Long Range Conventional Missiles: Issues for Near-Term Development

Edward R. Harshberger
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Long Range Conventional Missiles: Issues for Near-Term Development

Edward R. Harshberger
This dissertation was produced at the RAND Graduate School for Policy Studies while the author served as a Graduate Fellow for the period 1986 to 1991. It should be useful to policymakers and researchers in the fields of military technology or systems acquisition. Although this work was not funded directly by the Air Force, the author benefited substantially from contact with Air Force officers and participation in RAND Project AIR FORCE research efforts.
SUMMARY

Over the last 40 years, the United States has consistently focused on maintaining the superiority of individual U.S. weapon technologies vis-à-vis those of the rest of the world. This emphasis has been based largely upon an ongoing military competition with the Soviet Union, and a consistent emphasis on meeting Soviet and Warsaw Pact numerical superiorities with a lesser number of more sophisticated systems has been a prime example of this U.S. technology focus.\(^1\) As recently as the Reagan administration, this historical trend was codified in official policy statements. The "competitive strategies" initiatives sought to make the traditional U.S. predilection for high technology an explicit element of U.S. strategy, emphasizing U.S. comparative advantages in advanced technology and productive capacity as an element of military strategy and tactics.\(^2\)

The strategic argument advanced by competitive strategies proponents has largely fallen by the wayside, partly because of the current budgetary squeeze and partly because of the near collapse of the Soviet Union as a politico-military competitor. But the emphasis on high technology in military systems continues, with or without a comprehensive strategy as a rationale. While a focus on technology works toward decided U.S. advantages in aerospace engineering, it is not without its difficulties. The need for maintaining a technological edge has required U.S. decisionmakers to make a continual series of judgments on the merits of the latest "wonder weapon," with less than perfect success. Such high-tech gamesmanship is played for enormous monetary and political stakes, as the size of the U.S. defense budget (even in these times of fiscal austerity) amply demonstrates. This Note deals with the military technology decisions surrounding the near-term development and procurement of long range conventional missiles.

For the purposes of this report, long range conventional missiles (hereafter referred to as LRCMs) are land-attack missiles, armed with conventional payloads (either unitary warheads or submunitions dispensers), with ranges between 500 and 5500 kilometers (250-2750 miles). The U.S. capability to produce LRCMs arises from a combination of weapon technologies, most notably precision guidance, lightweight airframes, and lightweight

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\(^1\) See, for example, Soviet Military Power 1988, pp. 110-111, for a discussion of the numerical and qualitative relationship between NATO and Pact air and ground forces.

propulsion. The application of these technologies enables the design of weapons that combine the ability to fly long ranges with the accuracies required to make conventional weapons effective.

LRCMs can usefully be considered as a separate class of conventional weapons for both technical and political reasons. Technically, the ranges that define an LRCM (500-5500 kilometers) make effective manned guidance extremely difficult. Hence, LRCMs are and almost certainly will be autonomous systems, self-guided to their targets. The autonomous characteristic of LRCMs heavily affects both their component technologies and the concepts for their employment. Politically, LRCMs are explicitly differentiated from other weapons by the INF treaty. The INF treaty distinguishes between weapons with ranges greater and lesser than 500 kilometers and between weapons with ranges greater and lesser than 5500 kilometers. There is no differentiation made between conventional and nuclear weapons of these ranges; hence, any LRCM will potentially be subject to the restrictions of this treaty and possibly others.

In fact, some missiles which fit the definition of LRCMs are currently in the U.S. weapon inventory. Two current Navy variants of the Tomahawk Land Attack Missile, TLAM-C and TLAM-D, are examples of LRCM systems that are already fielded. These two missiles are members of a family of ground- and sea-launched nuclear cruise missiles of the same general design. TLAM-C/D has a range of roughly 1500 kilometers and enough accuracy to make conventional attacks against many land targets reasonable. TLAM-C and its companion submunitions dispenser version, TLAM-D, are scheduled for buys of 1486 and 1164 missiles respectively. Several hundred TLAM-C missiles have been fired in the Iraq conflict. This marks the first use of LRCM weapons in actual conflict.

The current conventional TLAM system is an important capability, but it has a number of clear limits on its operational utility, discussed in this Note. These limitations

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3 Current techniques for “man-in-the-loop” guidance involve linking the missile to an operator for target identification and/or weapon steering. Current weapon data links include: line-of-sight radio links, electric wire, and fiber optic cabling. None of these techniques will be effective at the ranges discussed for LRCMs. Clearly, some schemes could be devised for data linking, almost certainly involving satellite or high-altitude aircraft relay; however, the difficulties with maintaining a robust link are considerable.

4 The INF treaty between the United States and the Soviet Union defines intermediate range missiles as ground-launched ballistic or cruise missiles with ranges greater than 1000 kilometers and less than 5500 kilometers. Further, it defines “shorter-range missiles” as ground-launched ballistic or cruise missiles with ranges between 500 and 1000 kilometers. The treaty bans deployment or development of both “intermediate range” and “shorter range” ground-based missiles by either party. See Articles I-VII of the INF Treaty.

have led to a desire by the Navy to improve upon TLAM’s capabilities. Simultaneously, the Air Force has indicated interest in procuring a LRCM system. This heightened service interest resulted in both the Navy and Air Force issuing statements of need for long-range conventional cruise missiles.

The focus of this Note is on the choices and tradeoffs the United States will face in developing a new LrCM weapon system during the next five years. There are four broad questions that must be answered affirmatively if development of the next LRCM is to take place in the near term:

- Are there useful roles for weapons with the characteristics of LRCMs?
- Are capabilities beyond those of Tomahawk needed for these roles?
- If so, are there technically and operationally feasible alternatives to Tomahawk?
- Finally, is the next LRCMs affordable in both a fiscal and political sense?

USEFUL EMPLOYMENT OF LRCM FORCES

The first question has been answered affirmatively by a number of commentators in the past, and on the face of it, LRCM technologies appear to have a great deal of promise. This promise has been underlined by their apparently successful role in the Desert Storm air campaign. Section II discusses the characteristics, useful roles, and likely employment of near-term LrCM weapons.

Near-term LRCM characteristics are summarized in Table S.1.

Table S.1

<table>
<thead>
<tr>
<th>Characteristics of a Near-Term LRCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Can attack targets at ranges greater than 500 km</td>
</tr>
<tr>
<td>• Can utilize a mix of conventional munitions</td>
</tr>
<tr>
<td>• Can operate autonomously</td>
</tr>
<tr>
<td>• Can destroy fixed or localizable targets</td>
</tr>
<tr>
<td>• Can be launched from bombers and/or naval vessels</td>
</tr>
</tbody>
</table>

LRCMs can autonomously attack fixed or localizable targets with conventional munitions. Potential platforms include naval vessels and long-range aircraft. The major strengths of LRCMs in an operational sense are their accuracy, standoff capability, and responsiveness. The conventional munitions used in LRCMs require the missile to be accurate. Without a certain degree of accuracy, LRCMs are completely ineffective, and second, accuracy is critical.
in limiting the number of LRCMs required for any given attack. This accuracy provides two useful by-products: minimization of collateral damage and minimization of force. LRCMs with high accuracy and conventional warheads are seen as a way to inject a minimum amount of force into a conflict, maximizing effectiveness while minimizing collateral damage. The LRCM's standoff range capability can be important for several reasons: (1) standoff range decreases response time, a major concern for naval employment of LRCMs; (2) standoff avoids light or minimal defenses in situations where the U.S. goal is to completely avoid attrition to manned platforms; and (3) standoff avoids heavy defenses (where unacceptable attrition might occur) in situations where attrition is expected. Finally, when combined with heavy bomber or naval platforms, LRCMs could be capable of responding to a contingency more rapidly than other U.S. forces, such as ground-based tactical aircraft.

With these characteristics and strengths in mind, the Note discusses three major roles for LRCMs: (1) Rapid Response to Regional Conflict, (2) Deep Attacks During Regional Conflict, and (3) Punitive Attacks. Specific operational concepts for the employment of LRCMs are developed to address the operational objectives and tasks implied by these roles. Table S.2 summarizes the roles and the LRCM strengths that address the demands of these roles.

Table S.2
LRCM Roles and Strengths

<table>
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<tr>
<th>Roles</th>
<th>Strengths</th>
<th>Other Potential Forces</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Response?</td>
<td>Accuracy?</td>
</tr>
<tr>
<td>Rapid Response</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Deny or delay forces</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deny aircraft operation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destroy high-value targets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep Attacks</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Destroy high-value targets</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destroy fixed air defenses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Punitive Attacks</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Destroy high-value targets</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

NOTE: LRCMs are unique in that they eliminate possibility of losses to enemy fire.

