TECHNOLOGY AND NAVAL WAR

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PREFACE

Virtually all of my adult life has been spent working in one way or another on the development of vehicles, sensors, and weapons for naval warfare. My involvement in naval systems development has on the whole been extensive rather than intensive, so that in twenty years I have been close to perhaps 50 major programs, and a host of lesser ones. In a great many of these cases I have been in at the program's inception, or not long after. Virtually every one has been conceived in the very greatest of confidence in its efficacy and importance to our naval defense–a confidence deriving, in most of the programs, largely from magnificent advances in technology incorporated in the new system.

In the beginning I shared these enthusiasms in full: often could I, too, have sung, "Bliss was it on that dawn to be alive!" But in many cases my enthusiasms proved no more durable than Wordsworth's. Some programs were stillborn, others never came close to meeting our expectations of their impact on the naval balance. Sometimes the fault lay in the technology: we had misjudged what lay within grasp. But usually the system was, in the end, made to work much as we had envisioned–in the sense of meeting its stated performance requirements. Where we often failed was in foreseeing the real conditions of environment and threat which the system would face and the way in which it would actually be employed. Many of the technical people with whom I worked took the view that if the system met the performance requirements (or where these had been perceived by the technical community to be unachievable from the outset–as is all too often the case–if the performance of the system was all that could reasonably have been expected) then they had done their jobs and could look upon their efforts with pride regardless of what the system did or did not accomplish in service. But I was unable to be satisfied with this.

This sense of dissatisfaction has led me to devote much of my career to trying to improve the Department of Defense's institutional foresight concerning systems for naval warfare, working at the juncture of technology and requirements. Once I thought this would be an easy matter, a simple mixture of common sense, technical judgement, and engineering analysis. A decade's experience and study has taught me something of the awesome diversity and complexity of the factors which truly affect the military significance of any system. Gradually, some of my reflections began to resolve themselves into specific theoretical distinctions and propositions applicable, I believe, to naval systems and naval war generally.

Then, in the Fall of 1979, I received a very gracious invitation from Professor John Norton Moore, Director of the Center for Oceans Law and Policy at the University of Virginia, to participate in a seminar, "To Provide and Maintain a Navy: Planning for a Changing World," to be held in January 1980. Thus stimulated, I wrote a brief paper, "Technology and Naval Force Structure," which served as a vehicle to crystallize and present some of my ideas. The paper was well received by the distinguished company gathered at the seminar and was later published in the Center's *Oceans Policy Study 2:5*, March 1980. This, together with the many perceptive and appreciative comments of colleagues, was very gratifying, but I realized that much was undone.

There matters lay until early in 1981 when a friend put me in contact with Samuel Jay Greenberg, who was then starting an exciting new journal: *Military Science and Technology*. He was most interested in my earlier paper and suggested that I expand upon its themes for publication in *Military Science and Technology*, offering me the broadest sort of freedom. Thus deprived of my previous excuse for procrastination–that there was no medium or audience for such things–I set out to sharpen my ideas and present them at greater length. In the end there were six articles! This, I know, was a good deal more than Sam Greenberg had bargained for, but he smilingly accepted them all. The articles began appearing with Volume 1, Number 3 of *MST*, under the series title, "Strategy for Sea Power" (the titles assigned to the individual articles within the series vary).

Military Science and Technology provides an excellent forum: probing, yet lively and interesting. For certain readers, however, there is an advantage in having the entire text of these articles collected in one volume for concentrated study. It is for this reason that I have prepared the present monograph, "Technology and Naval War," providing section headings and an analytical introduction to further ease study and analysis. It contains the full text of the six *MST* articles, although, as a result of separate editing, it may diverge slightly in wording and style at some points.

I feel confident that "Technology and Naval War" represents a significant contribution to an important but little-explored field of inquiry. At the same time I remain very aware of how much more remains to be done. The small increment of time I have been able to spare for this effort–about 200 hours scattered over evenings and weekends–is but a tiny fraction of the need. I hope some day to have the opportunity to return to this subject at greater length, with special emphasis on sharpening and quantifying the analysis. In the meantime I invite all who are interested to communicate with me on these matters.

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Throughout the writing of this monograph and its predecessor, "Technology and Naval Force Structure," I have served as Director of Naval Warfare (which should more properly be understood as representing *systems* for naval warfare) in the office of the Under Secretary of Defense for Research and Engineering. My official responsibilities have provided a unique opportunity to study the relationship of technology and naval war, as well as a powerful stimulus to inquiry. But the results of my efforts, as expressed in these writings, are to be understood as purely personal musings and speculations, entirely without official or authoritative character.

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My first thanks are due to Professor John Norton Moore, Director of the University of Virginia's Center for Oceans Law and Policy, and Samuel Jay Greenberg, Editor of Military Science and Technology, for providing the stimuli and occasions without which my ideas would not have gained the form in which you now see them.

My thinking has been shaped and sharpened by countless interchanges with many colleagues. To name only a few is necessarily invidious, but I can not pass without expressing my thanks to David L. Anderson, Gerald A. Cann, David C. Hardison, and Charles E. Myers. Each of these men has played an important role in the development of my ideas and deserves a significant measure of credit for what is good and valid in them.

I wish to express my appreciation to Mrs. Carol Keefe, who carried out a very comprehensive and detailed analysis of World War II U-boat sinkings which contributed to many important insights and formed the basis for some of the statistics cited in this monograph. Thanks are also due to Mrs. Keefe, as well as to Captain John Peters, USN, for assistance in proofreading the typescript.

I have read many hundreds of books, monographs, reports, and articles which have contributed in one way or another to the facts cited or insights expressed here. Special mention must be made, however, of the three splendid and invaluable analytical histories written by Vice Admiral Sir Arthur Hezlet, Royal Navy: *The Submarine And Sea Power*, *Aircraft And Sea Power*, and *Electronics And Sea Power*. It is these works more than any others from which I have drawn the basis for my historical analysis.

Finally, my heartfelt appreciation to my wife, Anne Murphy O'Neil, for her encouragement, forbearance, and loving help.

W. D. O'N

INTRODUCTION

Our purpose here is to examine the relationship of technology and naval war with two ends in view: the better to know what technological developments should be pursued because they can be expected to have a large effect, and the better to foresee the future of naval war in an era of rapid technological development. The instruments of this examination include both abstract theoretical analysis and historical analysis. We take as the foundation of our theory the concepts of combat kinematics enunciated 65 years ago by F. W. Lanchester. However, we accept neither of Lanchester’s famous "laws," choosing instead to try to deal with the well-known divergence of historical combat experience from Lanchester’s theories by extending the theory to deal with the elements of choice and circumstance in determining concentration ratios. In so doing, we present an extended Lanchester theory which is not useful for computation but which serves greatly to clarify the interaction of technological, tactical, and strategic factors at a conceptual level. From this theory we draw the conclusion that technological innovations are most significant for naval warfare when they act to bring asymmetric changes in any or all of three dominant factors: the ability to concentrate forces, firepower, or opportunity to concentrate one’s own fire against the enemy while limiting his opportunity to concentrate his fire.

Turning in Chapter II to history, we observe that the dramatic technological changes of the middle years of the Nineteenth Century did not, indeed, have much effect on the fundamental strategic situation, just as Mahan had argued. The development of electrical and electronic communications did, however, change strategic conditions profoundly by permitting information to move faster than forces and by multiplying the opportunities for acquisition and compromise of secret intelligence. When the information asymmetries fostered by telecommunications were combined with the mobility asymmetries brought by the innovation of the airplane, the results proved explosive, resulting in some of the most strategically-notable outcomes in naval history. Equally dramatic was the impact of the first stealthy naval vehicle, the submarine, which created its own asymmetries in information and compensated, in part, for its lack of mobility advantage through proliferation and dispersal.

Chapter III applies the insights gained in Chapters I and II to the problems of the present and future, within bounds set by security. The technology of nuclear weapons has the potential to make naval war, along with other human pursuits, irrelevant; if applied on a narrower scale nuclear weapons might tend to tilt the naval balance away from forces depending on surface ships, but there is, as always, considerable room for disagreement about the extent to which it would be possible to limit use of nuclear weapons. On the subject of surveillance we argue that useful public discussion of the specifics of technology and performance is virtually a contradiction in terms but assert, on a priori grounds, that technology growth in electronics must continue to provide unprecedented potential for both acquisition and denial of critical information.

Examining the technology of naval vehicles we find that ship-attack aircraft have retained and expanded their mobility advantage over ships and can, accordingly, be expected to continue to dominate surface forces through their superior strategic concentration potential. We are not able to find any serious grounds for hope that dispersal of surface forces could affect this in any marked degree (unless the ships involved could achieve submarine-like stealth). On the other hand, it appears feasible to intercept ship-attack air forces with aircraft of yet greater mobility, which might severely erode their freedom and effectiveness of action. Stealth is a major variable, since there is the possibility (which can not be evaluated on the basis of published information) that it might permit ship-attack aircraft to evade more mobile interceptors while retaining their effectiveness in striking ships. Perhaps ships could also adapt themselves to stealth, but this would simply make them functionally equivalent to submarines. Considering the historical and technological evidence, we conclude that in the case of a stealth-dependent vehicle such as a submarine, fine gradations in degree of stealth can be very important: if faced with an opposing force of substantially superior mobility the stealthy vehicle’s effectiveness may be severely compromised by only occasional lapses in its concealment.

The submarine may be able to compensate for its greatest strategic weakness, its lack of advantage in strategic concentration, by adopting very long-range weapons (although it runs some considerable danger in doing so if the weapons are not also very stealthy). More generally, we argue that ships are potentially susceptible to attack from virtually unlimited standoff range, even by land-based ballistic missiles, creating a potential for dispensing with vehicles altogether in delivering anti-ship attacks. We are unable to discern comparable potential for long-range attack of submarines or aircraft–submarines because of their stealth and submergence, aircraft because of their mobility and low observables. Some sorts of land installations are even more susceptible to long range attack than ships but others–those which can be incrementally hardened–may be made essentially invulnerable to conventional standoff attack.

We do not proceed in this monograph to draw explicit conclusions about the implications of our theory and insights for the shape of naval warfare as a whole. This is due in part to the restrictions imposed by considerations of security and in large measure to the lack of time and space to develop the arguments to the extent necessary to support the sweeping, momentous, and necessarily controversial conclusions which would be involved.

CHAPTER I

THE FUNDAMENTAL THEORY OF TECHNOLOGY'S IMPACT ON NAVAL WAR

A. Historical Background: The Classical Analysis of Strategy

Navies have always been capital-intensive. What is more, the capital goods most used by navies have always had extraordinarily long lives, at least so far as wear-out and obsolescence govern. Thus it was inevitable, when the industrial revolution began to engender rapid technological changes in capital goods generally, that those responsible for naval capital procurements should become deeply concerned about the impact of technology on naval forces. The events of the ensuing 150 years have done nothing to abate that concern.

How would naval warfare be shaped by steam propulsion? What about the ram bow, breech-loading guns, torpedoes, the dynamite gun, zeppelins, airplanes? Each invention was greeted by a claque, proclaiming that here at last was the ultimate weapon which would sweep all before it and change the nature of war at sea beyond all recognition. Others, with equal certitude, scoffed that the invention was unworkable and would exert no positive influence.

Mahan and Corbett, and a few followers, attempted to divine the prospect for naval warfare through rational analysis: deducing the basic, unchanging principles of naval war through historical study and logical reflection and applying them to the mutable conditions. In general they were far more successful at deducing principles than at applying them in altered circumstances, frequently due to inadequate grasp of the technological possibilities. But this is not in itself an impeachment of the effort to apply rational analysis to the problem of predicting technology's impact on naval warfare.

As for principles, the judgement of strategic theorists, naval and military, may fairly be summed by B. H. Liddell Hart's aphorism: "The principles of war, not merely one principle, can be condensed into a single word–'concentration'." Practitioners have expressed the same view in different terms, as in Napoleon's dictum that, "The art of war consists in always having more forces than the adversary, even with an army weaker than his, at the point where one is attacking or being attacked." In this classical analysis of strategy the principal determinant of victory was the relative strength of the forces at the point of contact; the business of the commander was to ensure that his strength was superior at the point of contact or, conversely, to ensure that contact occurred only where his strength was the greater.

B. The Modern Analysis: F. W. Lanchester

The classical theory served well enough (in the sense that it seemed to match the observed actions of talented and successful commanders) for most of the history of warfare. It was undermined when rapid technological change started to bring forces of unlike equipment into contact with accelerating frequency. Given unlike forces, how should strength be measured? Specifically, how might one rationalize numbers with firepower? For it seemed to most that the effects of technology were seen principally in the growth of firepower. The problem was by no means unprecedented: advances such as shock cavalry and individual missile weapons had posed it, in other forms, to previous generations. But the scientific revolution had brought new tools of analysis and in 1916 an English engineer and aeronautical theorist named F. W. Lanchester, seeking to rationalize the airplane's place in warfare, applied them.

Lanchester analyzed two cases. In the first, it is assumed that two forces fight a general engagement in which each unit is able to direct its fire at any unit of the opposing force. Lanchester's Square Law states that, under such conditions, fighting strength (measured by ability to inflict casualties) will be proportional to the product of the ratio of the fighting values (in essence, firepower) of the two forces and the ratio of the *squares* of their numbers. Thus if the two forces are of equal numbers but each unit of A's force can deliver twice as much aimed fire as each unit of B's then fighting strength will be 2:1 in A's favor. But with equal unit fighting value, a force with twice the numbers will enjoy a 4:1 advantage. In the case of what Lanchester called the Linear Law it is assumed that circumstances permit only unaimed area fire, or only one-to-one combats between individual units. Here, Lanchester showed, fighting strength is simply proportional to the product of the ratios of the fighting values and the numbers engaged. Thus in a Linear Law case an inferiority by, say, a factor of two in numbers could be made good by a like superiority in firepower per unit; in the Square Law case a two-fold inferiority in numbers could only be balanced by a four-fold firepower advantage.

Thus Lanchester found not *a* relationship between numbers and firepower, but *two* relationships, their applicability depending upon the conditions of the combat. Clearly the Square Law was the more dramatic and surprising result and it has ever since appealed to analysts as representing the way things *ought* to be. Indeed, Lanchester himself characterized the Square Law as representing the conditions of "modern" war (already in 1916), while stigmatizing the Linear Law as embodying the conditions of ancient combat.

Lanchester bolstered the credibility of his Square Law by applying it to Nelson's tactical scheme at Trafalgar, showing that Nelson's plans were precisely those of a commander trying to optimize under the Square Law, and that the results were entirely consistent with the theory. But Lanchester did not present any real statistical evidence to support his theory, and indeed, very little relevant evidence of any sort was available in 1916. Half a century later, however, with a considerable body of statistics about a broad spectrum of land combats in hand, doubts began to spread. In truth, very few of these combats showed anything at all like Square Law behavior. To the extent that there was any discernible regularity in the data at all, the Linear Law seemed to provide the better fit. But neither model fitted well. These discoveries have been widely interpreted as discrediting the Lanchester theory of combat. Yet the theory can not possibly be wrong in the usual sense: Lanchester's mathematics were, at least in this case, quite impeccable. What is wrong is the *assumption* that it will always, or even usually, be possible to achieve the kind of concentration of fire that lies at the heart of the Square Law.

C. A Reification of Lanchester's Concepts, Taking Account of the Element of Choice in Fire Concentration

That battlefields are confusing places is, of course, proverbial. For most combat units, opportunities for deliberate, aimed fire are infrequent. Under such conditions it is scarcely surprising that combat results do not conform to the Square Law. More surprising is that anyone ever supposed they would. Actually, Lanchester (who was an extraordinarily clever man) seems never to have entertained any illusions that the ordinary run of land combats would conform to his Square Law. It must have seemed very natural in 1916 to suppose that the clearer, cleaner arena of air combat would permit a great measure of concentration of fire; indeed, it still seems so to many people.

Where Lanchester may perhaps be faulted is on his failure to carry through fully with his theories. He had already hypothesized that Nelson, who probably did not know what differential equations were and almost certainly had not used them for tactical analysis, had nevertheless possessed a very perfect and exact understanding of the implications of concentration under Square Law conditions. Was it not reasonable to go on to assume that even a commander of lesser genius would see that to allow the enemy freedom to fire deliberately and selectively at his force would be undesirable, particularly if the enemy already had a numerical edge? And did this not imply that commanders would always seek to vitiate the essential condition for the operation of the Square Law by making it difficult for the enemy to concentrate his fire?

A really clever commander, of course, may go a stage beyond this, arranging to permit his units to concentrate their fire while forcing the enemy to fire blind. This is the essence of a well-conducted ambush for instance. This is a case not analyzed by Lanchester, but his methods may be used to show that in such a mixed Square-Linear situation the larger force may easily be destroyed by the smaller.

In extending Lanchester's analysis to consider explicitly the whole range of possible relative abilities to selectively and deliberately direct fire at individual enemy units–and the impact of strategic and tactical choice upon those abilities–we cast the whole question of concentration in an entirely different light. In the classical view, what counted was numbers at the point of contact. Lanchester's original formulation amended this to include firepower as well as numbers, with the relationship between them determined (from among two possible cases) by the circumstances of the combat. Now we can envision many possible relationships, chosen by circumstances much within the control of the commanders. Moreover, in certain of these circumstances it is possible in theory (as we know it to be in truth) for a force inferior both in numbers and firepower to defeat one superior.

In one sense we have now come full circle to another doctrine of classical military thought: that everything depends upon the commander. But this extended Lanchester theory has important specific implications about the nature and limits of effective command. Specifically, the crucial task of the commander is to order things so as to minimize the enemy's opportunities for accurate, selective fire and to maximize his own. With sufficient advantage in fire concentration he may overcome any given discrepancy in numbers and firepower. But the greater the discrepancy in numbers and firepower, the greater will be the advantage in fire concentration necessary to prevail, and the greater the penalty if the necessary advantage is not achieved.

