Cruise Missiles and Modern War

Strategic and Technological Implications

David J. Nicholls, Lt Colonel, USAF

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Abstract

This study examines how the proliferation of technologies has remedied the historical shortcomings of cruise missiles to produce a weapon that has significant military capabilities. The argument in this study is that cruise missiles are more cost-effective weapons than manned aircraft and ballistic missiles. It argues, furthermore, that the proliferation of cruise missile systems and technologies will transform cruise missiles into important and perhaps decisive weapons in the twenty-first century.

The second theme of this study is that the United States must develop the ability to defend itself against a cruise missile attack. For a number of reasons, it is unlikely that U. S. defenses could entirely defeat such an attack in view of the difficulties of detecting and engaging a mass attack with cruise missiles that a determined enemy could use to overwhelm the defenses. Bearing in mind reasonable estimates of the numbers of cruise missiles that states could possess, this study concludes with the argument that the optimal strategy for an adversary against which the United States must defend itself is an attack against U. S. logistics and supply centers. This represents the nature of the asymmetric attacks that the United States will confront in the twenty-first century.

The Author

Lieutenant Colonel David J. Nicholls, USAF is a materials engineer with experience in resource analysis. Prior to entering the Air War College, he worked as an operations analyst for the Program Analysis and Evaluation Directorate within the Office of the Secretary of Defense. There he performed statutorily required cost estimates for major weapon systems such as the New Attack Submarine, the AIM-9X (Sidewinder) missile, the Joint Air to Surface Stand-off Missile (JASSM), and Tomahawk among others. He also performed economic/technical analyses supporting Secretary of Defense decisions concerning thc Seawolf submarine, the Crusader howitzer, comparing SLAM-ER vice JASSM, the Defense Nuclear Agency, and the number of public shipyards used by the Navy. Previously, he served two tours at the Air Force Academy where he served as an Associate Professor and Director of the Applied Mechanics Laboratory. There he directed and taught courses in composite materials, metallurgy, failure analysis, strength of materials, and systems engineering design. Prior to assignment at the Academy, he worked as a development engineer at the Air Force Materials Laboratory. There, as part of in-house research, he established their in-house capability to fabricate specialized composite materials and developed their process for evaluating small amounts of composite matrix materials. He also conceived and managed research contracts for thermoplastic composites (later used heavily on the B-2) and cheap composite fabrication methods. His professional military education includes Squadron Officer School, distinguished graduate of the Air Command and Staff College, and Armed Forces Staff College. He earned a Bachelor of Science from Rensselaer Polytechnic Institute, a Master of Science from the University of Dayton, and a Doctor of Philosophy from the University of Oxford. He has published a total of eighteen papers on topics ranging from metal fatigue to chaos in warfare. He is currently working advanced systems projects in Washington.

I. Introduction

The basic idea behind cruise missiles, which predates the outbreak of hostilities in World War 1, has inspired a number of devoted advocates ever since As early as 1915, the *New York Tribune* described the progenitor of the cruise missile as "a device likely to revolutionize modern warfare."[1] Later, Army General William Mitchell described cruise missiles as "a weapon of tremendous value and terrific force to air-power," and proposed that these weapons be used in his famous bombing tests against battleships to prove the efficacy of attacks from aircraft. [2]

The problem, however, is that cruise missiles have only recently begun to live up to the expectations that emerged during the first half of the twentieth century. As a number of technological developments have largely resolved the fundamental shortcomings of cruise missiles, these are now emerging as truly modern weapons that give states an unprecedented ability to destroy important targets in military campaigns. For example, during the air campaign against Kosovo in the spring of 1999, the NATO air campaign began with cruise missile strikes against communication facilities and air defense sites.

A number of significant advances in guidance and control technologies have dramatically improved the lethality, reliability, and accuracy of cruise missiles. For example, as a result of advances in propulsion technologies cruise missiles can now operate at ranges that are transforming them into significant weapons. At the same time, advances in stealth technology are increasing the inherent survivability of cruise missiles. As a result of these and various other technological developments, many states will be able to exploit the two inherent advantages of cruise missiles for military purposes: their relatively low cost and that fact that these weapons are uninhabited and, hence, expendable.

The dissolution of the Soviet Union is forcing states to develop different approaches to security, not the least of which is to rely on their own resources for national defense. As these states are freed to make their own decisions about weapons, it will inevitably increase the global demand for sophisticated weapons. To complicate matters, the global marketplace in defense technologies is being strengthened by the willingness of the technologically advanced states to use the sale of weapons to raise hard currency and promote their prestige as major players in the security market.

This climate is strengthened by the repeated use of cruise missiles by the United States against Iraq, Sudan, Afghanistan, and Yugoslavia. The United States has demonstrated that cruise missiles are militarily useful weapons, which may persuade states that cruise missiles are militarily significant and, further, that this realization will strengthen the global market for cruise missiles. As the laws of supply and demand affect weapons technology, the cost of cruise missiles is likely to decline substantially. For these reasons, it is highly likely that cruise missiles will be an important part of the arsenals that are possessed by both developed and developing nations.

The broad purpose of this study is to explore the nature of the threat posed by cruise missiles to U.S. security, and to examine the value of U.S. defensive strategies for managing the proliferation of cruise missiles. It explores the nature of the threat posed by cruise missiles, and examines how technological developments have remedied the historical shortcomings of cruise missiles to produce weapons that have significant military capabilities. One conclusion from this study is that cruise missiles will be cost-effective weapons for developing states in comparison with manned aircraft and ballistic missiles, and that the widespread proliferation of these systems and technologies will transform cruise missiles into decisive weapons for conflicts in the twenty-first century.

A second theme of this study is the nature of defensive capabilities against cruise missiles. It is unlikely that U.S. defenses could entirely defeat a significant attack with cruise missile in view of the difficulties in detecting and engaging cruise missiles, especially in the case of the mass attacks that would be designed to overwhelm the defenses. When one considers reasonable estimates of the number of cruise missiles that adversaries could develop, the best strategy for an adversary would be to attack U.S. supply lines and logistics centers. The broad implication of this study is that the United States must understand how to reduce its vulnerability to attacks with cruise missiles. This is an example of the asymmetric attacks that will pose a challenge to U.S. security interests in the future.

II. Improving Cruise Missile Technologies

The principal strategic and operational value of airpower is the ability to destroy targets that are well beyond the front line of enemy forces. This idea of "deep attack" is critically important because it means that aircraft or missiles can be used for the purpose of destroying the power grids, command and control facilities, social and economic infrastructure, and logistics systems that constitute the foundation of modern societies. In view of its technological superiority, the United States has been able to preserve its monopoly in deep attack, while denying this capability to its adversaries. This is an important reason for the unprecedented military superiority that is enjoyed by the United States at the end of the twentieth century.

Since the origins of powered flight, the notion of cruise missiles has competed with manned aircraft for the conduct of deep-strike attacks But for the reasons that are discussed in greater depth in the Annex, cruise missiles have not been able to achieve their maximum operational potential. The potential of cruise missiles has been weakened by a combination of low reliability, poor accuracy, vulnerability to intelligence deception, inability to adjust to changing conditions on the battlefield, range limitations, predictable flight paths that make them vulnerable to attack, and the vulnerability of launch platforms.

However, by the late twentieth century significant technological advances that accrued over the past thirty years have transformed cruise missiles into reliable weapons, which have militarily significant ranges, extraordinary accuracy, and a significant degree of survivability against sophisticated defenses. Not surprisingly, cruise missiles are now a fundamental part of the U.S. arsenal for conducting deep attacks against military and economic targets. The discussion in the following section focuses on the technological developments that have led to this transformation in the capabilities of cruise missiles.

Increased Range

The range of cruise missiles is crucial because it fundamentally defines the depth of attack. More importantly, greater depth increases the number of targets that can be attacked with cruise missiles, and thus prevents the enemy from establishing sanctuaries within which its military forces are safe from attack. This is more than a hypothetical concern. During the 1991 Gulf War the range of Iraq's SCUD missiles forced the United States and its coalition partners to station high-value assets, including its AWACs and JSTARS aircraft, in Yemen in order to keep those critical weapon systems well out of range of SCUD missiles. An additional advantage to increased range is that it allows cruise missiles to maneuver around threats, which also increases their survivability.

With a given amount of fuel, the range of a cruise missile is basically a function of the efficiency of its propulsion system and the drag of the vehicle itself. It is for this reason that the forces of technological innovation have focused primarily on the improving the range of cruise missiles. One method was to increase the propulsion efficiency of cruise missiles. For example, the United States developed a new generation of highly efficient, small turbojet engines, such as the Teledyne 402 engine, in the early 1960s. But in recent years these engines and the associated technologies have spread to a number of states. As an example, the United States sold the Harpoon missile to twenty-three countries, which directly raised the possibility that these states would be able to reverse engineer the technologies in cruise missile engines. To cite another example, Taiwan has followed this course in improving its engine technology.[3] In addition, China, France, India, and Russia have all developed have their own indigenous products. The overall effect has been to -develop technologies that increase the range of cruise missiles, which is often accomplished by moving the aerodynamic and mass centers of gravity closer together.[4] The other effect is to see the diffusion of this technology to other states.