The ability of specific forces to employ LRCMs in these roles depends upon both LRCM characteristics and platform characteristics. Naval forces and heavy bombers are compared on three major employment measures: volume, sustainability, and timeliness. Volume indicates the number of LRCM weapons that can be launched in a single attack.
Sustainability describes the ability to continue a series of attacks over time. Timeliness relates to the ability to respond quickly to a desired use of LRCMs. In general, both ship- and bomber-deployed LRCMs are capable of timely, high-volume LRCM attacks. However, bomber-carried LRCMs can be sustained over a longer period of time. This difference allows bomber-launched LRCMs to address the range of roles discussed above, while naval forces are capable of addressing only the Deep Attack and Punitive Attack roles. Table S.3 summarizes the discussion of LRCM roles and employment options. The potential for alternative forces to address these roles, particularly the B-2 bomber, is a critical concern in LRCM development.

### Table S.3
LRCM Roles and Forces

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapid Response</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>LRCM-equipped bombers</td>
</tr>
<tr>
<td>Deny or delay forces</td>
<td></td>
<td></td>
<td></td>
<td>B-2 bomber</td>
</tr>
<tr>
<td>Deny aircraft</td>
<td></td>
<td></td>
<td></td>
<td>operation</td>
</tr>
<tr>
<td>Destroy high-value</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>targets</td>
</tr>
<tr>
<td>Deep Attacks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destroy high-value</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>targets</td>
</tr>
<tr>
<td>Fixed air defenses</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Punitive Attacks</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destroy high-value</td>
<td>✓</td>
<td></td>
<td></td>
<td>targets</td>
</tr>
</tbody>
</table>
| Tomahawk and Future LRCMs

Tomahawk's future utility is less certain. The conventional Tomahawk missile variants are currently deployed on naval vessels worldwide, most notably on the many ships that have employed them in the Persian Gulf. Clearly, the Navy envisioned roles for Tomahawk when it procured and deployed it on U.S. ships. However, from the perspective of the Navy clear limitations exist on Tomahawk's individual capabilities. These technical limitations generally revolve around the Tomahawk's range, which may limit the targets that it can cover, and the accuracy and availability of the missile's terminal guidance, which may limit its lethality against some targets. The solution to these lethality limitations is likely to be found in one of the target-looking sensors discussed in App. B. In addition, each
of the sensor technologies discussed has a significantly better poor-weather capability than DSMAC, and each has much higher accuracy as well.

The changes that the Navy may desire in Tomahawk could, for a number of reasons, be viewed as elements of a block upgrade to the weapon, rather than an entirely new missile. A Block IV Tomahawk would incorporate new sensors (an imaging infrared sensor is the most likely near-term option) and propulsion (perhaps a propfan design), with the rest of the missile substantially equivalent to Tomahawk Block III.

In contrast, the Tomahawk appears unsuitable from the Air Force perspective. The Tomahawk guidance limitations are a specific problem, but just as important is the fact that the Air Force's bomber launch platforms are distinctly different from naval launchers, both in their technical constraints and their performance demands. These combined factors lead to a new Air Force LRCM that would differ significantly from Tomahawk in airframe, sensors, and propulsion. The airframe would probably be shorter and wider, the sensor would be a target-looking sensor (the imaging infrared sensor), and the propulsion could be a less efficient, cheaper turbojet design.

The guidance and propulsion technologies discussed as solutions to Tomahawk limitations currently exist but have not been integrated into missile designs.

POTENTIAL ROADBLOCKS

In designing and operating a new and more effective LRCM, the stumbling blocks are likely to be operational and institutional rather than technical. Specifically, the target information required to make accurate guidance technologies effective is difficult to acquire, and once such information is required it must be analyzed and manipulated. LRCM's target-looking sensors and scene-matching capabilities have a dual effect on LRCM operability and effectiveness. On one hand, these capabilities are central to the ability to attack targets autonomously with conventional munitions, the key tasks that define a LRCM. Unfortunately, the autonomous nature of LRCMs and the technologies that make this autonomous attack possible are likely to strain our ability to gather and organize the information required to support them.

Throughout the discussions of LRCM technologies, performance measures, and capabilities in the appendixes, a consistent element can be found: mission planning. Mission planning has a major effect, in multiple ways, on key LRCM capabilities, including LRCM lethality and survivability. Figure S.1 shows a schematic of the steps required to plan just the terminal area portion of a LRCM attack utilizing target-looking sensor technologies. The functional divisions are based on both institutional structure and location. The first set of
Fig. S.1—LRCM mission support process

Information Flow

Intelligence Agencies
- Identify targets of interest
- Intelligence photos of specific targets
- Identify target elements and aimpoint(s)

Mission Planning Center
- Validate transformation
- Transform photos to sensor-observed image

Operational Command
- Load images onto LRCMs

Rapid Response: Hours → Minutes → Minutes →
Deep Attacks: Days → Hours → Minutes →
Punitive Attack: Days → Days → Hours →
tasks are generally considered intelligence functions. They require either intelligence collection assets or analysis of intelligence data. Some of this intelligence must obviously be gathered in the field, and the institutions generally charged with developing and gathering this type of information are distinct from the individual armed services. The second set of functions is the actual process of generating a LRCM mission profile, including the terminal target scene and the cruise missile route to the target area. Some tasks are hybrids, and there is overlap between the first two functional categories. Because of the requirement to maintain large databases and support large computer operations, the mission preparation process would almost certainly be carried out in at most several centralized mission planning centers. The mission support process ends when the information generated in the preparation stage is transmitted to the operational command and loaded onto the missile.

The timelines required for the planning process are a close function of the LRCM roles discussed in Sec. II. Of the three major roles discussed, only the Rapid Response role requires both high-volume, sustained attacks in a timely manner. The Deep Attacks role requires a high volume of LRCM attacks, but the responsiveness of these attacks is not a major issue. In the Desert Storm air campaign, where Tomahawks were utilized in the Deep Attacks role, several months were used to plan the attacks. The Punitive Attack role requires neither large numbers of weapons nor rapid response. Given these facts, it seems clear that the general mission planning process utilized by the Navy for its Tomahawk system can address those LRCM roles for which the Navy is best suited, the Deep Attack and Punitive Attack roles. The key question, therefore, is the capability of our current process (and particularly the Air Force) to handle the Rapid Response role. Given the volume and rate of attacks discussed in App. E, planning timelines must be measured in minutes rather than hours.

Overall, this Note points to some key difficulties with supporting the Rapid Response role for LRCM. These difficulties point out two major changes that need to occur if the United States (particularly the Air Force) is to be able to operate the next LRCM effectively in this role. First, institutional arrangements must be made for procuring and evaluating intelligence in support of LRCM missions. LRCM weapons will place unique pressures on our ability to gather the correct information, analyze it within the correct framework, and present it in the correct format. This process will require a high degree of cooperation between the intelligence community and the operational community. Even so, LRCM targets will almost certainly be limited to a set of standard military targets supplemented by a small set of targets that emerge during crisis.
Second, and just as important, a new set of skills and specialties needs to be developed in our military. It includes people who are versed in both target vulnerability and the capabilities of weapons such as LRCM; these two components of target attack are linked with unusual closeness by precision weapons such as LRCMs. Also included are people who can operate interactively with target imagery and autonomous sensor algorithmic processes, a new field in the armed services.

These conditions will not come about without some serious impetus for change. The military and national intelligence agencies are notoriously poor at sharing information; security classification guidelines differ between branches of the government and can act to prevent information from flowing freely. A process for understanding and expediting the intelligence information needed by LRCMs needs to be started now if LRCMs are to be useful any time in the near future. In the Air Force, the path to promotion has always passed most quickly through the cockpit. Although this will in all likelihood remain the case, serious effort needs to be made now if the skills are to be available to exploit a LRCM capability.

CAN WE AFFORD LRCM FORCES?

In terms of affordability, it is very likely that the next LRCM will cost in the near neighborhood of $1 million per unit. This being said, it is very difficult to construct an argument that the United States would be unable, in an absolute sense, to procure LRCMs in the numbers envisioned by this report (3000–4000 units). Table S.4 summarizes estimates of LRCM program costs suggested in this report.

Naval costs are lower, based upon treatment of the naval LRCM as a Tomahawk block upgrade. The Navy can in all likelihood afford such a program, especially if it is spread out over several years. In addition, by treating the next LRCM as a simple Tomahawk upgrade the Navy avoids the difficulties associated with starting new programs.

