircraft for the Fleet Air Arm and to American aircraft in service with the R.A.F. differed in a number of details, which need not however be discussed here.

In general, the British system differed fundamentally from the system employed in America, where all modifications between say, the 1st and the 1,000th aircraft off the production line were introduced retrospectively into completed aircraft at special modification centres. Only at widely spaced intervals were bunches of modifications introduced collectively into the production line, after which the design was 'frozen' for another long period of mass production.

The British system was like the American only to the extent that it also placed the emphasis on retrospective modifications. Indeed it was the main concern of the modification system, as described in this appendix, to control the retrospective modifications to be incorporated in aircraft in service or store, although modifications were of course continuously being introduced into the production line. In so far as all retrospective modifications were bound to affect current production by diverting labour and materials to the manufacture of components and parts, the very close scrutiny and control of retrospective modifications according to their relative urgency undertaken by the Local Technical Committees and the Airframes Modifications Committee undoubtedly reduced this class of interference to the minimum. The control of modifications to the production line however was much less effective. Although the Local Technical Committees were responsible for sifting from the proposed modifications all those which were in any way expected to interfere with production, only about 30 to 40 per cent. of the total examined were in fact referred by the Local Technical Committees to the Airframes Modifications Committee at M.A.P. Of the remaining 60 to 70 per cent., the assumption is that they were incorporated in the production line as soon as practicable without causing any disturbance. The Airframes Modifications Committee in their turn only rarely sanctioned modifications which were known in advance to involve hold-ups of production or considerable waste of materials. Thus in theory modifications did not interfere with production, but the growing allowances of the Directorate of Materials Production for scrap from modifications was evidence to the contrary. Similarly, some loss of time results from every modification however small, and the aggregate effect of all modifications during a year, swelled by those modifications which were urgent enough to warrant delays and scrap, was greater than in theory it should have been. A good illustration of the affect on output of the continuous flow of improvements is the chart of Spitfire production prepared by Vickers-Armstrongs Ltd. (Supermarine Works).[1] Frequent falls in output are shown to coincide with the introduction of new marks. If a finer mesh were applied and the introduction of modifications were shown, the same fluctuations of total output would be noticed.

If the Local Technical Committees and the Airframes Modifications Committee, as the controlling authority, had been able to weigh accurately the need for the modification against its production cost, a much greater degree of control could have been exercised. But these two variable factors could only be supplied by the Air Staff and the individual firms. The Air Staff were, in practice, never able to arrange their demands for modifications in order of urgency, nor were the firms able to estimate in advance the cost and dislocation of a modification. Without a knowledge of these two variables, control of production modifications was inevitably a haphazard affair. But in defence of the system it may be

[1] Appendix IV.

said that it is not always easy even in retrospect to separate the production delays caused by modifications from those due to other causes. It is therefore possible that at least some of the delays were due to inefficiencies in the firms' own organisation. In the circumstances, M.A.P's rough and ready method of 'a generalised resistance towards all modification proposals, tempered by "spot guesses" as to probable dislocation value' did not work out so badly.

NOTE I

List of Local Technical Committees at designing and certain other firms

Firm	*Date of formation*
Airspeed (1934) Ltd.	9. 9.39
Sir W. G. Armstrong-Whitworth Aircraft Ltd.	13. 3.39
Automotive Products Co. Ltd.	15. 7.41
Blackburn Aircraft Co. Ltd.	9. 9.39
Boulton Paul Aircraft Ltd.	9. 9.39
Bristol Aeroplane Co. Ltd.	9. 9.39
Cunliffe-Owen Aircraft Ltd.	16. 5.40
de Havilland Aircraft Co. Ltd.	12.10.39
Dowty Equipment Ltd.	15. 7.41
Fairey Aviation Co. Ltd. (Hayes)	7.12.40
Fairey Aviation Co. Ltd. (Stockport)	30.10.39
General Aircraft Ltd.	6. 3.41
Gloster Aircraft Co. Ltd.	9. 9.39
Handley Page Ltd.	9. 9.39
Hawker Aircraft Ltd.	9. 9.39
A. W. Hawksley Ltd.	11. 9.42
Helliwells Ltd.—Under Boulton Paul Aircraft Ltd.	23.10.40
As an independent body	4. 6.43
Messier Aircraft Co. Ltd.	9. 6.43
Miles Aircraft Ltd.	9. 9.39
Percival Aircraft Ltd.	30.10.39
A. V. Roe & Co. Ltd.	9. 9.39
Saunders-Roe Ltd.	9. 9.39
Short Bros. Ltd.	9. 9.39
Slingsby Sailplanes Ltd.	12. 2.43
Vickers-Armstrongs Ltd. (Supermarine)	9. 9.39
Vickers-Armstrongs Ltd. (Weybridge)	9. 9.39
Westland Aircraft Ltd.	9. 9.39