Survivability

As a general principle, cruise missiles do not possess the defensive capabilities that permit them to withstand an attack. Therefore, the survivability of a cruise missile after it is launched is crucially dependent on minimizing the interval between the time that enemy air defense systems detect its presence and the time it takes for the cruise missile to arrive at its designated target. And this interval is a function of the speed of the cruise missile and the distance at which it is detected. One approach to increasing the lethality of cruise missiles is to significantly increase their speed, but significant improvements in speed are unlikely to appear in the future. One important exception, however, is the Russian *Alfa* cruise missile, which is capable of speeds in excess of Mach 4 (four times the speed of sound).

Another profitable route for increasing the survivability of cruise missiles is to invest in the technologies that reduce the ability to detect cruise missiles. The most publicized method is to reduce the radar cross section (RCS) of cruise missiles, which is known as low-observable or "stealth" technology. As with speed, stealth technologies essentially reduce the time between the initial detection of a cruise missile and its arrival (and subsequent detonation) at the target. The advantage to stealth technologies is to reduce the reaction time available to the defense, which in turn allows the cruise missile to get closer to the target before it, is detected. For example, if an AWACS type radar can detect an object with a seven-meter radar cross-section traveling at 500 miles per hour at a distance of roughly 370 kilometers,[5] it can be calculated that this radar would detect an object with a radar cross-section of -10 dB flying at 500 miles per hour roughly ten minutes before it would arrive at the target.[6] By contrast, if we use the same radar but are seeking to detect a stealthy cruise missile that has a radar cross section of -40 dB, the cruise missile would be detected less than two minutes before it arrived at the target.

There are other technological developments that will have significant consequences for minimizing the time between detecting a cruise missile and its impact at the target. One notable example is to use terrain maps and radar altimeters so that cruise missiles can fly at extremely low altitudes, often less than fifty feet. The ability to fly at low altitudes reduces the chances that a cruise missile will be detected because it forces an airborne radar to find the cruise missile in the ground clutter that occurs when radar bounces off trees, buildings, and other structures. Operating at low altitudes also improves a cruise missile's survivability against ground-based defenses because a low-flying missile is easily hidden by terrain. Yet another way to increase survivability is to use cruise missiles to attack radar sites in order to create holes in the radar coverage, or to program the missile to fly around defensive radar's in order to avoid detection altogether.

The survivability of cruise missiles has also been increased by the technological innovation associated with relatively small launch facilities For example, a significant tactical weakness of the German V-l missile during the Second World War was the need for a 1 80-foot long fixed ramp. As a result of technological advances, it is possible to launch a Tomahawk cruise missile from a tube on a surface ship or submarine that is scarcely longer than the Tomahawk missile itself. These difficulties of detection are exacerbated by the small size and the minimal infrastructure that is required to launch cruise missiles. This also makes it difficult to detect launch facilities, as exemplified by the U.S. failure to locate Iraqi Scud missiles during the Persian Gulf War, despite the extraordinary efforts that were devoted to locating mobile missiles.

Precision Targeting

A distinguishing feature of cruise missiles is their precise guidance systems. The fact that the power of an explosive decreases radically with the distance from the detonation, means that with relatively small explosive warheads, cruise missiles must arrive quite close to their target. The technological innovation of the late twentieth century that gives cruise missiles such great accuracy is the Global Positioning Satellite system, which is known as GPS. This technology permits cruise missiles to be guided toward their targets with a level of precision that is measured in feet. Cruise missiles with GPS can be guided to their target with constant position updates.

Prior to the development of GPS, cruise missiles typically used inertial guidance systems, which measure the position of the missile in terms of the rate at which it drifts from its initial position at launch. If inertial guidance systems are updated periodically with an accurate and independent source of navigation, such as that provided by GPS, the drift can be removed and cruise missiles can achieve even higher levels of accuracy. As an illustration, a cruise missile with a high-quality inertial guidance system that has a drift rate of 0.1 degree per hour would produce a guidance error that is equal to 580 feet over a distance of 250 miles at a speed of 500 miles per hour.[7] If, however, this system received an update from GPS at 50 miles from the target, the error could be reduced to 23 feet.

The accuracy of GPS guidance technologies for cruise missiles can be further improved by differential techniques, which requires a reference transmitter whose location is precisely known. This transmitter is located so that it receives the same GPS satellite signals as the missile. By comparing its actual known location to the calculated location based upon the CPS satellites, the transmitter can calculate instantaneously the error of the GPS signal and transmit that information to the missile. This technique is widely used by both commercial organizations and governments. The U.S. Coast Guard, for example, has installed 50 stations that provide an accuracy of less than five meters up to 400 kilometers from the U.S. coastline.[8] In tests conducted by the U.S. Air Force with munitions that are guided by inertial systems and GPS, the use of differential GPS decreased the average miss from 40 feet to 16 feet.[9] Not surprisingly, this technology has attracted the attention of other states, including China.[10]

A further advantage of GPS is the ability to determine the position of targets with great accuracy. Before the onset of hostilities, a potential adversary at little risk or no cost could send agents armed with GPS receivers and laser range finders into neighboring countries to determine the precise GPS coordinates of potential targets. While this technique is limited to non-relocatable (fixed) targets, it is possible to precisely locate a number of critical targets, including ports, airfields, electrical power units, pre-positioned logistics supplies, transportation nodes, and military bases. And to make matters more complicated, this targeting information is available from high-resolution satellite imagery that can be easily obtained from commercial firms.

These conditions are relevant to cruise missiles because precise knowledge about the location of targets and precise knowledge about the location of the missile itself is essential if a missile's flight control system is to guide it accurately to the target. As technological innovation has increased the speed and accuracy of cruise missiles, it has increased the military capabilities of cruise missiles. At the heart of this technological innovation is the development of digital control systems that, along with enormous advances in computer processing power, permit many states to develop flight control systems for cruise missiles that are highly accurate. As a result, cruise missiles now possess a measure of lethality that once were reserved to manned aircraft.

III. Proliferation of Cruise Missiles

The discussion in the previous section focused on the technologies that are improving the operational capabilities of cruise missiles. This has been accomplished by improving the range, accuracy, and survivability of cruise missiles. If nations are to deploy significant numbers of cruise missiles in their military arsenals, they must have access to the requisite technologies, and furthermore cruise missiles must be as cost effective as comparable weapon systems. The fact that states have access to cruise missile technologies, and that cruise missiles now give states significant operational advantages, constitutes a revolutionary improvement in military capabilities in the twenty-first century.

The discussion in this section focuses on how the proliferation of cruise missiles will affect U.S. national security and our ability to respond to the threat posed by the proliferation of advanced cruise missile technologies.

Availability and Affordability

The commercialization of pertinent technologies, widespread arms sales, and the indigenous development of guidance, propulsion, and survivability technologies have improved the capabilities of cruise missiles. The commercialization of technology has improved electronic and digital components, such as the computers that are required for autopilots and the GPS receivers that are required for locating targets and guiding missiles to that location. In addition, the commercialization of computer-aided design, when coupled with computer-assisted, precision-machining capabilities, have greatly enhanced the ability of states to make the precise parts that are necessary for modern cruise missiles. As a result, the number of states that can build cruise missiles has grown substantially. Nineteen countries currently produce cruise missiles, fifty-four countries possess them, and China reportedly will field a stealthy cruise missile by the year 2001.[11]

Nations that are unable to build their own cruise missiles will be able to buy them despite the restrictions imposed by the Missile Technology Control Regime (MTCR), which is a multinational agreement that is designed to prevent the proliferation of missiles. The problem with the MTCR is its focus on the strategic use of missiles, which means that the MTCR is concerned primarily with missiles that have a range of 300 kilometers and carry at least a 500-kilogram warhead. Some cruise missiles vendors have deliberately tailored their missiles to meet these requirements, and thus be exempt their missiles from the restrictions imposed by the MTCR A further problem is that some countries, such as China, are not signatories of the MTCR.[12]

One should not conclude from this analysis that all countries have the ability to build cruise missiles. While it is true that many of the components and manufacturing technologies are widely available, the knowledge required to integrate those components together into working systems still remains quite restricted. Even the United States has difficulties with the development of advanced missile technologies, as exemplified by the cancellation of the Tri-Service Standoff Attack Missile (TSSAM) in 1994. Originally designed to cost $250,000 per missile, TSSAM's projected unit costs tripled in real terms, while its development costs doubled before it was eventually cancelled. Although the components comprising TSSAM generally worked, the program encountered numerous technical and operational problems.