Lanchester's methods can be used to give this argument a mathematical form. But the resulting equations, like Lanchester's, contain parameters which can not independently be estimated for any particular combat. With the addition of an infinite range of possibilities for fire concentration, and with fire concentration entering as a dominant independent element, the possibility of statistical validation of the extended Lanchester theory seems to vanish. Pending a possible future quantification and independent measurement of the relative ability to concentrate fire, those who seek empirical confirmation or denial of this extended Lanchester analysis will have to content themselves, as Lanchester did, with examinations of particular cases.

D. Abstract Analysis of the Value of Technological Innovations, Based on the Extended Lanchester Theory

Generalized theories of combat have always been of relatively limited use to commanders who must solve a succession of particular and unique combat problems. But in trying to decide which kinds of systems and forces ought to be developed and acquired to meet future naval needs we face a very generalized problem, for which a theory of broad generality and great explanatory power may well prove the best possible guide.

The extended Lanchester theory tells us that the factors of importance in deciding the outcome of a combat are: numbers of units *at the point of contact;* firepower; and the ability to direct accurately aimed fire against the enemy; and the ability to prevent the enemy from directing accurately aimed fire against our own forces. These factors are by no means additive or independent; each can greatly modify the operation of the others and each can, in sufficient measure, overcome a deficit in the others.

Obviously, the implication is that an innovation is valuable just in proportion as, given some fixed level of resources, it permits enhancement in one or more of these factors without commensurate degradation in the others. But note that what affects the combat outcome is not the absolute magnitudes of the factors but, rather, their relative magnitudes in comparison with the opposing force. Thus, one seeks not simply to have *large* numbers at the point of contact but *superiority* in numbers, not simply *heavy* unit firepower but *superiority* in firepower. *An innovation which permits both sides equally to augment their numbers at point of contact, or unit firepower, will benefit neither.*

The effects of uniform changes in the factors affecting concentration of fire are more subtle. An innovation which permits both sides equally to direct their fire more selectively and accurately will tend to move the conditions of the combat closer to those of Lanchester's Square Law and must, as a consequence, operate to the advantage of the side able to bring greater numbers to the point of contact. Correspondingly, an innovation which uniformly reduces fire concentration would work to the disadvantage of the side having local numerical superiority, because it introduces conditions closer to those of the Linear Law.

But *the truly significant innovations are those which alter the factors asymmetrically, as between the opponents: those which bring essential and inherent changes in the balance of ability to concentrate numbers, or in firepower, or, especially, in the opportunity to concentrate one's own firepower while simultaneously limiting the enemy's fire-power concentration.*

CHAPTER II

HISTORICAL ANALYSIS OF THE IMPACT OF TECHNOLOGY FROM 1600 TO 1945

A. 1600 - 1850: Change in Tactics Without Change in Technology

In this chapter we review some naval history to see how it has been shaped by technological innovation, with special emphasis on the cases in which innovations have tended in some significant way to tip the balance toward one side.

In truth, technology has always been of the first importance for naval war: even the earliest of ships and naval weapons involve very remarkable technology. Many technological innovations brought major changes in naval warfare long before the industrial revolution. In some cases technological and tactical innovations were fused to bring a decisive advantage to the innovating force–the Korean "turtle ships" of the Sixteenth Century and their employment by Yi Sun-sin against the invading Japanese seem to provide a particularly notable example.

Our purposes, however, will best be served by concentrating on the technological changes that have come in the wake of the industrial revolution. These lend themselves to analysis both because they have been so numerous and because we possess relatively good historical evidence about them. The industrial revolution was a long time in reaching navies: ships and weapons at the end of the Napoleonic Wars in 1815 were somewhat larger and more refined than those which had fought the first Anglo-Dutch War 160 years earlier, but not fundamentally different. Yet, in certain ways naval war had changed quite a lot in this period, technological stagnation notwithstanding.

Through the Seventeenth Century and nearly to the end of the Eighteenth it generally proved impossible to fight sea battles through to a decisive conclusion, even with a considerable disparity in force. (Of course, battles which were quite indecisive tactically could and often did have far-reaching strategic consequences.) There were important differences of degree: a de Ruyter or Niels Juel or Hawke could inflict disproportionate punishment where lesser commanders could achieve only an even exchange. But the bulk of both forces almost always escaped to fight again. The exceptions, such as La Houge and Quiberon Bay, generally involved fleets trapped by geographical features.

With the coming of the end of the Eighteenth Century a series of British commanders–Hood, Howe, Jervis, Duncan, and, above all, Nelson–introduced purely *tactical* innovations which allowed far more decisive results. Their tactical schemes all differed, but all involved exploitation of asymmetries of mobility to achieve local concentration of force against exposed portions of the enemy fleet. They depended in some measure on the superior standards of discipline and seamanship of the Royal Navy, but much of their success sprang from sheer tactical insight. Camperdown and Trafalgar, in particular, probably represent the closest approaches to victories of pure maneuver, uninfluenced by considerations of concealment, known to military history.

The point of recounting these well known facts of naval history is to emphasize that major changes in the conditions of war can be effected without any help from technology. Thus, when we observe an important historical effect we must exercise care in assigning causes.

In contrast with the tactical progress towards the end of the Eighteenth Century, the strategic conditions of naval war had scarcely changed, in many important respects, since the Phoenicians. The fundamental strategical problem of naval war was (and is) that of finding the enemy: in most cases the ratio of force to space is miniscule. In Nelson’s time, as in Themistocles’, a commander at sea could know what was happening beyond the range of vision from his ship, or from those in immediate company, only through dispatches physically transported, most usually by other ships. Similarly, he could communicate with distant subordinates (or superiors) only by dispatch. The vessels which carried these dispatches were never substantially faster than the fleets whose tidings they carried: the differences in speed between ships of various types was, in strategic terms, slight.

Now let us suppose that a scouting or outlying force were to gain information about a hostile squadron and dispatch a report to a higher commander. If the dispatch vessel must sail a distance D at a speed V, it will take a time $T=D/V$ to do so. When the higher commander receives the dispatch he will know the position of the enemy squadron at a time T ago. But in the interval the enemy squadron can have been sailing at a speed similar to that of the dispatch vessel, which means that it can have covered a distance of $TV=D$ from its reported position. That is to say, a commander’s uncertainty about the position of a hostile (or friendly) force at sea not under direct observation was always at least of the order of its great circle distance from him. Similarly, delays in communication with distant friendly units were proportional to distance (with a constant of proportionality, in Nelson’s time, typically of the order of 0.20 h/km). And, unlike the case of contemporary land warfare, there was no force with significant superiority in strategic mobility, able speedily to exploit any information which did become available.

In such conditions it may seem remarkable, at first, that unwilling opponents could be found at all, given the vastness of the sea. But logic (or secret intelligence) might tell a commander that the enemy fleet could only serve its country’s war aims by achieving objective A, and that in order to do so it must pass near point X. By stationing his own force at point X, then, the commander could be certain of meeting the enemy sooner or later. In many cases such methods proved entirely reliable and adequate. The real difficulty arose when the enemy was fortunate enough (or wily enough) to have several attractive objectives in hand, or widely varying alternative routes to the same objective. Before both the Nile and Trafalgar, for instance, Nelson had to spend several months searching for an enemy whom he assessed as having various possible objectives. Nelson made it clear that he found the prospect of battle something of a relief after the long strain and anxiety of search.

It does not appear that the naval strategists of the late Eighteenth Century were better able to find their opponents than had been their predecessors in the mid Seventeenth Century, when due allowance is made for the overall strategic conditions. It is difficult to see, on the whole, how their performance could have been improved except by better luck (or better spies). Thus we are entitled to conclude that *the possibilities of strategic concentration were limited by fundamental technological factors.*

B. 1850–1914: Revolutions in Communications, Vehicles, and Weapons

Conditions in the long peace following Waterloo did not encourage vigorous exploitation of new technologies for naval warfare. It was not until after 1850 that steam truly displaced sail as the primary propulsion for major warships. Then the pace of innovation quickened as admiralties took up first steam propulsion and then improved artillery, armor protection, and metal construction. Some innovations were taken up eagerly, in hope of advantage, and others reluctantly, out of fear of loss. Both motives were sharpened by occasional incidents in which the side with obsolete equipment was mauled for its sins. But while failure to keep up with the pace of innovation could lead to much unpleasantness, there is little to suggest that any of those who forced the pace in the second half of the Nineteenth Century managed thereby to gain any lasting advantage over any major opponents. Indeed, one of the major implications of Mahan's arguments, advanced near the end of the century, was that all the new technology which had so bemused his contemporaries had had little or no effect on the strategic balance, which was still determined by much the same factors as had operated in the days of sail.

Mahan was no mossback. He understood quite clearly that the tide of technological innovation could not be stemmed, let alone turned back. He simply thought that the essential strategic conditions of naval warfare could not be effected by technology. But in his first major work, *The Influence of Sea Power Upon History 1660-1783*, Mahan observed, rather offhandedly, that an enemy blockading the eastern coast of the United States might well take advantage of submarine cables to maintain telegraphic communications between various detachments so that, "If, by some fortunate military combination, one detachment were attacked in force, it could warn the others and retreat upon them." This was in 1889, and submarine cables already girded the world, tying all major cities (and ports) together in a relatively reliable and rapid communications network.

So, for the first time, messages could travel faster than ships. It would appear that Mahan did not recognize the full significance of this development, which altered one of the oldest and most central verities of war at sea. While no major conflicts were fought in the cable era (that is, before cables had been supplemented with radio), there is little doubt that cables alone could have profoundly affected the strategic balance by making it easier for the stronger force to find and concentrate against the weaker.

In the late 1880s Herz demonstrated in the laboratory the reality of the electromagnetic waves whose existence had been inferred from Maxwell's theory. Less than a dozen years later the Royal Navy was successfully employing Marconi radio sets in a major exercise at sea–a remarkable record for dispatch in putting a newfound scientific principle to practical military use. By the outbreak of the Russo-Japanese War in 1904, all major navies had radio-telegraph equipment fitted aboard most cruisers and larger ships. Its major value was seen as the improvement of cruiser scouting efficiency by permitting rapid reporting of contacts, and it was in this role that it was chiefly employed by the Japanese during the conflict. The Japanese equipment was not really first class, giving ranges of only about 60 miles, but the organization and discipline of their naval radio service was superb, and they used it freely and effectively. Admiral Togo depended on radio communications in his dispositions, and was not disappointed. The Russians, whose radio service was woefully inefficient, got much less value from their radio communications. But they did on occasion get a good deal of value from intercepts of Japanese transmissions, several times slipping away from Japanese searches. And, in at least one case, Russian jamming of Japanese transmissions prevented effective shore bombardment.

Fundamentally, Togo used radio to improve his fleet's ability to concentrate. With radio communications, he was able to hold the bulk of his forces together at a favorable location and still feel confident of sufficient warning to be able to bring the enemy to action regardless of his movements. But in a few cases (not, unfortunately for them, the decisive ones) the Russians were able to employ intelligence derived from Japanese communications to evade contact altogether. Thus the earliest uses of radio in naval war foreshadowed many of the themes seen in later conflicts.

The next major development in naval technology was the submarine. The submarine is nearly unique in the history of naval technology in that it was quite deliberately created to fulfill certain tactical and strategic aims and largely did so, if not always precisely in the fashion intended by its inventors. The tactical aim was the creation of conditions in which the submarine could deliver deliberate, aimed fire, while its opponents would have to reply blindly. On the strategic level the submarine was to prevent the enemy from concentrating against it by keeping him in ignorance of its location until it chose to attack.

Hot on the heels of radio and submarines came aircraft. Neither the airplane nor the airship was initially envisioned as a naval weapon, but both were taken up by navies, if not with universal enthusiasm. The chief interest was in scouting, exploiting not only their speed (which was not, at first, so much in excess of that of fast warships) but their height of eye. A few officers, however, early developed enthusiasm for airplanes as weapon carriers, to attack ships.

C. Surface Forces in World War I: Information Advantage Proves Insufficient Without Mobility Advantage

Radio, submarines, and aircraft were not the only technological developments engaging the interest of navies in the period immediately preceding World War I. The battle fleets were reshaped by developments in gunnery and fire control which greatly increased effective engagement ranges. Torpedo craft flotillas were introduced, ready to attack by shock or by stealth, day or night. The steam turbine brought improved speed and endurance for surface ships generally. Most thought these developments at least as important as radio or submarines. Yet it was radio and submarines that tilted the balance in World War I. The submarine began the war by achieving several quite unexpected successes in sinking warships. Mines also took a worrisome toll. While neither inflicted major casualties, fear of them immobilized the battle fleets to a considerable extent. Where surface forces did meet, it proved almost impossible to achieve a tactical decision (although, as in the Seventeenth and Eighteenth Centuries, tactically indecisive battles could have important strategic results). The principal exceptions were Coronel and the Falklands, both marked by substantial technological disparities between foes and a notable lack of mine or submarine threat.

With close blockade precluded by the mine and submarine threats, it would seem that the weaker German battle fleet should have had a good deal more freedom than it would otherwise have enjoyed. But in fact this freedom was largely vitiated by radio. For one thing, radio permitted scouting submarines and aircraft to relay reports quickly. But by far the most important contribution came from communications intelligence. Through direction-finding, traffic analysis, and cryptology, the British usually gained early notice of German sorties. As the conflict wore on, the Germans, too, developed a communications intelligence service, and became correspondingly more aware of what their own communications might reveal. Both sides devoted great effort to communications security. But far-flung operations by massive battle fleets frequently demanded some sort of radio communication. And the sources of possible compromise were so numerous and subtle as to defy human control. Thus each side generally received some indications of the other's movements through communications intelligence. The British continued, for the most part, to hold an advantage in the efficiency of their communications intelligence service (although this was sometimes vitiated by their lack of an effective and integrated operational intelligence organization and their resulting failure accurately and promptly to assess the clues provided). But of what use was it? In more than four years of war the Grand Fleet brought the High Seas Fleet to action exactly once, at Jutland–with total casualties only about 11% of forces engaged (in terms of tonnage). At first glance it appears that both battle fleets were useless ornaments, with the Germans at least able to claim the slim advantage of having tied up the large British investment with a somewhat smaller one of their own.

Yet the High Seas Fleet was roughly two-thirds as large as the Grand Fleet. (The ratio declined through the course of the war, as the British built faster than their opponents.) Historical experience from the era of sailing ships would have suggested that a fleet of such size should have been able to accomplish some important positive results, given the quality of the German forces and the advantages of initiative. In fact the High Seas Fleet never did anything of substance and the Grand Fleet largely achieved its primary mission of preventing the German battle fleet from threatening Britain's sea control despite its spotty fighting record. It has been argued that the Germans gave the Grand Fleet its strategic victory through their excessive caution. Yet the High Seas Fleet never had the first prerequisite for effective action: possession of the initiative. The German commanders appear to have had a reasonably accurate perception of the limits but never understood that their principal origin lay in British communications intelligence. Despite its failings, British communications intelligence was always good enough to prevent the High Seas Fleet from conducting any sort of campaign of maneuver: the only possible result of any attempt was a swift collision with a fully-alerted Grand Fleet, on terms of Jellicoe's choosing.

It has sometimes been suggested that, this being the case, the German commanders ought simply have mustered their courage and faith in German arms and sailed forth to meet the Grand Fleet on the best terms obtainable: defeat could not have worsened the German situation much and victory could have opened the way to knocking Britain out of the war. This may be, but it lies beyond our concerns with the impact of technology on naval war. Indeed, it is difficult to see anything in the technological situation that would have permitted decisive defeat of one well-conducted battle fleet by another, leaving aside the possibility of some Nelsonian stroke of tactical genius.

As it happened the British were the masters of communications intelligence. (And it truly was a "happening": no preparations of any sort were laid, pre-war.) But more equal success by the Imperial Navy probably would have brought them only very limited benefits. There could scarcely have been fewer fleet engagements, however perfect German intelligence, and the Imperial Navy could have had all the action it wanted at any time, with no recourse to intelligence whatever. The British experience at Jutland bears ample witness that communications intelligence was of little value in a purely tactical sense, given the conditions of that time.

D. The U-Boat in World War I: The Advantages of Stealth

While knowledge won the British a decisive (if inglorious) victory in the surface war, ignorance nearly brought them to total defeat in the submarine war. British policy was the same toward all naval threats, surface or subsurface: seek them out and engage them at every opportunity, giving them no respite. It was a most excellent principle, taken all in all–but the technology of the day afforded no means to carry it into practice against the submarine. There simply were no means to gain adequate knowledge of the submarine's position and movements, and without that knowledge, "offensive sweeps" and the like were empty gestures. "Adequate" is an important qualifier. Communications intelligence was just as effective in determining U-boat locations as in fixing the High Seas Fleet. But where knowledge of the High Seas Fleet's position to within 50 nautical miles would ordinarily suffice to ensure contact (given favorably placed forces), a U-boat stood a reasonable chance of evading World War I ASW forces who knew its position initially within five miles. Intelligence was rarely that good, and thus the submarine remained effectively invisible on a tactical level. The Admiralty could concentrate its antisubmarine forces in areas known to contain U-boats but the sub hunters were seldom provided with an opportunity for deliberate, aimed attacks.

Finally in mid 1917 the British, who were losing a quarter of all the merchant ships that sailed, shifted more to a defensive emphasis with the introduction of convoying. The value of convoys was not so much in the protection afforded by the escort ships as in the opportunity it provided to make the submarine search for targets. Instead of being able to lie in wait, confident that one of the thousands of merchantman at sea would soon come along, the submarine was forced to try to seek out one of a much smaller number of convoys. (The U-boats were pretty much on their own in finding prey, since the German high command had little intelligence of convoy movements.) World War I convoys averaged only about 15 ships, but this still must have reduced the rate at which a U-boat could expect to encounter targets by a factor of perhaps eight or so, since its sweep width against convoys was not very much higher than that against individual ships, especially given the visibility limits frequently imposed by North Atlantic weather. Thus the British were able to vitiate the U-boat's principal strategic advantage: its ability to concentrate against a dispersed foe. The U-boat largely retained its tactical advantage, but its overall effectiveness was nevertheless greatly reduced.

