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TWO HISTORIANS IN TECHNOLOGY AND WAR

Sir Michael Howard
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U.S. Army War College

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Sir Michael Howard, at the Army War College's Fifth Annual Strategy Conference on "The Revolution in Military Affairs: Defining an Army for the 21st Century," discussed ways in which technology can change warfare. At the same conference, Dr. John T. Guilmartin analyzed the technological limits of strategy. Both presentations are included in this monograph.

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FOREWORD

In April 1994, the Army War College's Strategic Studies Institute held its annual Strategy Conference. The theme for this year's conference was "The Revolution in Military Affairs: Defining an Army for the 21st Century."

New technology is one of the most compelling aspects of the current Revolution in Military Affairs (RMA). Technological advance has offered advantages to one side or another at various times since the dawn of history and the advent of armed conflict; near simultaneous events. Because the current RMA profoundly affects the many aspects of armed conflict, the Army must understand this revolution in all of its parts. Just as importantly, professional soldiers must retain their professional perspective and avoid becoming enchanted with technology. They would do well to remember that while technologically sophisticated weapons can help secure victory, technology in and of itself cannot win wars. Ultimately, wars are won or lost in the minds of soldiers and their leaders.

Soldiers can learn about warfare from either personal experience or from studying history. Clearly, actual combat provides very obvious lessons, but the curriculum can be painful. Failure and death are often synonymous. The study of the history of warfare provides the student with an opportunity to examine critical aspects of warmaking without the same risk. Fortunately for those who study the reasons for, and results of, conflict, this year's Strategy Conference began with a keynote address by one of the world's foremost military historians, Sir Michael Howard. His address was followed, in the first formal session, by a paper presented by Dr. John F. Guilmartin, Jr.

Sir Michael and Professor Guilmartin are historians who have experienced warfare; indeed, have distinguished themselves in combat. Sir Michael Howard served in the Coldstream Guards in Italy in the Second World War. Dr. Guilmartin served two tours as a U.S. Air Force rescue helicopter pilot in Vietnam. Their personal experience with warfare is expressed eloquently in the following pages as they make the point that war is, as Carl von Clausewitz defined it nearly 200 years ago, a distinctly *human* endeavor.

Clausewitz wrote, "the nature of war is complex and changeable." Because the Revolution in Military Affairs makes warfare all the more complex and changeable, one would be well advised to heed another of Clausewitz's admonitions, "The use of force is in no way incompatible with the simultaneous use of the intellect." We have elected to present the thoughts of these two warrior scholars in one volume so as to provide the reader with something of the synergy they developed in their presentations during the Strategy Conference.

John W. Mountcastle

JOHN W. MOUNTCASTLE
Colonel, U.S. Army
Director, Strategic Studies Institute

BIOGRAPHICAL SKETCHES OF THE AUTHORS

SIR MICHAEL HOWARD was most recently the Robert A. Lovett Professor of Military and Naval History at Yale University. He distinguished himself by service in the Coldstream Guards in Italy during the Second World War, and was twice wounded. Sir Michael earned his B.A., M.A. and Litt.D. degrees at Oxford, where he has also been the Regius Professor of Modern History. He is the author of numerous books and articles, among the most notable being *The Franco-Prussian War* and *The Continental Commitment*.

JOHN F. GUILMARTIN, JR., LTC USAF (Ret), is an Associate Professor of History at Ohio State University, Columbus, Ohio, where he teaches military history, maritime history and early modern European history. He holds a B.S. in aerospace engineering from the USAF Academy and an M.A. and Ph.D. in history from Princeton University. He served two tours in Southeast Asia in long range combat aircrew recovery helicopters during 1965-66 and 1975. He was a Senior Secretary of the Navy Research Fellow at the U.S. Naval War College during 1986-87, and served as Leader of Task Force II, Weapons, Tactics and Training, for the Secretary of the Air Force/Gulf War Air Power Survey. He has published and spoken widely on pre-modern military and naval history and on the theory of war.

HOW MUCH CAN TECHNOLOGY CHANGE WARFARE?

Sir Michael Howard

There is a tendency among military professionals, particularly in the United States, to look to history for "lessons." This is not wise. It has been well said the words, "All History Teaches..." are usually followed by bad history and worse logic. History is simply what historians write, and what they write is often determined by their prejudices. The best that even the best historians can do, on the basis of their knowledge about the past, is to pose questions and issue warnings about the future.

The answer to the question posed by the title of this essay is obviously, "Quite a lot." The essence of war, however, remains the same no matter how one defines that essence. Carl von Clausewitz's definition of war as "an act of force to compel our enemy to do our will" is as valid today as it was two hundred years ago.[1] Violence is what turns a conflict into a war. Trade wars and tariff wars may involve conflicting interests, but unless there is an element of organized, sanctioned and purposeful violence, these are not war. I shall therefore work pragmatically on the assumption that, whatever changes brought about by social and technological transformation, the essence of "war" remains. Clausewitz likened it to a chameleon that takes the color of its surroundings. While warfare may seem to change, it remains as Clausewitz defined it, just as the chameleon, whatever color it adopts, remains the same animal still.[2]

All historians do agree, however, that a systemic change in the conduct, if not in the nature, of war was brought about during the 19th century by the technical transformations of the industrial age. So long as society depended upon manpower, waterpower, windpower, and animal power for its energy sources, warfare had consisted basically of battles or sieges conducted by armies whose size was narrowly constricted by logistical limitations. In consequence, there was little systemic difference between the campaigns of Julius Caesar and Scipio Africanus on the one hand, and those of Marlborough or Frederick the Great on the other. The study of the "Great Captains" of antiquity was, with good reason, regarded as being still the best preparation for the conduct of war in 18th century Europe. Technical innovations had indeed made incremental changes. The stirrup made cavalry a controllable instrument for organized battles as well as for sporadic raiding. Mobile heavy artillery transformed siege warfare as it had been conducted from antiquity until the end of the Middle Ages. The combination of the ring bayonet with the flintlock provided a force-multiplier for infantry, making every soldier his own musketeer as well as pikeman. The same kind of force-multiplying effect was gained when Jean Baptiste de Gribeauval's French army reforms resulted in a new generation of more mobile and accurate field guns in the mid-18th century.

Clausewitz held that battle is as essential to warfare as cash transaction is to business. Throughout the agrarian age war consisted, if not of battle, then of the search for battle. And battle consisted, or was seen to consist, in *corps-a-corps* fighting with "*cold steel*"–*the arme blanche*. All developments in fire power were perceived as ancillary to this. Artillery was developed to make it possible for infantry to close with the enemy, not to make it unnecessary. Infantry volley-fire was always preliminary to a charge.

Around this perceived necessity for the decisive *corps-a-corps* encounter, a whole military culture developed. In this social hierarchy those who delivered the "shock" in battle, the cavalry and elite infantry, were at the top. All ancillaries, including artillery, took their places lower down the pecking order. Napoleon Bonaparte became an artillery officer because he did not have the social standing to get into the infantry or cavalry. It is interesting to speculate whether he would have been quite so innovative in the conduct of war if his pedigree had been good enough for the cavalry.

During the agrarian age, the only fundamental changes that occurred in the conduct of war were the results of social and political factors rather than technological innovation. For instance, the chivalry of Western Europe, which had monopolized the conduct of war for half a millennium, was destroyed on the battlefields of France and Burgundy in the 14th and 15th century by soldiers wielding pikes and bows, weapons that had been around for quite a long time. It was not the advent of those weapons that eclipsed mounted, chivalrous warfare; rather it was a fundamental change in social attitudes that allowed peasant bowmen and pikemen to be promoted to the core of the English and the Swiss orders of battle. Further, it was only the development of the bureaucratic state in early modern Europe that made possible the development of professional, disciplined, long-serving armed forces, especially navies. (Part of their professionalism, incidently, consisted in the study and mastery of weapon technology.) And it was the French Revolution, not any technological breakthrough, that made possible the Napoleonic campaigns, which not only introduced a new operational concept into warfare but overthrew an entire political order in Europe and prompted Clausewitz to foresee a new era of "absolute" war.

Clausewitz prophesied better than he knew. The industrial age which was just dawning in his lifetime, and of which he was totally unaware, did indeed transform warfare. It did so by increasing the range, accuracy, and lethality of weapons, while logistical developments, in particular the railroad and the telegraph, made possible total war on a scale such as even Clausewitz had never conceived. Between them, these two developments produced the destructive deadlock of the First World War. The development of firearms, magazine-fed repeating rifles for the infantry and breech-loaded guns for the artillery made it impossible for armies to come to sufficiently close quarters to obtain the kind of decision that battles had always been fought to achieve. The development of railroads, telegraphs, and supply systems meant that the size of armies was such that their limitations were determined only by the size of the population and the economic capacity of the state to train and sustain them. The result was what might be called *Total War Mk. I*, on the assumption that Napoleonic warfare had been no more than an overture setting out the principal themes. In *Total War Mk. I*, the entire resources of the state were mobilized to sustain armies in the field whose only formula for victory was attrition and whose commanders were military managers like Ulysses S. Grant and Douglas Haig rather than the "Great Captains" of military legend. The object of operations became, not the destruction of the enemy army on the battlefield, but, by engaging that army in prolonged and inescapable battles of attrition, to bleed the opposing society to death. The first example was Grant's campaigns of 1864-65; the most notorious, the Western Front in World War I in 1916 and 1917.

Total War Mk. I was to be rendered partly obsolete by further technological innovations. Mechanization, the development and application of the internal-combustion engine, and radio communications restored mobility and decisiveness to the battlefield. Air power not only extended the battlefield itself, but made it possible to attack the social structure and the economic resources that maintained the armed forces in the field, and to do so more directly and, in many cases, more completely than naval blockade ever had.

In Europe, these developments of the later industrial age led to *Total War Mk. II*. In this phase of warfare civilians became involved, not just as part of the mechanism supporting the armed forces, but as targets almost more significant than the armed forces themselves; not only because of their role in producing the resources that made military operations possible, but because their morale was seen as a principal element making it possible to conduct war. The "ideal model" of *Total War Mk. II* was that of the air power enthusiasts who believed that it might be possible to decide a war without surface forces engaging at all, but this was never achieved in World War II. That conflict was also to be decided by attrition, victory going to the strongest industrial powers. Air power provided only an important additional dimension. Commanding generals such as Dwight D. Eisenhower, Sir Bernard L. Montgomery, Georgi K. Zhukov, and Gerd von Rundstedt were, essentially, military managers. "Great Captains," such as Erwin Rommel, George S. Patton, and the British commander in Burma, General William Slim, who carried on the heroic image of the agrarian age, were effective only under exceptional circumstances and then usually at the margins.