### Table S.4
Cost Estimates: 4000 LRCM Weapons (YR90s)

<table>
<thead>
<tr>
<th>Service</th>
<th>Unitary Warhead per Unit ($M)</th>
<th>Dispenser per Unit ($M)</th>
<th>Procurement ($B)</th>
<th>Development &amp; Test ($B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Force</td>
<td>0.65 – 0.85</td>
<td>0.95 – 1.15</td>
<td>3.2 – 4.0</td>
<td>– 1.2</td>
</tr>
<tr>
<td>Navy</td>
<td>0.9 – 1.15</td>
<td>1.2 – 1.45</td>
<td>– 1.0</td>
<td>– 0.5</td>
</tr>
</tbody>
</table>
In contrast, the Air Force would face a much larger LRCM program, one that might significantly affect other potential procurement options. Figure 5.2 shows one potential breakdown of Air Force procurement elements for the next few years. This detail sheds a great deal of light on the problems faced by LRMs in Air Force procurement battles. Roughly 70 percent of the FY1990 Air Force procurement budget is devoted to aircraft procurement or procurement related to maintaining the aircraft fleet. This leaves 30 percent, or roughly $6.5 billion, for missile-related procurement. However, of this amount only 25 percent is used to procure known missile systems. The other 75 percent is directed to a series of other support activities, which include space launch and unspecified classified programs (at least some of which must be intelligence activities). This leaves roughly $2 billion for open procurement of missiles. Of this $2 billion, roughly 60 percent is aimed at strategic missiles such as MX, the ACM, and SRAM II. Of the tactical missile portion, the largest procurement is for AMRAAM missiles, which constitute $890 million of spending.

Given these breakdowns, it becomes fairly clear that a LRCM procurement would force some serious tradeoff within the Air Force. A LRCM procurement would make up a sizable fraction of missile procurement. If included in the 1990 budget, it would be the third largest missile procurement item, behind MX and AMRAAM. If the buy size were cut in half (without quantity-related cost penalties) LRCM would drop to number four, behind ACM.

**LRCM POLITICS**

However, cost and fiscal issues are not the entire story; budgetary arguments are at least as political as they are economic. One potential stumbling block to LRCM could be arms control. LRMs could become involved with nuclear arms limitation treaties because of both their long range and their potential launch platforms. This Note presents an arms control regime that addresses this potential difficulty for air-launched LRMs. In its essence, this regime relies upon platform classification as a means of limiting creepout, coupled with platform limitations to limit the extent of inherent breakout potential.

A more serious concern for LRMs is service interests. In the past, both interservice and intraservice weapon development issues have directly (and generally adversely) affected LRCM development over a number of years; the LRCSW program is the most recent example. The Air Force, in particular, faces a very difficult set of decisions and concerns. The Air Force has never fielded a LRCM, and it has historically shown little interest in ever doing so. The reasons for this attitude are many and varied. First, LRMs are viewed as

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Fig. S.2—LRCM procurement comparison

programmatic threats to aircraft procurement. In this sense, the LRCM case is parallel to that of the ALCM nuclear cruise missile. The ALCM met severe resistance from the Air Force when it was proposed in the early 1970s, largely because it was perceived to limit incentives for further development of manned penetrating bombers.

In the conventional realm, LRCMs have been viewed as a competitor to both manned tactical aircraft (TACAIR) and penetrating bombers. In comparison to TACAIR, LRCMs operate in the same range regime, carry conventional payloads, and presumably could attack a similar set of targets. Commanders, seeing the potential competition between TACAIR and LRCMs, quite reasonably prefer TACAIR for the same reasons that their Navy counterparts prefer to have a carrier air wing: flexibility, responsiveness, and payload. The fact that TACAIR, either ground-based or sea-based, might be unavailable when needed seems to hold little weight.

The group within the Air Force that would seem to have the greatest interest in developing a LRCM is Strategic Air Command, which has command over the U.S. long-range
bomber force. A LRCM seems especially to complement the perceived strengths and weaknesses of current U.S. heavy bombers, the B-52 and B-1. The strengths of these aircraft include range, responsiveness, and heavy payload capability; the major perceived weakness of the B-52 and B-1 is potential attrition when penetrating enemy air defenses. The combination of the heavy bomber's range and payload capability with the LRCMs defense standoff capability seems a particularly good match. This good match has been negated to some extent, however, by the importance attached to the B-2 bomber. Current bomber platforms carrying LRCMs and B-2s with short-range weapons are alternatives that directly address some of the same potential tasks. Whether or not the B-2 and LRCM compete in any objective sense (they may in fact be synergistic), these two systems clearly compete in a subjective sense; LRCM is a public relations nightmare for the B-2. The Air Force has made very clear its continuing support for the B-2, with its greater flexibility and potential dual role as a nuclear and conventional bomber.

RECOMMENDATIONS

Based upon these arguments, the outlook for a near-term development of a LRCM capability is constrained. The Navy will, in all likelihood, wish to continue to upgrade the Tomahawk's capabilities in one way or another. The Air Force's view of LRCMs is bifurcated and based upon the existence or lack of the B-2. Based upon the analysis and discussion in this Note, the following policy recommendations are in order, generally aimed at the OSD decisionmaker:

- Because of clear technical and employment differences, development of LRCM airframes and propulsion should be a service, rather than joint, activity. Common airframes and propulsion are unlikely to meet either service's needs and will serve as a stumbling block to LRCM progress.

- The Air Force and Navy should jointly pursue development of target-looking sensor technologies and the intelligence and mission support equipment required to support them. As much commonality as possible in this area would minimize the strain on overburdened intelligence and planning assets.

- The terminal sensor technologies discussed in this document are a natural upgrade to Tomahawk's capabilities. Even in the absence of an Air Force LRCM program, the Navy should be encouraged to pursue an upgrade to the Tomahawk missile as an incremental step in developing and operating LRCM technologies.
If the B-2 is not procured or bought in small numbers, the Air Force should be directed to develop a LRCM force along the lines described in this report. It is imperative, therefore, that employment options on other aircraft such as the B-52 or B-1 not be forestalled prematurely by either arms control agreements or retirement of aircraft until the B-2 decision is made.

If the B-2 is procured in numbers, the Air Force should refocus LRCM development efforts toward both longer-term and shorter-range technologies. Shorter-range technologies would address the occasional need or desire for the B-2 to stand off at short range from terminal defense areas. Longer term technologies could include ongoing development of autonomous search and recognition technologies for a future where the B-2 could become less survivable.

Some of these recommendations conflict with current reality. In particular, there appears to be little coordination on these areas that most require them, terminal sensors and mission planning. LRCM weapons have a great deal of promise under the circumstances outlined in this Note. The ability to procure an effective LRCM force depends upon our ability to coordinate effort on a few key developmental and operational areas. Hard work in these areas could result in a substantial enhancement of U.S. military capabilities.
ACKNOWLEDGMENTS

This work would have been impossible without the support and encouragement of friends, family, and colleagues. I would like to thank the many who have read and commented on this document, including Jim Bonomo, Glenn Buchan, Myron Hura, Jim Quinlivan, David Ochmanek, and David Vaughan, for their time and valuable comments. In addition, I have drawn on the advice and analysis of many other RAND colleagues, including Harry Evans, David Frelinger, Roy Gates, and Al Zobrist. Of course, all errors are solely my responsibility.

My committee members, Michael Rich, George Donohue, and Robert Lemport, were supportive and constructive in their criticism. This document has progressed far from its origins with their help.

Finally, my family has been there for me with a positive word and a hug in the dark days when this document seemed a long way off. I would never have made it without all of them, and I will thank them always for never doubting me.
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I. INTRODUCTION

Over the last 40 years, the United States has consistently focused on maintaining the superiority of individual U.S. weapon technologies vis-à-vis those of the rest of the world. This emphasis has been based largely upon an ongoing military competition with the Soviet Union, and a consistent emphasis on meeting Soviet and Warsaw Pact numerical superiorities with a lesser number of more sophisticated systems has been a prime example of this U.S. technology focus. As recently as the Reagan administration, this historical trend was codified in official policy statements. The “competitive strategies” initiatives sought to make the traditional U.S. predilection for high technology an explicit element of U.S. strategy, emphasizing U.S. comparative advantages in advanced technology and productive capacity as an element of military strategy and tactics.

The strategic argument advanced by competitive strategies proponents has largely fallen by the wayside, partly because of the current budgetary squeeze and partly because of the near collapse of the Soviet Union as a politico-military competitor. But the emphasis on high technology in military systems continues, with or without a comprehensive strategy as a rationale. While a focus on technology works toward decided U.S. advantages in aerospace engineering, it is not without its difficulties. The need for maintaining a technological edge has required U.S. decisionmakers to make a continual series of judgments on the merits of the latest “wonder weapon,” with less than perfect success. Such high-tech gamesmanship is played for enormous monetary and political stakes, as the size of the U.S. defense budget (even in these times of fiscal austerity) amply demonstrates. This Note deals with the military technology decisions surrounding the near-term development and procurement of long-range conventional missiles.

For the purposes of this report, long-range conventional missiles (hereafter referred to as LRCMs) are land-attack missiles, armed with conventional payloads (either unitary warheads or submunitions dispensers), with ranges between 500 and

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1 See, for example, Soviet Military Power 1988, pp 110–111, for a discussion of the numerical and qualitative relationship between NATO and Pact air and ground forces.