The proliferation of anti-ship missiles also has accelerated the rate at which states are acquiring cruise missiles. While anti-ship cruise missiles are tactical in nature and thus were not the focus of the MTCR, the reality is that anti-ship missiles are functionally similar to land-attack cruise missiles. It is relatively easy to convert anti-ship missiles into land-attack missiles. The U.S. Tomahawk and Harpoon missiles are prime examples of systems that share both land-attack and anti-ship functions. As evidence of the ease with which anti-ship cruise missiles can be purchased, seventy countries in the world now operate them even though they are historically expensive (Harpoons cost about $1 million each).[13] For example, Taiwan is modifying the *Hsiung Feng* anti-ship missile to a version that has cruise-missile capabilities, which would give Taiwan the capability to conduct strikes against China's land-based missiles.[14]

Cost Effectiveness

With declines in the cost of modern technologies, the overall cost effectiveness of cruise missiles has increased Although the unit cost of U.S. cruise missiles has historically exceeded $1 million, this is likely to decrease in the future. For example, while the U.S.Tomahawk cruise missile has generally cost around $12 million historically, the U.S. Navy's new tactical Tomahawk is projected to cost only one half as much Similarly, the U.S. Air Force is on the verge of fielding the highly-capable Joint Air To Surface Stand-off Missile (JASSM) at a projected cost of $300K (in comparison with $2.4 million for the functionally similar, but canceled TSSAM).[15] Russian-made missiles, such as the *Alfa,* are expected to cost less than $300K. One U.S. defense contractor claimed that cruise missiles could be fabricated for less than $100K. As a result of these reductions in unit costs, cruise missiles are an increasingly affordable and cost-effective weapon in comparison with aircraft and ballistic missiles.

However, lower absolute costs alone are not sufficient to convince countries to allocate resources for acquiring cruise missiles. They must also believe that cruise missiles are cost-effective in comparison with other potential weapon systems, notably manned aircraft and ballistic missiles In comparing the cost-effectiveness of cruise missiles with that of aircraft for delivering munitions, the critical issue is the expected rate of attrition. Without attrition, bombs, even smart bombs, dropped from aircraft would always be more cost effective than cruise missiles. The reason that bombs are always cheaper than cruise missiles is that they do not require propulsion and guidance systems. However, the total cost of the munitions dropped from aircraft must include the cost of the aircraft that could be shot down while delivering the munitions as well as the additional costs associated with operating and maintaining a fleet of aircraft. Of course, the infrastructure costs associated with cruise missiles must be included, but these are typically substantially less than that of manned aircraft.

To provide a simple way to compare the cost-effectiveness of cruise missiles and munitions delivered by aircraft, the following assumptions were made in this study. First, the cost to acquire an airplane was assumed to be $30,000,000, which is roughly the cost of an F-16 aircraft, while the cost to acquire a cruise missile was assumed to be $300,000, which is the cost of a JASSM.

Second, it was assumed that each airplane carries four munitions per sortie (or mission), and that each would cost $20,000, which reflects the cost of the Joint Direct Attack Munition. Third, in accordance with U.S. experience, it was assumed that the cost of aircraft operations and support will be twice the procurement cost, and that aircraft which are shot down are halfway through their operational life Finally, it was assumed that, based on U.S experience, cruise missile operations and support will be 10 percent of the procurement cost.

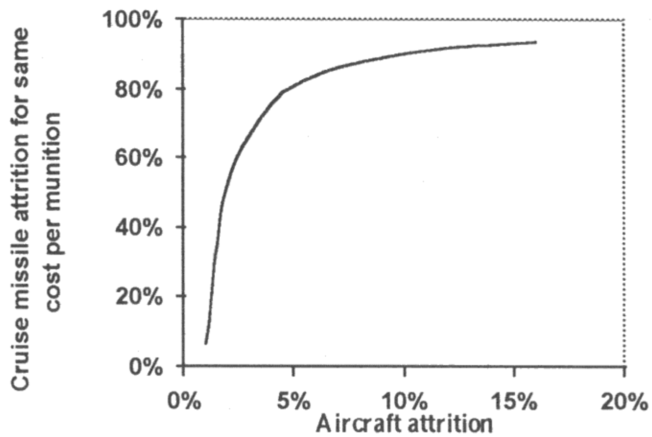

Figure I - Cost comparison of Cruise Missiles and Aircraft Delivered Monitions

Using these assumptions, it is possible to calculate the costs of delivering munitions with cruise missiles and aircraft for different attrition rates. For every assumed aircraft attrition rate, there is a corresponding cruise missile attrition rate that produces the same cost per delivered munition. Figure 1 displays this break-even function in terms of aircraft attrition rates. The break-point (or "knee") in this relative cost curve occurs at the point when the attrition rate of cruise missiles is 80 percent and the aircraft attrition rate is 5 percent. The plausible conclusion is that as long as the attrition of cruise missile is less than 80 percent, cruises missiles are more cost effective than manned bombers.

For decades, military theorists have argued that the fundamental value of airpower is its ability to destroy the key nodes in a state's economy or military that would cripple the opposing force and prevent it from fighting effectively.

This was the stated objective of the air campaign in the Persian Gulf War. It is unlikely that any nation will have aircraft that are capable of achieving air superiority against U.S. military forces in the foreseeable future, and thus could not mount a strategic bombing campaign. However, cruise missiles are so inexpensive and expendable that a state could mount a strategic bombing campaign with cruise missiles, and thus avoid the need to achieve air superiority. In this case, a state could use surface-to-air missiles to deny local air superiority to the United States without having to gain it with aircraft.

The cost-effectiveness of cruise missiles may alter the fundamental role of airpower. The evidence is that a comparison of the cost-effectiveness of cruise missiles and ballistic missiles will favor cruise missiles because these cost on average only 15 percent of the cost of ballistic missiles.[16] Since cruise missiles and most ballistic missiles deliver essentially one weapon, the expected attrition rate for cruise missiles would have to be about seven times higher than that of ballistic missiles for cruise missiles to be as cost-effective as ballistic missiles.

It is, therefore, not surprising that many states are moving in the direction of adding cruise missiles to their arsenals. As noted earlier, nineteen nations are thought to produce or export cruise missiles and fifty-four countries possess cruise missiles of some type.[17] For now, most of these are relatively unsophisticated cruise missiles that are intended for use as anti-ship weapons. But as the United States demonstrated that cruise missiles were highly effective in the Gulf War, against Serbia, and in the raids against Sudan and Afghanistan, it is almost certain that other states will be interested in acquiring cruise missiles.

IV. Strategies for Employing Cruise Missiles

On the most fundamental level, cruise missiles constitute a mechanism for transporting weapons that can overcome the defenses. There is no reason for developing cruise missiles if there are no defenses or if there is no need to transport a weapon from an area controlled by one protagonist to an area that is controlled by the other. The implication is that cruise missiles are not an attractive weapon for a state or a group that seeks to provoke and fight an insurgency because a truck generally is as effective as a cruise missile and requires much less effort. By exclusion, cruise missiles are most useful in limited conventional conflicts between states. For example, the United States used cruise missiles during the air campaign against Iraq in Operation Desert Storm, the military raid against Sudan and Afghanistan in 1998, a raid against Iraq in December 1998, and the air campaign against Yugoslavia in the spring of 1999.

This discussion focuses on several strategies that states could employ if their objective is to deter the United States from becoming involved militarily While the military objectives of the United States would likely range from defeating the aggression to inflicting sufficient damage to persuade the aggressor to withdraw militarily, the adversary would seek to prevent the United States from achieving its political and military objectives. Thus, this study considered the following four broad strategies that reflect a spectrum of possible alternatives: deter the United States from taking action; prevent the United States from deploying its forces, which is important in view of the fact that the U.S. geographical position requires it to deploy forces before it can execute a military campaign, attack the will of the United States and thereby persuade the public that further action will produce levels of casualties that are unacceptable to the U.S. public; and finally, inflict a tactical defeat that causes the U.S. to reassess the costs and benefits of further action.

Deter U.S. Involvement

While it might not deter the United States from involvement in a regional crisis, the threat to use weapons of mass destruction against the United States or its military forces would have significant political effects.

If we consider the case of cruise missiles that are armed with conventional warheads, it is highly likely that states would be willing to use these weapons in a conflict. The deterrent effect would depend on the ability of conventional cruise missiles to delay the deployment of U.S. forces, cause unacceptable casualties, or allow that state to achieve a tactical victory. Thus, the deterrent value of cruise missiles depends essentially on the extent to which policymakers in the United States believed that they faced a credible threat.

Since a successful deterrent requires a credible capability and a willingness to use that capability, cruise missiles armed with weapons of mass destruction constitute a highly credible threat. The relatively slow flight of cruise missiles contributes to their ability to disperse chemical and biological agents over a wider and more controlled area than a ballistic missile. For example, a cruise missile armed with 500 kilograms of the chemical agent sarin could cover an area of 190,000 to 320,000 square meters. The even more lethal case is a cruise missile that is armed with 500 kilograms of a biological agent, such as anthrax, which could deliver lethal doses over an area of 330-500 square kilometers.[18] The credibility of cruise missiles is further enhanced by the fact that their small size and minimal launch facility requirements create a very survivable basing scheme.