The atomic bomb seemed to epitomize the era of *Total War Mk. II.* After the Korean War, the battlefield itself was held in many quarters to be an anachronism; certainly in any conflict between nuclear-armed powers. Some laymen maintained that nuclear weapons would make war itself impossible. Even professionals had to accept that the conduct of war in any traditional sense would be possible only when political circumstances set strict limits to the likelihood of its escalation. Under those conditions, it seemed possible that traditional battlefield skills might again come into their own. Three Arab-Israeli wars pointed in that direction, even if the conflict in Vietnam did not. Whether the technology of the post-industrial age will renew the need for battlefield skills, or transform war in totally new directions, is a subject that is being discussed at war colleges throughout the world.

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Since Operation DESERT STORM, there has been a focus on the technological dimension of warfare. The social dimension however, is no less important–possibly even more. In fact, the two cannot be separated. Social structures and social needs produce technological innovation, while that innovation in turn affects, and sometimes transforms, the social system out of which it has developed.

In the agrarian age, as previously stated, the conduct of war was based on the concept of the decisive battle, and the conduct of battle on that of the decisive shock. This concept determined not only the structure of the military hierarchy, but that of an entire social and political order. Society was governed by a warrior caste whose primary function was leadership in battle. This remained the case in Europe through the 19th century and even into the 20th. The Emperors of France and Austria and the King of Prussia were present on the battlefields in 1859 and 1866. Napoleon III surrendered himself and his army to the King of Prussia to avoid further carnage at the Battle of Sedan in 1870. Kaiser Wilhelm II remained titular commander of the German armies throughout the First World War, while Czar Nicholas II, with General

Mikhail Alekseyev as his chief of staff, assumed personal command of the Russian Army on the Eastern Front.

Agrarian societies were thus based on a military hierarchy, and the classes that did not conduct war, the merchants and peasants, were socially subordinate to those that did. War was an acceptable, indeed a dominant and often a continuous activity. Further, horrible though war might be, peace was not much better. Disease, pain, suffering, and grinding hardship was the fate of all but a minute minority of the human race. Death came in violent and terrible ways to many who never experienced battle. Death in battle, at least, was accompanied by prestige and panache, while for those who survived, participation in a successful campaign held out hope of social and financial advancement.

With the dawn of the industrial age all this began to change. Increased life expectancy was accompanied by increased comfort expectancy. Violent and agonizing death became exceptional. The more societies "advanced," the more they considered war to be barbarous rather than heroic. This, paradoxically, was happening at a time when the conduct of war was becoming dependent on conscript armies. One of the great anxieties of European governments at the beginning of this century, indeed, was whether these conscript armies would actually fight, and how their populations, drawn from an increasingly urban environment, would endure the necessary hardships of war.

In fact in World War I, the populations endured astonishingly well. This was partly because of the social solidarity produced by national sentiment; partly because for many European armies, especially for those in Eastern Europe, the standard of living in the armed forces was rather higher than what they were used to at home. But mainly they endured because there remained, even in societies as industrialized as Britain and Germany, a considerable residue of the standards and values of the agrarian age. These values included a respect for authority, deference to the monarchy and aristocracy, and a surviving tradition among the ruling classes of heroic leadership. But national sentiment and disciplined obedience had its limits, and during that war, almost imperceptibly, a major transformation occurred in the conduct of battle

At the outset in 1914, artillery fire was still being used to make possible the decisive assault *a la baionnette*. But by the end of the war, the function of fire power was to make that assault unnecessary. In the words of the French, who took the lead in this development, "It is fire that conquers ground; infantry occupies it." Conscript armies showed themselves increasingly unwilling to die gloriously on the battlefield. If they did not actually mutiny, as did the Italians and the French, they showed other ways of making that unwillingness felt. At home, the civil populations increasingly did the same. By the end of that war, the concern among political, and to a lesser extent among military, elites throughout the Western democracies was how to use technology in future wars to prevent the troops from being killed.

This reaction did not affect the Germans to the same extent. Partly because their highly professional armed forces were limited in size by the Versailles Treaty until Adolf Hitler denounced its disarmament clauses and Germany began rearming in 1935, the Germans turned to the innovative use of technology to enhance the effectiveness of their smaller army through the use of *Blitzkrieg* tactics. Perhaps more important, the Nazi revolution did its best to indoctrinate the German people, especially the young German people, with all the warrior values of the agrarian age that the "decadent" West seemed to be losing. This they did exceptionally well, as indeed did the Japanese. Nazi Germany and Imperial Japan proved themselves such formidable adversaries because they combined the techniques of industrial societies with the values and skills of the agrarian age bolstered, respectively, by elements of Norse mythology and Bushido traditions.

Eventually the Allies wore down the Germans and the Japanese under conditions very comparable to those under which the industrialized Union wore down the armies of the agrarian Confederacy during the American Civil War. But it has to be admitted that, with all their technological advantages, the conscript armies of the Western democracies in World War II did lack battlefield skills. They did not excel at close-quarters fighting. For the most part they were very reluctant to run risks, and most of their generals were reluctant to make them do so. They committed their forces to action only if they could support them with massive fire-power and by air power. Furthermore, these forces were provided with supplies, and medical and recreational facilities that replicated, as far as possible, the standard of living they enjoyed at home. It proved a slow and expensive way of making war, but given the standards and expectations of late industrial societies, there really was no other way in which it could be done.[3]

All this tended to bear out the apprehensions of the 19th-century military analysts. Industrial societies no longer nourished the skills and virtues that had been needed in agrarian-age war. The expectation was that military technology would make the skills and virtues of the warrior unnecessary. The enemy, his military forces as well as the supporting society, could be destroyed at long distances from positions of comparative safety. Whether in the air or on the ground, increasingly it was felt that, insofar as close-quarter fighting was necessary, it should be left to small teams of specialists; commandos, paras, Special Forces, Special Operations aircraft, and the Special Air Service.[4]

This kind of war at long range seems very sensible and civilized, but a troubling question remains. In spite of all the technology of the industrial and post-industrial age, does there not still lie at the core of all warfare a need to engage in the basic, primitive encounters of the agrarian age? And was not the lesson of Vietnam that, if the capacity to do so disappears, no amount of technology is going to help? To put it in brutal terms, soldiers must not only know how to kill, but must also be prepared if necessary to die. More important, the societies that commit them to action must be prepared to see them die; and in these days of CNN quite literally so. Western societies have learned how to kill on an enormous scale, but they may still fight at a disadvantage against agrarian age armies who have not forgotten how to die and know well-enough how to kill. The Vietnam War and the recent experience in Somalia indicate that if those agrarian age armies are well-led, and if their leaders develop superior strategies, they can still prevail.

A readiness to engage in close combat in which there is a very high risk of mortality remains the basic requirement, not only of the specialists in violence, but of every man and woman in uniform. When they put on that uniform, they are accepting that risk.

So long as, in the words of Hilaire Belloc,

> We have got
> The Maxim gun,
> and they have not

the skills and virtues of the agrarian age may no longer be so essential as they were in the past. But even today our forces have to engage in combat against highly-motivated peoples whose primary concern is to kill them; and are willing to risk their own lives to do so. Furthermore, they may have the equivalent of the Maxim gun as well. Future conflicts will not be so conveniently one-sided as was the Gulf War. Will future technology be able entirely to eliminate the need for the armed forces of Western societies to be placed in situations where they are required not only to kill, but accept the risk of being killed, perhaps in large numbers; and will our post-industrial societies find that acceptable? In short, can technology change what has until now been the essence of warfare?

ENDNOTES

1. Carl von Clausewitz, *On War*, Michael Howard and Peter Parets, eds., Princeton, N.J.: Princeton University Press, 1989 ed., p. 75.

2. *Ibid.*

3. The United States, at least, perhaps because the final victory in World War II was so complete, did not seem to learn from the experience. The swimming pools, officer clubs, indoor and outdoor movie theaters, tennis courts, gymnasiums, even miniature golf courses, bowling alleys, and archery ranges built into the more lush American bases throughout Vietnam and Thailand a quarter century later, are testimony to that fact. Ed.

4. A technological case in point is the U.S. Air Force McDonnell-Douglas F-4 Phantom II fighter-bomber. It was conceived in the early 1950s for the U.S. Navy as an air-to-air missile launching platform to be used for fleet defense. During the Vietnam War, the Air Force and the Navy used it to perform attack missions. Only in its very last production models (the F-4Es

built in the late 1960s and early 1970s) was an internal gun included so that it could perform the "warrior-like" mission of aerial combat (called "dogfighting") more effectively. During the 1960s, despite evidence to the contrary resulting from aerial engagements in the skies over North Vietnam, training in air-to-air combat maneuvering and gunnery was practically nonexistent in the U.S. Air Force based on the assumption that advances in air-to-air missile technology would make old fashioned dogfighting unnecessary. Ed.

TECHNOLOGY AND STRATEGY: WHAT ARE THE LIMITS?

John F. Guilmartin, Jr.

technology, *n*., (1): the application of knowledge to achieve a physical effect by means of an artifact, object or thing (distinct from art, which involves the application of knowledge to achieve aesthetic effect). (2): the artifact itself; the class of artifacts to which it belongs. (3): the knowledge needed to design, manufacture, operate, sustain and logistically support the artifact or thing and its user(s).