Sinkings of U-boats rose substantially in the last two years of the war, but this had little to do with the introduction of the convoying system. The convoy escorts could do virtually nothing to prevent torpedo attacks, once the U-boat had made contact with the convoy. Their major functions were to prevent gun attacks, enforce convoy discipline, and deliver vigorous counterattacks (usually by running down the torpedo wakes). They never became major destroyers of U-boats, even late in the war. More important were a variety of measures to destroy U-boats in transit, often relying on information about transit routes furnished by communications intelligence. Even in the final stages of the war, however, U-boat losses remained relatively light.

In fact the Allies never defeated the German submarine force, even though the resources they devoted to antisubmarine forces were easily ten times as great as those the Germans put into their submarines. Instead, they managed to reduce the threat posed by the U-boats to tolerable levels by playing on the submarine's difficulties in acquiring targets. At the same time, the British (and, later, American) authorities proved far better able to accommodate to shipping losses through improvisations and improvements in efficiency than the German high command had calculated. Thus the submarine must be recorded as a technological innovation which might perhaps have changed the course of World War I–but in the end did not. The fight against it called forth a great deal of technological effort by the Allies, but technology did not defeat it and did not even play a commanding role in containing it. The key to neutralizing the U-boat's threat lay in recognizing and accepting that the fundamentally defensive measure of convoying could more effectively reduce the U-boat's crucial strategic advantage in concentration than could any feasible offensive measure.

E. Developments in Naval Technology, 1918 - 1939

The interval between the two world wars, brief as it was, brought many changes in naval technology. This is all the more remarkable when we consider how little most navies had to spend on development during this period, at least by later standards. Much of what they did spend was devoted to the improvement of battleships. Advances in steam propulsion technology permitted a 50% increase in battleship speed, to the point where destroyers and cruisers enjoyed little or no speed margin over the most recent battleships. But these machinery advances were largely adaptations of technology developed for commercial electric utility plants; the major naval efforts came in the fields of fire control, projectiles, and ballistic protection. The advances in these areas were such that many officers were convinced, by the eve of the war, that engagements would commence at ranges as great as 35,000 yards, and that the weaker or less efficient force might be virtually annihilated before it could close to 25,000 yards. With the combination of such weapon capabilities and increased battleship speeds, it was widely expected that battle line actions would be far more numerous and decisive than they had been in World War I.

The naval weapon which had very nearly decided World War I, the submarine, underwent little fundamental technological change in the inter-war interlude. In fact the two mainstays of Hitler's U-boat arm (Types VII and IX) were modeled on World War I prototypes (UB III and U81, respectively), and embodied only relatively marginal improvements in performance.

To combat the submarine, most major navies had developed one form or another of shipborne underwater acoustic echo ranging gear–active sonar, in today's terminology. Trials were limited and the results had been spotty, with many unexplained anomalies in detection performance, but naval opinion in Britain and the U.S. generally held that active sonar would foredoom any attempts to use the submarine as a commerce destroyer, as well as making submarine attacks on the battle fleet a very risky undertaking. The possibility that U-boats would make attacks on the surface at night (rendering them undetectable by active sonar) was recognized, since they had done this in World War I, but this was not regarded as qualitatively different from the threat posed by surface torpedo craft, and was viewed with relatively little alarm.

In contrast to the submarine, aircraft had developed beyond all recognition between 1918 and 1939. The British DH-4, a standard attack aircraft of 1918, could carry a 145kg bomb load to a radius of about 115 naut. miles (210km) and attack at a speed of about 110kt (200km/h). The German Ju 88A-1, introduced in 1939, carried a 1400kg bomb load to a radius of 215 naut. miles (400km) with an attack speed of 195kt (365km/h). Most of this advance had actually been realized in the five years immediately preceding the outbreak of war. [And aeronautical engineering progress continued and even accelerated through the war, so that by 1945 the American A-26C carried an 1800kg bomb load to a radius of 775 naut. miles (1435km), attacking at 315kt (580km/h)]. These were standard service aircraft, representing application of the best proven aeronautical technology of their day.

Airplanes had accomplished little of substance at sea in 1914-1918 but by 1939 there were many who expected (or feared) great things of them. Exponents of air forces as an independent (and dominant) third arm generally envisioned air power as sweeping fleets away altogether, except for subsidiary tasks. Naturally, few people so disposed were to be found in naval uniform. General naval opinion was that aircraft were a useful and important auxiliary to the fleet but that anti-aircraft guns, supplemented with carrier-based fighters, would reduce the hostile air threat to the fleet to tolerable levels. The air power advocates were so confident (and so starved for resources) that they largely failed to develop any realistic tactics and equipment for attacking ships. It was evident to anyone who looked at a map that the 200 to 250 naut. mile radius of attack aircraft like the Ju 88A-1 was going to put severe restrictions on their naval effect, leading to an emphasis on larger, longer ranged aircraft for maritime roles. In 1939 the most notable of these was the American B-17B, able to carry 1800kg of bombs to a radius of 1000 naut. miles (1850km), and achieve an over-target speed of 250kt (465km/h). But the B-17, large and not especially maneuverable, was really only suited for medium-altitude horizontal bombing attacks. With the unguided free-fall bombs of 1939 there could be little prospect of hitting a maneuvering ship in such an attack.

Carrier-based fighters were obviously going to be important in protecting the fleet from air attack but the general opinion among naval men was that ships needed to be able stand on their own, and that adequate anti-aircraft armament should enable them to do so. A broad spectrum of AA guns was developed in the late 1920s and 1930s, ranging from 50 caliber machine guns (to ward off strafers), through heavy machine guns of 20mm to 40mm calibers (to engage dive and torpedo bombers), to heavier guns of 3" to 5" calibers in high angle mountings (to fire time-fuzed shells at distant and high-altitude aircraft). For the larger guns, very elaborate electro-mechanical fire control systems were developed, intended to determine the target's flight path in three dimensions, predict its future path, and direct the gun so that the shell's path would intersect that of the aircraft.

Regardless of the mode of combating it, it was clearly essential to detect the attacking airplane while it was still some distance from the fleet. Recognition of this fact gave much of the impetus to naval development of radar. But radar, like aircraft, was one of those developments which did not proceed out of any single need. By the 1930s, radio technology had reached a point at which efficient radars could be made and development blossomed, independently, at several centers around the world, for a variety of applications. The development would never have taken place (at least not at such a pace) without the applications–but most of the applications were latent and reasonably obvious, awaiting only the advent of a technological development that promised their fulfillment.

Radio-electronic technology advanced in other ways that were to have great impact on World War II. By 1939 much of naval radio communication had shifted to the high frequency radio band (3 to 30MHz). Ionospheric refraction of HF transmissions permitted communication over distances of thousands of miles with radio sets compact enough for shipboard installation. In planning their communications, all major navies were conscious of the dangers presented by communications interception and cryptanalysis. Interception and direction-finding of HF signals presented technical difficulties which were thought by some communicators to be practically insurmountable, or at least very limiting. The inherent difficulties were multiplied by using very brief burst transmissions. The Germans, in particular, hoped by these means to limit intercepts and fixes of their signals to no more than a small proportion of transmissions.

Great technical advances had also been made in message encryption, using electro-mechanical rotor cipher machines. Even where cipher machines were not widely employed (as in Japanese naval codes), crypto-security systems were frequently much better than those of World War I. The communications services of all major navies felt confident that their crypto systems offered complete security for practical purposes. But the inter-war years also saw profound developments in cryptanalysis. In part, of course, cryptanalysis benefitted from the same advances in electro-mechanical information processing that led to cipher machines. But the decisive advances were purely intellectual–the application of some of the most arcane and powerful concepts of modern mathematics. Much vital evidence has never been released, but from what has been said it appears that during the 1920s and 1930s two very small teams–one in Poland and the other in the United States–quite independently developed the mathematical and practical bases for successful attack on complex machine ciphers. The British contributions, while of great importance, appear to have come later, for the most part.

F. World War II: The Dominance of Air Forces Over Surface Forces

The events of the first few years of World War II showed very clearly that the technological developments of the preceding twenty years had indeed profoundly altered the nature and balance of naval war. Many factors other than technology were at work, however, and few students have made a serious effort to isolate the purely technological effects. One clear lesson was the absolute dominance of the aircraft. It very quickly became apparent that it was simply impossible for surface naval forces to defend themselves in the face of determined and well-conducted attacks by suitably equipped and trained air forces. First class anti-aircraft armament could raise the price paid by the attacking air force–but not to a level which made attacks on ships unprofitable. (The term “air force” as used here means simply a military force armed with aircraft, regardless of organizational subordination. Our interest here is in the strategic and tactical effects of aeronautical technology and not the theologico-organizational questions surrounding the “independent air force.”)

The success of aircraft against ships in World War II (which stood in sharp contrast to their failure to achieve much against ships in World War I) was due to a combination of several factors. First of all, even with free-fall unguided bombs a relatively small, agile, fast aircraft could deliver its ordnance with reasonable accuracy against a large ship, whose speed and maneuverability were by comparison necessarily very limited, without unduly exposing itself to the ship’s fire–especially if it attacked simultaneously with several other aircraft so that the ship had to divide its fire. And aircraft, with their advantage in speed and their ability to maneuver in three dimensions, could always count on being able to deliver concerted attacks, if properly handled, and need never fear counterattack from ships. This was the tactical advantage of the aircraft, its superior ability to concentrate fire against ships while avoiding concentrated fire from the ships. It was a very important advantage, but a somewhat fragile one, for there was always the chance that the efficiency of the anti-aircraft fire from the ships would increase enough to nullify the airplane’s advantage in agility. This was not inherently implausible, since aircraft had to release their weapons at short range and ships could carry very bulky and complex armament and control systems. In fact we may speculate that just such a thing might well have happened if naval ordnance bureaus had better appreciated during the 1920s and 1930s quite how fast aircraft performance could advance.

But air forces also held a great strategic advantage over ships in their ability to mass very swiftly when and where conditions favored their arms. When the target ships lay within range of the air force’s bases the aircraft could generally execute an attack within no more than hours of the decision to mount it. For instance the Ju 88A-1 could reach its mission radius of 215 naut. miles in a little over an hour, while the A-26C could fly all the way out to its 775 naut. mile radius in less than four hours. To brief the aircrews and arm and ready the aircraft might take a day or more under some circumstances but this could be compressed to one to two hours when necessary. When the distances to be flown were not too great the air force might well be able to make two attacks in a daylight period. The airplane’s advantages were enhanced by its relatively low cost; the price of a warship would buy 100 to 1000 aircraft. But the relatively short range of World War II anti-ship aircraft was a severe limitation–even 775 naut. miles counted for little in some of the major maritime theaters. Thus air forces had to go to sea on aircraft carriers, tying them to the surface forces they had rendered so vulnerable. Aircraft were also handicapped by their inability to attack effectively in darkness or conditions of low visibility, especially as ships could operate reasonably freely in these circumstances.

In order to make effective use of its swiftness in massing, the air force had to be supplied with good information about the target’s location and movements. The information provided by communications intelligence was rarely precise or timely enough by itself; usually some search of the region indicated by the intelligence was necessary before the air force could strike. Visual search could be quite inefficient, especially in adverse weather or at night, so that even sizable groups of ships could sometimes escape observation and, hence, air attack. But the fitting of search radars as the war went on made air search far more efficient and consistent, and greatly decreased the surface force's chances of slipping by unnoticed. Surface ships could survive by staying out of range of air attack, or by going within range only in darkness or severe weather. Otherwise, the ships had to have help from some arm that could engage the opposing air forces on more equal terms. In practice, this meant that the surface force had to have its own protective air force. Ideally, this protecting force would have the strength to gain reasonably complete control of the air, allowing the surface force to operate without concern for air attack. But of course under such conditions the surface force did not have to face enemy ships at all–they could have no hope of operating without the protection of their own air force.

Control of the air on any continuing basis was really only possible where the whole area could be covered fairly densely by fighter aircraft operating out of land bases. At the start of the war fighter radii for offensive purposes did not exceed 140 naut. miles (260km), meaning that standing air superiority could be exercised, at best, only over limited coastal waters. By 1944 aircraft like the P-51D could reach out to radii as great as 600 naut. miles (1100km)–a substantial advance, but still far short of oceanic ranges. In reality, the potential for land-based air superiority over the sea was even more limited than the radius figures would suggest. Before an intruding enemy air force could be engaged and driven off–the essence of air superiority–it had first to be found. To do so with standing air patrols relying on visual search would imply huge forces, which might still fail because of poor visibility. It was just this situation, of course, that had led to such despair about land air defense in the 1930s. But there was no way to build a chain of radar stations on the sea, as had been done on land.

Thus the conditions of the Second World War tended to make it most attractive for the surface force to take its protective air force to sea with it. Indeed, the air force that went to sea in order to extend its striking radius found it essential to include a substantial portion of protective fighters (which also had strike uses, of course) to preserve its floating bases. Conversely, having included aircraft carriers for protection, the surface force found overwhelming logic in equipping them also with strike aircraft and entrusting these aircraft with its primary long-range strike missions. By these means the naval striking force became, in most circumstances, identical with the carrier force; other types of ships could serve both offensive and defensive purposes best by helping to protect and support the aircraft carriers.

Thus aeronautical technology (specifically, those branches of it which dealt with fixed-wing airplanes) resulted in a sweeping change in naval warfare. More particularly, the change was brought by the advances in aeronautical technology between 1918 (when airplanes were proven to be of only auxiliary importance in naval war) and 1940. The advance which has attracted most popular notice is that in speed, which certainly had its significance, but the more important advance really lay in range-payload performance.

The advances in performance brought substantial increase in cost, but as noted above the price of a major warship still bought a lot of airplanes. This was very important, and if the technology had operated in such a way as to yield the same performance at ten or a hundred times the cost then the impact of aircraft on naval war would have been much reduced. After all, cost of production is no more than a convenient way of expressing the sum of the required productive resources. Since a nation's total supply of productive resources is relatively inelastic, even under the pressures of war, a greater cost per airplane would necessarily imply production of fewer airplanes. But any marked reduction in airplane numbers would have tended on the average to have lessened the weight of each attack, bringing a reduction both in hits on the ships and in the attacking force's ability to dilute the ships' anti-aircraft fire. It is impossible to estimate with any accuracy how much of an increase in cost would have been necessary to vitiate the airplane's advantages, but it seems safe to say that an increase by a factor of 100 would have sufficed.

The technology of aircraft advanced a good deal during the six years of war, as the comparison between the Ju 88A-1 and the A-26C suggests. Great efforts were made by ship weapon developers to gain a lead on aircraft performance. The latest aircraft always maintained an edge over the latest ship defenses, but the sheer proliferation of shipboard anti-aircraft guns could make things distinctly uncomfortable for attackers, especially if they were not of the highest standard of performance and could not muster large numbers of aircraft. This in itself tended to confer a certain level of safety upon strong surface forces at the outer edges of enemy air coverage, where they were subject to attack only by the longest-ranged, least agile aircraft, which were never more than a minor numerical component in any air force.

This prompted one of the few major qualitative technological developments of the air war: standoff weapons. The Germans were first, with their "Fritz X" (SD 1400X) and Hs 293 command-guided glide bombs. Brought into action in the Mediterranean in mid-1943 these weapons were extremely successful, sinking or damaging a number of warships (including the modern Italian battleship *Roma*, sunk 9 September 1943 by two Fritz X hits) and some merchant ships. As allied fighter cover improved, guided bomb attacks became riskier for the launching and guiding aircraft. But by the beginning of 1944 hits were becoming rare even when fighters could not prevent attacks. The allies had found that steering orders were passed to the weapons by a VHF radio link and had equipped some ships with powerful jammers. After a few months the Germans withdrew the missiles from service.

It is worth digressing to observe that this pattern of brilliant initial success followed, after a longer or shorter interval, by partial or total vitiation has been repeated by most of the guided weapons which have seen combat since these two pioneers. No “smart weapon” is one bit better than its resistance to guidance countermeasures or attacks on its launchers.

The U.S. also developed a number of air-launched missiles, but most were employed only against land targets. (The results often did not seem to realize the inherent potential of the weapons; one contemporary report observes dryly that things might have been different if heavy bomber units had been rated on how many targets they destroyed, rather than the weight of bombs dropped.) The single guided weapon to see anti-ship service with U.S. forces was one of the most remarkable technological achievements of the war: the Bat, a winged glide bomb with a self-contained active radar homing system! It was employed only in the last few months of the war against Japan and had no noticeable effect on the conflict. But it did work, sinking several ships. The Japanese utterly lacked the technical resources to counter such a weapon and it could have had a considerable impact if the war had taken a different turn.

It is sometimes remarked that U.S. World War II guided weapons developments appear relatively crude when compared with their German counterparts. This reflects in large measure the German advantages in aerodynamics and propulsion technology. But in guidance and control the U.S. was generally ahead–a lead it has never relinquished in the forty years since.

G. Submarine Campaigns in World War II

Painful experience soon showed that daytime operations by dispersed surface ships in areas subject to enemy air attack were prohibitively costly. But this did not apply to submarines, at least not at war’s outset. The principal problem for all anti-submarine forces, air as well as surface, was to find the submarine in the first place, and at that the airplane had no great advantage over the surface ship–their performance was about equally bad.