NOTE 2

Analysis of modifications classified by a typical Airframes Modifications Committee meeting according to origin

Origin	*Number*	*Example of modification*
Operational Requirement	14	To provide stowage for air ambulance panniers and first aid outfits.
A.E.C. Submission	6	Introduction of automatic bomb distributor type VIII No. 1 with associated equipment.
Defects and Service Complaints	24	To improve sealing of pilots sliding window.
Maintenance Improvements	3	Introduction of access holes for fuel contents gauges.
American Bulletins or Orders	13	Installation of United States pattern flame dampers.
Design Improvements	7	Introduction of metal shelves for wireless crates.
Production reasons	20	Introduction of modified disc valve to facilitate assembly and testing.

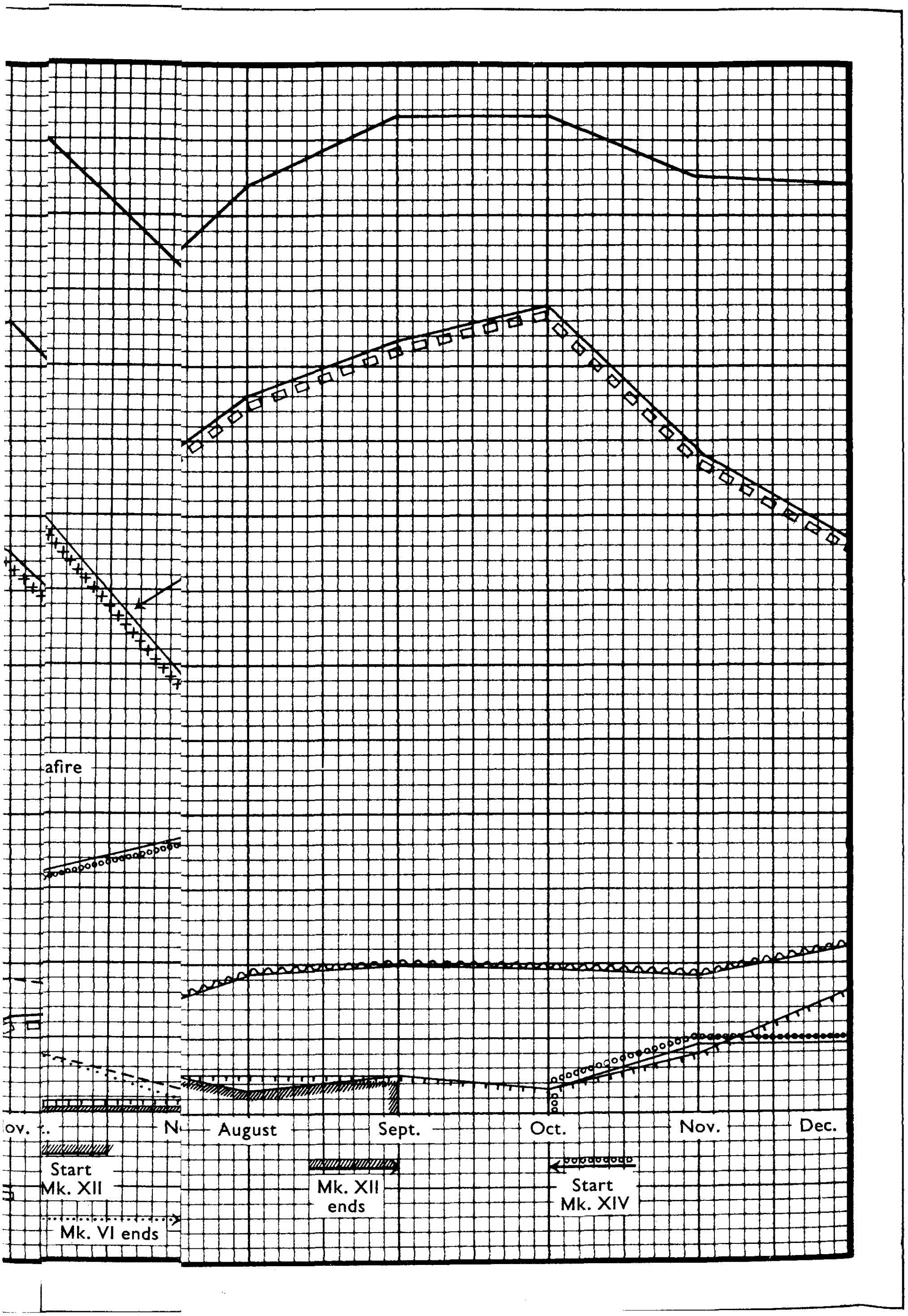
NOTE 3

Analysis of Class 1 and 2 modifications approved

Period	Number of Class 1 Modifications	Number of Class 2 Modifications
6.5.40–15. 7.40[1]	30	794
15.7.40–30.12.40	0	298
6.1.41–29.12.41	3	632
12.1.42–28.12.42	1	781
4.1.43–27.12.43	1	754
3.1.44–12. 6.44	0	471
	35	3,730[2]

[1] On 1st April 1940 a new system of classification was introduced; the period 6th May 1940–15th July 1940 therefore includes the figures for the reclassification of existing modifications in accordance with the new system, which accounts for the relatively large totals.