While cruise missiles are a credible platform for carrying weapons of mass destruction, it is not clear whether states would be willing to use Weapons of Mass destruction against the United States. During the Gulf War, Iraq refrained from using weapons of mass destruction against the U.S. and its allies even though it had the capability to do so. In part, Iraq may have been influenced by the explicit threats made by the United States and the United Kingdom that they would respond with devastating force if Iraq used such weapons. In addition, the Iraqi leadership may have believed that the use of weapons of mass destruction would provoke the United States to expand its military objectives from demanding that Iraq withdraw from Kuwait to unconditional surrender.

In the case of cruise missiles that are armed with weapons of mass destruction, we have fifty years of experience with understanding how weapons of mass destruction serve as a deterrent. A key consideration is that deterrence is credible if the weapon is based in a way that ensures its survivability.[19]

The fact that cruise missiles are smaller than SCUD missiles implies that the former generally requires a less sophisticated launch infrastructure. It is likely that very survivable basing schemes could be designed for cruise missiles, which would enhance their deterrent value as platforms for weapons of mass destruction. A second feature that contributes to the survivability of cruise missiles is their low cost, which is estimated to be roughly 15 percent of the cost of a ballistic missile. A reasonable estimate is that a state could build large numbers of cruise missiles, and that an attacker probably could not destroy all of these cruise missiles before they reached their targets.

Perhaps the most important deterrent effect of cruise missiles that are armed with weapons of mass destruction would be to give the nation the ability to limit the conflict. As an example, a nation could threaten to use cruise missiles that are armed with nuclear warheads against U.S. military forces if those posed a threat to that state.[20] Thus, cruise missiles armed with weapons of mass destruction might give a nation the latitude to pursue an aggressive path because it knows that it can back down before using those weapons rather than face the prospect of total defeat if it used these weapons.

Delay Deployment

If deterrence fails and the U.S. makes the decision to deploy troops, then an adversary may use cruise missiles to delay the U.S. deployment. At the very least, the ability to interfere with the U.S. deployment would delay the time before the United States could mount a counteroffensive, dislocate existing logistics plans, increase the risks for the United States, and provide time for other strategies to mature.

One strategy is to use cruise missiles to delay the U.S. deployment of military forces by launching direct attacks against key logistics nodes. In most regions, there are limited points of entry that have the capacity to support a large scale deployment, and these often have critical nodes which, if destroyed, sharply reduce the capacity of a port or airfield. Moreover, these points of entry often have bottlenecks (such as heavy cranes or docks) which effectively determine its capacity. These bottlenecks often have fixed known locations and would be severely damaged by the detonation of a 1,000 pound bomb.

For example, the logistics capacity of ports is a function of the number and size of the cranes that hoist cargo from ships. Even the roll-on, roll-off ships require a dock and access to the port. Airfield capacity depends upon cargo-handling equipment, the availability of an air traffic control tower, the amount of ramp space, and whether the runways are intact. In addition, cruise missiles could be used to attack other logistics infrastructure such as power generation facilities, bridges, and marshalling points as well as other fixed logistics infrastructure elements (such as power generation facilities, bridges, and marshaling points) that are similarly vulnerable. In military terms, all of these assets are vulnerable to cruise missile attacks.

An adversary could attack U.S. logistics units while they are enroute to the region of hostilities. The sites which contain prepositioned supplies are easily found, and could be attacked by cruise missiles that are launched from ships or submarines. At the same time, anti-ship cruise missiles could be used to attack supply ships that are in route to the theater or are in port. The bulk of U.S. equipment is still transported by ships, which are very vulnerable to attack because most cruise missiles that are designed to attack ships are not equipped with effective defenses. The loss of materiel and the need to use convoys to protect supply ships from cruise missile attacks would have the effect of delaying the arrival of equipment and materiel. It also might be possible to attack the U.S. logistics supply lines at sea with weapons of mass destruction because this would minimize casualties. For example, ships at sea and prepositioned supplies are usually located in isolated areas that are far from population centers. The sites of U.S. prepositioned supplies are well known, which renders them vulnerable to cruise missiles that are armed with GPS guidance systems. In all of these cases, attacks with cruise missiles would create significant delays while equipment was decontaminated, in particular if personnel were unsure whether the decontamination was complete.

Such attacks on U.S. supply lines would also compound lift problems because the U.S. would have to devote significant combat forces and logistics supplies to counter the threat. If supply ships were attacked, the U.S. would need to use convoys in the future in order to protect its ships from cruise missile attacks. It would take additional time to organize such convoys, which would slow the deployment and introduce bottlenecks if there are insufficient combat assets to protect the convoys.

Moreover, if there is a requirement to defend against cruise missiles, this would reduce the lift available for deploying other forces because theater missiles defenses require a significant amount of airlift or sealift. As noted earlier, one Patriot battalion of ninety-six missiles requires approximately sixteen C-5 aircraft to deploy it.[21]

Attack U.S. Public Support for Military Action

Another potential strategy for an adversary is to exploit the U.S. aversion to casualties, especially in conflicts that do not involve vital U.S. interests. For example, Iraq's strategy in the Gulf War hinged on forcing the U.S. into ground battles that would create higher casualties than the American people would accept. Saddam Hussein apparently believed that he could create enough public pressure on the Bush Administration to force the United States to settle on terms advantageous to Iraq.

There is no doubt that cruise missiles which are armed with weapons of mass destruction would cause large numbers of casualties and create political difficulties if innocent people were attacked indiscriminately. Conventionally-armed cruise missiles would avoid the political stigma associated with weapons of mass destruction and would cause fewer casualties. One way to understand the ability of conventional cruise missiles to produce civilian casualties is to consider the attacks conducted with German V-1 missiles against Great Britain in World War II.

Historically, each V-l missile attack that penetrated British defenses produced four casualties This number of four casualties per missile represents a lower range for the casualties that a modern cruise missiles could cause, principally because the V-l was inherently inaccurate. On the other hand, the precision associated with today's weapons allows such reliable targeting of people at barracks, command and control sites, transport ships in port, and airport terminals that these weapons would cause higher casualties. To bound the upper level of casualties, historical records suggest that at least one V-1 attack killed 121 people.[22] It is reasonable, therefore, for a potential adversary to assume that each cruise missile will produce roughly twenty casualties. One way to confirm this value is the fifteen casualties that were caused by Argentina's attack on the HMS Sheffield with an Exocet missile, as well as the 34 casualties caused by the two Exocet missiles that attacked the USS *Stark* in 1986. Using the figure of 20 casualties per missile, it would take 500 successfully penetrating missiles to produce 10,000 casualties, which assumes that there are 500 lucrative targets to be struck.

This number of casualties might not have a strategic effect on the United States if there was broad public support for the military operation, and this is the historical norm. For example, in the Korean War, 33,651 U.S. soldiers were killed and a further 103,284 wounded, while in the Vietnam War, 58,161 soldiers were killed and 153,303 wounded.[23] Despite these casualties, surveys indicated that a minority of the population favored withdrawal, while the majority favored an escalation of the war in order to achieve the nation's objectives.[24] Prior to the Gulf War, most estimates for U.S. casualties were much higher than those actually experienced. Despite this, in February 1991, 83 percent of Americans approved U.S. intervention in the Gulf War, even though 80 percent believed that "the situation will develop into a bloody ground war with high numbers of casualties on both sides."[25]

In order to estimate the number of casualties from cruise missile attacks, we must estimate the total number of cruise missiles that actually strike their intended targets. Earlier, this study estimated that only major regional powers, such as China, could field hundreds of cruise missiles per year, and therefore that smaller states would be able to field substantially fewer numbers of cruise missiles. The number of casualties produced, however, is not a function of the total cruise missiles produced, but a function of the number that successfully penetrate defenses and destroy their targets. The only historical measure of this is the attrition rate of 50 percent experienced by German V-ls during World War II. The actual attrition rate, of course, would depend upon the effectiveness of the defenses against the cruise missiles. If we assume that each cruise missile produces roughly twenty casualties and a state has 500 conventionally armed cruise missiles, then in broad terms that state could cause 10,000 casualties. However, the number of casualties would be less for two reasons. First, this calculation assumes that there are enough populated targets within the range of the cruise missiles. The second reason is that most nations would be reluctant to use all of its missiles because it would likely want to keep some missiles in reserve.

Although major regional powers might possess more cruise missiles, their ability to create more casualties may be limited by the fact that they cannot attack sufficient numbers of unprotected targets or that they fear a devastating U.S. response.

Another strategy is to use cruise missiles to threaten countries that offer basing rights and port facilities to U.S. forces. The theory is that these countries would be less able than the United States to protect themselves, and thus might be bullied into a neutral position rather than risk an overt alliance with the United States. If this strategy were successful, the United States might lose the basing rights, overflight authorizations, local supplies, and port facilities that are necessary for sustaining overseas military deployments and combat operations.

Inflict Tactical Defeat

The remaining strategy for using cruise missiles would be to inflict a tactical defeat on the United States. In view of the fact that most states possess relatively small quantities of cruise missiles, the optimum way to use cruise missiles is to attack critical nodes in U.S. military operations. While the U.S. defense budget far exceeds that of other nations and U.S. military capabilities are quite robust, there are several vulnerabilities that an adversary could exploit. For example, U.S. military capabilities are least robust in the systems that provide combat support, including tankers, airborne warning and control aircraft, of which AWACS aircraft is an example. Other vulnerabilities include command and control nodes and satellite ground stations.