In World War I the U-boat force had never truly been defeated. It had, however, been stymied by the convoy system, largely because convoying made it far more difficult for the submarines to find targets. Admiral Dönitz was well aware that finding the targets was one of the keys to success and laid plans for integration of all information sources and centralized control of his U-boats. It all worked very well, after an initial shake-down period, thanks in large measure to the terrible inadequacy of British codes, which German cryptologists broke with ease. Even perfect reading of British messages (which often was possible) could rarely give information good enough for direct vectoring of U-boats to intercept convoys. But decrypts (and other sources of intelligence) frequently provided information that permitted the U-boats to make best use of their very limited search capabilities.

The average convoy size in the Atlantic area was about 30 ships and allied ASW analysts estimated that ships in convoys of this size ought to have been about ten times as safe as if they were sailing independently. The actual ratio of safety was nearer 5:1, and much of the difference was probably due to the effect of intelligence. But it was not enough to tip the balance for the U-boat force–by May 1943 the allied ASW forces had defeated the U-boats, which never managed to regain the initiative thereafter. Technology played a large role in the defeat of the U-boats, but there were so many innovations that it is difficult to sort out the effects. Probably the key innovations, roughly in order of importance, were: long-range aircraft, radar, advanced cryptanalysis, and active sonar.

While aircraft had only the most limited ability to detect submerged submarines, they were quite effective in finding surfaced subs, particularly with radar. Thus widespread air patrols had the effect of forcing the submarines to stay submerged, reducing their ability to detect their targets and greatly curtailing their mobility. This had already been noticeable in World War I, when it had been found that air escort of convoys made submarine attacks much more difficult and infrequent. But at war’s outbreak the mainstay of RAF Coastal Command was the Avro Anson, with a patrol radius of no better than 250 naut. miles. Based in England, such short-ranged aircraft could cover only the immediate approaches; no air cover could be given convoys in mid-ocean.

By 1943, however, the heavy bombardment air forces of the U.S. and U.K. had been persuaded (with great difficulty) to spare a few B-24 Liberator bombers, to be used as very long-ranged ASW patrol aircraft. With a patrol radius in excess on 1,000 naut. miles, and operating from the network of bases that had been built up in and around the Atlantic, the Liberators could cover convoys virtually anywhere they might be. The expanded escort operations of ASW aircraft in 1943, many with radar, brought both a reduction in successful closure by submarines and an increase in U-boat kills. Aircraft also operated with considerable success against U-boats transiting the Bay of Biscay. In addition to sinking a number of subs, they cut the productivity of the survivors by forcing them to slow submerged transit. At one stage the U-boats increased their anti-aircraft gun armament and attempted to slug it out with the aircraft, but only succeeded again in proving that ships could not stand against properly conducted air attacks.

The sanguine attitude of many German experts about the security of U-boat communications proved even more unfounded than the British confidence in their naval codes. As has now become widely known the British (building and expanding on foundations laid by the Poles) broke many of the “Enigma” machine ciphers which the U-boats used for most of their operational traffic. Of at least equal importance, the British intercept service was able in large measure to overcome the technical challenges involved in high-frequency radio direction-finding (HF/DF). In at least a few cases the British successes in breaking the German naval ciphers permitted direct ambush of German submarines. And after HF/DF sets started to be fitted aboard convoy-escort ships late in 1942 (no mean technical feat in itself) U-boats shadowing convoys and transmitting positions were sometimes caught by ships or aircraft following down HF/DF bearings. But for the most part the value of these and other forms of communications intelligence lay in their ability to indicate areas for more intensive search–and, often of greater value, areas which convoys ought to avoid.

The exaggerated hopes for active sonar entertained before the war by British naval authorities have already been described. Because it did not fulfill these, it has sometimes been thought that sonar played only a minor role. In fact, sonar was the only means most ASW units possessed to detect submerged submarines and, as such, was the primary tool for limiting the submarine's tactical freedom to fire its torpedoes selectively while enjoying virtual immunity from counterattack. (The largely wakeless torpedoes of World War II vitiated the 1917-1918 tactic of running down the torpedo track to counterattack.) What the pre-war enthusiasts had lost sight of was that active sonar simply could not have sufficient coverage to play any significant role in denying the submarine's strategic advantage of covert transit.

A number of other technological innovations played significant roles in the war against the U-boat. One of the most interesting (and least known) was the U.S. development of a passive acoustic homing torpedo for dropping from aircraft. This "Mark 24 Mine" (a label adopted as a cover), or "Fido" was the first automated homing weapon ever employed in war and sank 37 U-boats–5% of all the U-boats killed at sea. Many other very remarkable technical achievements contributed to victory in the Battle of the Atlantic, but not with the large-scale impact of the four mentioned above. Like the Mark 24, most came into service only after the U-boat force's offensive had been defeated and played their role in continuing to hold the submarine threat in check.

Much the same can be said in reverse of the impressive German advances in submarine technology and design. The schnorchel served to reduce U-boat losses to aircraft (which probably would otherwise have made continued operations simple suicide) in the last years of the war, but exacted a considerable price in reduced mobility. The anti-escort homing torpedo was another guided weapon whose effect was much reduced because of its vulnerability to countermeasures. The Walther system of hydrogen peroxide propulsion might have had a considerable impact, but was never developed into a workable system. (Postwar experiments in other navies tend to cast doubt on the fundamental operational feasibility of the scheme.)

One other innovation which deserves mention was the escort aircraft carrier, or CVE, used to bring ASW aircraft to places inaccessible to land-based aircraft. This has sometimes been described as having a great impact on the campaign against the U-boat, but the truth is that the CVEs arrived only when long-range aircraft were already coming into use. CVE-based aircraft were useful in screening mid-ocean convoys, but land-based aircraft enjoyed important advantages in strategic mobility and economy which caused them to dominate the air side of the anti-submarine campaign throughout the war. Aircraft from CVEs accounted for 7.5% of all U-boats killed at sea and thus were a significant factor in the campaign, but by no means a dominant one. Land-based aircraft made 37% of all kills (ships, 38%). In the pivotal year of 1943 land-based aircraft made 51% of the kills at sea while 11.5% fell to CVE aircraft.

All that technology could accomplish had not been sufficient to deprive the U-boats of their tactical and strategic advantages: in the end they were overpowered by the enormous resources devoted to the conflict by the U.S. and, especially, Britain. (Of U-boats whose destroyers can be assigned a definite nationality, 73% fell to British and Commonwealth forces.) The function of technology against the U-boat was to create the conditions under which numbers could have any effect at all; the experiences of 1916 show all too clearly how powerless numbers could be when means were entirely lacking to find submarines hiding in the depths or the dark.

The same lesson was taught, in large measure, by the most successful campaign of the submarine's history: that waged by the U.S. Navy against Japan in World War II, resulting in the virtually total destruction of the Japanese merchant marine. (Aerial mines played an important role by choking off the final trickle of supplies to Japan at the end of the war, but submarines sank 4.9 million tons of shipping to the 400 thousand tons that fell to mining. In only four months in the entire war did mines sink more tonnage than submarines.) The U.S. submarines were superbly fitted for the conditions of the Pacific war. (The tale of the early failures of their Mark 14 torpedoes is too dismal and well known to bear repetition here, although those who would achieve the desirable ends of shortening the acquisition cycle and reducing development costs by the dubious means of skimping on needed tests should be compelled to review it again.) Their possession of an effective radar in the last years of the war was a great asset, as it gave a considerable increase in their ability to detect ships, especially at night. Even toward the end of the war, however, visual sightings accounted for 70% of all ship contacts.

It does nothing to diminish the accomplishments of U.S. submariners, however, to observe that the weakness of Japanese anti-submarine technology played an important role in the victory. The Japanese never broke the U.S. crypto systems and seem never to have had enough information on U.S. submarine dispositions to permit any useful offensive action or evasive routing. Their radar developments were late and weak and they never allocated adequate air assets to ASW. Japanese sonars were not particularly good (although allowance must be made for the very poor sonar conditions that prevailed in many of the areas the Japanese had to sail in) and at one point U.S. subs actually made a practice of hunting Japanese escorts–quite successfully. Amazingly, the Japanese never even fielded intercept receivers to tune in U.S. submarine radars. In short, the Pacific campaign showed a submarine force operating with its natural advantages largely intact, only slightly diluted by enemy technological measures. The submarines sank 60% of the Japanese merchant marine–47% in just two years–and there is little doubt that they could quickly have finished off the rest, if others (largely airplanes) had not gotten to it first.

Of course there were many factors beyond technology at work in the submarine/anti-submarine struggles–and for that matter, beyond numbers. Neither the Japanese, Italian, nor Soviet submarine forces ever accomplished anything at all consistent with their numerical or technical strengths. But without the technological factor none of the others could have come into play at all: the submarine was itself a deliberate product of technology, and without adequate technology for submarine detection the valor and skill of the submarine's pursuers could count for nothing.

H. World War II: Lessons

The world wars of 1914-18 and 1939-45 were linked in many ways and in some respects can usefully be regarded as a single conflict, with an intermission. Certainly a great deal of the naval materiel used in the second war was left over from the first, or closely modeled on World War I equipment.

Yet the character of the conflict in 1939-45 differed markedly from that two decades before, being on the whole far more swift-moving and decisive. Also notable is that from 1940 through 1943 Germany was able very seriously to challenge British and allied sea power, actually wresting a large measure of control over some critical sea areas, *without* a fleet. This is in sharp contrast with World War I when the Germans had possessed a very strong fleet but proved much less able to contest Britain's control of the seas.

The sudden turn toward a more decisive mode of naval war is reminiscent of the events of the latter part of the Eighteenth Century, when tactical innovations brought far greater decisiveness to clashes between sailing fleets. The analogy should be sufficient to counsel some caution in ascribing the decisiveness of World War II naval conflict solely to the influence of technology. Yet it seems clear that technology at very least set the stage for the recrudescence of decisiveness in naval combat.

It did so by creating the conditions under which the more foresighted or fortunate commander might endow his forces with a very substantial advantage both in knowledge and in ability to exploit knowledge. Electronic intelligence could give knowledge of the position, disposition, and movements of a distant enemy without necessarily revealing one's own. Aircraft could strike at the enemy force thus found while the information was still fresh, before an enemy surface force could flee or strike. Submarines could *deny* information to an enemy, but it was the combination of aircraft and electronic intelligence that largely supplied the tools for making naval war so decisive in 1939-45–and for permitting the Germans to exercise a large measure of control in Norwegian waters in 1940 and over the Mediterranean in 1941.

The importance of technology was not that it *added to* information or *increased* swiftness but that it created a potential for major *disparities* in these qualities. Electronic intelligence helped Nimitz know that the Japanese would attack Midway–but left Yamamoto to suppose that the Americans knew nothing of his plans. Technology left ships with important and indispensable functions so that they had to be retained, but created airplanes which ships could neither flee nor stand against. Who had the wit or fortune to seize and wield these and other technology-created disparities could crush an opponent with little loss to himself and very possibly alter the course of a campaign or even a war in the process.

CHAPTER III
CURRENT PROBLEMS IN THE INFLUENCE OF TECHNOLOGY

A. The Methodology of Foresight

With sufficient foresight any of the world's major navies could have spent the money it had in the 1930s more wisely–in terms at least of effect on accomplishment of its country's war aims in World War II. Let us consider, for instance, the U.S. Navy. During the 1930s the U.S. Navy spent a large portion of its development resources on the improvement of technology and systems for battleships and cruisers, and devoted much of its procurement resources to building ships of these types. Now all these ships were useful in the war, and the more modern ones were perhaps somewhat more useful than the older types. But it would be difficult to argue, particularly in the case of the battleships, that the results represented a high payoff on the resources expended. In the one campaign to which the cruisers and battleships made a pivotal contribution–that for the Solomon Islands–far higher returns could have been realized through a much more modest investment in training and equipment for night action.

On the other hand, a very small increase in effort expended on submarine torpedo development and testing could have paid great dividends–destruction of the Japanese merchant marine hastened by many months. And more efficient shipboard anti-aircraft systems and radars might have saved the three aircraft carriers (more than a third of its carrier strength) the navy lost to air attack in the first year of the war. Beyond this, even, suppose that the navy had more fully exploited the available technology base in some other ways. What about an airborne radar that could have detected ships and surfaced submarines? Even if its bulk had restricted its application to seaplanes and large land-based aircraft such a surveillance tool could have had enormous effects on a number of important battles, not to say the U-boat campaign. Or what about a stand-off anti-ship weapon–a command-guided glide bomb–to transform the heavy bombers and patrol planes into a genuine striking force. These things lay within possibility in the late 1930s and could have had a great influence on the course of the war.

Such historical speculations are, of course, idle in themselves. But they serve to introduce and particularize the question: Could the leaders of the U.S. Navy (or any navy) have done better in its development and acquisition strategy simply by making more efficient use of the information then available to them? Our answer clearly must be that they could have. They could have started with the extended Lanchester theory of warfare presented in the first chapter–for this was derived from first principles, without reference to any specific historical experience. It would have told them, first of all, that the critical factors in war, so far as materiel is involved, are the degrees of *advantage* gained in: numbers of units *at the point of contact;* firepower; the ability to direct accurately aimed fire against the enemy; and the ability to prevent the enemy from directing accurately aimed fire against our own forces. The emphasis on *advantage* is essential: what is needed is not *large* values of these qualities but a large *disparity* in our favor.

So our minimum requirement should be that each development or procurement should contribute in one or another of these critical factors. But it is evident that we should wish to go beyond this and insist that indeed our developments and procurements should be those which *best* contribute to gaining the advantage. Suggestions of this sort always raise from practical military men the objection that we do not know the scenario of the future conflict for which we build and can not, therefore, say what is best. This uncertainty about scenarios is usually dealt with by concentrating resources on those types of systems believed to have proven of greatest value in the past, making such improvements as experience suggests as most useful within the limits of technological capabilities and available resources. In making the critical judgements the experiences of war (usually but not always the most recent war) are often supplemented with those gained through exercises and war games in which an effort is made to simulate what is known of the equipment and practices of potential enemies.

The objection that we do not know the scenarios is borne out by history: it is impossible to name a major naval conflict in the past two centuries in which naval authorities on both sides were not seriously surprised and embarrassed by some significant aspects of the actual course of events. The historical record is equally clear in demonstrating the inadequacy of the method of incremental improvements as a means of dealing with uncertainties about scenarios.

The problem is that the scenario *depends* in large measure on the technological choices we make: our decision to develop system X will affect, in general, both the developments pursued by potential enemies and also the manner in which they will employ their forces. Thus the procedure sometimes followed of picking a scenario or some small set of scenarios regarded as typical or representative and studying the impact of various patterns of development and procurement within the fixed framework can be dangerously misleading, for, as we have seen in our historical studies as well as through logical analysis, technological advances can have a profound effect on even the broadest aspects of strategic action and response. Scarcely less dangerous is the opposite procedure of selecting one or a small set of technological possibilities and studying the action and response patterns to which they lead on the assumption that the potential enemy will respond in kind: his best response may well involve another set of technological possibilities altogether, or expedients of a tactical or operational nature.

Thus in searching for the optimum among our military and technological alternatives we can not avoid the need to search simultaneously and conjointly through the entire range of both. Nor can we neglect to consider the military and technological alternatives open to potential enemies as well as ourselves, lest we fall into the trap of neglecting their possible responses. Given the broad range of possibilities potentially available even a few years in the future the dimensions of the problem grow vast: it is essential to have an efficient way to conduct the search. This is further complicated because it is not possible even in principle to write down a list of either the military or technological possibilities in advance; many (usually including the most important) are *latent,* waiting to be evoked in the minds of creative engineers and strategists by the stimulus of perceived need or, more realistically, *opportunity*. This if nothing else should deter us from any notion of finding the best solutions through exhaustive mechanized search, although computers can play important auxiliary and supporting functions.

In engineering work the role of scientific theories and models is to organize and guide the search for efficient and practical solutions. To fill this role in the search for military-technical solutions a theory must unite technological and tactical effects in a framework allowing for action and response. This criterion is met by our extended Lanchester theory. As this theory appears consistent with the historical evidence we are justified in regarding it as a potential basis for finding the solutions we seek.

It is immediately evident from this theory that the solutions which will produce desirable outcomes include those which:

- Give the commander the ability to know the position, movements, status, and disposition of the enemy's forces, while concealing the extent of his knowledge.
- Enable him to mislead the enemy concerning the position, movements, status, and disposition of his own forces.
- Afford him the opportunity to exploit such disparities in knowledge while they persist through swift movement.
- Make it possible for him to control his forces effectively.
- Permit his forces which are in contact to sense the enemy while remaining hidden from the enemy's sensors.
- Allow his forces to employ their weapons effectively while remaining out of reach of counter fire.

With deeper analysis we can derive additional information, such as the tradeoffs between the various properties–the extent to which it would make sense to give up advantage in standoff in order to gain concealment, for example. But the theory is at too high a level of abstraction to yield much concrete information, or to aid much in specific calculation of outcomes or figures of merit; its real value lies in the insights it provides about where to look for good solutions.

Certainly the ideas presented earlier about things the U.S. might profitably have done in the years just before World War II are consistent with and proceed naturally out of these insights. Moreover, it is clear from the actual course of history that they would have been valuable. This congruence between history and theory can not be guaranteed, of course–many factors affect the actual course of events that are in no way touched upon in our extended Lanchester theory–but neither is it entirely fortuitous.

Now in applying the theory it is essential to have a broad range of technical knowledge *and good technical judgement.* One must know, in the early 1930s, that airborne radar and radio command guidance are within grasp while, for instance, infra-red aircraft detectors and laser death rays are not. And one must have the judgement to make reasonable estimates of how much development effort will be needed to bring things to fruition and what sort of resources will be needed for production, operations, and support.