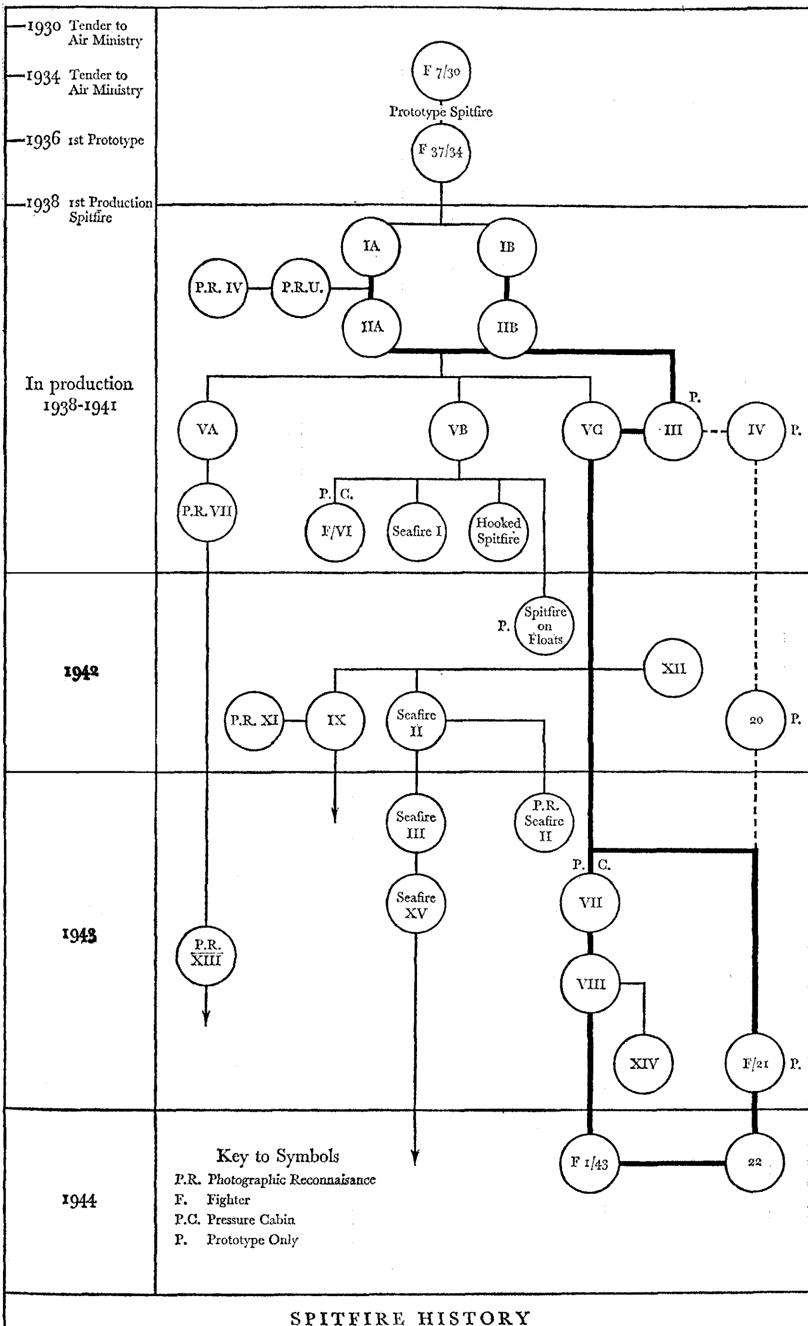
[2] The average number of Class 2 modifications per week over a period of 4 years was 14.