Author's working definition

Sometime around the beginning of the fourth millennium BC an anonymous metalworker in the Fertile Crescent, no doubt after consultation with his village hero, the defender of fields and agricultural surplus, smelted a quantity of imported ore and cast a small sphere of copper pierced with a hole tapered to accept a haft. Breaking the object from its mold, he dressed and polished it and inserted the haft, fashioned from wood carefully chosen for strength, resilience, and perhaps magical properties. He then fixed the sphere securely in place with wedges, thongs or perhaps glue, a chore of vital importance, for the bond between haft and sphere would have to reliably resist unprecedented accelerational and vibrational forces in the harsh arena of combat, and structural failure would expose the user to lethal risk. Invoking the blessings of the deities who presided over the smelting and hafting processes and had permitted him to penetrate their mysteries, he presented the finished object to the hero. In so doing, he completed the research and development (R&D) cycle of the acquisition program of the first weapons system—or for that matter any system—to use metal for other than ceremonial or ornamental purposes: the copper-headed mace.[1]

To this point, the production of food, clothing and shelter had been the leading edge of technology. The development by selective breeding in late Paleolithic and Neolithic times of plant and animal sources of food and fiber was perhaps the most impressive achievement, though the development of seafaring, fired pottery and polished stone implements for cutting and grinding was not far behind.[2] The earlier development of the bow, no doubt for hunting though arrows could kill humans as well as game, was a major benchmark as well. Whether the application of animal traction to agriculture came before or after the development of the stone-headed mace is not known. What is clear is that the appearance of sedentary agriculture and storable food surpluses made the specialist combatant both possible and necessary.[3] We know little about the first military specialists, but it is clear that their ideas about weaponry, its production and uses, diverged sharply from those of hunter-gatherers who might supplement their larder by raiding neighboring tribes. From that change in attitudes emerged the specialized technology of war, and with the appearance of the copper-headed mace military applications assumed a leading role in the development of technology which they have rarely relinquished since.

We can surmise the rest of the story from the archaeological and historical record. The hero, skilled in the use of the stone-headed mace, adjusted his swing and footwork to the new and more powerful weapon, no doubt with the aid of a sparring partner. The results were sufficiently encouraging to prompt adoption of the new weapon. Operational test and evaluation (OT&E) was a smashing success, both figuratively and literally. Invoking the protection of the gods of the village and battle, the hero demonstrated the effectiveness of the new weapon, laying out for divine and human inspection in Chalcolithic body count the barbarian warriors whose crushed skulls were proof of its power–and of that of the gods which sponsored its development. As fabricator and wielder hoped, the bold use of a new technology had yielded important advantages in combat. But copper was scarce and smiths able to work it scarcer still. Copper-headed maces were wielded only by the select of the gods and the possession and use of such weapons became closely associated with divine approbation and earthly power. Significantly, the earliest known inscription in which an individual human being is identified by name, the Palate of King Narmer dating from around 3,100 BC, depicts the first Pharaoh of Upper and Lower Egypt ceremonially smashing the forehead of a prostrate enemy with a mace.[4]

The copper-headed mace in the hands of a powerful champion remained the world's premier weapons system for a very long time, but then as now both technology and the political ends to which it was applied were subject to change. In Egypt and regions of the Fertile Crescent blessed with broad river valleys and fertile soil, villages gave way to cities. Competition for resources and favor in the sight of the gods increased and the defenders of cities fought one another as well as barbarians. The barbarians responded to increasing prosperity among the civilized polities with increased aggression and to advances in civilized weaponry by augmenting the power of their traditional weapons, notably the bow. Proliferation became a reality as barbarians adopted metal points for their spears and arrows. The smith provided the hero with protective armor of leather-backed Electrum to shield his body from stones and arrows and to protect his head from the crushing blow of a mace. Early in the third millennium, Sumerian smiths responded to the appearance of effective head protection by developing a whole new technology, first manifested in the piercing axe of arsenic bronze. The appearance of the piercing axe accelerated the race between offensive and defensive weaponry which continues to this day and ushered in a whole new age, the Bronze Age.

The above summary, of course, is simplified. Examined in detail, the interplay in late prehistoric and early historic times among developments in the design and production of weapons systems; changes in the way in which they were viewed and used; evolution of the social, ideological and economic systems they served; and—the crux of the matter—changes in the ways in which weapons systems served political ends, both in perception and reality; were far more complex. Regions slipped into and out of the Bronze Age as reserves of easily-worked ores were depleted and better smelting technologies were developed. Long distance trade in strategic materials became increasingly important.[5] "Barbarians" engaged by hydraulic civilizations as mercenary warriors overthrew their employers and established their own dynasties, merging languages and cultures.

From the military and technological perspective, the lessons are clear. Advances in technology have yielded important military advantages from the earliest times. More often than not the demands of war press technological change first and farthest. The technology of war is developed and applied within a cultural and social context of which supra-rational beliefs are an important part. Evaluation criteria revolving around tactical success are an integral part of the process of selection or rejection. Finally, the production of high technology weaponry may well depend on imported materials.

Finally, this example from remote antiquity makes a two-fold point: first, that the decision-making matrix within which the technology of war is developed, tested, adopted or rejected, and applied in combat is at bottom culturally-derived; and, second, that the essential categories in that matrix have seen remarkably little change over the ages. In short, history is relevant.

After briefly describing the establishment of the geo-political, technological and cultural context within which our military institutions presently operate, this monograph will then trace the technological developments which formed the backdrop for the supposed military technological revolution of the recent past. For a number of reasons, the story begins in 1914. First, by then the national boundaries and perceived national interests of the major economic and military players in today's international arena were in place. Second, the basic notions of national interests, national policy objectives and the appropriate national and military strategies for pursuing them were also in place or emerged shortly thereafter. On a technical military level, the continuing influence of Alfred Thayer Mahan's Theory of Sea Power, promulgated in the late 1890s, substantiates this point. Finally, one can argue that our basic notions of military strategy and tactics at the national level, and professional military officers' ideas of how to go about implementing them, are firmly rooted in the experience of World War II and largely derived from World War I. The fact that the United States participated in both wars served to reinforce their lessons. Much of our technical military vocabulary comes to us directly from the two world wars: front lines, frontal system (as in weather forecasting), barrage, strafe, flak, spotting artillery and calling out bandits by clock position; so do our approaches to recruiting, training, weapons system procurement and organization of the national industrial and scientific base for war. Having briefly delineated this baseline, offered as a war paradigm, this monograph will then examine recent changes in the technology of war and address the proposition that they are of sufficient magnitude to require a paradigm shift.

When Gabrilo Princip shot Archduke Franz Ferdinand of Austria in Sarajevo to start the First World War, the essential elements of our war paradigm, though not their interpretation, were in place. Industry, and through industry science, had been firmly and more or less formally harnessed to war, though navies were more clearly aware of the link than armies and more skilled at exploiting it.[6] Air forces existed in nascent form. Artillery technology on land and at sea had been brought to a level which differs from today's only in degree by the universal adoption of nitrocellulose-based propellants; high explosive shells with time delay fuses; hydro-pneumatic recoil systems; and breech loading, quick fire mechanisms. Armies throughout the world had standardized on small arms using ammunition which differs in no essential way from the predominant form in use today: a fixed round consisting of brass case, nitrocellulose propellant, impact primer and jacketed lead bullet.

The determinant of strategic capability subject to the greatest change over the next three quarters of a century lay not in weaponry, but in the industrial base. In 1914, industrialized nations with adequate reserves of coal and iron ore were essentially militarily self-sufficient, dependence on natural nitrates for high explosives production having been eliminated as a strategic consideration by the recent German discovery of atmospheric nitrogen fixation. Transportation and steel production were the critical determinants of military strategic power, manifested in weapon and munitions production, capital ships and railroad mobilization. All were fueled by coal. Indeed, industrial capacity, and hence military capacity, was almost congruent with coal and iron ore reserves, Japan being the only exception though, for the moment, a minor one. To be sure, the successful adaptation of the internal combustion engine to military applications was a harbinger of things to come. During the Great War, gasoline-fueled aero engines would absorb only a tiny proportion of fuel energy expended, but aircraft would exercise a disproportionate influence on land operations by its end. The same point applies to the strategic impact of diesel-powered submarines at sea. In the run-up to war, Britain had begun construction of a new class of capital ships powered by oil-fueled steam turbines, the *Queen Elizabeth* class battleships, to exploit of the substantial advantages of oil over coal in thermal and volumetric efficiency, consciously accepting the strategic vulnerability implicit in dependence on imported oil–and hedging its bets by seizing the recently-discovered Iranian oil fields.[7]

Imports in certain specialized niches were important to the conduct and outcome of the First World War; significantly, these took effect at the high end of the technology spectrum: American spruce was important to French and British aircraft production. Petroleum was sufficiently important strategically—most critically for aviation gasoline though gasoline-powered trucks and tractors performed certain essential tasks beyond the capacity of horses—and the Central Powers' reserves sufficiently small that only Romania's obliging declaration for the Allies in 1916 saved Germany and Austria-Hungary significant embarrassment by placing the Ploesti oil fields in their hands. The petroleum-based lubricants of the day broke down under the temperatures produced by high performance rotary radial aero engines and the British blockade denied Germany supplies of the castor oil they required, effectively grounding some of Germany's best fighters of 1918. On the whole, however, the war economies of the powers whose military forces dominated the conflict were self-sufficient and coal powered.

By the eve of the Second World War, oil had supplanted coal and iron as the critical determinant of military power. Coal and iron ore retained their importance to war production, to be sure; steel was vital to weapons manufacture and coking coal was needed to smelt steel. Moreover, while bunker oil had largely replaced steam coal as the fuel of navies and merchant marines, coal-fueled steam locomotives and electric power plants played a vital role in the war economies of the contending powers. Indeed, the sophistication with which German industry squeezed every possible advantage from the Third Reich's coal deposits gave the German war economy a remarkable robustness and probably lengthened the war by six months to a year.[8] But in the final analysis, the enduring economic and industrial importance of coal notwithstanding, tactical success at the cutting edge, and thus strategic advantage, depended on machines fueled by gasoline, diesel fuel and bunker oil.

If high performance aircraft were a critical determinant of the outcome of the First World War on land, they were an absolutely indispensable ingredient of victory on land and at sea in the Second. Moreover, the capabilities of military aviation had increased to the point that entire air campaigns were mounted. At least one, the Battle of Britain, was clearly decisive and others were arguably so, though not always in a form highlighted by conventional measurements of victory and defeat. An example can be seen in the devastating effect on the German war effort of the massive losses of trained aircrew which the Luftwaffe incurred in the spring of 1943 in efforts to reinforce and then evacuate German forces in North Africa.[9] Tanks, fueled by gasoline and diesel oil, became a critical tactical determinant of victory on land wherever terrain permitted their use. Armies spearheaded by armored fighting vehicles were supplied, at least in the attack, not by rail but by truck convoy; trucks and tractors replaced horses as field artillery prime movers. That Wehrmacht petroleum reserves were so scant that the German Army had to rely on horse traction for tactical logistics and field artillery mobility would seem, with full wisdom of hindsight, to have virtually preordained defeat.