5500 kilometers (250–2750 miles). The U.S. capability to produce LRCMs arises from a combination of weapon technologies, most notably precision guidance, lightweight airframes, and lightweight propulsion. The application of these technologies enables the design of weapons that combine the ability to fly long ranges with the accuracies required to make conventional weapons effective.

LRCMs can usefully be considered as a separate class of conventional weapons for both technical and political reasons. Technically, the ranges that define an LRCM (500–5500 kilometers) make effective manned guidance extremely difficult. Hence, LRCMs are and almost certainly will be autonomous systems, self-guided to their targets. The autonomous characteristic of LRCMs heavily affects both their component technologies and the concepts for their employment. Politically, LRCMs are explicitly differentiated from other weapons by the INF treaty. The INF treaty distinguishes between weapons with ranges greater and lesser than 500 kilometers and between weapons with ranges greater and lesser than 5500 kilometers. There is no differentiation made between conventional and nuclear weapons of these ranges; hence, any LRCM will potentially be subject to the restrictions of this treaty and possibly others.4

In fact, some missiles which fit the definition of LRCMs are currently in the U.S. weapon inventory. Two current Navy variants of the Tomahawk Land Attack Missile, TLAM-C and TLAM-D, are examples of LRCM systems that are already fielded. These two missiles are members of a family of ground- and sea-launched nuclear cruise missiles of the same general design. TLAM-C/D has a range of roughly 1500 kilometers and enough accuracy to make conventional attacks against many land targets reasonable. TLAM-C and its companion submunitions dispenser version, TLAM-D, are scheduled for buys of 1486 and 1164 missiles respectively.5

3 Current techniques for "man-in-the-loop" guidance involve linking the missile to an operator for target identification and/or weapon steering. Current weapon data links include: line-of-sight radio links, electric wire, and fiber optic cabling. None of these techniques will be effective at the ranges discussed for LRCMs. Clearly, some schemes could be devised for data linking, almost certainly involving satellite or high-altitude aircraft relay; however, the difficulties with maintaining a robust link are considerable.

4 The INF treaty between the United States and the Soviet Union defines intermediate range missiles as ground-launched ballistic or cruise missiles with ranges greater than 1000 kilometers and less than 5500 kilometers. Further, it defines "shorter-range missiles" as ground-launched ballistic or cruise missiles with ranges between 500 and 1000 kilometers. The treaty bans deployment or development of both "intermediate range" and "shorter range" ground-based missiles by either party. See Articles I–VII of the INF Treaty.

Several hundred TLAM-C missiles have been fired in the Iraq conflict. This marks the first use of LRCM weapons in actual conflict.

The current conventional TLAM system is an important capability, but it has a number of clear limits on its operational utility, discussed in this Note. These limitations have led to a desire by the Navy to improve upon TLAM's capabilities. Simultaneously, the Air Force has indicated interest in procuring a LRCM system. This heightened service interest resulted in both the Navy and Air Force issuing statements of need for long-range conventional cruise missiles.

The focus of this Note is on the choices and tradeoffs the United States will face in developing a new LRCM weapon system during the next five years. There are four broad questions that must be answered affirmatively if development of the next LRCM is to take place in the near term:

- Are there useful roles for weapons with the characteristics of LRCMs?
- Are capabilities beyond those of Tomahawk needed for these roles?
- If so, are there technically and operationally feasible alternatives to Tomahawk?
- Finally, is the next LRCM affordable in both a fiscal and political sense?

The first question has been answered affirmatively by a number of commentators in the past, and on the face of it, LRCM technologies appear to have a great deal of promise. This promise has been underlined by their apparently successful role in the Desert Storm air campaign. Section II of this Note discusses the characteristics, useful roles, and likely employment of near-term LRCM weapons.

Tomahawk's future utility is less certain. The conventional Tomahawk missile variants are currently deployed on naval vessels worldwide, most notably on the many ships that have employed them in the Persian Gulf. Clearly, the Navy envisioned roles for Tomahawk when it procured and deployed it on U.S. ships. However, from the perspective of the Navy, clear limitations exist on Tomahawk's individual capabilities. These technical limitations generally revolve around the Tomahawk's range, which may limit the targets that it can cover, and the accuracy of its terminal guidance, which may limit its lethality against some targets.

The changes that the Navy may desire in Tomahawk could, for a number of reasons, be viewed as elements of a block upgrade to Tomahawk, rather than an entirely new missile. In contrast, the Tomahawk appears unsuitable from the Air
Force perspective. The Tomahawk guidance limitations are a specific problem, but as important is the fact that the Air Force's bomber launch platforms are distinctly different from naval launchers, both in their technical constraints and their performance demands. These combined factors lead to a new Air Force LRCM that would differ significantly from Tomahawk.

From the broader perspective of defense policy as a whole, the interest in LRCMs recently resulted in the formation of a joint program office to coordinate the development of a new LRCM system, termed the Long-Range Conventional Standoff Weapon (LRCSW), with the Navy as the lead service. Fourteen million dollars were appropriated for fiscal 1990 for this effort, with further critical review planned. However, in December 1990 the LRCSW effort was downgraded to a technology development program, foundering in the wake of budget austerity and interservice differences. This Note argues that a new near-term LRCM is not likely to be a completely joint effort, given the differences in Navy and Air Force LRCM designs.

In designing and operating a new and more effective LRCM, the stumbling blocks are likely to be operational and institutional rather than technical. Guidance and propulsion technologies currently exist that are capable of addressing the main technical limitations of Tomahawk identified in this Note. However, the target information required to make accurate guidance technologies effective is difficult to acquire, and once such information is required it must be analyzed and manipulated. The time that such a process will almost certainly require places a great deal of pressure on the ability of the United States to integrate intelligence and planning to an unprecedented degree for LRCM weapons. An inability to do so could severely limit LRCM operational effectiveness in some roles.

In terms of affordability, it is very likely that the next LRCM will cost in the near neighborhood of $1 million per unit. This being said, it is very difficult to construct an argument that the United States would be unable, in an absolute sense, to procure LRCMs in the numbers envisioned by this Note (3000-4000 units). However, an absolute ability to procure LRCMs is not the issue; budgetary arguments are at least as political as they are economic. In the case of the LRCM, both interservice and intraservice weapon development issues have directly (and generally adversely) affected LRCM development over a number of years; the LRCSW program is simply the most recent example. For the Navy, the solution to this

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6 Aviography  99 week and Space Technology, October 17, 1988, pp. 28-29.
problem may lie in treating the next LRCM as a simple Tomahawk upgrade, thus avoiding the difficulties associated with new programs.

The Air Force, however, faces a very difficult set of decisions that are directly tied to its B-2 bomber program. Current bomber platforms carrying LRCMs and B-2s with short-range weapons are alternatives that directly address some of the same potential tasks. Whether or not the B-2 and LRCM compete in any objective sense (they may in fact be synergistic), these two systems clearly compete in a subjective sense; LRCM is a public relations nightmare for the B-2. The Air Force has made very clear its support for the B-2, with its greater flexibility and potential dual role as a nuclear and conventional bomber.

Based upon these arguments, the outlook for a near-term development of a LRCM capability is constrained. The Navy will, in all likelihood, wish to continue to upgrade the Tomahawk's capabilities. The Air Force's view of LRCMs is bifurcated and based upon the existence or lack of the B-2. Aside from informing debate over these issues, this report makes specific recommendations as to the future course of action on issue of LRCM weapons.
II. USEFUL EMPLOYMENT OF A NEAR-TERM LRCM

The recent use of the Tomahawk missile in Operation Desert Storm inaugurated the use of LRCMs in armed conflict. Even before Desert Storm, however, LRCMs have generated interest among military and political analysts. This chapter addresses the question of LRCM utility in both broad and detailed terms.

NEAR-TERM LRCM CHARACTERISTICS AND STRENGTHS*

Before one can discuss any particular roles for LRCMs, one must define in at least simple terms the major characteristics of LRCM weapons. The broad characteristics of a near-term LRCM are relatively simple to describe and are driven both by technology and by operational considerations. They are listed below in Table 2.1.

Table 2.1
Characteristics of a Near-Term LRCM

- Can attack targets at ranges greater than 500 km
- Can utilize a mix of conventional munitions
- Can operate autonomously
- Can destroy fixed or localizable targets
- Can be launched from bombers and/or naval vessels

The first basic characteristic is simply a definitional requirement; for the purposes of this Note, LRCMs have operational ranges beyond 500 kilometers. The second characteristic is somewhat more important. The current Tomahawk LRCM consists of two variants: unitary (TLAM-C) and dispensed submunition (TLAM-D). Apparently, only the unitary version was employed in the Desert Storm operation. Although there is some debate over whether these munitions should be interchangeable in the field for a new LRCM, it is sufficient for our purposes that the next LRCM should in some way be capable of carrying both types of payload.