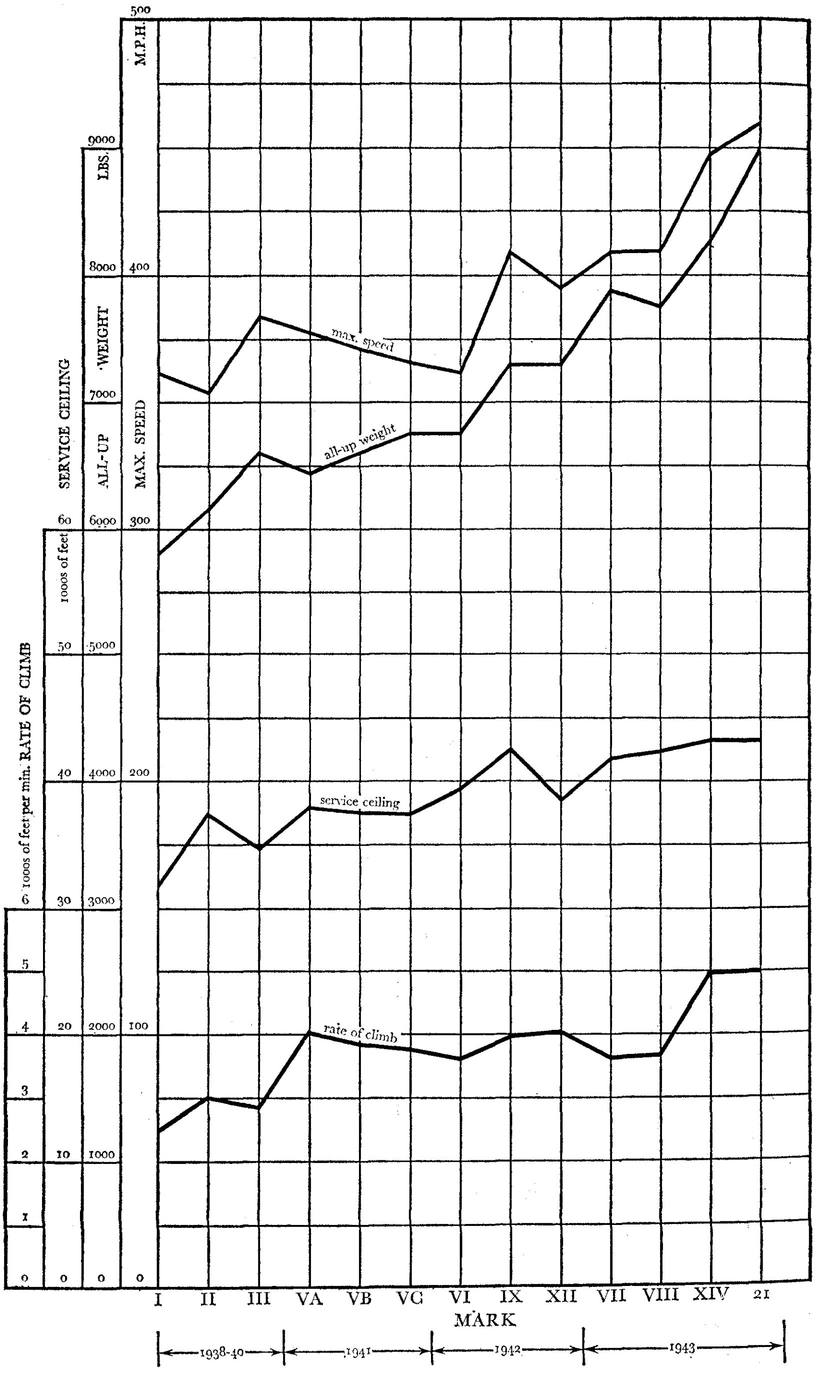
afire
lov.
N
August
Sept.
Oct.
Nov.
Dec.
Start
Mk. XII
Mk. VI ends
Mk. XII
ends
Start
Mk. XIV

APPENDIX V

Spitfire Genealogical Table



Analysis of Spitfire Performance



APPENDIX VI

Factors Involved in the Conception of the 8-Gun Fighter

Note by the Controller of Research and Development
(Air Marshal Sir R. Sorley)

By 1933 the evolution of the monoplane, designed as we have come to know it now, was becoming clear. Although there were still many controversial features it seemed that by adopting the monoplane layout there were many advantages to be gained, but certain fundamental features that would be new to its use by the average pilot would have to be accepted. Because of its ability to carry greater loads for its relative size compared with the biplane, the performances which could be obtained were highly attractive. To take full advantage, the variable pitch propeller appeared to be necessary but at that date although a lot of work had been done there was no fully successful type of propeller evolved. While the fighting view obtained with a monoplane layout was incomparably better than that possible with the biplane, there was considerable doubt on such features as high degree of manoeuvrability, strength for full aerobatics and terminal velocity dives; and in order to carry the loads which seemed necessary a considerable increase in the landing speeds compared with the biplane would have to be accepted. Moreover, the all-up weight of a fighter of this type would be considerably greater than that of the customary biplane type, and this in the eyes of those who held closely to the exceptional manoeuvrability characteristics obtainable by the biplane, was likely to prove unacceptable.

At the same time this formula of design offered to the twin-engined bomber a performance in speed very nearly equal to that of a single engine fighter. In other words, if the power in the bomber could be increased to a sufficient extent the comparable fighter was likely to have a relatively small advantage over the bomber for purposes of interception and pursuit.