The number of people who possess such broad technical foresight is small, and very much smaller than the number who imagine that they possess it–most people do not know what they do not know. The value of this foresight is so great, however, as to suggest great efforts to nurture and exploit it. The most common deficiency is want of judgement concerning resources, especially about the resources necessary for development and production. This is especially critical because major underestimates of these resources can lead to an inability to complete programs as resources run short, while substantial overestimates (which are rarer but by no means unknown) can result in important programs never being undertaken at all.

Even the best of technical foresight does not extend very far into the future; it is probably accurate to say that no person alive in 1950 could have foreseen what the infant technologies of automatic computation, solid-state electronics, and photo micro lithography would combine to accomplish by 1980. This is not to say that people could not predict great advances in computation, for they could and did–but these were speculations for which no very concrete justifications could be put forth. Thus, for the longer run it is necessary to support a very broad range of programs aimed at building the technology base in general, often without any very clear idea about where a given program will lead or how we might be able to make use of its products.

But reasonably good judgement about what projects, if undertaken now, will yield what products within the next dozen years and at what cost is both essential and possible. It is a slow-developing growth, planted on a ground of analytical temperament and broad technical education, nurtured through technical and management involvement with the greatest possible number and range of development and acquisition programs, following them through from inception to completion. To possess it one must remember his failures as well as his successes.

B. Nuclear Weapons in Naval War

The real interest in our theory lies in its application to the problems not of the past but of the future. To a first approximation, commentators on current military technology may be divided into two classes: those who may tell all they know because nothing they know is of real importance, and those who know too much to be candid. Some of the reasons for and significance of this distinction will become clearer a little later on. In any event the author is compelled at this point to observe that he belongs to the latter category. This is meant not as any sort of claim of omniscience but only as an aid in understanding the limitations inherent in the remaining part of this discussion. It goes without saying that the opinions expressed here are in any case personal and not official.

In commenting on technology and modern war one must begin with the observation that the great division in contemporary military thought is one of technological origin: nuclear war versus non-nuclear war. The distinction is sometimes treated as being more hermetic than is altogether reasonable, but there is no denying that the character of all war, including naval war, depends very greatly on whether nuclear weapons are employed.

If madmen were to employ nuclear weapons in a contest of unlimited annihilation, as some expect, then naval war, like all other human activities, would become irrelevant and quickly impossible. Many believe that *any* use of nuclear weapons, however limited initially, must quickly lead to this, through some blind, irremissible escalatory process. (Some, indeed, believe that this process would inevitably take hold in *any* conflict between "superpowers," even if initially limited to non-nuclear weapons. This makes the concept of naval warfare virtually a nullity; those who hold this faith are accordingly invited to read no further.) Obviously, however, it is impossible to cite any direct historical evidence for this theory. Since there has moreover never even been a convincing psycho-social mechanism advanced for the necessary development of the dementia involved in the escalatory process, we are free to speculate on the possibility of purely tactical employment of nuclear weapons–employment only against targets of recognized military significance under circumstances in which the collateral damage will not be sufficient to threaten the basic processes of civilization and the mechanisms of social control which have heretofore served to place some limits on the ferocity of war. (The author does not in any way wish to *advocate* tactical use of nuclear weapons, only to admit the possibility that they might be so used.)

It is possible to imagine essentially non-destructive tactical uses for nuclear weapons–high altitude bursts to disrupt high-frequency radio communications by disturbing the ionosphere, for instance. Also conceivable are destructive but non-lethal modes of employment, such as widespread destruction or at least disruption of electronic equipment through generation of violent pulses of electromagnetic energy. Such possibilities should not be dismissed too lightly, nor should their potential effects on naval war. But the major impact of nuclear weapons would come with their employment against naval units and facilities.

In the at-sea aspects of a tactical nuclear war we can see a significant asymmetry. Submarines and airplanes can in general be destroyed without particular difficulty with conventional explosives; the problem with these targets is to locate them and to get a weapon into the proper vicinity. Thus against airplanes and submarines, nuclear weapons can be expected to make only a relatively marginal difference. Ships by contrast are comparatively easy to locate and to guide weapons to, but not to kill–both their inherent damage resistance and their powers of self defense make attack with conventional weapons costly and uncertain. Thus nuclear weapons, which can give a single-shot kill even when exploded outside the range of much of ships' self-defense armament, are very advantageous in attacking ships.

This would seem to suggest that a nation which relied, as Nazi Germany did, on submarines and land-based aircraft would enjoy an enormous advantage in tactical nuclear naval war over a nation more dependent on ships. Before we can conclude this, however, we must consider how far bases and facilities on land can be considered immune from or invulnerable to nuclear attack. If the answer is, "not very far," then we can expect war at sea to degenerate very rapidly into a matter of lone-wolf operations by submarines, groping for targets in the absence of outside surveillance or communications support. By the same token, destruction of port facilities could largely choke off ocean commerce, depriving naval operations of much of their point. In any event, the naval advantage in a tactical nuclear war seems to lie with the side whose aim is sea denial, rather than sea control.

There are certain technical options for hardening ships and vital shore facilities to resist nuclear attack. The literature on ship design contains references to strengthening structure to resist blast over pressure and thermal radiation, provision of sealed "citadels" within which crew members can fight protected from fallout (and chemical and biological weapons as well), water wash systems to decontaminate topside areas, and formation of Faraday cages around electronic equipment to shield it from electromagnetic pulse (EMP). Clearly, such measures can make a worthwhile difference in particular cases. Given the clear limitations on the extent to which they can be applied in practical ships, however, and the gigantic power possible with nuclear weapons, it is doubtful whether they can make a decisive difference in force capability in the face of nuclear attack.

Much the same can be said, *pari passu*, of critical shore facilities: the greater freedom available in hardening these is somewhat counterbalanced by the ease with which nuclear weapons may accurately be guided to them.

If one can not survive as a hedgehog or an armadillo then it is perhaps best to play the chameleon. One recipe for survival in nuclear war is to prevent the enemy from knowing where you are. Indeed, this is an important option in modern naval war generally, which we will explore at greater length. First, however, we should deal with the question of surveillance.

C. Surveillance

It bears repeating: the fundamental strategical problem of naval war is that of finding the enemy. Up to about 100 years ago it was usually possible only to reason out where the enemy *should* be on the basis of logical inference from his known or presumed strategic objectives. The introduction of electronic communications brought many new sources of intelligence, most notably those deriving from intercepts of enemy communications. But while they could be decisive on occasion, these new sources of intelligence left a good deal still to be desired as means of surveillance: their information was not sufficiently regular or predictable in its arrival and often too vague, inaccurate, or delayed to be of much use. Moreover, there was always the awful risk that if the enemy *knew* how you were gaining the intelligence he might be able to plant false information and thus draw you into a trap. Thus a great deal of effort has been devoted to other means for surveillance and intelligence gathering at sea. While the undertaking has not claimed a major share of naval budgets, the total resources devoted to it over the past quarter century have run to many billions of dollars. This naturally has not gone unnoticed and the popular and semi-technical literature on naval matters makes many references to surveillance and intelligence gathering systems with arcane code names and misty powers. Almost all of it is wrong to the point of being ludicrous; it is absolutely impossible to make any valid assessment of naval surveillance capabilities and potentials on the basis of what has been published.

Many people find this difficult to credit: the data published on ships, aircraft, weapons, even ship and aircraft sensors, are generally reasonably complete and accurate; why should those on surveillance systems be so different? First, the technology involved in surveillance systems is usually a good deal more recondite, and thus more difficult for outsiders to evaluate. But more importantly, reliable data on any naval system can usually be traced in one way or another to official sources; in the case of surveillance systems there is often no official admission of their existence, let alone any description of their construction or operation. There are several excellent reasons for this official reticence. First, and perhaps most important, the function of surveillance is the creation of *disparities* of information. Now if A knows B’s position when B remains in ignorance of A’s, there is a disparity of information. B’s knowledge that A knows his position does not void the disparity, but the disparity certainly is greater if B is unaware of A’s knowledge, and greater still if B is falsely convinced that A is also in ignorance. (The ultimate degree of disparity is achieved when B further falsely believes that he knows A’s position.) Obviously then, our ability to create desirable disparities of information will be enhanced by keeping the enemy in ignorance of our surveillance systems, and may be still further enhanced if we can actively mislead him.

Further reason for secrecy may be found in the seemingly inherent weaknesses of surveillance systems as a class. All surveillance sensors (and indeed, all sensors of whatever kind) face the problem of distinguishing “signals” (energy received from the target or sources associated with the target) from “noise” (energy received from all other sources). Signals necessarily arise from some characteristic or characteristics of the target, and target characteristics, as a class, are all mutable, at least in principle. And there is always the possibility that the enemy might deliberately create noise with especially target-like features to confuse or mislead the surveillance. These problems are compounded by the long signal propagation paths that are more or less unavoidable for a sensor intended to provide surveillance over broad areas of ocean. In any event, wide experience with such sensors has yet to show one which is not subject to disturbances, upsets, or outages of various sorts. Every such peculiarity is a potential weakness which an enemy might exploit if he knew how–so obviously we must do everything possible to prevent him from knowing how.

Of course secrecy is not the only way in which navies attempt to compensate for the necessarily fragile and adventitious nature of surveillance. Diversity and, especially, complimentarity are important elements in surveillance architecture. Most desirable is the situation in which the enemy’s efforts to avoid detection by one surveillance system must necessarily increase his exposure to another. Failing this, one must strive at least to ensure that no countermeasure can be effective against all one’s surveillance sources. But what one does in practice is limited by physics and technology, resulting, perhaps, in irremediable lacunae. These must be papered over especially carefully through secrecy or indirection.

Thus every consideration leads us to an iron law concerning dissemination of information about surveillance systems: It is good that an enemy (potential or actual) be kept in ignorance of a surveillance system’s peculiarities, better that he not know what signals the system looks for, better still that he remain unaware of the system’s existence altogether, best that he believe such a system to be physically impossible. Military authorities even in the most open of societies are generally of the opinion that the people’s right to be defended takes precedence over their right to know the necessarily recondite facts about their country's surveillance systems and hence feel no compunction about suppressing, manipulating, or even (where necessary) falsifying news of these systems.

This ought to ensure that everything that is publicly known about surveillance systems falls into one (or, preferably, both) of two classes: the obvious and the untrue. This is not quite the case, principally because even important officials sometimes do foolish things. Since fools are not to be trusted and wise men sometimes act the fool for devious purposes, however, it remains dangerous for outsiders to tread beyond the solid ground of fundamental physics in discussing surveillance–and often difficult for them to discern just where solid physical ground ends and speculative marsh begins. Remaining safely at the level of the obvious, we can observe that, living as we do in an age in which electronic technology will continue to flourish, it is inevitable that there will continue to arise new opportunities for innovation in surveillance–and in means for denying or deceiving surveillance. We may be sure that great strategic benefits will continue to accrue to the side which seizes these opportunities most promptly and effectively.

D. Vehicles

The disparities in information created by surveillance and denial of surveillance are inevitably transitory, so that the value to be derived from them depends upon the commander's ability to exploit them while they last. We have seen earlier how the World War I Royal Navy, possessed often of excellent secret knowledge of High Seas Fleet movements, was unable to force a decisive engagement out of lack of any force which could respond quickly enough.

In speaking of war at sea, where man may neither walk nor build, the concept of force is inextricably bound up with vehicles. (One must acknowledge, however, that sometimes the vehicles are expendable and integrated with weapons, and that the time is rapidly approaching when these weapon-vehicles will in some cases have transoceanic range.) The characteristics of vehicles which exert the greatest influence over the promptness with which a commander may exploit a disparity in information are those which pass under the rubric of mobility. Mobility is a matter not only of speed but of range and endurance–and other things as well. In truth, what a commander demands of his forces in a strategic sense is not a certain set of technical characteristics but the capability of massing in the necessary strength at the point of his choosing, to remain until the need for action has passed. Many things may affect this capability in this circumstance or that and thus take on great strategic importance, but the triad of speed, range, and endurance are of pivotal importance over a broad range of circumstances, and it is these that we shall take as comprising mobility for purposes of abstract discussion.

E. The Pursuit of Advantage in Mobility

The vehicle which comes to mind most immediately in connection with naval war is the ship. (Indeed, it is still a near-universal custom to denominate a nation's naval strength almost solely by the number or tonnage of its warships.) As a class, ships are incomparable in respect to endurance. Long range also is characteristic. But in speed they have been wholly eclipsed by aircraft. We have seen that as soon as aircraft ranges had grown to be of the same order as the typical separations between strategically-critical points of land, (that is to say, by 1940) commanders began to exploit their speed advantage to throw masses of them against ships, generally with devastating results. Now it clearly is not quite accurate to say that the airplane of World War II enjoyed an absolute advantage over ships in mobility; while superior in speed it was generally inferior in range and much inferior in endurance. But its range was often adequate for the geo-strategic situation and its short endurance was compensated by its swiftness of action–while its speed advantage was so great that ships could be regarded, to a first approximation, as standing still for the duration of its flight. For many strategical purposes this did indeed represent superiority in mobility. Of course the airplane's lack of endurance could be a strategical disadvantage when the commander did not know where and when to dispatch his forces: ships were far better adapted to sitting around a convoy, waiting to receive an attack, for instance. But this is simply to say that air forces tended naturally to be employed in situations of strategic advantage while the characteristics of ships tended to relegate them to situations of strategic disadvantage.

Nuclear power has now raised the practical cruising speed of major warships to nearly twice the values typical 40 years ago, and extended the range of warships very greatly. In the same period the typical cruising speeds of ship-attack aircraft have rather more than doubled. More significant, the operating radii of some ship-attack aircraft have now reached values comparable to the dimensions of many major ocean basins. Thus aircraft have maintained or even increased their speed advantage while greatly reducing the areas in which ships can operate without fear of air attack: air forces have retained their strategic concentration advantage over surface forces while extending its area of application.

By exploiting surface effect technology to its fullest, surface forces might double their cruising speeds once more, although this would entail great reduction in range and endurance, substantial operational limitations, and a major rise in costs. But the technical barriers to doubling aircraft cruise speeds are substantially lower, and without penalty in range. Indeed, the Lockheed SR-71 reconnaissance aircraft, developed more than fifteen years ago, has demonstrated that it is able to cruise at speeds in excess of 1600 knots (more than triple typical ship-attack aircraft cruise speeds) over transoceanic ranges. There is no reason why such an aircraft could not be employed for ship attack, if the need arose. In practice, however, the speed advantage even of current aircraft is so great that a doubling of ship speeds could probably be accommodated with only the most marginal penalties in air force strategic concentration capabilities.

It is worth digressing to observe that the SR-71, the Anglo-French Concorde and Soviet Tu-144 Charger airliners, and (possibly) the Soviet MiG-25 Foxbat interceptor are the only in-service examples of "super-cruisers"–aircraft which preferentially cruise at supersonic speeds. The distinction to be drawn between a supercruiser and the many other bomber and fighter aircraft which are capable of supersonic dashes is one of efficiency in supersonic flight. A supercruiser can fly as far or further in supersonic flight for a given amount of fuel as it can in subsonic flight–and approximately as far as an optimized subsonic aircraft of similar size. By contrast, the typical fighter or bomber can fly only one-half to one-fifth as far supersonically as it can subsonically.

Now as observed above, there is no reason in principle why a ship-attack aircraft could not be designed as a supercruiser. Supercruisers, however, are a good deal more costly than subsonic aircraft, even when the subsonic aircraft are designed for brief bursts of supersonic speed. It is for this reason that all existing ship-attack aircraft are fundamentally of subsonic design. But with today's technology it would be possible to build a supercruise interceptor with an intercept radius of 1500 to 2000 nautical miles at a speed four to five times as great as the cruising speeds of subsonic ship-attack aircraft. Clearly such a supercruise interceptor would enjoy much the same kind of potential advantage in strategic concentration over subsonic ship-attack aircraft that subsonic aircraft enjoy over ships. Actually there is nothing new in this: the Lockheed F-12 interceptor of the mid-1960s (the interceptor counterpart of the SR-71) would, if it had been produced, have had a large measure of potential strategic advantage over subsonic aircraft–it was intended to have an intercept radius in excess of 1200 naut. miles (2200km) at Mach 3. But in either case the interceptor's mobility advantage yields only a *potential* for strategic advantage–its realization depends strongly on the extent, reliability, accuracy, and timeliness of surveillance and tracking of the subsonic prey. With their very limited endurance and restricted ability to search for their fleeting targets, super-cruise interceptors are even more dependent on good surveillance and direction than ship-attack aircraft.

It is well known of course that subsonic ship-attack aircraft can successfully be intercepted by subsonic fighters, with a supersonic dash capability being useful to the interceptors in some cases. What is not so clearly understood by those who have little experience in these things, however, is just how limited are the circumstances under which such intercepts are possible. In general the interceptor will need to be supported by exceptionally effective surveillance and direction, and even so will not be able to effect intercepts at radii of more than a few hundred miles from its base. Thus conventional interceptors can not be said to possess any marked *strategic* advantage over ship-attack aircraft except when special geo-strategic circumstances limit the area of conflict very sharply. For this reason, attempts to counter air attack over any large area (as could well be necessary in any widespread naval campaign) usually involve expedients such as continuous rotating airborne patrols or distribution of interceptors among a number of dispersed bases. These expedients inevitably dilute concentration of the interceptor force and may easily pass the advantage of concentration to the ship-attack air force.

From a technico-strategic point of view there can be no doubt that the correct solution to the problem of the ship-attack air force lies in opposing it with a force of much more mobile interceptors (supercruisers are the only immediate possibility; the longer-term prospects for long-range anti-air missiles will be taken up in a later section) guided by an efficient, broad-coverage surveillance and direction service. Given the expense of developing supercruise interceptors and the unvarying desire to devote greater resources to systems of traditional type, however, there is bound to be strong opposition to such a step, despite the clearly ruinous consequences (to those who place military reliance on ships) of failing to counter the ship-attack air threat and the clearly ruinous costs of attempting to counter this threat in ways which accept a disadvantage in strategic concentration. Fortunately for the West, the peculiarities of its geo-strategic situation may permit a halfway solution: because the Soviet Union's ship-attack air forces (which pose by far the most serious potential threat to western naval forces and sea routes) have relatively long and constrained transit corridors through which they must pass, it may be possible to achieve a not too-unfavorable balance of strategic concentration against them with a moderately-dispersed force of high-performance interceptors of traditional type, given highly efficient surveillance and direction and access to suitably located bases. Whether this would in fact be less costly than an equivalently-effective solution using supercruise interceptors is not clear at this time, but it might be quicker to implement.