The pivotal importance of oil to the war at sea is even more apparent. The lack of petroleum reserves in the Home Islands forced the Japanese militarists to go to war or back down in

December 1941. The vulnerability of Japanese merchant shipping, oilers in particular, to attack by American submarines placed the Japanese war economy in an ever-tightening noose from 1943 on, a noose made even tighter by air-dropped mines in the final year of the war. Though the American war economy was effectively self-sufficient, that of Britain was anything but and German U Boats and aerial commerce raiders posed a similar threat to the Western Allies. From the British standpoint, the critical strategic logistic requirement from the beginning was the provision of sufficient stocks of petroleum to support naval and air operations from British bases, a requirement which expanded to encompass the support of U.S. air forces from 1942 and the support of Allied ground forces on the continent after D Day. The war at sea intersected with that in the air and on land in the critical importance of British petroleum stocks, for those stocks had to be replenished from American and Iranian oilfields by ship.

The importance of oil to the conduct and outcome of the Second World War extended well beyond quantitative, macro-economic considerations. High octane aviation gasoline gave British and American aircraft, particularly fighters, a critical performance boost not enjoyed by their Axis equivalents; indeed, some have gone so far as to attribute British victory in the Battle of Britain to 100 octane gasoline. Axis engineers were well aware of the performance advantages conferred by high octane, but the refining process was highly inefficient, many more barrels of crude being required per barrel of refined gasoline as octane increased. So long as their sea lanes stayed open, Britain and America could afford the inefficiency; the Germans, Japanese and Italians could not, and their fighter pilots entered combat at a significant handicap.

Beyond the critical importance of petroleum as a fuel, the relative importance of coal and iron was further eroded by the emergence in the interwar period of new structural materials with critically important properties which could not be obtained with steel. Moreover, in most cases if not all, reserves of these structural materials lay beyond the boundaries of the major powers. Far and away the most important was aluminum, the preeminent structural material for high performance aircraft from the mid-1930s.[10] Rubber, the raw material of pneumatic tires, O rings, aircraft de-icer boots and a host of other essential sub-technologies, was a tropical import. Rubber could be synthesized from petroleum and coal, but the product was inferior, the process inefficient and the raw materials valuable. Tungsten carbide was required to give hardness and durability to machine tool cutting heads. Only small quantities were needed, but there was no substitute and Germany lacked tungsten deposits, a fact with implications beyond the machine shop floor. Tungsten carbide is not only extremely hard, but extremely dense and German engineers developed highly effective anti-tank ammunition using sub-caliber tungsten carbide penetrators. Guns designed to fire this ammunition were much lighter and more mobile than their Allied equivalents and were among the most powerful anti-tank guns of the war, but shortages of tungsten forced their abandonment in 1942.[11]

In sum, the preeminence of oil as the crucial determinant of strategic capability and tactical effectiveness in World War II is clear. The result was a war in which the ability to move raw materials over extended distances by sea was both a vital determinant of victory and a potentially lethal vulnerability. At a lower level of abstraction, the ability of design engineers to harness the propulsive energy of petroleum distillates and apply them to the propulsion of military vehicles played a major role in shaping the outcome of the war. Within this matrix, the design and production of fighter aircraft was arguably the most critical node, though the design and production of bombers, tanks, torpedoes, submarines, artillery pieces, escort and anti-submarine vessels, assault landing craft, trucks, prime movers and so on in approximate–and debatable–descending order of importance followed closely behind. More important than their individual tactical power and strategic importance, none of these critically important technologies could be approached in isolation, either from one another or from the production and logistical apparatus which built and supported them.

Moreover, the increasing tactical and operational interdependence of the various technologies of war and their sophistication lent a new importance to the human factor. The establishments which selected and trained the crews upon whose skill the effectiveness of military hardware depended were of pivotal importance. To cite a critical and illustrative example, the ability of the U. S. and Commonwealth air forces to generate large numbers of well-trained pilots played a major role in the defeat of the German and Japanese air arms, while poor planning and worse execution in this area by the Germans and Japanese went far to ensure Axis defeat.[12] Nor was the importance of recruitment, selection and training limited to operation of the most expensive and sophisticated weapons systems: the increasing power and diversity of infantry weapons and the increasing sophistication of infantry tactics posed serious challenges for training establishments, not least of all in the United States where a small peacetime Army and Marine Corps had to expand enormously in very short order. Raw nationalism had sufficed to mobilize and motivate millions of recruits at the outset of war in 1914-17. By 1939-41, disillusionment with the ideologies of an earlier day called for more sophisticated appeals.

Finally, the Second World War brought home to the Americans and British, at least, the verity that science not only could contribute to the war effort but was essential to its prosecution. If the war was run and won on petroleum, it was guided, directed and shaped by electronics, optics and acoustics. Just as coal gave way to oil, telegraph wires and submarine cables gave way to the vacuum tube. As with the internal combustion engine, there were harbingers in the First World War: wireless telegraphy was used to control fleets, and at times armies, and was exploited for intelligence; field telephones came into common use; the artillery preparations which broke the back of the German Army in the last year of the war depended on aerial photo-mapping and photographic reconnaissance for their effectiveness; sophisticated electronic and acoustic sensors were used to direct counterbattery fire.[13] Between the First and Second World War there was an increase in communications and sensor capability of at least an order of magnitude: radar, sonar and electronic cryptanalysis have received the lion's share of attention; but on a day-to-day basis aerial photo reconnaissance was of at least comparable importance, particularly to the British and their American understudies who used it most effectively; and voice radio and intercommunications systems had enormous impact across the board.[14] But the most important change was not in capability, but in use: Sensors and electronic communications were tactically and operationally important in World War I, and at times played a vital role. In World War II, they not only totally recast the face of war tactically, they had direct strategic impact: the British, and then Anglo-American, systematic, centrally-directed collection and analysis of photographic, electronic and human intelligence is the most dramatic example, though by no means the only one.

Still, both world wars were won as much by production as technique, though the quality of what was produced was important to the outcome, particularly in the second. In sum, both wars were won by engaging and overwhelming the enemy production and population base. In World War I, this was accomplished indirectly though attrition of manpower and material at the front and by eroding the war economy and civilian morale through naval blockade. Direct attack on allied sea lines of communication by submarine had the potential to cause the collapse of the British war economy, but inadequate resource allocation doomed the German U Boat campaign to failure. In World War II, production and population bases were exposed to direct attack by aerial bombardment, and economic attrition by submarine attack came into its own, though the Germans once more put inadequate resources into the effort.

The military leaders of the United States and their civilian superiors learned the lessons of World War I as well as the leaders of any major power. Granted, the British taught the Americans some vital lessons in technique, but it is safe to say that by 1944-45, the U.S. military establishment had embraced and mastered a war paradigm which corresponded very closely to strategic reality. It is important to note that this paradigm incorporated a keen appreciation of the importance of technological advantage and of the need to systematically pursue that advantage in time of peace. This perception stemmed largely from painful memories of the unpreparedness of its air arm and field artillery when the United States entered World War I.[15] That perception found expression in the steady expansion of aerodynamic knowledge by the National Advisory Committee on Aviation (NACA) during the interwar years which yielded important dividends in World War II.[16] It also found expression in the design of a range of thoroughly capable artillery pieces, already in production when war came, and a rationalized scheme for the production of trucks and prime movers.[17]

Still, at bottom, insofar as technology was concerned, the central focus of the American war paradigm was on production. The creation after World War II and continued existence of the Industrial College of the Armed Forces provide eloquent testimony to that emphasis, an emphasis which is deeply imbedded in the U.S. military services' corporate memories and thought processes. John Patrick has neatly encapsulated that reality in his perceptive description of the U.S. Army, Navy, and Air Force as "classic industrial institutions."[18]

The fundamental underpinnings of the paradigm, however, were shaken by the advent of the nuclear age. After a brief period of unexploited monopoly, nuclear proliferation set in. The United States and its primary allies faced the reality of the Cold War; they also faced a situation in which their industrial bases were secure from direct attack save by a massive nuclear strike which would surely have been answered in kind.

In the United States, the immediate response at the national level was to embrace a new and radically different war paradigm under the rubric of massive retaliation. Confident under the atomic and then thermo-nuclear umbrellas, Presidents Harry S. Truman and Dwight D. Eisenhower drew down conventional forces. To their great credit, elements within the Army and Navy challenged the validity of the new paradigm but it took the Korean War to demonstrate that defense could not be bought on the cheap with nuclear weapons. The lesson was that the United States needed deployable divisions, carrier task forces and the draft. After the Korean War, the two paradigms uneasily coexisted side by side and the resultant inconsistencies produced problems: the Air Force, at least, continued to assume that air power should be applied as it had been in World War II. Consequently, the United States bombed North Korea as if it were Nagoya or the Rhur. Over a decade later, the essence of Air Force plans for bombing North Vietnam was not substantially different.[19]

As the U.S. defense establishment relearned the value of conventional forces, concern for the cost of national defense came to the fore, and defense dollars became tight. The attention of senior military officers and staffs was directed increasingly to the competition for funding for weapons system procurement. Secretary of Defense Robert S. McNamara's establishment of rules for the competition in the form of PPBS (Planning, Programming and Budgeting System) only formalized and accelerated an ongoing trend. By focusing preemptively on rigorous quantitative analysis of cost benefit effectiveness, PPBS subtly inhibited technological innovation: to calculate whether or not something is worth its cost, one must know precisely what it will do. Since by definition it is impossible to precisely predict the effect of something which has never been made before, advantage in the PPBS arena accrued to systems which offered incremental improvements of tried and true technologies whose effect *could* be predicted with reasonable accuracy. Should anyone be surprised, then, that an extraordinarily high proportion of weapons systems procurement programs which have yielded major advances in military capability were the product of "black" programs, originated and managed outside the PPBS mainstream? The bureaucracies that blossomed throughout the defense establishment were managed by military accountants who, in addition to confusing efficiency with effectiveness, also inhibited imagination and innovation. One should not be surprised that black programs, on the other hand, seem to have been more successful than those which have had to run the entire PPBS gauntlet.[20]

At the same time, while the awesome power of nuclear and thermonuclear weapons was monopolizing the attention of defense intellectuals and PPBS that of military professionals, emergent new technologies were beginning to gnaw away at what we might term the classical, World War-derived, war paradigm and its massive retaliation-derived supplement. Salient among these technologies in rough chronological order were: digital electronic computers; new sensor systems, particularly in the infrared spectrum; new structural materials, first simple ablatives for ICBM (intercontinental ballistic missile) warhead heat shields, and then entirely new materials such as phenolic resin honeycomb, reinforced carbon and fiberglass boron fiber composites; and, last but most decisive in net effect, transistors and the miniaturized and more powerful analytical computers which they spawned. One could add to the list the turbojet engine, which fit the existing war paradigm very nicely, but which in the form of very small, highly fuel efficient powerplants for cruise missiles and RPVs (remotely piloted vehicles) challenges it directly today.