Based upon the range of the the LRCM, near-term LRCM targets will be attacked autonomously. Current techniques for "man-in-the-loop" guidance involve linking the missile

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to an operator for target identification and/or weapon steering. Current weapon data links include line-of-sight radio links, electric wire, and fiber optic cabling. None of these techniques will be effective in the near term at the ranges discussed for LRCMs. Clearly, some schemes could be devised for data linking, almost certainly involving satellite or high-altitude aircraft relay; however, the difficulties with maintaining a robust link are considerable, and data links will not likely be employed for a near-term LRCM.

Autonomous attack drives the most critical of the LRCM capabilities: the targets that the next LRCM will be required to attack will be fixed or limited to a relatively small number of fixed locations (hereafter referred to as “localized targets”). This is based upon the fact that near-term LRCM weapons will require a stable image of the target scene on which to lock. The algorithms and sensors required for flexible autonomous target recognition (ATR) lack sufficient maturity for deployment in an operational system in the near term. There is a great deal of work being done in this area, but most would agree that robust operational algorithms remain some distance off. In addition to algorithmic questions, the mission preparation and planning requirements for autonomous flight and scene-matching sensors will require enough time to prevent attack of highly mobile targets. For fixed targets, this process requires a photographic image of the target area, selection of appropriate aiming points, and transformation to a sensor-observed image, in addition to enroute terrain planning to avoid missile contact with the ground. For autonomous target recognition of mobile targets, the same enroute planning would in all likelihood be required along with information about the terrain in the target area to be searched. Furthermore, the LRCM must then fly to the target area, which could take up to hours. For mobile targets, these planning and flight time considerations probably obviate the use of near-term LRCMs for these uses. Although an ability to perform flexible ATR could be the subject of a future LRCM upgrade, it will not be included in a system based upon technologies available in the short term. Many of these issues are discussed at length in Apps. B through D.

As a final characteristic, a near-term LRCM weapon could in principle be launched from either heavy bomber platforms or naval vessels. In some situations, one or the other of

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1 Most discussion of autonomous attack of mobile targets has been couched in terms of shorter-range weapons to attack fairly dense and localized concentrations of targets, such as might have been found in a Central European scenario. See, for example, "Martin Pursues Development of Autonomous Cruise Missile," Aviation Week and Space Technology, May 1, 1986. The autonomous target recognition work described in this article was funded under a $15 million, 30-month contract for the Defense Advanced Research Projects Agency, indicative of its very early developmental nature.

2 As noted before, ground-launched LRCMs are banned by the INF treaty.
these platforms may be the preferred option, and this issue is discussed in detail in succeeding chapters.

The capabilities discussed above imply broad instances where LRCMs are likely to be useful and situations where LRCM strengths are most likely to bear fruit. The three main strengths of LRCM's are standoff, accuracy, and responsiveness.

**Standoff**

The LRCM's standoff range capability can be important for several reasons:

- Standoff range decreases response time, a major concern for naval employment of LRCMs.
- Standoff avoids light or minimal defenses in situations where the U.S. goal is to completely avoid attrition to manned platforms.
- Standoff avoids heavy defenses (where unacceptable attrition might occur) in situations where attrition is expected.

Recent years have witnessed a growing preponderance of sophisticated air defense, ground attack, and sea attack systems, even among less militarily and economically powerful countries. This growth has resulted from emergence of the non-U.S. and non-Soviet arms export trade (Brazil, France, Israel, etc.) and the continued sales of U.S. and Soviet systems. These systems include advanced aircraft (e.g., Mirage, F-16, Mig-29), precision standoff weapons (e.g., Exocet, Silkworm), and sophisticated surface-to-air missiles (e.g., Stinger, Hawk, and various Soviet systems).³

A glaring example of this trend confronted U.S. forces in the deserts of Saudi Arabia. The air forces and ground-to-air defenses of the Iraqi armed forces were numerous and fairly advanced. The United States found itself confronting its own technology in the Hawk surface-to-air missile system. Meeting this threat required an ongoing and relentless Suppression of Enemy Air Defenses (SEAD) campaign involving large numbers of specialized Air Force and Navy aircraft, coupled with an ongoing sea campaign to minimize threats against naval vessels.

The standoff capability of LRCMs might directly address the heightened worldwide threat environment. In general, lower-scale conflicts involve both a relatively weak opponent

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and a keen desire to avoid any U.S. casualties. In higher-scale conflicts losses are expected, but defenses are denser, have longer ranges, and are more sophisticated. Long-range standoff could allow LRCM bomber launch platforms to attack some targets while remaining outside of enemy air defense coverage, unattacked. Naval platforms employing LRCMs could launch land attacks outside of naval defense ranges, potentially without the necessity for heavy air defense cover. Obvious questions arise concerning survivability of the LRCMs themselves (a subject considered later in this Note); however, loss of a LRCM results in the loss of neither an expensive platform nor its even more valuable crew.

Accuracy

The conventional munitions used in LRCMs require accuracy on the part of LRCM weapons. First, without a certain degree of accuracy, LRCMs are completely ineffective; second, accuracy is critical in limiting the number of LRCMs required for any given attack. This accuracy provides two useful by-products: minimization of collateral damage and minimization of force. LRCMs, with high accuracy and conventional warheads, are seen as a way to inject a minimum amount of force into a conflict, maximizing effectiveness while minimizing collateral damage. Clearly, minimization of collateral damage is of paramount importance in small-scale attacks such as the U.S. raid on Tripoli, but as Operation Desert Storm has so clearly underlined, a desire for precise attacks can extend even to large-scale uses of military force.

Force minimization through accurate attack also has the potential of enhancing cost-effectiveness. Recently, Secretary of Defense Cheney asked each Armed Service to examine its systems in light of large budget cuts. Estimates of a yearly 5 percent real decline in the defense budget are now common. "Smart" guidance and sensors, it is argued, might make LRCMs a more efficient weapon system than current munitions. Smart weapons might provide a force multiplication effect, allowing fewer expensive platforms and crews to perform a given set of missions. LRCMs could have the additional advantage of extending the useful life of current platforms, potentially saving costs for new procurements. The LRCM cost-effectiveness arguments are by no means proven at this point in time and in fact are difficult to determine conclusively. LRCM costs and measures of effectiveness and cost-effectiveness

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4 See App. D for a discussion of LRCM accuracy-versus-lethality tradeoffs.
are discussed in later chapters, as well as the impact of constrained budgets on a nominal procurement program associated with an LRCM.

Responsiveness

Finally, when combined with heavy bomber or naval platforms, LRCMs could be capable of responding to a contingency more rapidly than other U.S. forces, such as ground-based tactical aircraft. With the decreasing focus on Central Europe has come a heightened realization of U.S. political and military commitments around the globe, with Desert Storm the most obvious recent example. Of primary importance is America's continuing economic interdependence with Southwest and Southeast Asia. This interdependence includes the reliance of our major economic and military allies (and to a lesser extent our own reliance) on Southwest Asian oil reserves and the global shift of industrial capacity to Southeast Asian economies.

Southwest and Southeast Asia demand continual U.S. attention, given the continued political instability and increasingly uncertain U.S. basing in both regions. In Southwest Asia, the United States is unlikely to ever again enjoy the unlimited access and time afforded the Desert Shield and Desert Storm operations. The importance of timely response to future crises should not be underestimated in light of the Desert Shield and Desert Storm experience. The United States would have had few responses in the event of a decisive early attack into Saudi Arabia by Iraqi forces. Both operations have underlined the cost and logistic demands of maintaining a far-flung military presence. In Southeast Asia, continued instability in South Korea, continued solidification of the Vietnamese military presence, and increasing uncertainties associated with Philippine basing are causes for concern.

LRCMs are one element of a response to these trends, especially when coupled with naval or long-range aircraft platforms. The firepower projection capability embodied by such forces might increase both the responsiveness and effectiveness of U.S. forces in critical regions around the world. At the same time, enhancing the capability of either of these projection platforms would lessen demands on constrained foreign basing.

STRATEGIES TO TASKS: A FRAMEWORK FOR DEVELOPING SPECIFIC LRCM ROLES*

LRCMs are interesting in that their strengths seem to address national security trends of ongoing concern to U.S. defense decisionmakers. However, issues such as those discussed above are broad and unfocused. Development of a truly useful LRCM capability

* I am indebted to RAND colleague David Ochmanek for his aid in developing this strategies to tasks discussion.
will depend upon a clear understanding of the role of a LRGM weapon system within the framework of U.S. operational strategies and the operational concepts for performing tasks implied by these strategies. The strategies to tasks framework, which has been used successfully in a number of RAND analyses, provides an analytic structure linking national goals, objectives, and strategies to operational concepts for the employment of military forces and weapons. A discussion of this framework can be found in several RAND documents.\(^7\)

Figure 2.1 illustrates a conceptual framework linking broad national goals and objectives to military strategies and the capabilities of forces assigned to implement these strategies. Each of the five distinct operational strategies is relevant to a different type of warfare or contingency. Within each strategy are variants for regions of the world in which such conflicts might occur.