This then was the problem confronting us in 1933 when the Specification F.5/34 for the 8-gun fighter was first conceived. It was essential to provide a fighter of the highest possible performance in order that it should have the best advantage possible of attacking bombers in the short time available. The specification opens on this note.

The relative performances of the two classes of aircraft seemed to indicate that the chances of repeated attacks would be slender indeed. Thus, the second problem was to provide a means of obtaining a decisive result in the minimum of time while at the same time increasing the chances of obtaining this result at longer ranges than were covered at the time. For the solution of this problem it was assumed that it would only be possible for the pilot to hold his sight on the target for a space of two seconds, either because of the short time in which he would be able to be in range or because of the difficulty of keeping the sight constantly on for a greater length of time, particularly at the 'high' speeds then envisaged.

The question then to decide was what form of armament could fulfil these conditions in the best way. What was needed was a lethality of fire power which could be built up in the two seconds which were thought to be essential.

The choice lay between the .303″ gun, the .5″ and a new 20 mm. Hispano gun which was attracting very much the attention of the French, and in fact most countries in Europe who could obtain knowledge of it from the French.

During 1934 the gun was experimental and details of its performance and characteristics were hard to establish. On the other hand, designs of better .303″ guns had been tested over the preceding years with the result that the Browning appeared to offer the best possibilities from the point of view of rate of fire. Our development of guns of this calibre had been thorough but slow, since we were in the throes of economy and considerable stocks of the old Vickers gun still remained over from the last war. The acceptance of a new gun in the numbers likely to be required was a heavy financial commitment. The .5″ on the other hand had developed little and although it possessed a better hitting power, the rate of fire was slow and it was a heavy item in respect of installed weight and ammunition.

The solution to the problem lay in making the best assessment possible of the decisive lethality which could be expected in the very short time of fire available. By using 8 Browning guns it should be possible to build up a density of 256 rounds in the time available.

To enable the fighter to obtain the best possible speed in relation to the contemporary bomber it was necessary that it should be kept as slim as possible, thus the size of the fuselage was of great importance. The mounting of guns in the fuselage tended to increase the cross-sectional area, thus it seemed necessary, if we were to go for more guns than 4, that these should be placed outside the fuselage. The monoplane wing offered a space in which the guns might well be mounted. This would entail mounting a battery of 4 guns in each wing, which in its turn would demand a rigid mounting and the provision of many new features described below.

The .5″ gun although attractive from the point of view of hitting power did not lend itself to the rapid build-up of lethal density within the limits of weight which could be allowed for the armament of such a fighter at that time.

The 20 mm. Hispano was demonstrated during a visit to France from which it transpired that the gun was super-sensitive to rigidity of mounting. Because of this the French had designed their Hispano engine so that the gun could be mounted on top of it and thus fire through the propeller boss. Consequently the possibility of increasing the number of such guns at that time appeared small.

The Polish P.Z.L. had tried to mount two of these guns under a wing but it seemed that their mounting was insufficiently rigid and they were in continuous trouble with stoppages.

The broad conclusion was that the Hispano gun would not fire successfully unless the mounting was extremely solid. Nevertheless the demonstration of results obtained on a metal aircraft with a 20 mm. solid shell were extremely attractive. Once again the weight of the gun and ammunition were against it, and there seemed little possibility of being able to obtain the decisive result required by this means and in spite of the advantages of using a larger calibre, viz.

(1) that the whole of the target was vulnerable to hits,
(2) that the trajectory was flatter,
(3) that the range might possibly exceed that for effective machine gun fire,
(4) that such long range would increase the time available for developing effective fire,

and the desired answer did not then seem possible with the 20 mm. gun.

This controversy was something of a nightmare during 1933–34. It was a choice upon which the whole conception of the aeroplane would depend but a trial staged on the ground with the $8 \times .303''$s was sufficiently convincing and satisfying to enable the 8 guns to carry the day.

A further complication had to be considered, whether the tactical methods current at the time of attack by squadrons or flights in formation could hold good. Squadron or flight formation attacks were necessary in order to produce a concentration of fire of fighters armed with no more than two .303″ guns. They required a high degree of skill and extensive training of pilots. This factor, in conjunction with the greatly increased speed to be expected, and the very short time for decisive action, pointed to the need for new tactical methods and much thought was put into this aspect during 1934–38.

Thus it was that the F.5/34 Specification came into being. It envisaged a radial, air-cooled fighter which was placed with Messrs. Gloster.

However, at the same time there were two aeroplanes being designed by Messrs. Hawker and Supermarine as experimental orders which were to be built around a Merlin engine in order to test out the monoplane conception, and the engine rather than as operational types. It had been envisaged that should these aircraft be successful, 4 guns might be installed in the fuselage. Mock-ups of these two aeroplanes were reaching completion; and their general layout fully accorded with that envisaged for the F.5/34. Both Mr. Camm and Mr. Mitchell, the designers, were confronted with the 8-gun theory and soon were enthusiastic to adopt the principle.