As U.S. defense budgets continued to decline and the costs of advanced weapon systems increase, the underlying economic forces will complicate U.S. military strategy in at least two ways. The first is that continued declines in U.S. defense budgets will drive the United States to favor combat systems in their defense purchases, and thus reduce the numbers of high-value assets, including tankers, AWACS, command and control nodes, Patriot missile batteries, and satellite ground stations that the United States will be able to purchase. The second mechanism that could reduce the robustness of U.S. forces is that as the United States enters a crisis with relatively few assets in theater, it will be forced to make difficult choices about what forces must be deployed first.

Depending on the nature of threat posed by cruise missiles, the military assets that are deployed early in the crisis may not include the forces that defend against cruise missiles because these involve the use of considerable airlift and sealift assets. Thus, if cruise missiles are to be used to achieve tactical victories, it is essential to exploit U.S. military vulnerabilities by attacking the critical nodes that support U.S. military operations.

It is for this reason that this study examined the possibility of using cruise missiles to attack U. S. airpower, which is a center of gravity for U. S. forces and an instrument that the U.S. often uses to achieve its strategic goals. To date, the U.S. has benefited from the fact that airpower has generally been relatively invulnerable. The reality is that an adversary could not achieve air superiority or prevent the United States from achieving air superiority. However, it is conceivable that the judicious use of cruise missiles could be used to cripple U.S. airpower if the adversary could destroy sufficient numbers of targets on the ground.

The U.S. Air Force, as with any complex military system, contains critical nodes that are essential to the conduct of effective military operations and which are vulnerable to attack [26] While the adversary could attack potential nodes of the logistics system, command and control nodes, personnel, and aircraft on the ground, using cruise missiles to attack aircraft on the ground is quite impractical. This is fortunate for the United States because such an attack can be an extremely effective in a military sense, as the Germans demonstrated during the first two days of Operation Barbarossa when they destroyed 1,489 Soviet aircraft on the ground.[27] Cruise missiles, however, are inherently more capable of attacking fixed targets because their guidance systems can steer the missile to a fixed point or home in on targets that are actively emitting. However, aircraft that are deployed at bases are not placed in fixed positions, are moved quite frequently, and as a rule do not emit sources of radiation that could be tracked by an incoming cruise missile.

This means that using cruise missiles to successfully attack aircraft on the ground would involve significant numbers of missiles. While cruise missiles can carry clusters of submunitions which could be highly effective, the reality is that most states do not possess the technical capability to effectively disperse submunitions. However, this operational complication could be minimized by using biological or chemical agents, as long as the adversary understands the political consequences.

V. Defending Against Cruise Missiles

This discussion has focused on understanding the military capabilities of cruise missiles and the reasons why many countries will find these capabilities to be important. In particular, the improvements in military capabilities are a function of developments in precision, survivability, and range. At the same time, cruise missile technologies have proliferated in large measure because gradual decreases in their unit cost have increased their overall cost-effectiveness in comparison with aircraft and ballistic missiles. At the same time, international regimes, notably the MTCR, have not inhibited the proliferation of cruise missiles. For these reasons, it is necessary for the United States to understand the role of defenses against cruise missiles.

A further evaluation of the threat posed by cruise missiles requires that we compare U. S. defensive capabilities against cruise missiles with the capabilities of cruise missiles. This study differentiates between defenses that rely on destroying cruise missiles and their supporting infrastructure with defenses on seek to defeat the military effects of cruise missiles. This distinction is important because the technologies for destroying cruise missiles will seek to defeat their tactical capabilities, while the technologies for defeating their effects would be based on organizational and doctrinal solutions.

The current U S. doctrine for dealing with the cruise missile threat divides the defense into active defense measures, attack operations, passive defense measures, and command, control, communications, computers, and intelligence (C4I).[28] Active defense operations are defined as operations that destroy the cruise missile during its fight. Attack operations are defined as operations that destroy either launch sites, command and control nodes, or missile stocks and the supporting infrastructure. Passive defense measures are defined as steps that are taken to reduce the vulnerability of U.S. assets and to minimize the damage caused by an attack with cruise missiles. Finally, C4I refers to those systems that coordinate and integrate the defenses.

This doctrinal syntax is useful because it helps to differentiate between tactical defenses and strategic defenses. Using this language, active defense operations and attack operations are essentially tactical missions because they seek to destroy cruise missiles.

If sufficient numbers of cruise missiles can be destroyed, then the adversary will not be able to achieve a strategic effect by the use of cruise missiles. By its nature, these operations are heavily dependent on technology because it is inherently difficult to detect and engage cruise missiles. By contrast, the objective of passive defenses is to minimize the strategic effects of cruise missiles, and thus to focus on organizational and doctrinal solutions to preventing the adversary from using cruise missiles to produce strategic effects. The discussion in this section focuses on tactically-oriented attack operations and active defense, while the subsequent section examines the concept of passive defenses.

Offensive Attack Operations

The concept of offensive attack operations rests on the principle of using offensive military operations to destroy cruise missiles before they are launched. For the United States, this means to develop the capability to attack cruise missiles that are located deep within the territory of the adversary. These operations involve the ability to successful locate and attack cruise missile launch sites, command and control nodes, and missile stocks and infrastructure in enemy territory. Given that cruise missiles have the ability to be moved to different locations, attack operations will succeed only if accurate targeting information can be forwarded to military forces as quickly as possible. Only then is it possible to attack cruise missiles before the launchers are moved to other locations.

In reality, attack operations against cruise missiles are extremely challenging, principally because a resourceful enemy can employ a number of effective counter-measures. For example, during World War II the Allies conducted a massive bombing campaign against the launching sites for V-1 missiles in which 98,000 tons of bombs had been dropped by the end of the war. Despite this sustained attack, the Germans were able to build numerous secret, smaller sites that were rarely attacked successfully, often because these sites were concealed by vegetation and the use of non-standard configurations.[29] German deception measures also succeeded because these sites also were constructed without French workers, which prevented the Allies from exploiting an important source of intelligence about the sites.

To further deceive the Allies, the Germans repaired some of the larger V-l launch facilities to create the impression that the bombing campaign was effective and that these sites were still being used. Nevertheless, the Allies successfully found and destroyed two out of three V-l sites. However, perhaps the most successful operations were those that were conducted against the transportation system because this resulted in the destruction of roughly one-third of all V-ls that were produced.

As these examples illustrate, offensive attack operations seek to destroy the launch sites, command and control nodes, missile stocks, and the supporting infrastructure that and associated with the use of cruise missiles. The problem is that these operations can be difficult to conduct, as exemplified by the fact that U.S. forces were unable to find Iraqi SCUD missiles during the Gulf War. Further, cruise missiles do not require an extensive launch infrastructure, which means that it is difficult to find launch sites or cruise missile storage locations. In conclusion, while attack operations would be a highly desirable method for countering cruise missiles, the success of these operations is highly dependent on timely and accurate information. And if an adversary conducted competent counter-intelligence and deception operations, the overall effectiveness of offensive attack operations could be quite low.

Active Defenses

The concept of active defenses is to intercept and destroy incoming cruise missiles. As with defenses against aircraft, the ability to employ active defenses against incoming cruise missiles requires an extremely capable command and control system that can detect incoming cruise missiles, select the proper defensive forces, communicate with those forces, and move those assets to the best location for engaging the cruise missiles.

The case of an individual cruise missile attack vastly simplifies the command and control problem. With only one target to handle, there is no need to make prioritization decisions, and all of the time from the initial detection of the cruise missile is available for the defense. Therefore, the optimum strategy for the attacker is to launch multiple cruise missiles in order to complicate the defense. Furthermore, mass attacks increase the possibility that the defenses can be saturated with more missiles than the defender can handle.

For this reason, this study focused on the problems raised by multiple cruise missile attacks because this is the most dangerous and demanding type of attack that can be conducted with cruise missiles.

The ability to engage cruise missiles encompasses the full range of activities from the detection of the cruise missile to attempts to destroy it. This includes selecting defensive assets, communicating with those forces, and moving those forces to a location where they can engage the incoming cruise missiles. The time required to engage the attacking cruise missiles is important because it determines whether there is sufficient time to engage the cruise missiles, and the number of times that each missile can be attacked. The factor that determines how many times a cruise missile can be engaged is the time that it takes the defender to assess the nature of the attack and respond accordingly. In the case when attacking cruise missiles are not destroyed the first time, the attack must be assessed and communicated so that the defender can decide whether to reengage the attacking cruise missiles.

One approach for saturating the defenses is to launch more cruise missiles against the defender than it can manage. For example, in the case of a defensive combat air patrol (CAP) against cruise missiles, a number of aircraft would be apportioned to that role and armed with missiles. To illustrate, consider the fact that thirty-two cruise missiles could saturate a combat air patrol which consisted of four F-15 fighter aircraft, each of which is armed with eight air-to-air missiles. The assumption is that the F-15s have sufficient time to maneuver as they engage the cruise missiles before they arrive at their targets and that a cruise missile is disabled during each engagement. While some cruise missiles theoretically could be shot down with the guns on the F-15s, the anecdotal evidence is that this is very difficult.