![Diagram](image)

**Fig. 2.1—Strategies to tasks analytic framework**

Each strategy can be disaggregated into a series of objectives and tasks military forces will perform. The strategies are not "pure types." Some tasks will appear beneath multiple strategies—for example, the need to move forces and support assets rapidly, both into theaters of operations and within them, or the need to locate hostile command elements. But many of the tasks are unique, as are the capabilities required to perform them. The forces needed to successfully execute an operational strategy of limited intervention or of

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unconventional operations are generally not simply a "lesser included case" of forces appropriate to major regional contingencies.

In the context of new weapon systems, the most important level of analysis in the strategies to tasks framework is the level of operational concepts. Operational concepts detail, in concrete terms, the ways in which support assets (e.g., surveillance systems, control elements, communications), platforms, and weapons are employed in combat to perform each task that comprises the operational strategy (the "Tasks" level in Fig. 2.1). With this in mind, near-term LRCMs are most relevant to the performance of tasks under strategies for regional contingencies (e.g., Desert Storm) and punitive attacks (e.g., the Eldorado Canyon raid on Tripoli). For these two regional strategies, Hosmer and Kent\(^8\) discuss several operational objectives and develop operational concepts involving the use of heavy bombers to accomplish several operational tasks, including:

- Denying or delaying insertion, reinforcement, and supply of enemy forces.
- Neutralizing enemy capabilities to operate aircraft from specific bases.
- Destroying high-value enemy targets with precision.
- Suppressing enemy air defense assets.

For some of these tasks and for some bomber platforms, Hosmer and Kent correctly note that a standoff weapon could be required for the heavy bombers. This Note is an extension of the Hosmer/Kent analysis in two ways. First, this analysis considers the potential of naval platforms for the delivery of LRCMs in addition to heavy bomber platforms. Second, the specific characteristics, costs, and operational issues surrounding the employment of LRCM weapons are investigated in greater depth in the rest of this Note.

**Role 1: Rapid Response to Regional Conflict**

There is no shortage of relatively plausible scenarios for future U.S. conventional armed conflict. As noted above, Hosmer and Kent describe four such scenarios, and Simons\(^9\) discusses these in some detail. However, all of the scenarios where LRCMs could play a role strike a few common themes: (1) they place a premium on the rapidity of an initial U.S. response, (2) they involve holding or delaying actions, buying time for other U.S. forces, and

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(3) they are fought against opponents with relatively sophisticated militaries, including air defenses.

Some of the most useful applications for LRCM's may lie in the critical early days of these large-scale campaigns, during which the United States is forced to move ground and air forces large distances. Even if prior permission is received from host countries to base air and ground forces, a substantial period of time might be required to move these forces into place. The buildup in Saudi Arabia prior to Desert Storm, for instance, required several months. If the United States had been required to take action during the early days of the crisis, we would likely have been limited to actions performed by naval forces on station or long-range aircraft operating from outside the theater of interest. Such would have been the case if Saddam Hussein's forces had continued down the Arabian Peninsula instead of halting at the Saudi border, and the fact that this outcome did not occur in this instance is not an argument against its possibility.

Based upon the characteristics of LRCMs discussed above, the following operational concepts for LRCMs can be envisioned:

- **Denying or delaying insertion of enemy forces.** LRCM-equipped heavy bombers or naval vessels, launching from beyond the range of enemy defenses, attack key bridges, tunnels, and chokepoints with unitary warhead LRCMs. Extensive support aircraft, other than tankers, are not required.

- **Neutralizing enemy capabilities to operate aircraft.** LRCM-equipped heavy bombers or naval vessels crater runways and attack parked and revetted aircraft with submunition-dispensing LRCMs.

- **Destroying high-value targets.** LRCM-equipped heavy bombers or naval vessels attack fixed political and strategic sites, such as command posts and chemical warfare production and storage, with unitary LRCMs.

These operational concepts take advantage of all three of the LRCM strengths discussed above. Responsiveness is the key element of this role, since it must be performed in the critical early days of a conflict. Standoff capability enables platforms to remain outside defenses early in the campaign, before they have been significantly degraded. As is discussed in the technical appendices accompanying this Note, accuracy is necessary to attack some of the targets discussed above.
Role II: Deep Attacks During Regional Conflicts

A key element of the Desert Storm campaign was the prolonged air campaign against Iraqi strategic, political, and economic targets. These attacks clearly affected both Iraq's command and control of its armed forces and its long-term capability to produce destabilizing armaments and prosecute an offensive war. The air campaign may or may not have had psychological impact beyond these physical realities. Destroying targets of high value to the enemy and assets designed to defend them has the potential for coercion, driving an enemy to settlement. As Hosmer and Kent note, "In both the Korean and Vietnam conflicts, the United States eventually had to rely on intensified air campaigns—rather than offensive ground operations—to create battlefield leverage to encourage war termination."\(^{10}\)

Based upon this premise, the following operational concepts can be developed:

- **Destroying high-value targets.** LRCM-equipped heavy bombers or naval vessels attack fixed political and strategic sites with unitary LRCMs.
- **Suppressing enemy air defenses.** LRCM-equipped heavy bombers or naval vessels attack fixed radar and SAM locations with a mixture of unitary and submunition LRCMs, opening targets to further attack with other air assets.

This role for LRCMs is distinct from the previous Rapid Response role in several ways. First, this role almost certainly exists as a single element in a coordinated operation. Other forces, such as naval air and ground-based tactical aircraft would in all likelihood be present. Second, there is no fixed time period implied for the Deep Attack role. As part of a coordinated operation, rapid response of the LRCM force in the absence of other forces is probably not critical. However, LRCM accuracy and standoff are important considerations for this role. Accuracy is necessary for attacking some of the targets discussed above, and is the key consideration in avoiding collateral damage. LRCM standoff provides an additive capability to attack deep or heavily defended targets without risking valuable platforms.

There is evidence that Tomahawk addressed this role in the Desert Storm operation.

Role III: Punitive Attacks

This role is perhaps the most discussed role for LRCMs. Ideally, punitive attacks are carried out in order to show resolve and destroy some specific threatening or valuable targets. The U.S. raid on Tripoli and the Israeli attack on Iraqi nuclear power facilities are

\(^{10}\) *The Military and Political Potential of Conventionally Armed Heavy Bombers*, p. 14. Specific mention is made of the Korean "pressure" air campaign and the Christmas bombings in Vietnam.
examples of this type of mission. The political stakes in such attacks are generally extremely high, and the military goals are, therefore, equally stringent. In general, such punitive attacks must (1) succeed at the first attempt, (2) minimize U.S. losses and prisoners, and (3) minimize collateral damage.

These stringent requirements arise from the political constraints that operate when such attacks are considered. Mission success on the first attempt is desirable in a military sense because of the wish to maintain the element of surprise, but it becomes politically critical as a matter of demonstrated national military competence. Minimal casualties and prisoners (with a strong preference for none at all) are key elements for maintaining domestic support for such an action. Finally, an overwhelming desire to minimize collateral damage and noncombatant fatalities is aimed at insuring moral "high ground."11

There is an inherent tension between many of these constraints and a traditional military outlook toward conflict. From a military perspective, overwhelming force is the best insurance of military success. In a small contingency, such as an antiterrorist retaliation, the United States should be capable of mustering enough force to make destruction of targets a near certainty in nearly any reasonable firepower projection scenarios. However, the political requirements (i.e., minimizing losses and collateral damage in response to domestic and world opinion) weigh against creation of such a large and highly destructive force. Hence, the United States appears to have prosecuted an extremely limited strike against Tripoli, utilizing precision-guided weapons and sophisticated aircraft.

Given these arguments, an operational concept for a punitive attack involves the following:

- *Destroying high-value targets.* LRCM-equipped heavy bombers or naval vessels conduct precision attacks against fixed targets with unitary and/or submunition LRCMs.

Punitive attacks can clearly be carried out by any number of forces. Bombers, naval, and ground-based tactical aircraft have all carried out punitive attacks in the past. Such attacks are generally carefully planned for all of the reasons discussed above, so responsiveness of forces is generally not a primary consideration. The accuracy of LRCMs results in minimization of collateral damage to civilians, but the primary (and perhaps unique)

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advantage that LRCMs bring to such a role is their standoff range and the absolute guarantee that it provides of (1) no losses of aircraft to hostile fire and (2) no potential for prisoners.