The wing installation involved a number of new installation problems and departures from current thought and practice. By having the guns in the wings one could dispense with the complication of interrupter fire gear necessary for gun firing through the propeller. This offered a saving in weight and complication and enabled the guns to fire freely at their own rate of fire instead of at a restricted rate due to the interrupter gear. At once, however, the question of clearing stoppages and re-cocking the guns became a point of controversy. Access by the pilot to his guns had for long been customary and the idea of having the guns completely out of reach gave rise to considerable discussion. However, it seemed obvious that with the freedom of the guns to work without interruption we were likely to obtain fewer stoppages than hitherto and even if one or two did stop then there were plenty left. So re-cocking and clearing of stoppages was waived aside. Then there was the question of instantaneous firing of a number of guns by the pressure of the pilot's finger or thumb. The old Bowden control had always a time lag between pressure of the trigger in the cockpit and the firing of the gun, even though they were closely adjacent. Such time lag could not be afforded if the lethal density was to be built up in the time required. And so a new departure was taken to provide pneumatic firing by the pressure of a button on the pilot's stick, and a new technique had to be evolved by Dunlop's.

Then came the argument as to whether sighting accuracy would be as good with the guns off-set from the centre line of the fuselage, and the best alignment of the wing batteries to produce the density of fire at a given range. Although there was and remained a school of thought which held strongly that the accuracy was better when the guns were on centre line, it was an argument which had to be dismissed and the guns aligned so that the trajectories would cross over at a range of 400 yards in front of the aircraft.

The Supermarine and the Hawker aircraft differed essentially in one important feature. The Supermarine was designed for a thin wing whereas the Hawker design was a thick one. As a result the installation of the guns in the Hawker aircraft was a somewhat easier problem enabling the 4 guns to be grouped together. In the Supermarine, the depth of the wing entailed the guns being installed separately. In fact the outer guns of the 4 on each side were well out towards the tip of the wing. Nevertheless it all became quite possible and so it was that the Spitfire and the Hurricane were born for Service, under Specification F.36/34 and F.37/34.

Consequent upon the main problem of the time for intercepting and attacking the bomber, it was by no means certain that the single-seater, single engine fighter would succeed. It was therefore necessary to look at the problem in yet another way and the single engine, turret fighter was conceived in a Specification F.9/35.

In this approach to the problem it appeared that by accepting a slightly reduced performance it might be possible to take the load of a 4-gun power-operated turret as well as an increased fuel capacity into the air with the object of attacking formations of bombers from a standing patrol. In this case the speed margin between the fighter and the bomber was even less than with the single-seater fighter but, to counter that, it was envisaged that the method of attack might be from any position in which the fighter could get itself relative to the bomber rather than the more stringent condition of obtaining the essential position astern which was necessary for the single-seater, forward-firing fighter.

The specification was undertaken by both Boulton Paul and Messrs. Hawker who evolved what became the Defiant and the Hotspur respectively. The whole design was founded around the power-operated turret mounted behind the pilot with an all-round field of fire in the upper hemisphere accepting that the target would more usually be above the fighter than below it. It was for these two aircraft that the 4-gun power-operated turret was first conceived. In the one case Boulton Paul used the basic scheme of a Frenchman, redesigned and developed it, and the result became the standard B.P.4. gun turret.

In the other case Frazer-Nash designed a battery of 4 guns separated from the gunner and thus introduced one of the first remote control systems. Because Hawker's were fully occupied with the Hurricane, their Hotspur took long to mature and fell behind the Defiant which became the only aircraft of this type which was introduced into service.

Although the conception of this class of fighter might have resulted in greater success, it fell to the lot of the Defiant on one day only during the Battle of Britain to score very effectively. Due to the great shortage of aircraft during the battle and possibly due to the fact that there were not enough aircraft to operate as standing patrols, the Defiant was used very largely as an interceptor type in which of course its performance was not fully suitable. But it was from the work on these turrets that the 4-gun power-operated turrets for the defence of bombers were evolved, and thus the results, although applied in a totally different direction, were of the utmost value.

As time went by there was a school of thought that believed that the only solution to the problem was to be found in a twin-engine multi-turreted fighter. This had its basic tactical conception on just the same principles as the Defiant except that the performance might be better. This argument was at its height about 1935, and as a still further re-assurance a type was evolved on these lines. The weakness appeared to be that by having to instal a number of turrets and yet achieve the very high performance required it would fall completely between two stools. However the figures at the time appeared attractive enough.