It is worth noting, however, that many of these new technologies were developed and initially exploited for explicitly military purposes during World War II. The story of the turbojets' independent development in Germany and Britain is well known. Ablative materials were discovered more or less accidentally in the V-2 program and computer technology got an enormous boost from the demands of cryptanalysis in the United States and Britain. The guidance mechanism on the later V-2s was the first reprogrammable electronic analog computer.[21]

For a time, these innovations fit our bifurcated war paradigm reasonably well. But of greater importance over the long term, the application of the paradigm continued to promote effective innovation. In the 1950s systematic development of jet engine technology combined with innovative airframe design and far-sighted military requirements to produce the jet bombers which made nuclear deterrence a strategic reality pending the development of ICBMs. Those same jet bombers, with the B-47 as the seminal design, spawned the Boeing 707 and its imitators, giving air transportation a whole new strategic dimension.[22] They also forced the development of air-to-air refueling which gave U.S. air operations an unprecedented flexibility which no other nation can match. Ablative heat shields combined with the discovery by NASA engineers of the aerodynamic and thermal advantages of detached shock wave reentry to make the ICBM a practical reality.

Then, beginning in the 1960s, the new technologies began to combine synergistically with unprecedented and largely unanticipated impact. Perhaps the first concrete indication of the potential of the new technologies came with the fielding by the U.S. Navy of a massive underwater passive sonar array to track Soviet ballistic missile submarines. The use of passive sonar to locate submarines was hardly new; the use of analytical computers with logic and memory circuits capable of discriminating between the whisper of a nuclear submarine's passage and the rumbles, squeaks and whistles of the sea was. The Vietnam War produced yet other harbingers: the Army fielded the first operational stealth aircraft, the Lockheed YO-3A used for night observation.[23] Navy and Air Force airmen made effective use of electro-optical and laser-guided bombs (EOGBs and LGBs) to strike heavily-defended targets with unprecedented accuracy in the Linebacker bombing offensives.[24] These developments, however, took effect in isolation.

By the late 1980s, the emergent technologies were rapidly converging to produce an unprecedented array of new capabilities. The driving force was the transistor: transistors immediately permitted order of magnitude reductions in size for the same computing capacity, directly because transistors are much smaller than vacuum tubes which perform an equivalent function and indirectly because they require far less power and emit far less heat. Of at least equal importance transistors are infinitely more reliable than vacuum tubes. The magnitude of the difference and the speed with which it was exploited is illustrated by two examples: the SM-64 Navaho, a sophisticated vertically-launched airbreathing cruise missile of the mid- to late 1950s with a cruise vehicle about the size of an F-15; and the mach 2 capable B-58, which entered service in 1957. The Navaho was an aerodynamic success and the rocket engine which powered its piggy-back booster was a direct ancestor of rockets which put man on the moon, but the unreliability of its vacuum tube circuitry earned it the name "Never-go Navaho," even as a research vehicle. Like the

Navaho, the B-58 was an aerodynamic success and an operational failure, though not for the same reason; fast as it was, it could not outrun Soviet air-to-air missiles. The core of the B-58 bomb-nav system was a 1,200 pound electronic analog computer, the largest ever made, with a ticker tape readout.[25] The guidance and navigation computers of the Tomahawks and ALCMS (Air Launched Cruise Missiles) used in DESERT STORM, designed to do the same basic job as those of the Navaho and B-58, are not much larger than a carton of cigarettes.

But the importance of the size and reliability of avionics components is not the only lesson to be gleaned from the Navaho and B-58 stories. Each system exploited mature technologies which were at or near their limits of development and, barring the development of novel replacement technologies, are likely to remain so. The Navaho cruise vehicle tested the aerodynamic theories which were the basis for the development of our current generation of air-to-air fighter aircraft, pioneering the outward-splayed twin vertical stabilizers which are a feature of every high performance multi-engined U.S. fighter since the F-14. The Navaho booster's liquid oxygen/kerosene-fueled rocket engine represented a significant improvement over earlier rockets in thrust-to-weight ratio and efficiency, but subsequent advances have been modest for reasons rooted in unalterable physical reality: the chemical energy resident in known oxidizer/propellant combinations and the molecular weights of their decomposition products.[26] As one progresses to more energetic and efficient fuel/oxidizer combinations, the difficulties of containment and handling increase exponentially, yet improvements in performance are comparatively modest.[27] For certain high priority applications, of course, the incremental increase in performance justifies the increased technical risk and cost, but it is worth noting that the Titan, a mid-1950s design, is still our workhorse booster for heavy unmanned payloads and the even older Atlas booster and Agena upper stage remain first-line equipment.[28]

The same point can be made with regard to the J-79 turbojets which powered the B-58. The turbofan engines which power today's first line fighters and bombers are far more fuel efficient than the J-79, but as a practical matter few of the aircraft they drive are much faster than the B-58. USAF F-4G "Wild Weasel" anti-radiation attack aircraft powered by J-79s were first line equipment in DESERT STORM, and if their fuel-guzzling engines required more trips to the tanker than newer strike aircraft, the F-4Gs were at no great disadvantage in speed, ordnance carriage or maneuverability. Simply put, given kerosene-based jet fuels and aluminum structures, performance improvements for manned combat aircraft have been marginal since the mid-1960s and are likely to remain so.[29] Granted, exotic engines burning exotic fuels can drive specialized airbreathing platforms made of exotic materials to much greater speeds; the largely titanium SR-71 cruised at mach 3.5+ and its successors will be considerably faster (perhaps already are) but such vehicles are expensive, highly specialized and require enormous amounts of skill and care to operate. The one area in which the United States can anticipate major improvements in aerospace vehicle propulsion over the short term is in extremely small airbreathing engines for remotely-piloted vehicles and cruise missiles, and here the improvement will be in not in speed, but in compactness, fuel efficiency and range.

To return to the main argument, shrinkage of avionics packages with the advent of transistors was only the tip of the iceberg, for transistorized circuitry also permitted enormous increases in computing power. On a mundane level, the increased power of design computers turned finite element stress analysis from an exotic, time-consuming routine applied only to the most critical of complex stress analyses to the workhorse of structural engineering in the mid- to late 1980s. On a more exotic level, powerful design computers made feasible the complex multivariable analyses of radar returns as function of aspect, geometry, reflectivity and structural properties which made stealth aircraft a reality. The result was a revolution not only in the capabilities and reliability of existing categories of systems, but an ability to design entirely new kinds of weaponry.

The tactical results were demonstrated dramatically in DESERT STORM. In terms of operational impact, the salient capabilities were: LGBs used in combination with night-capable target acquisition and tracking devices; sophisticated night-capable tank fire control systems; the ability to operate at night in general; the operational debut of stealth in the form of the F-117A; long range cruise missiles capable of genuine precision, notably the Tomahawk; the widespread use of secure voice communications and facsimile machines for command, control and coordination; the massive use of air refueling, as much for operational flexibility as for simple range extension; the advent of beyond-visual-range air-to-air combat as an operational reality; and the operational debut of airborne radar systems like JSTARS, capable of monitoring the land battle in detail.

The fact that they were deployed against an enemy inferior in many critical systems and training notwithstanding, the application of these capabilities in combination struck with unprecedented tactical and operational impact. They also produced unanticipated problems, notably in the difficulty of applying our intelligence systems and analytical methods to the unprecedentedly swift tempo of the war.

A handful of predictable errors notwithstanding, American ground and air forces were remarkably successful in conducting and supporting a highly mobile, highly lethal, land war without defined fronts. This was a training achievement of the first magnitude: total U.S. casualties approximated in number what a cynic might have expected to ensue from that many men and women driving that far, that fast and at night over the same terrain without opposition. The quality of American aircrew training was equally apparent: for the Air Force, at least, the aircraft accident rate, indeed the total loss rate per flying hour, went down.

One's first reaction on appreciating the full magnitude of what U.S. and allied forces had achieved in DESERT STORM was to draw a parallel with Robert Clive's victory at the battle of Plassey in 1757 in which 850 British troops and 2,100 Sepoys trained to British standards prevailed over a force of some 52,000 Indians and 200 French mercenaries.[30] Just as well-trained and equipped Western European armies and navies of the late 18th and 19th centuries were able to defeat forces not trained to European standards almost without regard to numerical odds, it is likely then that a balanced U.S. force of all arms, properly equipped and supported and competently led, could defeat any number of anything else. Certain of our allies, notably the British, can achieve similar results when backed by specialized U.S. support in critical areas such as electronic warfare.

Turning from technology and tactics to strategic limits poses two questions: to what extent does the revolution in military technology expand strategic capabilities; and to what extent does the prevailing war paradigm hold true? Of the two, the second may be the more critical understanding of the nature of war; and how it is waged will directly determine no only tactical and operational effectiveness in future conflicts but also strategic success. The technological and tactical revolution witnessed over the last decade was undergirded by evolutionary adjustments in the war paradigm which have the potential to yield major strategic dividends. At the same time, the threat has changed in ways which are so fundamental as to require an extensive rethinking of the strategic equation.

As suggested above, the primary technological constraints to U.S. strategic capabilities in the two world wars in which this basic war paradigm was forged involved productive capacity rather than tactical capability. Note, however, that the tactical capabilities of individual weapons systems were more important to the outcome of the Second World War than the First and that the United States and its principal ally, Britain, were rather successful in anticipating the shift and planning for it. In this sense, the development of the technologies fielded in DESERT STORM was more an evolutionary trend than a revolution in military thought. This encouraging thought must be balanced by a more sober one: as noted implicitly at the outset, the geopolitical and social contexts of the two world wars were strikingly similar. Indeed, some have suggested that the Second World War was merely a continuation of the First, an argument which makes a good deal of sense. By contrast, the geographic, economic, political and social contexts of the wars of the present differ dramatically from those of the two world wars, and it is likely that those of the 21st century will diverge even more sharply from the conflicts in which the American war paradigm was forged. Not only has the economic and diplomatic structure of the international system undergone radical change in the wake of Tiananmen Square, the collapse of the Soviet Union and the unification of Germany; social and economic expectations around the globe have changed as well.