Later discussion compares the design constraints, employment, and operational issues for Air Force and Navy LRCMs carrying out the operational concepts underlying these roles. It should be noted that the strategies to tasks framework does not itself specify weapons, platforms, and other components of capability. Rather it invites competition among alternative operational concepts and items of equipment. In particular, each of the tasks described could be addressed in alternate ways. Table 2.2 summarizes the three LRCM roles discussed here and the LRCM strengths they exploit, along with some forces that provide possible alternatives to LRCM. Use of land or carrier-based tactical aircraft for these roles is possible, although their availability for the Rapid Response role is suspect. Alternatively, a stealthy penetrating bomber such as the B-2 could be employed. As can be seen from Table 2.2, penetrating bombers can address each of the LRCM roles discussed here, and this outcome has important implications for near-term LRCM development.

EMPLOYING LRCM FORCES: BOMBERS VERSUS NAVAL FORCES

The different Navy and Air Force LRCM platforms have a critical impact on the employment of LRCM weapons and on the roles that various LRCM-equipped forces can address. The employment differences between Air Force heavy bomber platforms and Navy platforms can be compared on three basic parameters: volume, sustainability, and timeliness. Volume indicates the number of LRCM weapons that can be launched in a single attack. Sustainability describes the ability to continue a series of attacks over time. Timeliness relates to the ability to respond quickly to a desired use of LRCMs. In general, both ship and bomber-deployed LRCMs are capable of timely, high-volume LRCM attacks. However, bomber-carried LRCMs can be sustained over a longer period of time. This

\[12\] It can easily be noted that each of these LRCM roles has been discussed in one form or another by authors other than Homer and Kent, notably and individually by Palim, Burt, and McCaw in Richard K. Betts (ed.), Cruise Missiles: Technology Strategy Politics, Brookings Institution, 1981. The advantage of the discussion above is that the roles are placed into a specific analytic framework and the focus is solely on conventional weapons.
Table 2.2
LRCM Roles And Strengths

<table>
<thead>
<tr>
<th>Roles</th>
<th>Response?</th>
<th>Accuracy?</th>
<th>Standoff?</th>
<th>Other Potential Forces</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapid response</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>B-2 bomber</td>
</tr>
<tr>
<td>Deny or delay forces</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deny aircraft operation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destroy high-value targets</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep attacks</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>B-2 bomber</td>
</tr>
<tr>
<td>Destroy high-value targets</td>
<td></td>
<td></td>
<td></td>
<td>F-117, F-111, F-15E</td>
</tr>
<tr>
<td>Destroy fixed air defenses</td>
<td></td>
<td></td>
<td></td>
<td>A-6, F/A-18</td>
</tr>
<tr>
<td>Punitive attacks</td>
<td>✓</td>
<td>✓</td>
<td></td>
<td>B-2 bomber</td>
</tr>
<tr>
<td>Destroy high-value targets</td>
<td></td>
<td></td>
<td></td>
<td>F-117, F-111, F-15E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>A-6, F/A-18</td>
</tr>
</tbody>
</table>

NOTE: LRCMs are unique in that they eliminate possibility of losses to enemy fire.

difference allows bomber-launched LRCMs to address the range of roles discussed above, while naval forces are capable of addressing a subset of those roles.

Volume

How many LRCMs could Air Force or Navy platforms launch in a given attack? The answer can be important for a number of reasons. First, if one needs to attack a number of targets at one (or even one complicated target complex), a number of missiles might need to be expended rapidly. Second, if faced with significant air defenses, a large attack can help to saturate local or area defenses. This ability to saturate defenses at need without attendant loss of a pilot or multipurpose aircraft is one of the chief advantages accorded to cruise missiles. This concept is discussed at length in App. D.

The number of weapons that a given bomber is capable of carrying will, of course, depend on the size and weight of the missile. The current B-52 ALCM pylon can carry 6 ALCM cruise missiles, for a total of 12 missiles carried externally. If the ALCM pylon were unusable (perhaps for arms control reasons), the conventional Heavy Stores Beam can be adapted for LRCM launch. For short missiles, this beam could carry up to 6 weapons per wing, for a total of 12 missiles. Longer LRCMs, Tomahawk or ALCM length, could fit in quantities of 3 or 4, for a total of 6 to 8 external weapons.

The B-52 bomber is considered a reliable workhorse; in contrast, the B-1B bomber has encountered a number of difficulties since its inception. One of these problems has been a questionable ability to carry cruise missiles externally. The B-1B carries cruise missiles on three rows of dual stations along its fuselage, giving it a nominal capability to carry 12 cruise missiles externally. For this purpose, the B-1 is equipped with the external hardpoints
required for attaching weapon pylons. However, for arms control reasons these hardpoints have been covered in operational aircraft and will not likely be used in the near future. The B-1B is counted as a penetrating bomber under the START protocols currently being negotiated, and if external pylons were attached, the non-ALCM designation would be in jeopardy.\(^\text{13}\)

The nonpolitical problems with B-1B external cruise missile carriage center on the acoustic levels to which the cruise missiles are subjected when carried externally. Noise and vibration, presumably related to the proximity of the engines, can reach higher than cruise missile design tolerances when the B-1B is at low altitudes. These problems are probably not of great concern; a 1988 CBO report characterized the problems as “minor,” and suggested that real concern would probably center on the two aft, outboard weapon stations. Avoidance of these two stations would reduce external LRAC carry from 12 to 10 missiles, two less than the B-52.\(^\text{14}\)

The internal carriage constraints of heavy bombers are less straightforward to calculate than outboard pylon constraints. Cruise missiles are generally carried on rotary launch systems when carried internally aboard bombers. These rotary launchers are cylinders around which the missiles are arrayed; the cylinder rotates, bringing each missile successively to its launch position and releasing it. Rotary launchers provide a greater overall launch reliability (since any one missile launch failure will not affect the launch of the other missiles), but they constrain and complicate the missile carriage capability of the bomber.

The missile carriage capability for a rotary launcher depends not only on the diameter and shape of the missile (affecting the number of missiles that can fit around the cylinder), but also on the combined width of the launcher and missiles in comparison to the bomb bay of the bomber. The B-52 has a single bomb bay, equipped with a rotary launcher capable of holding eight ALCM or TLAM-sized missiles. The B-1 normally has three shorter bomb bays (designed to hold SRAM missiles), but the bulkhead between two of these bays may be moved, allowing the installation of one longer rotary launcher. This launcher is similar to that carried on the B-52 and can also carry eight ALCM or TLAM-sized missiles. A wider missile (or one shaped differently) could cut down internal carriage from eight missiles to six.

\(^{13}\) Penetrating bombers count for fewer weapons under the START treaty than do ALCM carriers. A change in the B-1 designation would have a major effect on the U.S. treaty-compatible nuclear force structure.

or four missiles quite readily. For a B-52, the combination of internal and external carriage would allow for anywhere between 16 to 20 LRCMs; the B-1B could carry between 14 and 18 missiles.

The LRCM carriage capabilities of the B-1 and B-52, therefore, range from 14 to 20 weapons per aircraft. It is clear then that the volume of LRCMs available for any one attack is proportional to the number of bomber aircraft available. The most optimistic assumption is a fully loaded B-52 with 20 missiles, the most pessimistic assumption is a constrained B-1B with 14 missiles. Simple arithmetic yields the volumes associated with a ten-aircraft attack, roughly 140 to 200 LRCMs, with the number rising linearly for larger attacks.

Recent budget negotiations appear to be moving toward a force of roughly 30 dedicated conventional B-52G aircraft, but the precise number of aircraft available for a single attack will depend both on the total number of aircraft in the force and on the sustainability demand, discussed below.

The volume of LRCMs available to the Navy is not easy to calculate, since it depends on several factors, including (1) specific ship classes participating (how many total launch tubes are available) and (2) how many LRCMs are actually loaded into these tubes. In this respect, it is important to remember that under most circumstances the primary missions of ships equipped with missile launch systems is not conventional land attack.¹⁵ Fleet air defense, anti-surface warfare, and anti-submarine warfare are generally the primary roles for most of the Navy's missile launch vessels. Therefore, a substantial number of launch tubes will be filled by surface-to-air, anti-ship, and anti-submarine weapons. In addition, some fraction of the remaining land attack tubes will be filled by nuclear missiles, leaving an uncertain margin of LRCMs.

Table 2.3 shows the number of launch tubes available to various classes of naval vessels. In addition, estimates are made as to the number of launch tubes available for land attack missiles, with a further estimate of how many of these land attack launchers will be dedicated to LRCMs. The assumptions underlying this table are as follows:

- Ships with primary air defense duties use 50 to 70 percent of their tubes for air defense missiles.
- Surface ASW ships allocate 30 to 50 percent of their launch tubes to ASW weapons.
- Submarines allocate 50 to 70 percent of their potential missiles to ASW weapons.