With advanced-development technology, efficient interceptors with speeds as high as Mach 4 to Mach 4.5 (2300 to 2600 knots or 4200 to 4800 km/h) and intercept radii of 2000 to 2500 naut. miles might be built. Further development effort might bring still greater mobility performance in the future: aeronautical theorists have investigated aircraft with cruising speeds as great as Mach 10 to Mach 12 (5700 to 6900 knots or 10,600 to 12,800 km/h). Burning liquid hydrogen and flying at altitudes of the order of 100 km, such aircraft might hurtle halfway around the earth in less than two hours without refueling. The technical difficulties of flight in this regime are immense, however, and the likely costs correspondingly astronomical. It may well be that needs for travel at such speeds and over such distances will be met, with lesser efficiency but also at lesser cost for development, by descendants of the space shuttle, spending much of their transits beyond the sensible atmosphere. But there are also ways to exercise naval force at a distance without employing vehicles, in the usual sense, at all; we discuss these below.

Where vehicles are involved, their bases always represent a potential vulnerability. Mobile logistic support and nuclear power have diminished the importance of forward bases for ships and submarines, but not entirely. Aircraft, because of their limited endurance, are more sensitive to base attack or denial. Thus, the Allies finally sealed their control of the Mediterranean in 1943 by overrunning the Luftwaffe's bases on its southern littoral. But the great advances in aircraft range have made it possible for many aircraft bases to be placed far from the theater of conflict, where they are protected by the full mass of rear-area defenses. Not only does this make attacks on them difficult and very costly, but the massive, dispersed nature of airbases on land tends to limit the damage which may be done by reasonable non-nuclear weapons. In recent years special measures have been taken to further harden airbases regarded as especially exposed.

Nevertheless, airbase attack remains a serious concern, especially for shipboard aircraft. This has led to an increased interest in aircraft which make minimum demands for bases–specifically, vertical take-off and landing (VTOL) aircraft. Unfortunately, VTOL aircraft must almost always pay a rather substantial penalty in size, fuel consumption, complexity, and cost when compared with conventional aircraft of otherwise comparable technological level, mobility characteristics, payload, and mission. The resulting exacerbation of demands for logistic support tends in large measure to vitiate any potential for increased dispersal, except in special cases. One such case is that of ships where, if one is ready to accept a substantial increment in ship size and cost to accommodate the aircraft and their support, it is possible to base a small number of aircraft on each of many dispersed ships. This is the present-day analog to the carriage of low-performance float planes by cruisers and battleships so commonplace fifty years ago. (The analogy is sharpened because it is indeed usually necessary with VTOL aircraft, just as it was with floatplanes, to accept some considerable sacrifice in mobility and payload performance in order to achieve tolerable size and cost.) It can be of considerable interest in those cases where a small number of aircraft of limited performance can perform some function of real military value–but, now as half a century ago, such cases are anything but the general rule in serious naval conflict. In most circumstances, we can feel certain, our enemies will, by themselves pursuing strategic advantage through superiority in concentration, compel us to do likewise if we are to prevail. Thus the technical deficiencies of the VTOL airplane, sometimes dismissed as marginal or insubstantial, are in fact sufficient in most cases to debar it from serious consideration.

F. The Influence of Stealth on Strategic Concentration

Disparities in strategic concentration can be secured by coupling an advantage in knowledge with an advantage in mobility, but this is not the only road to that end, and mobility is not the only quality of vehicles which may contribute to achieving it. Specifically, given the pivotal role of surveillance, the vehicle property to which the word “stealth” has recently been attached can be of great importance. We are fortunate in possessing a wealth of historical evidence about the impact of stealthy vehicles, since stealthy ships–submarines–have been in service for more than eighty years. As has been observed earlier, the stealthiness of submarines greatly reduces the opportunities their enemies have to concentrate against them. It is also true that submarines have sometimes been able to sneak up upon or ambush ships of substantially greater speed potential, simply because the target was caught unawares. On the whole, however, historical and kinematic analyses have shown that maintenance of a speed greater than that attainable by the submarine has offered relatively good security, at least in transit, even with no means of submarine detection whatever. This is clearly a general truth about the limits of stealth in positively aiding concentration.

To the extent that they can actually achieve stealth, ship-attack aircraft could reduce the possibility that forces with still greater mobility could intercept them, while also avoiding any compromise of their offensive capabilities. This is too great a promise to be passed by lightly, so it is probable that nations with a strong interest in attacking ships will pursue stealth technology for their aircraft with considerable vigor.

As noted above, in functional terms a submarine just is a stealthy ship; there may be secondary reasons for trying to make surface ships *per se* more stealthy but it does not appear that the results of any such efforts can have strategic characteristics fundamentally different from those of submarines, which probably will continue to represent the limiting case of stealthiness. But it must always be borne in mind that stealth is only a *conditional quality* of vehicles, depending not only on the vehicle's characteristics but also on those of the surveillance systems it is intended to defeat. This suggests that officials can be expected to treat the stealth characteristics of vehicles with the same secrecy and indirection attending discussion of surveillance. It may well prove extraordinarily difficult for fully-informed officials, let alone the general public, to form an accurate impression either of our surveillance systems' capabilities against a potential enemy's stealthy vehicles, or of our stealthy vehicles' ability to avoid detection by a potential enemy's surveillance.

For a submarine (or any other vehicle) possessed of perfect stealth the relative mobility of its opponents is irrelevant. The nearest approach to this situation in practice is seen in the ballistic missile submarine which is, in most cases almost entirely undetectable in any operational sense. Ballistic missile submarines normally patrol at very slow speeds in order to still the noises by which they might otherwise be detected. This automatically gives a substantial mobility advantage to any opponent, but the advantage is otiose so long as the submarine is in fact successful in remaining undetectable. But submarines which must actually fight in a naval campaign are quite another matter: they do not always enjoy the freedom, as SSBNs do, of remaining in areas remote from undersea surveillance, and their missions often require them to go fast (especially to chase surface ships), causing them to become much noisier and hence more detectable. At very least, they can scarcely avoid advertising their presence when firing their weapons–the sudden sinking of a ship in deep water without any visible agent is normally and properly taken as the occasion for a submarine hunt. We may characterize submarines (other than SSBNs) as *almost*-perfectly stealthy vehicles: usually undetectable, with occasional brief glimpses of visibility.

Paradoxically, the almost-perfect stealth of submarines increases the premium on mobility for their opponents–it is essential to reach the point at which the submarine was glimpsed as quickly as possible if one is to have any chance of locating and killing it. This is the chief explanation of the importance of long-range "patrol" aircraft (patrol is in fact the least and least useful of their anti-submarine functions) as submarine-killers which is observed historically and to an even greater extent in current analyses and exercises: it is simply that these are the anti-submarine vehicles with the greatest strategic mobility. (Other factors important in the long-range aircraft's anti-submarine success include the tactical utility of its speed for weapons delivery, its broad horizon circle when at altitude, and its low vulnerability to submarine counterattack–but these are distinctly secondary.) The prominence of the role played by long-range aircraft serves as an indicator of the balance in any submarine-anti-submarine campaign: when conditions permit the anti-submarine forces to make effective use of the aircraft's strategic mobility they are clearly winning; when the submarines manage to stay stealthy enough to escape attention from long-range aircraft they have at least the potential to seize the strategic initiative. A nation whose naval posture is weak in long-range anti-submarine air forces (or some other anti-submarine force, so far undiscovered, of comparable strategic mobility) is acknowledging that it has forsaken hope of any strategically-decisive action against non-SSBN submarine threats.

Again, the example of the submarine has given us a general truth about stealthy vehicles: against a perfectly-stealthy opponent, advantage in mobility is unavailing; against an almost-perfectly stealthy opponent, advantage in mobility is paramount.

The extent to which even perfectly-stealthy submarine forces can actually seize the strategic initiative will depend in very large measure on the price paid for stealth in terms of mobility. Submarine noise rises very sharply with speed, so that even "quiet" submarines may be detected and tracked at very great ranges when they steam at high speeds. If submarines were to be held to speeds no more than one-half or two-thirds those of their prey then their efficiency as ship-killers would be greatly reduced–so much so, perhaps, as to permit the submarine threat to be controlled if not defeated. (This was essentially the situation in the campaign against the U-boats in 1944 and 1945: Allied anti-submarine technology was inadequate for long-range detection of slow submerged subs, but neither were the U-boats able to find and sink targets very efficiently when forced to stay submerged and, hence, slow.) Slow, quiet submarines could, in principle, compensate for their immobility with highly mobile weapons (as ballistic missile submarines do), targeted with the aid of some external agency. Long-range weapons today are not themselves unduly difficult to detect, so that the submarine would in fact compromise its stealth in launching them, but the future may hold promise of stealthy weapons, too. In such a case much would depend upon the characteristics and vulnerabilities of the agency which provided the information for weapon targeting.

G. Economics and Dispersed Forces

The submarine was in large measure innovated originally in order to permit dispersed naval forces to operate successfully in an era when the possibilities for dispersed operations of surface ships were narrowing sharply. As the submarine was pursuing dispersed campaigns with considerable success in 1914-1918 and 1939-1945, the expansion of communications and surveillance, and finally the flowering of the aircraft, progressively rendered dispersed operations by surface ships in contested areas so hazardous as to become, in the end, almost suicidal. There is today a renewed interest in dispersed operations by surface ships, stimulated in large measure by developments in standoff weapons (of which more later). Clearly, any realistic hopes for such a revival must be founded in some scheme or another for overcoming the factors of efficient surveillance and swift concentration of force which doomed dispersed surface forces in earlier eras and now operate even more strongly. Public discussions of dispersed surface force concepts have not dwelt upon this issue but one forms the impression that dispersed surface ships are sometimes envisioned as simply swamping the opposing surveillance and ship-attack forces by sheer numbers, presenting more targets than can be tracked or destroyed in a reasonable time. In the absence of good public information about surveillance capabilities it is certainly possible to speculate that a substantial increase in the numbers of task forces at sea would indeed overwhelm them, although anyone familiar with the explosive growth in the electronics technology which underlies surveillance is bound to wonder whether it is conceivable that ships could be built or manned fast enough to keep ahead of it for long. As for attempting to overcome the great potential for swift strategic concentration inherent in modern ship-attack air forces by throwing masses of dispersed ships against them–this is the naval analog to the notion of charging machine guns with horse cavalry.

Many of the arguments often heard in connection with proposals for the resurrection of dispersed surface forces are properly neither military nor technological in character but, rather, economic–the potential enemy is envisioned not as being defeated militarily but as being bankrupted in his attempts to avoid defeat. Naval vehicles have come to cost so much as to make such ideas not entirely farfetched, acknowledging that there is a legitimate question about who will bankrupt whom. At the end of World War II a 60,000 ton aircraft carrier cost about $100 million, while today a 95,000 ton carrier costs roughly $3 billion. Thirty-five years ago 15,000 pound jet fighters were being bought for $100,000 or so; today one must pay $30 million for 45,000 pound F-18 fighters. Thus it would seem that the prices of carriers have gone from on the order of $1.5/kg to $30/kg–a factor of 20x–in the same period that jet fighter prices have soared from $15/kg to $1500/kg–a factor of 100x. Figures like these have sometimes been quoted as evidence that the costs of aircraft are rising much more rapidly than those of ships.

A somewhat different picture is painted when it is recognized that cruisers and destroyers could be built for $2/kg to $2.5/kg in 1946 while the most modern missile cruisers and destroyers now cost of the order of $100/kg–a factor of 40x to 50x. At the same time, the F-18 is scarcely a typical current jet fighter (in part because it is only just entering production); 69,000 pound F-14As at $28 million and 54,000 pound F-15Cs at $22.5 million both work out to about $900/kg, or about 60x more than 1945 prices. In fact if one compares the costs of very sophisticated ships (such as missile cruisers or antisubmarine frigates) with those of very sophisticated aircraft (such as all-weather attack airplanes) over the past two decades it appears that on the whole both have risen by approximately the same factor–10x. The past decade has seen an acceleration in price rises for both ships and aircraft, in both cases now reaching rates of roughly 20% per year!

The causes of these vast increases in costs have been much discussed but not very satisfactorily analyzed. Increasing sophistication accounts for some, but less than is popularly supposed: much of what is often passed off as increasing sophistication can be shown actually to reduce costs, and ships and aircraft whose characteristics have not changed materially in a decade have nevertheless experienced sharp price rises in that period–price rises that far outpace changes in prices in the economy as a whole. To assert that inflation has been especially severe in defense goods sectors is self-evidently true–but not very illuminating.

Logically, it is necessary to deal with the matter of vehicle prices in any discussion of vehicles in relation to strategic concentration; given some limit on resources, price can be as important as mobility in determining ability to mass force. The unsatisfactory state of understanding of the mechanisms underlying price movements places serious limits on the breadth or generality of what can be said. We can begin by repeating our earlier conclusion that the relative speed advantage of ship-attack aircraft has changed little since 1945–ships remaining essentially stationary targets in strategic terms–while their maximum ranges have been substantially increased. The increased ranges of ship-attack aircraft are fully usable in most geo-strategic situations, as they are only now approaching the dimensions of typical ocean basins. (The increases in ship ranges permit them better to avoid strikes by remaining in regions beyond range of air attack, but the increases are strategically *usable* in this way only where the geo-strategic situation permits the ships to make some important contribution while steaming in these remote areas.) If we take the range of ship-attack aircraft as having grown by a factor of about two–so that the area which can be covered by aircraft flying from a particular base is greater by a factor of four–we see that in the ideal or limiting case a force having a certain number of aircraft distributed in squadrons over a theater whose dimensions are large compared to an aircraft radius will be able to bring just as many aircraft to bear on a given target at short notice as would a force having four times as many aircraft each with half the range. We note also that the effective daily sortie rate for attack aircraft also has increased over the past 35 years by a factor of something like two times, so that a force of aircraft today can sustain the same weight of attack as twice as many could then. On this basis, we could accept that a diminution of the affordability of aircraft relative to that of the ships on which they prey by a factor of two or even a factor of four would not have been sufficient to reverse the change in strategic balance between ships and ship-attack air forces. As we have seen, the diminution of relative affordability has been very much smaller than this. We can not rule out the possibility that future increases in aircraft costs will be sufficient to damage their advantage in strategic concentration, but there is no reason visible at this time why they should.

Of course the same effect could be achieved by a reduction in ship costs, or at least a slowing in their rise so that it becomes much less than that of aircraft costs. Proposals are frequently made for reducing ship costs (and for reducing aircraft costs as well). Generally, on examination these proposals are found to turn on changes in requirements or design practices rather than in technology. Technological advances have played a worthwhile role in reducing the costs of certain shipboard subsystems and components, but the effects on total ship costs have for the most part been relatively minor in proportional terms. Some of the advances now available or visible for the future could permit development of ships (or vaguely ship-like vehicles) to operate outside of the presently-feasible mobility envelope, but none would substantially reduce the costs of ships operating within the present envelope. Confusion on this score sometimes arises because there are unexploited technologies which would permit reductions in ship *size.* (In many cases a considerable reduction in displacement could be achieved by building the hull out of aluminum, to give one example.) But in ships size is only weakly coupled with cost–so much so that attempts to reduce ship sizes by fiat have sometimes increased costs as designers adopted weight-saving but high-cost technologies. Thus again we can not rule out the possibility of substantial future reductions in ship costs relative to those of aircraft, but we can see no technological prospects at this time for accomplishing this.

H. General Conclusions About Vehicles

On the whole it does not appear that there is any technological prospect for overturning or even reducing the fundamental advantage in strategic concentration that ship-attack aircraft enjoy over ships. Indeed, likely growth in the effective radius of such aircraft will still further extend the advantage by reducing the extent of ocean areas out of range of air threat. At the same time it would be possible (assuming the feasibility of the necessary surveillance) to build an interceptor air force with sufficient mobility advantage over subsonic ship-attack aircraft to gain a substantial advantage in strategic concentration. The ship-attack air force could respond by increasing the speed of its aircraft, but the high costs involved would force a reduction in numbers which could diminish the air force's effective concentration advantage over ships. Or the ship-attack air force might equip itself with stealthy aircraft in order to nullify the interceptor air force's advantage in strategic concentration by denying it the essential surveillance information. But the effectiveness of this approach *might* be vitiated by some unexpected development in surveillance technology, and stealthy operation probably would exact some penalties in effectiveness or cost. The effect of the ship's disadvantage in strategic mobility could be reduced by application of stealth technology to ships (assuming this to be feasible), but this would in large measure be functionally equivalent to replacing ships with submarines, the original stealthy vehicles.

Decisive action against the submarine is only possible to the extent that its occasional lapses from stealth are exploited with vigor and, above all, swiftness. While strategic missile submarines can remain essentially perfectly stealthy and hence essentially perfectly invulnerable, this is not possible for those submarines participating in a naval campaign, which must move rapidly and launch weapons. Long-range stealthy submarine-launched weapons might give the submarine a capability for strategic concentration against ships without exposure (while reducing the submarine to a more passive, weapons-carrier role). In the absence of any possibility that submarines can match aircraft speeds, any submarine role against aircraft would turn entirely on long range surveillance and weapons; the technical obstacles seem overwhelmingly formidable.