The second approach for saturating the defenses is to minimize the time available to the defender for engaging the cruise missiles. If we assume initially that there is one defender and that the cruise missiles have perfect lethality, the number of incoming missiles that will saturate defenses is determined by the number of times that the defender can engage.[30] When the lethality of cruise missiles is not perfect, the number of missiles that will saturate the defenses is reduced by multiplying this value by the probability of kill.

When there is more than one defender, the number of missiles that will saturate the defenses is increased by multiplying this value by the number of defenders, if we assume that there is no redundancy in allocating defensive forces against incoming missiles.[31]

This equation, as shown in the notes, provides a means for estimating the saturation levels at a given level of defense. For example, consider the case of the F-15 combat air patrol that employs four aircraft. If we assume that this force engages cruise missiles that are flying at five hundred miles per hour in their last fifty miles, the total time available to engage those cruise missiles is roughly six minutes. If we further assume that the defender's missiles have a probability of kill of 0.7 and that each engagement will require two minutes, it is likely based upon the total armament carried by the F-15s that eight cruise missiles will saturate the defenses rather than the 32 previously calculated. In order to engage all thirty-two missiles, the engagement time would have to be decreased to thirty seconds, the number of aircraft in the CAP would have to increase to sixteen aircraft, or the engagement range would have to increase to two hundred miles.

One reason for developing this equation is to gain insights into the fundamental nature of defensive capabilities against cruise missiles. For example, the effectiveness of the defender is determined by the choice of weapon system. If we use the current generation of weapon systems to defeat cruise missiles, this value is fixed, which means that the defender's only choices are to buy more weapons or to increase the total time between the detection and impact of the cruise missile. In order to avoid saturating the defense, these two alternatives are equally effective. However, early detection has the additional advantage of engaging and destroying cruise missiles earlier, which is profoundly significant if the incoming cruise missile is armed with weapons of mass destruction. Therefore, the fact that early detection is essential offers insights into why the U.S. Department of Defense is interested in improving its early-warning capability against cruise missiles. Some of these efforts focus on sensors, while others focus on the links between the sensors in order to create a "system of systems" that permits the United States to build a more robust and complete picture of the attack.

Regardless of the exact assumptions that are made, it is obvious that the number of cruise missiles that will saturate the defenses is determined by the defender's response time. It is also likely that this number would be smaller in the early stages of the U.S. deployment into a theater of operations In view of competing requirements for strategic lift, it is important to understand that theater missile defenses will require significant amounts of airlift and sealift. To use one example, a Patriot battalion with ninety-six missiles requires approximately sixteen C-5 aircraft loads to deploy it into a theater.[32] The most effective strategy for a state with cruise missiles would be to launch a mass attack as soon as important U.S. forces had arrived in the theater. In view of the problems associated with detecting incoming cruise missiles and saturating the defenses, it is unlikely that U.S. defenses would be able to stop all of the attacking cruise missiles.

The probability of kill for the current U.S. defensive systems that are currently fielded, such as Patriot, is very low.[33] For this reason, there is considerable interest in the development of new weapon systems for destroying cruise missiles. One approach is to use directed energy weapons for cruise missile defenses, which would have the advantage of dramatically reducing the engagement time because the time required for the energy to travel to the cruise missile is essentially zero. However, the actual time for engagement would not be zero because it takes some time to aim the beam at the cruise missile and for the kill mechanism to have its desired effect. The principal disadvantage to directed energy systems is that they are essentially line-of-sight weapons. In the case of ground-based systems, its view of incoming cruise missile would be obstructed by the ground, while the view of air-based systems would be obstructed by clouds and would have to be concerned about the power requirements and collateral effects of look-down shoot-down attacks against cruise missiles. Nevertheless, the U.S. Navy, which has a significant interest in defending against cruise missiles, favors line-of-sight point defense weapons because aircraft may have problems getting into the proper position for engaging incoming cruise missiles.

The choice between these alternatives depends upon the exact nature of the tactical situation. For example, in the case of conventionally-armed cruise missiles, it is less beneficial to detect cruise missiles earlier than it is in the case of cruise missiles that are carrying bacteriological or chemical warheads.

The reason is that the defender will want to detect the missile as early in its flight as possible to minimize the collateral damage that would occur if the bio-chemical agent were released when the cruise missile is attacked. The U.S. Navy has favored point defense with a combination of Gatling guns and missiles because it has to protect a limited number of naval vessels in a large ocean area. The broader problem with point defenses for land-based targets is that there is likely to be more high-value targets that the defender could protect with point defenses. Furthermore, the problem with point defenses is that current systems, such as the Patriot, have very low probabilities of kill against cruise missiles, perhaps on the order of less than 10 percent.[34] For this reason, point defense systems, such as HAWK battalions, have been completely eliminated.

Passive Defenses

The objective of passive defenses is to reduce the strategic effects of cruise missile attacks in contrast with the more tactical objectives of destroying cruise missiles before they are launched or actively disrupting or destroying cruise missiles as they approach the defender's targets.[35] The doctrinal foundation for responding strategically to cruise missiles is contained in the sections of the U.S. Joint Chiefs of Staff Joint *Publication 3-01. 5,* which discusses the concept of passive defense According to *Joint Publication 3-01.5,* the principal approaches to passive defense include receiving tactical warning of an attack, reducing the effectiveness of the adversary's targeting, reducing the vulnerability of U.S. military forces, and establishing measures for recovering and reconstituting U.S. military capabilities.

However, the fundamental problem is that U.S. doctrine does not distinguish between the defense of cruise missiles that are armed with conventional warheads and those that are armed with weapons of mass destruction. This consideration is important when the type of warhead dramatically changes the quantity of the missiles that the adversary might launch against the United States as well as the types of defenses that are necessary to defeat it and the success of the attack. Nor is it clear how the characteristics of cruise missiles relate to the defenses that the United States must develop. For example, precision has a significant effect on the strategic capabilities of conventional cruise missiles because the relatively small payloads of cruise missiles are militarily ineffective unless the warhead detonates near the target.

One notion of passive defenses is to interfere with their precision guidance system through intelligence techniques that seek to deceive an adversary about to the locations of key targets through camouflage or interfere with the GPS signal that guides the missile to the target.

By far the most serious shortcoming of the U.S. doctrine for passive defense, as articulated in *Joint Publication 3-01.5, is* the failure to deal explicitly with the vulnerabilities of the U.S. Logistics and supply system. The logistics system is always likely to represent an asymmetric vulnerability for the United States because in most cases U.S. military forces must be transported across the oceans to the region in crisis. Potential adversaries, however, will already have their forces in that theater. While U.S. forces can be protected by dispersing them once they arrive in the theater, the larger problem is to protect forces while they are in transit to the theater. Cruise missiles are well suited to attacking logistics nodes because these are fixed, and thus can use GPS guidance for attacking port facilities. Another problem is that the logistics system relies heavily on the use of ships, and most cruise missiles are designed as anti-ship missiles. Finally, there is no guidance for the early stages of deployment when U S. defensive systems are not fully developed and when lift priorities are in the greatest demand.

The doctrine for passive defense does a better job of dealing with the other three generic strategies that are described earlier in this paper, notably exploiting the U.S. aversion to casualties, achieving tactical victories, and deterring the United States. In terms of exploiting the U.S. aversion to casualties, it deals explicitly with dispersing U.S. forces in order to minimize the number of lucrative targets, train civilian authorities in procedures for dealing this missile attacks, and defend against the use of weapons of mass destruction. If the adversary's strategy is to inflict a tactical defeat on the United States, then a useful approach is to attack the United States in ways that enhance the adversary's combat capabilities. The concept of passive defenses also outlines other techniques, such as deception and dispersal, which would be effective in defeating this strategy. Deterrence strategies depend on a credible threat and the will to use it, and of these the most credible threat is cruise missiles that are armed with weapons of mass destruction. Most importantly, this doctrine does not discuss this issue.

It should be understand, however, that *Joint Publication* 3-01.5 is above all else doctrine, which means that U.S. forces are not committed to following this doctrine or that sufficient budgetary resources have been committed to this capability. Nor does the existence of doctrine mean that the United States should stop funding the technologies that will improve its ability to defend against cruise missiles. After all, the British developed the doctrine for air defense in the early 1920's, but had not developed the technological capability, notably radar, that gave them the ability to dramatically improve their air defenses. The valueoctrine is to organize how military forces examine a problem and provide a framework for using technologies to solve, in this case, the problem of defending against cruise missiles.

VI. Conclusions

The central purpose of this study is to examine how technological developments have remedied the historical shortcomings that were associated with cruise missiles, and which have now produced a weapon that has significant operational capabilities. This study concludes that cruise missiles will be more cost-effective weapons than manned aircraft and ballistic missiles, and that this cost-effectiveness, when combined with the widespread proliferation of cruise missile systems and technologies, suggests that cruise missiles will be an important element of the military arsenals for many states in the twenty-first century.