In sum, the threat has changed substantively but the war paradigm has not. The ancient warrior, now wielding a bronze piercing axe and wearing a helmet of Electrum, must face not only enemy champions, but a host of smaller, more subtle and more elusive foes whose objectives are not always apparent. The excellence of this hero's weapons and his strength and skill in using them still count, but he and his smith must anticipate major changes in the weaponry which he can expect to be used against him and those he is sworn to protect.

What technologies, then, should the American military expect to face in the 21st century? Beginning at the top of the spectrum of technological sophistication and working down, nuclear proliferation will remain a major concern. Indeed, sub-proliferation might be a better term, since the possession of nuclear weapons in the hands of political entities below the level of the nation-state is apt to become a reality soon, if it is not already. The bad news is the relatively easy availability of plutonium and enriched uranium on the international black market. The good news is that those most inclined to develop and use nuclear weapons lack the scientific, engineering and technical resources to build compact weapons and sophisticated delivery systems. At least the first wave of "outlaw" nuclear weapons will be relatively large and crude.

One terminal effect of nuclear weapons, however, which does not require the detonation of the device in close proximity to the target demands attention. Electro-magnetic pulse, or EMP, the wave of highly-charged electrical particles proceeds from the nuclear event like an expanding bubble at speeds approaching that of light. EMP, which takes effect as an extremely short burst of very high-voltage electrical energy, has the capacity to do enormous damage to electrical circuits. Transistorized circuits, on which the day-to-day functioning of modern society is increasingly reliant, are particularly vulnerable. A cursory review of the historical record suggests that the detonation in low earth orbit or the upper atmosphere of a relatively crude nuclear device would wreak havoc over a wide area on a host of transistor-dependent systems, including electrical power generation and transmission; telephone, radio and television transmission and reception; information storage and retrieval systems; aircraft avionics; truck and automobile ignition and fuel control units; and medical life-sustaining and monitoring equipment.[21] Circuits can be protected against EMP by "hardening," that is shielding, and critical military systems have been hardened on a selective basis, but hardening is an arcane science and expensive.

On a more mundane level, the allies experienced great difficulty with mobile ballistic missile systems in DESERT STORM, and the system involved was the primitive first generation Soviet SS-1 "Scud." Such systems have enormous potential for mischief, particularly if mated with chemical or bacteriological warheads. The problem is not just military, but political as well, for there are many regions of the world where the launch of such a missile could be credibly attributed to more than one entity, making the appropriateness as well as the effectiveness of the military response an issue. Fortunately, the relatively long-range ballistic systems are, in principle, subject to interception and destruction by defensive missiles. Since ballistic trajectories are predictable, the interception problem is relatively straightforward, though highly demanding of sensor, avionics, booster, fusing and warhead systems. The problem of terminal defense against ballistic missiles is solvable given the willingness to commit the necessary resources.

Stealth cruise missiles present a greater challenge. While it is unlikely that any enemy will be able to approach the U.S. lead in the design and production of piloted stealth aircraft for the next few decades, the suppression of radar signatures becomes easier by a geometric ratio as the size of the vehicle is reduced. It is thus much easier to make a very small vehicle stealthy, a consideration which becomes more relevant in light of the advent of the extremely small, extremely efficient air-breathing engines mentioned above. Moreover, the United States has provided potential enemies with the basis for a precision guidance system in the form of uncoded signals from Global Positioning System (GPS) satellites. The ability to develop long-range, stealthy cruise missiles with precision accuracy, at least against stationary targets, is within the grasp of many national aerospace industries and such vehicles would be exceedingly difficult to defend against.

All the above concerns address conventional munitions and delivery systems. More frightening are the less traditional systems. The design of sophisticated chemical agents does not require massive technical infrastructure and computer-assisted design capability. Moreover, such agents need not be lethal in an immediate physiological sense, and the development of agents with sophisticated psychological effects, whether transient or permanent, is a possibility that must be considered. Finally, there are nontraditional targeting and delivery methods to be considered: chemical agents can be delivered by introduction into the water supply and food chain as well as the atmosphere.

The same undemanding technical and economic constraints on design and delivery apply even more powerfully to bacteriological and viral agents than to chemical weapons. At the lower end of the technology spectrum, the use of natural selection to develop microorganisms with desired immunities and lethalities has the potential to produce highly destructive agents at extremely low cost. At the upper end, the use of genetic engineering to produce novel agents would still be relatively cheap. Disease agents offer a wide range of terminal effects which could be tailored to strategic goals. A highly virulent, fast-acting disease organism with high lethality could quickly kill off the bulk of the populace in the target area and burn itself out, leaving a depopulated area open for occupation. Conversely, moderately virulent, slow-acting bacterial or viral agents with moderate lethality, perhaps engineered to produce chronic rather than acute effects, would be at least equally difficult to counter. The longer the incubation period and the slower-acting the disease, the greater the difficulty of detection and the greater the damage done prior to identification. In either case, the disease organism could be aimed at crops, domestic animals, or perhaps the environment, rather than directly at populations. Selective targeting could be achieved through the use of insect or animal vectors, and disease organisms biologically engineered to strike selectively according to age, gender, race or behavior are entirely possible. Such agents would have enormous potential for social and political disruption, particularly if used in concert with a well-crafted psychological warfare campaign. The remarkably wide acceptance of the story that AIDS was a capitalist or racist plot hints at the potential of such a coordinated campaign. More simply, political targeting could be accomplished by a combination of biological engineering and physical distribution. It would be a relatively easy matter to develop a strain of staphylococcus immune to available antibiotics. Inadvertently, this has nearly been done through the widespread, indiscriminate use of antibiotics. Such an agent could be used to attack segments of a national health care system catering to a given socioeconomic strata or ethnic group and the disruptive effect of such an attack could be amplified by a coordinated campaign of propaganda and disinformation designed to exploit the predictably defensive responses of public health officials.

Returning to electronics, American society, the U.S. economy, and the world trade system are increasingly dependent on the exchange and analysis of information by electronic means. Those means are vulnerable to physical attack, electronic disruption, and manipulation. As with bacteriological attack, an electronic assault could be mounted with minimal capital investment: the successes of computer hackers in gaining access to restricted data bases and planting electronic viruses in data exchange networks speak for themselves. Intrusion into classified Department of Defense and contractor databases is an obvious possibility as is compromise of militarily sensitive command and control circuits, analytical computers, and classified data bases. These circuits are presumably well-protected and monitored. However, such an attack would be the electronic equivalent of a frontal assault, likely to be detected quickly and repelled. More subtle, and more likely to produce strategic results, would be a sophisticated attack on selected nodes of the American social and economic fabric, again accompanied by a coordinated psychological warfare campaign. An attack on financial market and stock exchange data bases to subtly manipulate interest rates, profits, and losses so as to erode the savings–and the confidence–of selected segments of society is an obvious tactic. International credit, currency conversion and banking systems are vulnerable as well. As with biological attack, a slow-acting, moderately virulent "disease" would be harder to detect and counter than a fast-acting, highly virulent one. Moreover, a campaign of subtle electronic sabotage would very likely trigger a defensive reaction from governmental and semi-governmental regulatory agencies and denials that anything was amiss would add credibility to charges that the government was deliberately inflicting injustice.[32] Intrusion into the data bases of the Internal Revenue Service and state revenue systems to introduce injustices and inequities, perhaps by selectively targeting particular groups for audits and seizures of assets, has obvious potential as well. Any such attack would have to be undergirded not only with a deep understanding of the workings of the markets in question, but of the social, economic and political dynamics of American society; that having been said, the potential vulnerability in this area is enormous.

Having surveyed the technological face of the threat environment, this monograph concludes with a brief examination U.S. capabilities and posture. Here prescriptions are mainly intellectual rather than technological and tactical. Just as the Chalcolithic hero girded himself for battle and for the evaluation of new technologies with an appeal to the gods of war and his village, so, in secular guise do today's planners, programmers, and budgeters. The gods are, however, changing and mortals must take account of the change. First, some cautionary observations.

PPBS made a good deal of sense in an era in which technological change was incremental and attacks on the enemy war economy and population base were the primary strategic focus. The assumptions no longer hold and the "theology" badly needs revision, and the term theology is used literally. There is no credible demonstration that the rigorous application of cost benefit effectiveness analysis to the weapons system acquisition process under the aegis of PPBS has, in fact, had a beneficial effect. PPBS has been accepted not as a methodology with demonstrable benefits, but as a verity accepted on faith and the rational basis of that faith badly needs reexamination. If PPBS is a false god, the American military may be well-advised to consider the cost of its misplaced devotion sooner rather than later.

The evidence suggests that a technological plateau has been achieved in terms of speed, firepower, armor protection and mobility. Barring the development of revolutionary new structural materials and technologies of propulsion which violate the laws of physics as now understood (a possibility which cannot be discounted), current state-of-the-art aircraft, ships, and land vehicles go nearly as fast and can expend about as much firepower as will be the case for the foreseeable future. The significant technological advances will come in sensors and detection systems; avionics, guidance and fire control systems; stealth technology across the board; electronic warfare systems; the biological sciences; "virtual reality" training; and, most important, analytical computers, particularly for analysis and design. Planners must be careful to avoid temptations to expend disproportionate amounts of treasure and energy to achieve incremental improvements to existing technologies. In the past, sufferers from what I term the "technological attractive nuisance syndrome" attempted to field the caseless cartridge, the diesel aircraft engine, and the atomic airplane. To cite an example of current relevance, if liquid artillery propellants offer operational advantages over those now in use which are sufficiently compelling to justify major expenditures of scarce R&D funds, the point is not readily apparent.[33]

Granted, there are areas of more of less traditional technology where we are still an appreciable distance from the edge of the performance envelope: high speed vertical takeoff and landing aircraft with sufficiently low rotor downwash velocities for general battlefield utility and very small RPVs are cases in point. There are also areas where the incremental advantage is worth the price: hypersonic atmospheric reconnaissance platforms are an obvious candidate. Cryptography would seem to have reached a plateau of security, but that is what the experts have wrongly concluded in the past on several occasions. Clearly, obsolescent equipment has to be replaced as it wears out and there are important advances to be made in reliability and stealthiness in the process, but on the whole, R&D money and energy will be far better spent on software than hardware.