I. Combat

Any student of naval history can cite many instances of hard-fought combats whose results were in no way decisive in a strategic sense. Other examples can be found in which strategically decisive results were obtained with little exchange of fire. It remains true in most cases, however, that combat is a necessary component of any decision in naval war, and that it usually plays a very important role.

By combat we mean here the destruction, capture, or damaging of enemy units by fire, contact, or other physical agency, thus excluding for the most part matters such as "radio-electronic combat" (except as it involves physical destruction of electronic equipment) or "psychological combat." This is not to say that non-physical or non-destructive forms of "combat" are of little significance–it is simply that in dealing with the implications of technology it is convenient to preserve the distinction.

The objective of the naval commander in committing his forces to combat is generally to destroy as much as possible of the enemy force while suffering the least possible casualties to his own. The relative importance of inflicting damage on the enemy and of avoiding it oneself will vary with the strategic situation, but it is always true that total destruction of the enemy without loss to one's own forces is the best possible result. Moreover, anything which allows us to inflict more damage on the enemy without greater loss to ourselves, or to reduce the loss to ourselves without lessening damage inflicted, is bound to be valuable. Of course the damage done to a force is often not simply a question of the number of units destroyed or put out of action–depending, rather, on which units are hit and their qualities and relationships to the others–but destruction of any additional enemy unit is almost always desirable, and loss of any additional unit of our own is almost always undesirable. These simple observations provide a framework within which to evaluate possible combat innovations.

A number of techniques have been used to permit units to attack without risk (or with little risk) of effective retaliation, including:

- Firing from positions out of reach to enemy weapons. This may be a simple matter of using longer-ranged weapons, or it may involve playing on some subtler limitation of the enemy's weapons.
- Employing vehicles too fast or agile to be hit by enemy weapons. For example, speed and maneuverability gave ships a measure of protection against attack by straight-running torpedoes, and shipboard anti-aircraft fire was only moderately dangerous to high-performance attackers at least up to the end of World War II.
- Taking advantage of natural or artificial screens interposed to shield one's units from view by the sensors upon which the enemy's fire control or weapon guidance depends. Thus submarines hide under water and torpedo craft made smoke to conceal themselves.
- Employing natural or artificial means to interfere with the physical operation of the enemy's fire control or weapon guidance sensors, as when an aircraft dives out of the sun, or a fire-control radar is jammed.
- Decoying enemy fire to valueless (or less valuable) targets. The best- known example probably is the Foxer underwater noisemaker used to decoy German acoustic homing torpedoes in World War II.
- Armoring or hardening one's vehicles so they will not be damaged, or not severely damaged, by weapons which do hit.
- Launching or deploying weapons or barriers to destroy enemy weapons en route. The anti-torpedo nets formerly deployed from capital ships are one example, and today's anti-anti-ship missiles are another.

It is not at all evident that these techniques exhaust the logical possibilities; it is certainly conceivable that there may be others. At the same time, however, they make a list of some length and diversity. In discussing the impact of technology on combat, therefore, we will be constrained by space as well as security.

J. Information Disparity and Fire Concentration

It is difficult to name a major action between ships in which greater range of armament on one side played a decisive role in itself. Perhaps the nearest thing would be the Battle of the Falklands in 1914, in which the British battle cruisers with 12" (305mm) guns held and endeavored to exploit a range advantage over the German armored cruisers whose heaviest guns were of 210mm caliber. But in truth much of the action was fought within range of the German guns, which made a number of hits. This was because, due to a combination of inadequate fire control technology and unfavorable conditions, the British ships were unable to obtain an adequate proportion of hits when firing at long range.

By contrast there were a few occasions in World War II in which one major surface force destroyed or badly mauled another which found itself wholly unable to reply effectively. Some examples include destruction of the Italian cruisers *Pola*, *Zara*, and *Fiume* by British battleships at the Battle of Cape Matapan; the Japanese victory at Savo Island; the U.S. victory at Surigao Straits; and the sinking of the *Scharnhorst.* These actions (and some similar ones earlier in this century) were all fought within range of the defeated force's armament. The victors in each case derived much of their advantage from having better fire control information–they were able to see an enemy who could not see them. The purest examples of this sort of situation are to be seen in cases where destroyers were able to deliver unopposed torpedo attacks because they had radar and their targets did not. These are all cases of *tactical* advantage gained through superiority in information, analogous to the strategic advantages we have explored earlier. It is clear that superiority in fire-control and target-acquisition sensors can contribute to combat superiority.

Much of what was said about sensors earlier in connection with surveillance applies equally here. In particular, anyone who finds a way to gain an advantage in fire control sensor technology is usually a fool to talk about it, so that no public forecast of such advantage is likely to have much value: those knowledgeable enough to make reliable forecasts will not publish them. Another lesson that carries over from the surveillance case is that of the importance of diversity and complementarity of fire control sensors.

But at best, reliance on superiority in technology for target acquisition and fire control is a very risky business. In many cases during World War II an advantage was gained through radar, but the long and dismal record of maulings of radar-equipped U.S. surface forces by radarless Japanese forces in 1942 and 1943 should serve to caution against any simple equation of superior sensors with military superiority. The Japanese benefited from superiority in training–particularly for night action–which frequently gave them detection performance comparable to what the U.S. was able to achieve with radar. In addition, of course, the Japanese enjoyed a marked superiority in torpedo performance as well as an important disparity in information: the U.S. commanders appear to have been unaware of the performance of the Japanese oxygen torpedoes until well into 1943.

K. Standoff Weapons: Determinants of Effectiveness

In fact of course, fire control information is never sufficient in itself; just as surveillance information must be exploited by highly-mobile forces so fire-control information must be exploited with weapons able to reach the targets. Indeed, mobility and especially advantage in mobility (relative to the target) are important qualities for weapons just as they are for vehicles. And they are very complex qualities which can be captured in simple quantities such as “range” only to a very limited extent. Mobility can play a large role in hitting, as in the case of an unguided projectile fired against a moving target where the faster projectile permits less opportunity for the target’s motion to carry it away from the aim point. But hitting is also influenced by the weapon’s ability to conform to the intended or predicted path. The best that could be achieved in terms of mobility and random path dispersion with unguided gun projectiles never led to very satisfactory results in firing against ships at ranges greater than 25 km (14 naut. miles), and the effective range even for large guns (in theory capable of 40 km (22 naut. mile) ranges) could be substantially less than 15 km (8 naut. miles) when conditions did not permit bias correction through accurate visual spotting of the fall of shot. Against aircraft, with their greater speed and agility, gun systems of comparable refinement were never good for ranges more than a fifth of these, and did well to get one hit for every thousand rounds fired.

But it was aircraft themselves which first demanded guided weapons. To begin with, World War II aircraft had no very accurate means of locating submerged submarines, creating a need (filled as previously related by the “Mark 24 Mine” in 1943) for a weapon which could search for and acquire the submarine after entering the water. Aircraft attacking ships or land targets normally had reasonable success in locating their targets–even at night or in bad weather, once provided with radars. But the dispersions involved in bomb-dropping could be very large: bombing from heights of 6000 to 8000 meters, World War II “strategic bombers” had to drop hundreds or even thousands of bombs to hit a small target–more yet if the target were a moving ship. Even reducing the bombing altitude to 3000 to 4000 meters did not permit effective bombing of ships. With smaller, more agile aircraft, bombs could be released from a steep dive at a distance of only a few hundred meters, giving reasonable hitting even against ships. But as the war progressed, anti-aircraft defense efficiency and intensity progressed enough to make these and other close-approach attack tactics quite hazardous.

The need to combine the accuracy of dive bombing with the relative safety of high-altitude bombing led to the development of guided bombs and missiles. These and their modern successors are often referred to as “precision guided weapons,” but the suggestion of the rubric–that they are remarkable chiefly for their accuracy–is misleading: their fundamental function is to preserve accuracy when launched at long range, making the alternative description, “standoff weapons,” more appropriate. Dozens of different types of standoff weapons were employed during World War II, and hundreds more since. Almost all of them are now as obsolete as the javelin. As a class, guided standoff weapons have had effective service lives far shorter than those of conventional weapons. It is often suggested that this is a reflection of the “immaturity” of standoff weapon technology (an impression strengthened by the popular misconception that standoff weapon development did not begin until sometime in the 1950s or even 1960s) and that standoff weapon designers will soon produce “ultimate” weapons able to overcome the limitations that have made their predecessors so short-lived.

We are compelled to question, however, whether these millennial standoff weapons will appear ever, let alone soon. As has been observed in Chapter II, many of the standoff weapons that have been employed in war over the past forty years have shown brilliant initial success, only to be faced with swiftly-mounted countermeasures which greatly reduced their effectiveness. The countermeasures have assumed a wide variety of operational and technological forms but most have been directed either at the weapon’s launch vehicle (or site) or its guidance system. The standoff weapon’s raison d’etre, of course, is to make it more difficult to attack launch vehicles, but the very destructiveness and expense of standoff weapons often makes it quite worthwhile for the enemy to make the effort to surmount this difficulty at the same time that standoff weapons of his own may make it more possible to do so.

But it is attacks on their guidance systems that have inflicted the most dramatic casualties on standoff weapons. Although they are widely touted as “smart weapons,” possessed of almost superhuman discrimination and judgement, all standoff weapons so far built or envisioned are in fact colossally stupid. Even the most sophisticated merely look for and fasten upon some very limited aspect of the target’s physical manifestations–its reflectivity in a certain electromagnetic frequency band, for instance, or its heat radiation at certain wavelengths. The subtlety and sophistication of their guidance systems has indeed increased as technology has advanced, but the same advances have equally served the development of guidance countermeasures. There is no clear physical basis for making general predictions about whether final victory will go to guidance systems or the countermeasures arrayed against them; so far as can be seen this will continue to be determined on a case-by-case basis, with the cleverness and foresight of the guidance system and countermeasures designers–and their intelligence and counterintelligence services–counting for a great deal.

Strategies for countering standoff-weapon guidance include raising the noise received by the guidance sensors until the target can no longer be distinguished (analogous to blinding an opponent with a strong light), providing false target-like signals, and reducing the target’s “observables” (that is, the physical manifestations looked for by the guidance) to such an extent that it fades into the noise. Obviously, these strategies may be used in combination: if the target’s observables are reduced then it will take less jamming to swamp them, or it will be less difficult to confuse the guidance system with decoys.

Destroying the standoff weapon's launch vehicle is the most decisive countermeasure and deceiving or blinding its guidance system is the most elegant, but there are other options. In some cases it has been possible to outmaneuver weapons, or to operate in a regime of speed and altitude (or depth) beyond the weapon's reach. (The most famous example is the use of maneuver tactics against Soviet SA-2 Guideline missiles.) A final option is to shoot back at the standoff weapons themselves in an attempt to destroy them in flight–usually with other standoff weapons.

In sum, we must conclude that the impact of guided standoff weapons is relative rather than absolute in nature–there are always limits, potential or actual, on their effectiveness. But they certainly have the potential to alter the relative advantage of various vehicle types and modes of combat, and thus to exert a profound effect on naval war. Let us consider the factors which affect a naval vehicle's susceptibility or immunity to standoff-weapon attack. First there is the question of permitted media for attack: earth, water, air, or space. In general the denser media place severe restrictions on weapon mobility. Although these can often be minimized by arranging things so that the weapon spends most of its transit in air or space, the weapon ordinarily can not begin its homing function (if its guidance includes such a phase) until it enters a medium which includes the target. This may be very important in connection with another factor: that of the target's speed and maneuverability. In general it is unrealistic to plan for naval vehicles to outrun or outmaneuver standoff weapons: facing lesser demands for range or payload, standoff weapons can in most cases be endowed with speed and maneuverability far more readily and cheaply than their prey. But speed and maneuverability *is* costly in terms of weapon expense and size, and tends to place limits on its range. Moreover, target speed and maneuverability increase the size of the volume of uncertainty–the envelope of points to which the target might have traveled in the interval between weapon launch and homing system activation. Obviously, the greater this volume the greater the demands that are placed on the weapon's guidance, and the greater the opportunities for guidance countermeasures. On the whole, target speed and maneuverability tend to constrain the effective range at which it is possible to employ standoff weapons.

A factor of great importance is the target's observability–its susceptibility to detection and tracking by the weapon's guidance and fire control sensors. Submarine and subterranean vehicles and installations enjoy the advantage of immersion in media in which known sensors do not function very effectively, while stealth technologies may confer comparable benefits on vehicles which extend into the air or space. Much will depend on the extent to which it finally proves possible to preserve stealth in the face of sensor advances. It is worth emphasizing in this connection that even without application of special stealth technology the delectability of vehicles tends to be far more strongly influenced by configuration and design details than by sheer physical size. Jet fighter and attack aircraft, for instance, typically have radar cross sections smaller than those of automobiles one tenth their weight, while the configurations of ships tend to drive their radar cross sections to enormous values.

Targets which can not evade or hide from standoff weapons may find it advantageous to shoot back at them. This is particularly true of ships and land installations where the weight of anti-missile systems can be accommodated without excessive costs. The costs of the anti-missile systems themselves tend to be quite high, however, because of the severe demands imposed upon them by the need to intercept substantial numbers of small, fast, agile targets which may appear in brief, concentrated bursts. Unless the enemy is somehow constrained in the size and density of his missile raids the defender is inevitably driven to a multi-layer defense in which the outer layers, in particular, involve systems of formidable complexity. The emerging technologies of high-energy lasers and charged particle beams may eventually bring new types of anti-missile weapons, but nothing seen to date suggests that they will be greatly more effective or economical than anti-missile missile and gun systems after due allowance is made for the sorts of protective measures likely to be adopted by designers of anti-ship missiles.

The final resort of the standoff weapon's target is passive protection, to enable it to absorb hits without serious damage. In certain cases vital land installations could be given protection which renders them invulnerable to any known weapon, including direct hits by the largest nuclear weapons. Even at more reasonable levels of expense, many types of fixed installations can be given very high levels of passive protection against explosive weapons through concrete and piled-earth bunkering. Vehicles ordinarily can not be protected to this extent, but still can have useful protection against light weapons and near misses and measures to mitigate the damage from hits by heavy weapons.

L. Standoff Weapons vs. Vehicles

Ultimately we can only assess the balance between standoff weapons and naval vehicles in quasi-economic terms, much as we would analyze the natural balance between competing populations of predators. We shall deal with each category of naval vehicle in turn.

1. Land Installations

Let us start with land installations, continuing our practice of regarding them as a sort of special category of naval vehicle. (It is well to remember that no class of naval force is truly "sea-based" and that thoroughgoing destruction or denial of its land facilities will quickly reduce any fleet to impotence.) As mentioned before, good passive protection can often be provided at reasonable cost for land installations, and active defenses against standoff weapons tend to be easier and cheaper to contrive on land than for vehicles. But in most cases the scope for employment of guidance countermeasures in protecting fixed installations is quite limited; against such targets standoff weapons frequently employ absolute or area navigation guidance systems which tend to have great countermeasures resistance. Moreover, against fixed installations whose location is known there is virtually no limit to potential standoff weapon range–the weapon does not face an uncertainty about target position which grows with range, as weapons which must attack vehicles do. Thus the weapons can be designed with whatever range is needed to penetrate the installation's defenses without hazarding the launch vehicle (or launch installation); there is nothing inherently impossible about a standoff of half the earth's circumference.

But in order to attack heavily defended, hardened land facilities the enemy will need large missiles (to get long range and carry enough payload to do any good against hardened targets) and a good many of them (to saturate defenses and provide sufficient damage). This is clearly a very expensive proposition. However, it is also true that many land targets are very important and expensive, and thus may be worth attacking even if the price is quite high. It would be virtually impossible to envision any practical means to defend and preserve most of the land facilities essential for naval warfare against nuclear attack. (Certain types of facilities can be protected by deep burial, where the great expense of this is warranted.) Yet many of these facilities are located in or near major population centers and attacks on them would be indistinguishable from general attacks on cities. This if anything would be what would drive men mad with pain and guilt and fury and despair so that they might wield those forces which would send us all "from light/ into the kingdom of eternal night." No man who holds his sanity does not fear it, and this of all things may preserve the race of Adam–and, quite incidentally, many installations. Of course these installations might yet be attacked with large numbers of conventionally-armed standoff weapons, using guidance accurate enough to avoid undue collateral damage. Even if it took 25 weapons costing $2 million each (as well it might) the attacker might consider it worthwhile to destroy a pivotal airfield, say, or some other vital installation.

Yet there is one factor, operating especially with land targets, which may sometimes tip the balance in their favor. In many cases there is no real limit to the extent to which land facilities might be hardened against conventional weapons, and often there is the possibility of adding further hardening relatively quickly by means such as changing dispersal patterns, laying on a few additional centimeters of concrete, or piling the earth another few meters higher. In these cases the defender can watch his opponent's standoff weapon developments, assess the effectiveness of their warheads, and then (if he chooses) add whatever hardening is needed within a few months. Since development and production of a new standoff weapon with a substantially improved warhead is bound to take years (and a great deal of money), this could easily be a no-win proposition for the attacker. For this reason there may be at least some types of land targets which can be made relatively safe from non-nuclear standoff weapons, simply because it could be made prohibitively expensive to try to develop the necessary weapons. On the other hand, installations of high value which are not suited to incremental hardening (or other short-term incremental protection) are inherently at considerable risk to standoff weapon attack and can be expected to stimulate the development and deployment of serious threats.

2. Ships

Turning to ships we find that the uncertainties introduced by target motion can take on considerable importance. Consider, for instance, a typical low-altitude cruise missile with a transit speed of Mach 0.6 (400 kt or 735 km/h near sea level) and a radar seeker which is capable of acquiring and homing on large ships lying anywhere within 20 naut. miles (37 km) of nominal aim point. If the target's position is known precisely at the time the missile is launched and if the missile navigates accurately but receives no aim-point updates in flight then the launch range can be no greater than 265 naut. miles (490 km) if the missile is to be reasonably certain of successfully attacking a 30 kt (55 km/hr) target. Given realistic values of initial target-position uncertainty (say, 5 naut. miles or 9 km) and missile cumulative navigation error (another 5 naut. miles, say) then the maximum effective range will be further curtailed (to 250 naut. miles or 460 km in this example).