A more specific conclusion is that potential adversaries may want to use cruise missiles given that improvements in cruise missile precision, survivability, and propulsion have dramatically improved their tactical capabilities. At the same time, the costs, both absolute and in comparison with other aerial weapons, make cruise missiles a cost-effective choice for many countries. Moreover, cruise missiles and associated technologies are continuing to proliferate rapidly throughout the world. Finally, the tactical capabilities of cruise missiles imply that it will be exceedingly difficult to defend against cruise missiles, in part because of the possibility that the defenses could be saturated by mass attacks.

One conclusion that emerges from this study of cruise missiles was that it is unlikely U.S. defenses could entirely defeat cruise missile given the difficulties of detecting and engaging cruise missiles. Furthermore, it is relatively easy for an adversary to overwhelm the potential defenses with mass attacks. And in view of the numbers of cruise missiles that most states could deploy, this study concludes that the adversary's best strategy is to use cruise missiles to exploit U.S. vulnerabilities rather than attempt to defeat the U.S. While there are numerous countermeasures that the United States can use to neutralize this threat, the fact is that the U.S. supply lines which stretch from the continental United States to potential theaters of operation are highly vulnerable to cruise missile attacks. The evidence is that this is the greatest strategic vulnerability of the United States that adversaries could exploit with cruise missiles.

The unavoidable conclusion is that cruise missiles will be a strategically significant weapon in the twenty-first century because these weapons can deliver ordinance over great distances, with a high degree of accuracy, and in a cost-effective fashion.

When this capability is combined with the technologies that enable precise attacks, it is inevitable that cruise missiles will give states the ability to deny U.S. forces the sanctuaries that existed in the past. To the extent that the United States faces vulnerabilities in theaters of operation, cruise missiles now give states a powerful tool for exploiting those weaknesses. A related issue is that cruise missiles represent a more cost-effective approach to air power than the current emphasis on stealthy forces, which because of its significant cost may be obsolete sooner than is commonly understood.[36]

For minor regional powers, the most effective use of cruise missiles, particularly if those are armed with weapons of mass destruction, is to deter U.S. military involvement. While these states will not be able to field sufficient number of cruise missiles for other missions, cruise missiles are more relevant in a deterrent sense because these weapons increase the credibility of a nation's threat to deliver weapons of mass destruction.

In conclusion, many states could deploy cruise missiles in quantities that are sufficient to support a number of political and military strategies. Above all, the key factor in the emergence of cruise missiles is a critical defense technology that this weapon could used to exploit U.S. vulnerabilities, and thereby complicate U.S. defense planning. This technological development has the potential to revolutionize the military capabilities of states that want to counterbalance the overwhelming military superiority possessed by the United States at the beginning of the twenty-first century.

Annex

Historical Effectiveness of Cruise Missiles

The purpose of this annex is to identify the deficiencies associated with cruise missiles that historically limited their overall operational and strategic effectiveness. Specifically, it will be shown that the major historical problems with cruise missiles include low reliability, poor accuracy, vulnerability to intelligence deception, operational inflexibility, limited range, predictable flight paths, and highly vulnerable launch platforms.

Early cruise missiles had a dismal record of test failures because of their immature flight and control technologies. The V-l fielded by the Germans in World War II was the first successfully deployed cruise missile. It was powered by a pulse jet, which could not operate at velocities less than 150 MPH and thus needed a booster for launch. For this, the Germans used a catapult that accelerated the V-1 along a 180 foot ramp. The V-1 had a range of roughly 175 miles and achieved a final speed of 400 miles per hour. For guidance it used a gyroscopically-based autopilot to control the direction of flight and a barometer to control altitude. Aiming the V-l was a function of the heading given to the autopilot and a small propeller device which, after a preset number of revolutions, fired two detonators which locked the elevators and rudder while deploying spoilers on the tail.[37]

In operational terms, the German V-l was plagued by numerous limitations. First, it was a very inaccurate weapon that had an average error of 8 miles over a range of 127 miles. In strategic terms, the V-l was essentially a terror weapon that could attack large cities because even with its very modest level of accuracy, the aim point was highly dependent upon German intelligence. The British exploited this vulnerability when they used their captured German agents to convince the Germans to shift their aim point four miles to the southeast, which reduced by some estimates the number of casualties by roughly 12,000 per month.[38]

Second, the necessity for a catapult was a significant drawback because it limited the V-l to fixed launch-sites, and thus increased its vulnerability to attack. Third, the necessity for a fixed location combined with its limited range and single main target meant that the V-l flight path was highly predictable.

When the British were able to concentrate their defenses along a narrow zone, they were able to shoot down roughly half of the incoming V-ls. Fourth, reliability problems continued to plague cruise missiles as it had prior to World War II, which in operational terms meant that 2,000 of the 9,000 missiles fired at Britain crashed during or shortly after take-off. Finally, the relatively small warhead limited the amount of destruction that the V-l could create when it reached the assigned target.

Even with these limitations, the V-l was able to penetrate British air defenses at a time when German aircraft could not because their relatively high speed, small size, and low penetration altitude made it difficult to detect and destroy V-ls. According to one British estimate, V-1s were eight times more difficult to attack than manned aircraft, even when one considers that the V-l was not able to evade defenses by maneuvering. British defenses were also complicated by the danger of fratricide, which required constraining rules of engagement between artillery units and fighter aircraft. Because V-ls were unmanned and cheap, with an approximate cost of $4,000 each (or 2 percent of the U S. cost of building a B-17 bomber), loss rates that would have been unacceptable for manned aircraft were quite acceptable for unmanned vehicles.[39]

Overall, the Germans fired 20,000 V-ls, which resulted in 39,000 casualties or about two casualties for every V-1. However, the V-1 failed to satisfy Germany's strategic objective of terrorizing the British. Although not an explicit strategic objective at the time, the German V-l may have forced the British to allocate more resources to defending against the V-1 than the Germans expended in producing them. According to a detailed British wartime study, the British had to spend about 38 times as much to defend Britain against the V-1 as it cost the Germans to produce them.[40]

U.S. efforts to produce cruise missiles were largely unsuccessful in the two decades following World War II, principally because the demands for performance far exceeded existing technological capabilities. The U. S. Air Force development of the Snark missile illustrates this problem In 1945, the AAF established a requirement for a 600 mph, 5,000 mile range missile with a 2,000 pound warhead. Northrop's goal for accuracy was a CEP of 1.4 nautical miles.

By comparison, all of these performance characteristics greatly exceeded the capabilities of the V-l. Of these goals, the most challenging was the guidance system, which Northrop estimated would consume 60 percent of the development effort. Northrop proposed an inertial navigation system that was aided by automatic stellar navigation, which turned out to be an analog to modern inertial/GPS systems. This system weighed almost one ton and was not reliable. In 1950, without any successful flights to date, the U.S. Air Force nevertheless increased the system requirements to include a supersonic dash at the end of the mission, a 6,500 mile range, a payload of 7,000 pounds, and an accuracy of 1,500 meters. This system was finally fielded in 1960, but was retired in 1961 because it was plagued by reliability problems. Similar difficulties with missile reliability, especially in guidance, were common in other cruise missiles during these two decades.

Although no successful systems were developed during this time, the maturation of several technologies provided the basis for the new generation of cruise missiles that were built in the 1970s. Inertial guidance systems with reduced drift were developed, and these guidance systems were supplemented by systems, such as TERCOM, which used terrain features to correct any remaining inertial drift. At the same time, the technological problems with reliable, small, and inexpensive jet engines were overcome. Computers were developed to support more complicated guidance and control features. Finally, as many of these components, including nuclear warheads, became much smaller and lighter, it reduced the overall weight and cost of cruise missiles.

These technologies permitted the design of several cruise missiles that are now in the U.S. inventory, including the Harpoon, Tomahawk, SLAM, and ALCM. While all of these missiles have demonstrated exceptional reliability over the years, only the operational effectiveness of the Tomahawk can be evaluated because it has been employed in several military operations.

During the Gulf War, 288 Tomahawks were fired. The fact that only six of these missiles failed to launch properly attests to improvements in reliability in comparison with earlier generations of cruise missiles. Overall, it can be stated that the Tomahawks destroyed most of the targets that they attacked, as demonstrated by the fact that 85 percent of the Tomahawks launched hit their assigned targets.[41]

Tomahawks were also the only weapon used to attack Baghdad during daylight, and were used against a wide variety of targets, including command and control centers, electrical power plants, industrial facilities, and SCUD missile sites.

However, due to the limited nature of their use, Tomahawks did not have a decisive effect on the outcome of the Gulf War or the December 1998 attacks against Iraq. Perhaps the principal advantage of the Tomahawk is that they were unmanned and hence did not put American servicemen at risk. This feature later made them the weapon of choice in the raids against Sudan and Afghanistan in August 1998, against Iraq in December 1998, and during the Kosovo air campaign in the spring of 1999.