The United States increasingly depends on imported materials for the production and transportation of war materiel, petroleum being the most critical requirement in the short term but by no means the only one. At the same time, as in the Vietnam War, the American military is apt to go up against adversaries whose war production and population base reside in other countries. The United States was not successful in dealing with this problem in Vietnam at any level: tactical, operational, or strategic. Fortunately, this problem has received objective analysis from a cadre of historians like Larry E. Cable, Mark Clodfelter, Andrew F. Krepinevich, and Earl H. Tilford, Jr. Their analyses warrant careful consideration by scholars and military professionals.

On a more positive note, there are no serious prospects of the U.S. lead in the design of high technology weapons systems being challenged in the near term, or even over next few decades–if it is careful to preserve it. The analytical and design capabilities which made possible the Tomahawk, the M1A1 fire control system and the F-117A were the products of many decades of continuous intellectual tradition and governmental support. They could not be reconstituted overnight with the wave of a budgetary wand. Just as the Chalcolithic hero depended on his smith, so are today's progressively less numerous champions dependent on their engineers.

In addition, there is a downside to these impressive technological capabilities: specifically, improved tactical capabilities breed heightened strategic expectations. The ability to take out a single building with a single bomb on a single pass fosters not only the expectation that this can be done routinely, but that to do so is *strategically relevant*. On a practical level, to make that capability relevant one must know with some precision what is inside the building, why it is important and when it will be there. Note that the answers to those questions are as likelv to be political as military, posing a significant challenge for intelligence gathering and dissemination agencies. For the foreseeable future, the United States is more likely to be engaged in relatively small-scale regional conflicts where leadership, cultural symbols and political motivation are key factors than in major conflicts where we can target the industrial base. In the past, the United States has not always been spectacularly successful in evaluating such intangible, human factors. It badly needs to improve its intelligence and analytical capabilities.

The ability to minimize collateral civilian casualties, an ability demonstrated spectacularly in DESERT STORM, the bombing of the Al Firdoz bunker notwithstanding, carries with it the assumption that any collateral civilian casualties are unacceptable, however reprehensible enemy policy goals and however vicious enemy tactics. Similarly, the ability to minimize losses to enemy fire throws even minimal losses to "friendly fire" into stark relief. Military leaders must be forewarned not to mis-advertise their capabilities. Furthermore, they must educate their civilian superiors, all the more so because of the political attractiveness of certain of those capabilities.

High technology weaponry is highly dependent on user skill and training for tactical effectiveness. DESERT STORM was as much a triumph of hard, realistic, combat-oriented training as of design engineering. Indeed, many military professionals would argue that training was more important, and some have gone so far as to speculate that we could have exchanged systems with the Iraqis and still won. That is no doubt an overstatement, but the point behind it is valid. Our military services learned the value of combat-oriented training the hard way in Vietnam and we now enjoy a huge lead in this area, but such training is expensive and operations and maintenance budgets will remain under intense pressure. We must be extremely careful not to throw away our advantage in this critical area.

Finally, the nature of the strategic, operational and tactical environment in which our forces will operate in the 21st century must be rethought and force structures adjusted accordingly. The recent military technological revolution has provided unprecedented, and for the moment unchallenged, tactical and operational capabilities. As was demonstrated in DESERT STORM, the American military can exploit its technological advantages when faced with a conventional threat. The challenge is to harness those capabilities to the less conventional kinds of wars which will surely arise with increasing frequency. The crux of the matter is not our ability to put bombs on target or men, munitions, and vehicles on beaches and landing zones; the pivotal issue is the identification of strategically relevant targets, beaches and landing zones, an area where improvement is imperative.

The very precision offered by technologically advanced munitions demands an equivalent precision and timeliness in targeting. That, in turn, demands timely and accurate intelligence, not only before the fact, but afterwards in accurate bomb damage assessments. The focus of the preceding observation was on air operations, but if anything the demands of ground combat for timely and accurate intelligence are even greater, if for no other reason because intelligence failure in ground combat tends to produce more friendly casualties. The need for swift, accurate intelligence is increased exponentially by the reality of smaller force structures, justified in part by the capabilities of precision-guided munitions, an observation which requires a cautionary note: certain categories of target do not lend themselves to attack by PGMs, but are best dealt with by massive, nonprecision bombardment. Mobile ground formations on the move, dug in defensive lines and major storage and production facilities are cases in point. Despite the tactical fascination with PGMs, there will always be a need for massed artillery bombardments and large numbers of "dumb" bombs dropped by small numbers of large aircraft.

In sum, intelligence must be more subtle, timely and accurate. The services can no longer afford the luxury of the compartmentalized intelligence functions which were a logical product of the old war paradigm, the cold war focus on nuclear weapons. Rather, the intelligence function must be integrated with operational planning and execution more closely than ever before. Intelligence must also expand its focus to address the sorts of nontraditional threats outlined above, a venture in which exchanges of information with civilian law enforcement agencies will become pivotal and in which the specialist noncombat arms will have an important role to play. The sticky constitutional issues raised by the prospect of close interaction between civilian law enforcement agencies and military intelligence must be resolved and indicate the changing face of strategy. The Army, by virtue of its structure and historical past, will inevitably be at the epicenter of such changes. The Corps of Engineers would seem a logical institutional locus for assessments of the vulnerability of urban areas and public utilities to attack and sabotage. Similarly, the Medical Corps should become centrally involved in assessments of hostile chemical and bacteriological capabilities and the development of appropriate countermeasures. Judge advocates must develop hands-on familiarity with the nitty-gritty of operational planning and tactical execution so as to be able to provide commanders and planners with timely, relevant and accurate legal guidance.[34] The central importance of news media coverage of military operations demands that public information personnel develop a similar familiarity with operational planning and tactical execution. By the same token, commanders and operational staffs must become more sensitive to the importance of input from such specialists.

In conclusion, two basic points are clear: if strategy could ever be approached as a straightforward technical exercise in the movement of military formations across country, war on the map as Jomini put it, followed by an equally straightforward, though considerably bloodier, exercise in fire and maneuver on the battlefield, that time is long past. Similarly, if there was ever a time when war could be approached as an exercise in production line engineering, as the U.S. Army Air Forces did in preparation for World War II, that time is long past, as well.[35] The maneuver of conventional forces and industrial production will remain important integers in the strategic equation, but they are no longer preeminent.

And so this analysis of the technological limits of strategy ends on a cautionary note about the essentially human nature of war. The Chalcolithic hero understood implicitly that success in war was determined not just by strength and technological advantage alone, but by the effective application of those qualities in human context. The perceived force of his blow was increased by faith in his gods and fear of them. Just as the gods of his village presided over his swing, understanding of policy goals presides over our application of military force. Whatever the technology, war remains as Carl von Clausewitz characterized it, a test of will and faith. Do not lose sight of that reality.

ENDNOTES

1. The dating is speculative; see my introduction to "War, Technology of," *Encyclopedia Britiannica* (1992) and Yigael Yadin, *The Art of War in Biblical Lands in the Light of Archaeological Study,* 2 vol., London: McGraw-Hill, 1963, Vol. I, p. 40. Though now dated, *The Art of War in Biblical Lands* remains thc best single source on very early military technology and is valuable by virtue of having been written by a competent military professional. The Chalcolithic era, by definition the period in which man had learned to smelt copper and precious metals but still relied on stone implements for grinding and cutting, is generally held to have begun in southern Anatolia and the Fertile Cresent around the middle of the fifth millennium BC. Though archaeological evidence for mace heads of stone is abundant, that for copper is understandably scant since copper mace heads would have been melted down for bronze after the mace became obsolescent.

2. As indicated in the definition above, I consider technology to encompass human manipulation of biological processes. In this light, the development of natural grasses into food grains, perhaps best understood with regard to the Amerindian development of maize, was a technological achievement of the first order.

3. William Hardy McNeill, *The Pursuit of Power: Technology, Armed Force and Society since A.D. 1000,* Chicago: University of Chicago Press, 1982, p. vii.

4. The start of Narmer's reign is generally dated from *circa* 3,100 BC. The palate does not tell us what the head of his mace was made of; my point is the symbolic importance attached to the mace.

5. This was true from a very early stage. Arsenic bronze was soon superseded by tin bronze and as McNeill, *Pursuit of Power*, p. 1, notes, "copper and tin ores are not found in the same regions."

6. See Jon Tetsuro Sumida, "Forging the Trident: British Naval Industrial Logistics, 1914-1918," in John A. Lynn, ed., *Feeding Mars: Logistics in Western Warfare from the Middle Ages to the Present,* Boulder, Colorado: Westview Press, 1993, pp. 217-249. As Sumida makes clear, the Royal Navy had much closer ties with industry than did the Army and was far more experienced at negotiating its interests in the industrial/ governmental arena; in consequence, the Navy preempted industrial capacity which would have been dedicated to supporting the land war in any rationally prioritized scheme, a reality which had much to do with the munitions shortages on the Western Front. Nor was the advantage only quantitative: I would point to the generally superior quality of aircraft procured by the Royal Naval Flying Corps compared to those procured by the Royal Flying Corps in 1915-16.

7. Ian Marshall, *Armored Ships,* Charlottesville, Virginia: Howell Press, 1993, pp. 106-110, for a concise and perceptive summation.

8. See Alfred C. Mierzejewski, *The Collapse of the German War Economy, 1944-1945: Allied Air Power and the German National Railway*, Chapel Hill and London: University of North Carolina Press, 1988, esp. pp. 22-34. The estimate of how much sooner Nazi Germany would have collapsed had the coal-based war economy not been so efficient is my own.

9. Williamson Murray, *Strategy for Defeat: The Luftwaffe, 1933-1945*, Maxwell AFB, Alabama: Air University Press, 1983, pp. 159-156, makes this point both explicitly and implicitly; see particularly p. 148, Table XXX, which demonstrates graphically how the enormous German aircraft losses in the Mediterranean between March and May 1943 combined with subsequent losses incurred in Italy, at Kursk and over the Reich to break the back of the Luftwaffe.