Once the construction of the Hurricane and Spitfire had proceeded far enough to see the strong construction it was necessary to put into them, the possibility of turning over to 4×20 mm. Hispano guns came within reach. By late 1935 we had seen more of the work of Mr. Birkigt of Hispano and because the thick wing of the Hurricane was designed so essentially for stiffness it offered the real solution to the problem of adopting heavier armament. By then the variable pitch propeller was in sight and so the load could be increased. By adopting 4 such guns the decisive result still required in the two seconds of fire appeared to be obtainable taking account of the very devastating effect which the heavier shell had upon the target. Undoubtedly there were engineering problems to enable the guns to be mounted within this wing and to provide the essential rigidity of mounting; and the proposal was made at the end of 1935 that the Hurricane should be so developed. But it was not until late 1939 that this changeover to armament was achieved, and even then the difficulties of rigidity of mounting took a long time to overcome.

Finally, it is of historical interest to quote an unsolicited testimony which is to be found in Air Interception Report 159/45:

> 'Later Goering became more confidential and asked the Kommodores for their frank opinion of German aircraft and armament. One of the Kommodores said bluntly that German fighter armament was consistently inferior to that of the Allies, whereupon Goering said "Hitler wants you to have wing mounted armament and you want to develop cannon-firing through the propeller boss. What am I to do?" No-one apparently told him.'

6th May 1945

APPENDIX VII

List of Development Tanks Assigned 'A' Numbers

<table>
<tr><td>A.1</td><td colspan="2">'Independent' Vickers. 1 pilot 29 tons. Designed 1926.</td></tr>
<tr><td>A.2, E.1</td><td colspan="2">Medium Tank Vickers Mk. I. 'Japanese' suspension, 1924?</td></tr>
<tr><td>A.3, E.1</td><td colspan="2">3-Man Tank, O.F. (Ordnance Factory) 1925.</td></tr>
<tr><td>A.4</td><td colspan="2">Vickers 'Carden-Loyd' light tanks, 1929 onwards. Various types and pilots produced.</td></tr>
<tr><td>A.5</td><td colspan="2">Vickers 'Carden-Loyd' 3-man light tanks, 5 tons. 1 pilot. Probably designed about 1928. Scrapped 1934.</td></tr>
<tr><td>A.6, E.1, E.2 and E.3</td><td colspan="2">Experimental 16 ton tanks, pilots of the Medium Mk. III. Designed by Vickers-Armstrongs about 1928. The three machines had variations in the transmission.</td></tr>
<tr><td>A.7, E.1, E.2 and E.3</td><td colspan="2">Experimental medium tanks designed by Chief Superintendent of Design and built in R.O.F., Woolwich. 14–18 tons. Armour 14 mm. Abandoned on account of unreliability of A.E.C. engines and suspension. 1929–37.</td></tr>
<tr><td>A.8</td><td colspan="2">Experimental medium tank ordered from Vickers at Elswick. Two Rolls-Royce Phantom engines. Never completed. 17.5 tons. 1934–37.</td></tr>
<tr><td>A.9</td><td colspan="2">Pilot of Cruiser Tank Mk. I. Designed by Sir John Carden of Vickers as a 'Woolworth' medium tank. Weight 10 tons. 1935.</td></tr>
<tr><td>A.10</td><td colspan="2">Pilot of Cruiser Tank Mk. II. Originally designed as the first Infantry tank with 25 mm. armour, but accepted later as Heavy Cruiser. Vickers, 1935–38.</td></tr>
<tr><td>A.11</td><td colspan="2">'Matilda' Pilot of Infantry Tank Mk. I. Designed by Sir J. Carden of Vickers. Armour 60 mm. Weight 11 tons. 1936–38.</td></tr>
<tr><td>A.12</td><td colspan="2">'Matilda II' Pilot of Infantry Tank Mk. II. Designed by Mechanization Board and Vulcan Foundry. Armour 70 mm. Weight 24 tons.</td></tr>
<tr><td>A.13 Mk. I</td><td>Pilot of Cruiser Tank Mk. III.</td><td rowspan="2">Based on original Christie purchased from U.S.A. Designed by Mechanization Board and Nuffield Mechanizations & Aero Ltd. 1937.</td></tr>
<tr><td>A.13 Mk.II</td><td>Pilot of Cruiser Tank Mk. IV.</td></tr>
<tr><td>A.13 Mk. III</td><td colspan="2">Pilot of Cruiser Tank Mk. V. 'Covenanter' based on original Christie purchased from U.S.A. Designed by Mechanization Board and L.M.S. Railway. 1937.</td></tr>
</table>