Although the consensus is that Tomahawks are a highly successful weapon, these weapons have several limitations. One of these is that their flight paths are relatively predictable, which is a function of the fact that some terrain, notably deserts, provides relatively few features for terrain-following guidance. A second problem is that mission planning for terrain-following guidance systems is more time consuming and complicated in terms of intelligence requirements than one might expect. For example, to use Tomahawks a unit would have to request a targeting package from such agencies as the Defense Mapping Agency to gather the data necessary for a mission. A third limitation was that Tomahawks could not be used against hardened targets because the 1,000 pound warhead, the weapon's accuracy, and its final kinetic energy when it hits the target do not produce high probabilities of kill. The final limitation was that Tomahawk cruise missiles cannot attack moving targets because they are guided to a position rather than to a specific target. Similarly, a Tomahawk cruise missile could not attack relocatable, that is mobile, targets because these may move while the mission is being planned or during the flight of the cruise missile.

Notes

1 New York Tribune, October 21, 1915, p. 1.

2 W Mitchell, *Lawrence Sperry and the Aerial Torpedo, U.S.* Air Services, January 1926, p. 16.

3. See wvvw.cdiss.org/tabanaly.htm, p 2.

4 While this has the effect of reducing drag, it also requires improvements in fight control Notes capabilities to counter the resulting instabilities.

5 I Lachow, *GPS-Guided Cruise Missiles and Weapons of Mass Destruction* (Santa Monica, CA: The RAND Corporation, RP-463), p 12.

6 From radar physics, there is a fourth order relation between the size of the RCS and the range at which it can be detected.

7. This analysis is based on the author's calculations.

8. See Elliott D Kaplan (editor), *Understanding GPS - Principles and Applications (Artech* House, 1996), p 321.

9 Gregg D Constabile, E*xploitation of Differential Global Positioning System (DGP.S) for guidance Enhancement (EDGE) test and Evaluation,* AFDTC Technical Report 95-31, January, 1996, p. 3-2.

10 See Liao Chaopei, *Precision Strike Concepts Associated with the Utilization of Relative GPS Technology,* Feihang Daodan (Winged Missiles Journal), No. 1, 1996, pp. 55-61.

11. See http://www.cdiss.org/cmthreat.htm.

12 While China is not a signatory to the MTCR, it has pledged to adhere to the guidelines established in the MTCR. Nevertheless, there are reports that China has sold missiles or missile technology to Syria, Saudi Arabia, and Pakistan among others.

13 W. Seth Carus, *Cruise Missile Proliferation in the 1990s* (Washington, DC: The Washington Papers, Center for Strategic and Intentional Studies, 1982), p, 15.

14. "Taiwan Puts $600m into Missile Programs," *Jane's Defense Weekly,* March 10, 1999, p 4.

15 These cost figures are based on the author's experience as a missile analyst in the Directorate for Program Analysis and Evaluation within the Office of the Secretary of Defense in the Pentagon.

16. Comment by a visiting speaker at the Air War College, 1998,

17 See www.cdiss.org/tabanaly.htm, p 1.

18 Irving Lachow, *GPS-Guided Cruise Missiles and Weapons of Mass Destruction* (Santa Monica, CA: The RAND Corporation, RP-463, 1995), pp. 18-20.

19. The principal reason for deploying nuclear weapons on submarines was to enhance the survival of nuclear weapons, which rested on concealing the location of the launch sites.

20 See Henry A Kissinger, N*uclear Weapons and Foreign Policy* (New York: Harper and Row, 1957), p 201, for the comment that, "A power possessing thermo-nuclear weapons is not likely to accept conditional surrender without employing them. It is the task of our diplomacy to make it clear that we do not aim for unconditional surrender" Several thousand years earlier, the Chinese strategist Sun Tzu said, "To a surrounded enemy you must leave a way of escape. Show him that there is a road to safety and so create in his mind that there is an alternative to death. …Do not press an enemy at bay. Wild beasts whole at bay, fight desperately. How much more this is true of men." See Sun *Tzu, The Art of War,* Samuel B Griffin, editor (Oxford University Press, *1963), p. 109.*

21. Author interview with individual at the Air Mobility Command Studies and Analysis Division.

22 See Kenneth P Werrell, *The Evolution of the Cruise Missile* (Montgomery, AL: Air University Press, *1985), p. 47.*

23 Eric Victor Larson, *Ends and Means in Democratic Conversation -Understanding the Role of Casualties in Support for U.S. Military Operations* (Santa Monica, CA: The RAND Corporation, *1994), p 24.*

24.Ibid., p. 1.

25. Ibid., p. 2.

26. See J. A. Warden, *The Air Campaign: Planning for Combat* (Washington D.C: Brassey's *1989),* for the argument that, The layman tends to associate air superiority with destruction of enemy aircraft ...it is not the only approach. A potentially vulnerable sequence of events (the aircraft chain) most take place before an aircraft fires a missile or drops a bomb ... it is possible to eliminate and air force by successful attacks at any point in this chain."

27. Richard Muller, *The German Air War in Russia* (Nautical and Aviation Publishing Company of America, *1993), p. 44.*

28. Doctrine for Joint Theater Missile Defense, Joint Publication 3-01.5, February *22, 1996.*

29. F. W. Heilenday, *V-1 Cruise Missile Attacks Against England Lessons Learned and Lingering Myths form World War II* (Santa Monica, CA: The RAND Corporation, *P-7914, 1995).*

30 This time can be calculated as the total time available from the detection of an attack to the time when the cruise missile hits the target, divided by the time required by the defender for each engagement.

31 We can express this logic in the following equation.

$$N_{sat} = N_{defenders} P_K \frac{t_{total}}{t_{engage}}$$

where,
N_{sat} is the number of cruise missiles that saturate the defenses
$N_{defenders}$ is the number of defending assets
P_K is the probability of kill in a single engagement
t_{total} is the total time for engagement or the time from cruise missile detection until it arrives at its target, and
t_{engage} is the average time required for each asset to engage an incoming cruise missile.

32. Author interview at the Air Mobility Command Studies and Analysis Division.

33. S B Frosch, *A Critical Analysis of Ground-Based Air Defense During Joint Expeditionary Operations, U.S.* Army Command and General Staff College, 1997, p. 82.

34. *Ibid.*

35 It is difficult to define precisely what we mean by the strategic effects that could be achieved with cruise missiles. One example to which we can turn is the U.S. experience in the Persian Gulf War in which 8,000 tons of precision guided munitions were dropped for the explicit purpose of producing strategic paralysis in Iraq. (See Glosson, "Impact of Precision Weapons on Air Combat Operations," *Airpower Journal,* Summer, 1993, p. 5). If we assume that conventional cruise missiles have one thousand pound warheads, an equivalent attack would involve 16,000 cruise missiles, which exceeds by an order of magnitude the cruise missile production capacities of most nations. A preliminary analysis suggests that precision guided munitions are roughly thirty times more effective than imprecise munitions. However, this estimate of the number of cruise missiles required for strategic attacks is low, for three reasons. The first of these is that U.S. and coalition delivery platforms that were used during the Gulf suffered no significant attrition. The only real source of attrition would be that inflicted by the defenses, and historically the only relevant data is the British experience of shooting down 50 percent of the V-ls launched against them. If this is a realistic attrition rate, then the number of cruise missiles necessary for strategic attacks

would double to 32,000. The second reason that this estimate is low relates to the increased effectiveness of munitions used during the Gulf War, notably the U.S. ability to choose tailor-made munitions for specific functions (weapons designed for soft, dispersed targets versus weapons designed for hard targets). Other states may not have the same options. Third, this approach assumes that a nation will expend all of its cruise missiles without keeping any in reserves, which is highly unlikely. A broad conclusion is that adversaries could not use cruise missiles to conduct strategic level attacks against the United States unless there were dramatic increases in production Thus, the better strategy for adversaries is to focus their strategic attack on potential U.S. military vulnerabilities rather than seeking to generate strategic paralysis, as exemplified by the U.S. air campaign against Iraq in 1991. The more practical conclusion is that an adversary would seek to exploit an asymmetric vulnerability, in the United States rather than trying to conduct strategic attacks.

36 See George Donohue, The *Pole of the B-2 in the New U.S. Defense Strategy* (Santa Monica, CA: The RAND Corporation, P-7744, 1991), for the observation that, "Stealth technologies would only marginally improve the B-2's ability to penetrate Soviet air defenses, and would certainly not justify the system's tremendous cost. More importantly, even if stealth technologies guaranteed that every B-2 would penetrate, it would still be a less cost-effective weapon than…the cruise missile."

37 K P Werrell, *The Evolution of the Cruise Missile* (Montgomery, AL: Air University Press, 1985), p 43.

38 *Ibid.,* p 47.

39 *The Army Almanac* (Washington, DC: United States Government Printing Office, 1950), p. 241.

40. *Ibid, p 61*

41 W. S. Carus, *Cruise Missile Proliferation in the 1990s* (Washington, DC: The Washington Papers, Center for Strategic and International Studies, 1982), p 1.

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