10. See: Eric Schantzberg, "Ideology and Technical Choice: The Decline of the Wooden Airplane in the United States, 1920-1945," *Technology and Culture*, Vol. 35, No. 1, January 1994, pp. 34-69. Comparisons between aluminum and other aircraft structural materials, notably wood, were by no means as lop-sidedly favorable to aluminum as most general aviation histories suggest. Until the advent of jet propulsion, properly designed and fabricated wooden structures were as efficient as their aluminum equivalents if not more so, that is they represented a smaller percentage of the weight of the fully-loaded aircraft. The fastest, and

arguably most successful, reciprocating-engine combat aircraft of World War II, the de Havilland Mosquito, had an entirely wooden structure except for the engine mounts, landing gear, and flight control attachment points. Wood, however, was difficult to work with and wooden structures did not hold up well under high heat and humidity. Lockheed, producer of the most efficient aircraft structures of the interwar period, converted from wood to aluminum in the mid-1930s and kept its competitive edge, but this is more a commentary on the excellence of Lockheed's design team than the inherent disadvantages of wood. It is worth noting, too, that aluminum production was extremely energy-intensive, relying on massive amounts of electrical power–mostly produced by coal-burning power plants!

11. John Batchelor and Ian Hogg, *Artillery*, New York: Scribner, 1972, pp. 90-99; my main reference is to the Krupp 75mm PAK 41.

12. While pilots were the critical node, the point applies to a crew generally and to maintenance personnel. Aircrew training was a major Allied success in both world wars, yet remarkably little has been written on the subject.

13. Shelford Bidwell and Dominick Graham, *Fire-Power: British Army Weapons and Theories of War 1904-1945,* London: George Allen and Unwin, 1982, pp. 141-146; Roy M. Stanley II, *World War II Photo Intelligence,* New York: Scribner, 1981, pp. 20-32.

14. For an insightful treatment see Stanley, *World War II Photo Intelligence*, esp. pp. 1-14.

15. Attempts to produce the French '75 in the United States were a fiasco and the American Expeditionary Force was equipped almost exclusively with French artillery.

16. Notably in the empirical development of methods of reducing engine-associated drag, the most dramatic application of which was in the North American P-51, arguably the most successful fighter of the second half of the war.

17. Daniel R. Beaver, "Deuce and a Half, Selecting United States Army Trucks, 1920-1945," *Feeding Mars: Logistics in Western Warfare from the Middle Ages to the Present*, pp. 251-270.

18. Remark from the floor, "The Revolution in Military Affairs: Defining the Army for the 21st Century," Carlisle Barracks, Pennsylvania, first afternoon session, April 27. Mr. John J. Patrick is Program Manager at Techmatics, Inc. of Arlington, Virginia.

19. This is the basic point of Earl H. Tilford, Jr., *Crosswinds: The Air Force's Setup in Vietnam,* College Station, Texas: Texas A&M University

Press, 1993. In fairness to the planners who laid out the initial targeting for Rolling Thunder, interdiction of Communist manpower and supplies occupied a high priority, but this, too, was very much in the tradition of our air interdiction efforts in Korea and World War II. We should also note that the Air Force did a number of clever and successful things in Vietnam which cut against its doctrinal grain, including the widespread use of aerial FACS (forward air controllers), the development of the side-firing gunship and the creation of a specialized long-range combat rescue force. These innovations and those involved in implementing them, however, were never regarded as being in the professional mainstream.

20. The dead hand of PPBS is, of course, not the only factor involved: "black" programs are more glamorous than openly acknowledged ones and enjoy high priorities, thus presumably attracting more capable engineers and managers.

21. I am indebted to James Tomayko of Omaha State University for this information.

22. Peter J. Hugill, *World Trade Since 1431: Geography, Technology and Capitalism*, Baltimore, Maryland: Johns Hopkins University Press, 1993, pp. 290-291.

23. Bill Sweetman, *Stealth Aircraft: Invisible Warplane, Black Budget*, Osceola, Wisconsin: Motorbooks International, 1989, pp. 53-55.

24. Tilford, *Crosswinds*, pp. 150-51.

25. R. Cargill Hall, "To Acquire Strategic Bombers: The Case of the B-58 Hustler," *Air University Review*, Vol. XXXI, No. 6, September-October 1980, pp. 1-20.

26. The basic measurement of rocket efficiency is specific impulse, written I_s, a measurement of the number of pounds of thrust produced each second by each pound of propellant. Though expressed in seconds by mathematical reduction, I_s is in fact a dimensionless ratio, the higher the value the greater the propulsive efficiency. The engine of the World War II German V-2 weighed 2,484 pounds and produced 56,000 pounds of thrust with an I_s of 199 seconds. The Navaho booster weighed 1,230 pounds and produced 120,000 pounds of thrust with an I_s of 230 seconds. Liquid oxygen and kerosene, the oxidizer/fuel combination used in the Navaho and still used in the Atlas booster, has a theoretical maximum I_s of 294 seconds. Liquid oxygen and liquid hydrogen, the combination used in the Space Shuttle's main engines, yields a theoretical maximum of 391 seconds, but at a considerable cost in technical complexity and risk. Liquid hydrogen is notoriously difficult to deal with and, for reasons bound up in cryogenics and the molecular physics of known structural materials, the technology for a structurally efficient, reusable liquid hydrogen tank does not exist. Liquid

fluorine and liquid hydrogen, the most efficient propellant combination known, would yield a theoretical maximum I_s of only 410 seconds and the practical difficulties of containing and controlling liquid fluorine are immensely greater than those posed by liquid oxygen. Dieter K. Huzel and David H. Huang, *Design of Liquid Propellant Rocket Engines*, 2nd ed., NASA Special Pamphlet SP-125, Washington, DC, 1971, pp. 21-27, 36.

27. I am indebted to Jeff Cooper, Strategic Director of SRS Technologies, for pointing out to me the strikingly modest improvement in rocket engine efficiencies since the late 1950s after my spoken remarks on April 27.

28. A telling detail which indicates how quickly American engineers mastered the basic physics of rocket propulsion is the Atlas' stage-and-a-half configuration in which the vehicle leaves the pad with three engines firing and subsequently jettisons two of the three. A two stage design, in which a first stage booster with its own tankage is jettisoned prior to second stage ignition, is inherently more efficient and was recognized as such, but the Atlas was designed so early in the game that engineers were unsure that the fuel and oxidizer would ignite spontaneously in the hard vacuum of space.

29. I do not mean that aircraft technology will remain static, or that there is no point in investing in improved piloted combat vehicles. Clearly, such platforms as the B-2 and F-22 represent major advances in combat capability, but in terms of speed, range, and load-carrying capability and efficiency, they are not all that different from their predecessors.

30. For a useful summation, see David Chandler, *Atlas of Military Strategy*, New York: Free Press, 1980, pp. 78-79.

31. The key event was the detonation of an American nuclear device in the upper stratosphere over Johnson Island during the Kennedy presidency. Having negotiated a nuclear test ban with the USSR, the administration came under attack by critics who argued that the Soviets were playing us for suckers and preparing a nuclear test series for immediate implementation when the ban expired. In the event the critics were right, we would be unprepared to follow suit. Embarrassed, the President ordered the AEC (Atomic Energy Commission) to conduct an immediate nuclear test. The only thing the AEC could come up with on short notice which might produce useful data was a detonation in the lower reaches of space. To the surprise of all, EMP from the test wrought electronic havoc generally and blew out street lights as far away as Honolulu.

32. A telling and relatively recent example of such a defensive reaction can be seen in statements made by officials of the Red Cross, the American Association of Blood Banks, and the Council of Community Blood Centers

in January of 1983 that there was no "hard" evidence that AIDS was being spread by blood transfusions and arguing against the use of laboratory tests to screen blood donors. At the time, the Center for Disease Control (CDC) was arguing persuasively that AIDS could, in fact, be spread by transfusions and contemporary internal Red Cross memos recently leaked to the press indicate a clear awareness that this was the case. Having drawn their line in the sand, however, the Red Cross, *et. al.*, held their ground until March 1985 when they were forced by an overwhelming weight of evidence to adopt mandatory AIDs testing for blood donors.

In fact, the circumstances surrounding the debate over mandatory donor blood testing in January of 1983 were more complicated than the above summary suggests: CDC argued for a "surrogate" test for hepatitis B, which it maintained could have been in place by March 1983, on the grounds nearly all AIDS patients also suffered from hepatitis B. The counter argument, still supported in May 1994 by a senior Red Cross official privy to the internal deliberations and decision to reject testing ("Red Cross knew of AIDS risk, documents show," *The Columbus* [Ohio] *Dispatch*, Sunday, May 15, 1993), was that the hepatitis B test would have produced a large number of false positives, thus (my interpretation) excluding many potential blood donors. It was difficult at the time, and it is difficult now, not to conclude that economic imperatives outweighed humanitarian and medical concerns in the deliberations of the agencies regulating our blood supply.

The point of the above example is not to portray the officials of the Red Cross, *et. al.*, as ogres; rather it is to illustrate the deeply ingrained reluctance of official and semi-official regulatory agencies to admit error. In this instance, that reluctance was not turned against them, or the government, to major political effect, in part because the segment of society most affected by the AIDS epidemic at the time, the gay community, was ambivalent on the issue. The point is that such reluctance is real, is endemic, and is a point of potential vulnerability. The appearance of outbreaks of necrotizing fascitis, caused by a "flesh eating" strain of streptococcus, first in Britain and now in the United States, has produced a similar wave of dismissive statements by public health authorities. See: "Flesh-eating Bacteria Aren't New to This Area," *The Columbus* (Ohio) *Dispatch*. June 9, 1994.

33. I owe the addition of the diesel aircraft engine to the list to a comment in 1986 by Mr. Maxime Faget of Eagle Engineering, Houston, Texas. Faget is generally recognized as the guiding spirit behind the detailed engineering of the Space Shuttle.

34. I am indebted to W. Hays Parks, Colonel USMCR, Chief Counsel for the Secretary of the Army, for this point. An example cited by Colonel Parks of the kind of problem which can be resolved by timely legal guidance in the planning process involved the initial refusal of logistical planners during Operation DESERT SHIELD to provide Marine air units with napalm,

based on the mistaken belief that the use of napalm was in violation of the laws of war.

35. See Barry D. Watts, *The Foundations of U.S. Air Doctrine: The Problem of Friction in War,* Maxwell AFB, Alabama: Air University Press, 1984.

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