A.14	Modified G.S. Specification Heavy Cruiser. Designed by Mechanization Board and L.M.S. Railway. Pilot built and abandoned after trials. 30 mm. armour. Thornycroft V.12 engine. Weight about 23 tons. 1938.
A.15	Pilot of 'Crusader' *Cruiser Tank Mk. VI.* Designed by Mechanization Board and Nuffield Mechanizations & Aero Ltd. Armour 30 mm. Weight 18 tons. 1938–40.
A.16	Development of A.13 as Heavy Cruiser. Built by Nuffield Mechanizations & Aero Ltd. and tested. Armour 25 mm. Weight 18–21 tons. Forward turrets added and heavy duty suspension. 1938.
A.17	Pilot of *Light Tank Mk. VII* 'Tetrarch'. Designed and built by Vickers. Armour 16 mm. Weight 7 tons. 1939.
A.18	Projected Cruiser tank based on A.17 designed by Vickers but abandoned later. Turret used for later cruisers 1939.
A.19	Projected Cruiser tank with auxiliary turrets on top of main turret. Project by Mechanization Board. Abandoned 1939.
A.20	Original pilot for 'shelled area Infantry tank'. Design by Mechanization Board and Harland & Wolff. Two pilots built by Harland & Wolff which were run but never entirely completed. Armour 80 mm. Weight 35 tons.
A.21	Projected development of A.20. Never got beyond stage of schematic drawings.
A.22	Pilot of *Infantry Tank Mk. IV* 'Churchill'. Development of A.20 carried out by Vauxhall's under direction of Department of Tank Design. Armour 80 mm. Weight 37 tons.
A.23	Projected lighter version of A.22. Never proceeded beyond sketch stage.
A.24	Pilot of *Cruiser Tank Mk. VII* 'Cavalier'. Designed by Mechanizations & Aero Ltd., 1941.
A.25	Pilot of 'Harry Hopkins', *Light Tank Mk. VIII.* Vickers, 1941.
A.26	Projected lighter and faster version of A.22.
A.27	Two pilots of A.27(M) 'Cromwell' *Cruiser Mk. VIII Tank.* 26½ tons, Meteor engine and Merritt-Brown steering. A.27(L) was pilot of 'Centaur' which was almost the same as Cromwell but had Liberty engine instead of Meteor. All A.27 pilots built by Birmingham Railway Carriage & Wagon Co. Ltd., designed by Birmingham Railway Carriage & Wagon Co. Ltd. in conjunction with Rolls-Royce and Department of Tank Design. 1941–42.
A.28	Cromwell (A.27M) with increased armour and skirting plates over suspension. Weight 28 tons. December 1941.

Abandoned at paper stage. Designed mostly by Rolls-Royce.

A.29 Large Cruiser to carry 17 pdr. gun. Weight about 45 tons. Twin track with Cromwell engine compartment. Abandoned at paper stage in favour of A.30. Rolls-Royce design.

A.30 Challenger lengthened Cromwell with lightened armour and one extra suspension unit per side. 17 pdr. gun. About 31 tons. Building of pilots and parentage of design same as A.27. 1941–43.

A.31 Cromwell with heavier armour. 32 tons. Abandoned at paper stage. Rolls-Royce design.

A.32 Cromwell with armour increased to standard of A.22. New suspension. 34½ tons. Abandoned at paper stage. Rolls-Royce design.

A.33 Pilot Assault tank. 40 tons. 6 pdr. gun and heavy armour. Built by English Electric Co. Meteor engine. American T.1 suspension and track. 1942–43.

A.34 'Comet' Cromwell type Cruiser tank with new turret to take 77 mm. gun and slightly heavier frontal and thinner side armour. Stronger suspensions and wider track than Cromwell. 31 tons. Built by Leyland Motors, 1942–44.

A.35 Heavier version of Cromwell type with increased armour and stronger suspension. 36 tons. Never progressed beyond scheme stage. Design by L.M.S. Railway and Rolls-Royce.

A.36 Heavier version of A.30 with increased protection and stronger suspension. 17 pdr. gun. Rolls-Royce scheme. Never passed paper stage. 41½ tons.

A.37 Heavier version of A.33 with an extra suspension bogie per side, longer hull and 17 pdr. gun. Schemed by English Electric and Rolls-Royce. 52 tons. Never passed paper stage.

A.38 'Valiant I' with General Motors Corporation engine and A.E.C. gearbox. 27 tons. 'Valiant II' with Meteorite engine and Rolls-Royce gearbox. 27 tons. Pilots of Valiant I building 1943–44 by Ruston & Hornsby. Design parentage had been Vickers then Birmingham Railway Carriage & Wagon Co. Ltd. before Ruston & Hornsby. Design parentage Ruston & Hornsby and Rolls-Royce.

A.39 'Tortoise' Heavy Assault Tank. 37 pdr. 75 tons. Nuffield Mechanizations Ltd. 1942–present (1944). Pilots being built.

A.40 Heavier version of A.30, with 4″ frontal armour. 17 pdr. 35½ tons. Design parents Birmingham Railway Carriage & Wagon Co. Ltd. and Rolls-Royce.

3rd April 1944