Standoffs of this sort might well put the missile launch vehicles in some jeopardy, so that the attacker may wish for more. He has fundamentally three choices: increase the uncertainty the missile can tolerate by giving it more capability to search about its aim point, improve the aim point by tracking the target as the missile flies and radioing revised instructions to the missile, or hold time of flight constant while increasing the standoff by raising missile speed. (Other measures such as improving navigation accuracy can also be valuable and worthwhile but have only second-order impact.)

It is easy to see that the missile might be given more search capability by allowing it to fly higher and providing it with a longer-range sensor (e.g., a more powerful radar). Both these measures tend to increase the warning given to the target that it is under attack and, hence, to increase the missile's vulnerability. Moreover, adding search capability tends to make things more complex for the missile by increasing its chances of detecting ships other than its target.

For instance if the normal density of shipping in the area is one per 10,000 square naut. miles then a missile which searches out an area with a 20 naut. mile radius will have approximately a 13% chance of detecting a ship other than its target, while for a 30 naut. mile radius of search this rises to about 28%. Clearly, if it is not simply to be a random agent of destruction a missile with a large search capability must, if it is to operate in areas of any shipping density, be endowed with some means of distinguishing its intended target from ships whose destruction would yield small or negative benefits. Such discrimination can certainly be implemented, but it can be costly and can also introduce vulnerability to countermeasures (e.g., those which make the target ship seem like an innocent merchantman). Thus the combination of vulnerability and cost serves to exercise some constraint on the search capabilities provided in anti-ship missiles. Continuing advances in processing technology will perhaps tend to relax these constraints, but the concomitant advances in countermeasures will probably not permit great search expansion.

Aim-point updating is straightforward and attractive–but only if the attacker has a reliable and survivable source of real-time information about the target ship's position. The necessary radio communications to the missile also introduce a potential weak link. In most of the aim-point updating schemes so far put into service the launch vehicle (or some other vehicle working in cooperation with it) winds up having to close to within line-of-sight range of the target, which largely spoils the advantage of increased standoff. (Even at an altitude of 12 km the radar horizon lies only about 240 naut. miles or 445 km away.)

Increasing the speed of the missile (or, more precisely, increasing the ratio of its speed to that of its target) can do much to increase its potential effective range. Let us consider a few examples using the same missile sensor coverage (20 naut. miles radius) and target location error (5 naut. miles) assumptions as before. (Missile navigation error is neglected in these examples because if one is going to pay the price for the sort of speed performance we are considering then one will certainly want to pay the relatively small increment for a first-class navigation system.) Missile A, having a speed of 1500 knots (2780 km/h), could be launched up to 970 naut. miles (1795 km) from the 30 knot ship. With a speed of 3000 knots, Missile B can reach out to a range of 1935 naut. miles (3590 km). And with an average speed of 4.8 km/s (9,300 knots), Missile C can be launched anywhere within 6,000 naut. miles (11,100km) with assurance of reacquiring the target.

Now Missile A's speed represents Mach 2.3 at sea level or Mach 2.6 at 10 km. A missile of this speed (presumably cruising at altitude, with perhaps a sea-level final run-in) and a range of 1000 naut. miles is well within the current state of the art, although it would be substantially larger than a Mach 0.6, 250 naut. mile missile and would cost several million dollars. To build Missile B, with a range of 2000 naut. miles at Mach 5.2 at high altitude (low altitude operation at these speeds being out of the question), would be a very challenging and costly undertaking today, but by no means impossible. Missile C of course corresponds to a long-range ballistic missile. With a conventional warhead the re-entry vehicle would have to have a homing system and a substantial capability for endo-atmospheric maneuver, but this, while costly, would certainly be possible. In today's terms Missile C would probably cost $25 million to $50 million per round, but since it would largely eliminate the need for launch vehicles (let alone vulnerability of launch vehicles) and since its targets would be warships of great importance whose costs are measured in hundreds of millions if not billions of dollars, it is conceivable that such a thing may be thought worthwhile.

It is clear then that there is no real technological limit to the standoff distances which are possible for anti-ship missiles, and that even the economic limits are not very restrictive. For this reason, ship forces can no longer count on evening the balance between themselves and their attackers by exacting high casualties against the vehicles from which the attack is mounted; if needs be, the attacker can dispense with vehicles altogether, at least for missile launch. (Surveillance and targeting may be another matter.) In practice of course, attackers may well continue, either through inertia or overconfidence, to rely on launch vehicles which must approach to distances which subject them to counterattack. To the extent that they do so, launch-vehicle destruction will probably remain the best means to secure ship force survival and utility.

It is sometimes proposed that ship speed or maneuverability be increased as a means to counter anti-ship missiles. It is true that certain anti-ship missiles make use of the severely limited tactical mobility of conventional ships to simplify their terminal guidance problems and that a more agile ship might enjoy a measure of immunity to these missiles. But these missiles would soon be modified or replaced; given the costs of agility in ships and the rather low limits on what is possible in this direction, it scarcely seems worthwhile to pursue it. Of course greater speed increases the area of uncertainty which the missile must search out after any given delay in reaching its aim point. As we have already seen, this drives the attacker to measures which increase the cost of his attack. In most cases examined so far, however, the cost to the ship force to increase speed is greater than that incurred by the attacker in compensating for the increase. (But increased cost to attackers must be a factor when greater speed is being considered for other reasons.)

The most prominent means of self-preservation adopted by ship forces today is the mounting of armament intended to destroy anti-ship missiles in flight. These defensive anti-missile systems face severe challenges. On the one hand, high altitude missiles may approach at very high speeds, while on the other hand, slower missiles may approach at extremely low altitudes. In either case the effect is to provide only a very brief interval in which the defensive system may engage the attacker. There are defensive systems which can surmount these challenges, but they are very costly. Moreover, each has some finite saturation limit: there is some weight and intensity of attack with which it can not cope, so that attacking missiles will begin to "leak" past the defenses in large numbers. Because of the challenges facing these defensive systems it is almost always found that it is less expensive for the attacker to increase the severity of his attack than for the defender to raise the strength of his defenses. It is possible of course that some new technology will be found which will increase the efficiency of the defense without benefiting the attack, but there is none yet in evidence. A more immediate and concrete possibility is that the application of stealth technology to anti-ship weapons will still further increase the challenges facing shipboard defenses.

Traditionally, ships have also employed many measures to prevent, or at least limit, damage in event of a weapon hit. There is a natural limit imposed by the requirement that the ship (unlike a land installation or a tank) must have an average density appreciably less than that of seawater, but nevertheless the level of protection possible is impressive, particularly in larger ships. Unfortunately the situation is somewhat reversed by comparison with the land installation case: once built the ship can not readily be made to accommodate incremental improvements to its protection. The attacker may thus find it worthwhile to observe the protection levels of his opponents' ships and then develop new standoff weapons tailored to deal with them, given the high costs and long lives of ships.

Perhaps the most efficient way to counter anti-ship missiles is to derange their guidance. Guidance countermeasures tend inevitably to be highly specific to the particular anti-ship missile and its guidance system, and news of their efficacy is always closely guarded. One factor which tends to favor the missile is the large radar cross section of ships. Proposals have been seen in the press to build ships with reduced observables and this may indeed prove possible, but the obstacles are formidable. It is a question not merely (or even primarily) of the size of ships but of their configuration, which tends to result in a very large number of corner reflectors–including the very large ones formed by the intersection of the sides of the hull with the water. But even if only partially successful, efforts to reduce the radar cross sections of ships might make it more feasible to counter anti-ship missile seekers by means such as jamming or production of false targets.

3. Submarines

In the case of submerged submarines the process of radar cross section reduction has been carried to such a point as to make radar guidance quite impossible. Standoff weapons for use against submarines are either nuclear depth bombs (which attempt to compensate for aim-point uncertainties through sheer explosive power) or underwater missiles–torpedoes–with acoustic homing systems. The torpedo homing systems may work by passive listening–as the very first homing weapon, the so-called Mark 24 Mine did, forty years ago–or by active echo-ranging, or by a combination of both techniques. The explosive power of nuclear depth bombs has practical limits, especially because the weapon's force is greatly reduced at the point at which the gas bubble formed in the water by the explosion reaches the surface and vents to the atmosphere. The speed of underwater missiles also has practical limits–a 50-knot (93 km/h) torpedo has all the drag of a low-altitude Mach 2.2 missile of similar size, owing to the density of seawater (about 835 times that of sea-level air, under standard conditions). Moreover, the range of the sonar upon which the torpedo depends for guidance is also limited by attenuation and by the relatively slow speed of sound (about 1.5 km/s in seawater, typically). The effect of all this is that both the nuclear depth bomb and the homing torpedo must reach their aim points with the target submarine no more than a few thousand meters away to have any chance of killing it–and best results will be obtained when the target is no more than a few hundred meters distant.

This illustrates how well the submarine's stealth serves it, tactically as well as strategically. The whole key to standoff attack against a submarine lies in very accurate localization–with resources adequate for that task the attacker generally finds that he can deal with the other problems of anti-submarine weapon delivery. Conversely, the submarine usually finds that its best course is to devote all its resources to preserving stealth. Thus decoys and jammers are used with great circumspection, lest they give up more than they gain, and the option of defensive armament is normally rejected out of hand.

Because they must be built to resist the pressures of the deeps, submarines are inherently much "harder" than surface ships. Paradoxically, however, warhead weights of the order of 100 kg TNT-equivalent are normally considered adequate to deal with submarines, where 1000 kg is thought none too large for a surface ship. This is because a hole ten centimeters in diameter, a thing of no consequence in a surface ship's upper works, is a first class emergency when appearing in the pressure hull of a submarine. It has been suggested in the press recently that large double-hull submarines whose outer fairings are several meters removed from their pressure hulls may be too much for existing torpedo warheads. Even if this should prove to be true it would not, in itself, be sufficient argument for building such submarines: their cost would greatly exceed that of the larger torpedoes which they might require to counter them.

The Soviet Union has introduced a new class of nuclear submarine, code-named "Alfa" in the West, which is believed to be a good deal deeper-diving and faster than previous types, leading some to suggest the possibility that submarines might gain sufficient agility to escape from underwater weapons altogether. In practice this does not appear likely, since the torpedo always retains the advantage of needing little endurance (compared, at least, to the submarine). Given the great cost and military value of submarines, torpedo designers could, if necessary, justify very expensive expedients in order to retain an adequate performance margin over their prey. However, increases in submarine agility could be quite troublesome if combined with reductions in submarine acoustic observables through reduction in noise and perhaps reduction in delectability by torpedo active sonars–possibly using some acoustic analog of the technology used in reducing aircraft radar observables. Here again much would depend upon the success of torpedo sonar designers in finding technical measures to overcome the reduction in acoustic observables.

4. Aircraft

The speed, agility, and inherently low observables of airplanes make them very difficult standoff weapon targets. (This is reflected in the costs of anti-air missiles, which are a vastly larger fraction of the costs of their targets than is the case with anti-ship or anti-submarine weapons.) In most cases, anti-air missiles can not deal with any volume of uncertainty whatever and must be guided continuously from launch. Some of the more recent missiles do perform an autonomous search to reacquire the target, but their tolerable radii of uncertainty are very small by comparison with those typical of anti-ship missiles. (Much of this, naturally, reflects the fact that an anti-ship missile needs search only in two dimensions.) A four naut. mile (7.4 km) autonomous reacquisition range would be difficult and expensive to achieve–but against a Mach 0.8 maneuvering target this would allow a Mach 5 missile an effective free flight range of no more than 25 naut. miles (46 km). To attain a free flight range of 200 naut. miles (370 km), say, with a Mach 8 missile (which would be pushing the state of the art in airframe and propulsion) would imply a reacquisition range of 20 naut. miles (37 km), assuming a Mach 0.8 maneuvering target. Such a missile would be very large, enormously costly, and probably very vulnerable to guidance countermeasures. (The major exception to this rule would be in the case of a missile tailored to home on some powerful and specific active electromagnetic emission known to be associated with its target, such as radar or jamming transmissions.)

Anti-air missiles as a class are particularly subject to guidance countermeasures. Indeed, the serious introduction of anti-air missiles in war over North Viet Nam in the mid 1960s quickly evoked a variety of guidance countermeasures, and guidance countermeasures have been successfully employed against several different types of missiles on many occasions since then. The severe kinematic demands on missile seekers are one cause of their vulnerability to countermeasures, while the low radar cross sections of airplanes also play a major part since they make it relatively easy and cheap to present a radar seeker with a false signal stronger than the real return from the aircraft. If stealth technology proves effective in still further reducing radar returns, and is widely applied, life will become even more difficult for the anti-air missile.

One of the major problems facing anti-air missiles is their need to have a lot of energy in hand to deal with last-minute target maneuvers. Even with optimal homing the missile needs to be able to turn at rates somewhat in excess of those of its target. But since the missile also needs to be appreciably faster than its target this implies a need to generate transverse accelerations at least two to three times as great as those of which the target is capable. Thus against a 9g tactical aircraft such as the F-16A the anti-air missile will need to be able to make a 20g to 30g terminal maneuver. If the situation permits the aircraft to decelerate to Mach 0.4 and still pull 9g then the missile might be forced to as much as 60g. (This can be mitigated somewhat if the warhead can be given a large enough kill radius, but this involves added weight or complexity or both.) If the missile's motor has burnt out by the time the missile reaches its target, so the missile has only its kinetic energy to draw upon, this can often be the principal factor limiting effective range. Our hypothetical Mach 8 missile, by contrast, has all the kinetic energy it could possibly need to engage a Mach 0.8 target, but may have to pull 100g in doing so, which can cause its own problems.

It is clear that the missile's problems become easier if the target aircraft is large, slow, and ponderous. But even against B-52s, North Vietnamese SA-2 missiles were rendered virtually useless by countermeasures. And even the largest aircraft retain the option of flying very low, merging their radar return with the far more powerful ground return. There are technical counters to these problems, but they increase the missile's cost and size.

So far we have dealt only with subsonic target aircraft. Obviously, speed gives the airplane a better chance of running away from a missile; a Mach 2.5 missile, launched 10 naut. miles (19 km) astern of a Mach 2 airplane will have to fly 50 naut. miles (93 km) to overtake it. But in most practical cases, missiles may better be outmaneuvered than outrun. The situation in which speed would be of real value would be against a missile with a long free flight, which had to reacquire the target on its own. For instance, consider the case of a missile which flies a minimum-energy ballistic trajectory to a range of 1000 naut. miles (1850 km), reacquiring and homing on the target aircraft after re-entry. Figuring a lapse of 280 seconds between aim-point setting and seeker turn-on, we see that a Mach 0.8 aircraft can cover 36 naut. miles (66 km) in the interval, while a Mach 3 supercruiser will fly 134 naut. miles (248 km) in the same period. Even acknowledging limitations imposed by the restricted turning rates typical of supercruisers, this results in a very severe reacquisition problem for the missile, unless some a priori constraints on target aircraft maneuvers can be invoked (e.g., on the grounds of special requirements imposed by the airplane's mission).

Generally, aircraft have been so well served by their mobility and low observables in combating anti-air missiles that they have not had recourse to defensive armament, whose weight makes it most unattractive for aircraft. By the same token, while aircraft designers often incorporate some level of protection against fragments and consequential fires, loss of an aircraft which suffers a missile "hit" is usually accepted as unavoidable and no attempt is made to fit heavy protection.

For all their shortcomings and limitations, standoff weapons have vastly increased the threat to aircraft. An effective range of 5 naut. miles (typical of air-to-air missiles, and surface-to-air missiles when engaging low-flying aircraft) may not be much, but it is a great advance over the few hundred meters that was the typical anti-air weapon range in an earlier day. This has stimulated air forces to adopt their own standoff weapons in an effort to outrange the anti-aircraft missiles. This has often been successful, but the effects on aircraft size and cost have been substantial. In some cases aircraft-launched standoff weapons ranges are approaching the point at which it becomes questionable why one should buy an expensive airplane to launch the missile; why not simply put a booster on the missile and launch it from the ground?

5. Summary and Comparison

Summarizing now our observations about the prospective effects of standoff weapon developments on the relative viability of the various categories of naval vehicles we begin by noting that unprotectable (or at least unprotected) land installations will increasingly come at risk, even when located well back from enemy territory or waters. At the same time, however, those facilities ashore which lend themselves to incremental hardening (or which can be made to so lend themselves) might well acquire a near immunity to standoff weapon attack, except perhaps in nuclear war. In the case of ships we found that their mobility was so slight by comparison to that achievable with standoff weapons as to put them virtually in the same class as land installations–unprotectable installations, since economical incremental hardening of ships seems largely infeasible. The anti-missile defensive systems on which ships so largely rely appear to face very unfavorable odds, which could grow worse if stealthy anti-ship missiles should appear. Perhaps the only thing that might possibly tip the weapon balance more in the ship's favor would be to deny the attacker the ability to target his weapons through electronic countermeasures and stealth. If done successfully enough this would put the ship in the category of the submarine, whose survivability in tactical engagements seems unlikely to be much affected by weapon developments, being almost entirely a function of its ability to deny the attacker the knowledge necessary to deliver a weapon. Airplanes, in many ways the most refractory standoff-weapon targets among naval vehicles, seem unlikely soon to be driven from the skies by standoff weapons, but paradoxically may well lose many of their functions to standoff weapons launched directly from other vehicles (or shore), eliminating the airplane's function as middleman. As standoff weapon threats drive airplanes to greater and greater sophistication and cost, standoff weapon competition for airplane missions will become increasingly severe.

THE END