¹⁵ This point is arguable for the refitted battleships. However, these ships are slated for retirement.
The tradeoff between nuclear and conventional land attack is based on the projected inventory fraction of conventional versus nuclear Tomahawk, roughly 66 percent conventional.

These assumptions are reasonable, but clearly not definitive.

Table 2.3
Notional Navy LRCM Allocations

<table>
<thead>
<tr>
<th></th>
<th>Dedicated Launchers</th>
<th>Multi-Purpose Launchers</th>
<th>Total Land Attack</th>
<th>Total LRCM</th>
</tr>
</thead>
<tbody>
<tr>
<td>BB (ABL)</td>
<td>32</td>
<td>--</td>
<td>32</td>
<td>21</td>
</tr>
<tr>
<td>CGN (ABL)</td>
<td>8</td>
<td>--</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>CG (VLS)</td>
<td>--</td>
<td>120</td>
<td>36–60</td>
<td>24–40</td>
</tr>
<tr>
<td>DDG-51 (VLS)</td>
<td>--</td>
<td>96</td>
<td>30–48</td>
<td>20–32</td>
</tr>
<tr>
<td>DD-963 (ABL)</td>
<td>8</td>
<td>--</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>DD-963 (VLS)</td>
<td>--</td>
<td>64</td>
<td>32–45</td>
<td>22–30</td>
</tr>
<tr>
<td>SSN-637 (CLS-T)</td>
<td>--</td>
<td>26</td>
<td>8–13</td>
<td>5–8</td>
</tr>
<tr>
<td>SSN-688 CLS-T(V)</td>
<td>12</td>
<td>25</td>
<td>20–25</td>
<td>12–16</td>
</tr>
</tbody>
</table>

NOTE: Attack submarines carry 28 torpedo-launchable weapons. Battleships and some cruisers and destroyers will continue to be equipped with Tomahawk-dedicated Armored Box Launchers.

Navy ships do not travel alone; they travel in specific formations. It is these specific formations that will determine the number of LRCMs available for any given attack. Note, however, that a reasonable number of these ships together would have more than one hundred available LRCMs. A force containing a battleship, two VLS-equipped Aegis Cruisers, and two VLS-equipped missile destroyers would, according to these estimates, have anywhere from 109 to 165 available LRCMs out of a total of 400 launchers. A carrier battle group, which would not contain a battleship, could have anywhere from 88 to 144 LRCMs available out of 368 launchers. Even presupposing a change in philosophy, it is difficult to conceive of more than 200 to 300 LRCMs being present in a day-to-day situation. These
numbers of ships would generally be considered to be formidable gatherings of naval strength.

The discussion above takes into account normal, day-to-day circumstances, under which the Navy stresses multiple mission capability on each of its platforms. Given an amount of time and sufficient incentive, the Navy can reload the VLS system to provide a greater number of conventional land attack missiles. Such was the case with the Desert Storm operation, where the Navy reportedly loaded an Aegis cruiser completely with land-attack Tomahawks, presumably conventional. At the end of October 1990, or roughly three months after the crisis began, the Navy reportedly had 350 conventional Tomahawks in the theater. Given this demonstrated flexibility, it is conceivable that the Navy could bring even more Tomahawks, perhaps approaching a thousand, to bear at once.

Sustainability

The initial volume of an attack of LRCMs can be the crucial determinant of success. However, some situations require an additional capability to attack and reattack targets over time. For this type of situation, heavy bombers have a distinct advantage over naval vessels, since they can return to base, reload, and reattack with LRCMs. Naval vessels cannot reload LRCMs at sea and are therefore limited to their initial load of missiles.

This difference can be quantified. Figure 2.2 indicates the number of LRCMs that could be delivered over time by the heavy bomber and naval forces discussed above. Note that the scale on the left for bombers is measured in days. The curves plotted are for a total force of 30 bombers, each of which flies every third day, allowing 10 bombers per day to attack. The range of the bomber result is based upon the uncertainty in LRCMs per bomber discussed above. The naval result is based upon the discussion above. The curve corresponding to roughly 350 weapons deliverable over 12 weeks corresponds to reports on available forces for Desert Storm. The curve corresponding to 1000 weapons deliverable over 12 weeks is theoretical, based upon a much greater emphasis on land attack missionary than is currently the case. It is also important to remember that while the curves shown for naval forces are smoothly rising functions, in reality they would be a "stair step" shape, as ships arrived over time.


17 This is a reasonable assumption, in that the longest missions from bases in the continental United States would be on the order of 30 hours total duration. This allows two days for refueling, maintenance, and crew rest.

18 Navy News and Undersea Technology, op. cit.
Note that initially the volume of attacks could be similar for naval and bomber forces. However, the sustained firepower capability of the bomber rapidly outpaces any likely number of naval weapons available. The magnitude of these differences underlines the insensitivity of this comparison to changes in assumptions.

Timeliness

Timeliness of response is the slipperiest of the three employment comparisons. It is a fact that aircraft move more swiftly than ships; a bomber can reach areas in hours that a ship may take a number of days to reach. However, such a simplistic comparison obscures several important factors. First, the U.S. Navy is routinely deployed overseas. Hence, even if there were no warning of a contingency and instant use of LRCMs were required, there is a possibility that naval vessels would be in position to respond. Second, cases of "no warning" are so rare as to be nonexistent; the real cause for concern is "warning, but no response." Therefore, it has long been a standard response to dispatch naval vessels as a relatively nonprovocative response to heightened tensions, increasing the likelihood that naval vessels carrying LRCMs would be in position to respond. Finally, the United States has never made
it a practice to enter lightly into shooting wars. If the United States initiates aggressive action, it comes only after a painstaking and time-consuming review process, further increasing the likelihood of effective naval positioning.

Nonetheless, there is a possibility of naval "malpositioning" for fast-response contingencies. The Navy has recognized this possibility in formulating its range requirements for the next LRCM, which are roughly triple those of the current TLAM-C.\textsuperscript{19} With this extended range, the odds of naval malpositioning are further reduced, and perhaps eliminated. A comparison of timeliness for naval and bomber platforms is, therefore, something of a wash. Any uncertainty in naval timeliness is probably eliminated by a longer-range missile, although the range extension will probably generate higher costs.

PLATFORMS AND FORCES TO ADDRESS LRCM ROLES

The platform comparison above clarifies the discussion of potential LRCM roles. The Rapid Response role calls for several important characteristics for the LRCM force, including timely response, high volume of fire, and sustained attacks over time. The number of LRCMs needed for attacks to support the Rapid Response role can become quite large, based simply upon the reattack requirements against typical military targets which are subject to repair. Appendix E discusses the LRCM force requirements to sustain a series of LRCM attacks over a 20-day period. The number of LRCMs required swiftly rises to several thousand for a fairly modest target set, given reasonable reattack assumptions against airfields and bridges, key tasks in the Rapid Response role. Both bomber and naval forces are capable of timely response and initial volume of attacks, but the sustainability characteristics of bomber employment are required to sustain the ongoing Rapid Response attacks over time. A force of LRCM-equipped bombers is the only LRCM force that can fill the Rapid Response role.\textsuperscript{20}

In contrast, the Deep Attack role makes lesser demands on a LRCM force. If early reports are to be believed, the several hundred naval Tomahawk cruise missiles fired in

\textsuperscript{19} "Navy's ASLCM Could Broaden Cruise Missile Industrial Base," \textit{Aerospace Daily}, April 6, 1988. This issue is discussed further in the following chapter.

\textsuperscript{20} The ability to sustain high-volume attacks is desirable for reasons other than simple attack requirements. First, such an ability could be necessary as a response to increasing threats and countermeasures. The ability to saturate or overwhelm defenses with concentrated attacks and increased attack sizes could be critical, given the increasingly sophisticated character of air defenses around the world. This type of response works toward some of the inherent positive characteristics of LRCMs. Perhaps as important, the U.S. ability to sustain air attacks over time in the recent Desert Storm operation appears to have had a major impact on the course of the war.
Operation Desert Storm were used largely in the Deep Attack role described above. In comparison to the Rapid Response role, the number of weapons required for the Deep Attack role is likely to be lower. First, the number of high-value fixed sites is likely to be limited in most contingencies, as will the number of fixed radar installations. More important, most of these targets by their nature do not require the sort of reattacks needed for bridges and airfields. As can be seen in App. E, the number of LRCMs needed for Deep Attack is unlikely to rise above a thousand if the LRCMs are individually fairly effective. Finally, some period of time is likely to exist during which the necessary number of weapons could be amassed and other forces brought to bear. Given the number of weapons and the amount of time that is likely to exist, it is conceivable that either bomber or naval vessels could be used for employment in the Rapid Response role.

Finally, the quantity of LRCMs required to address the Punitive Attack role is some quite small number, perhaps in the tens or low hundreds. The number of targets for any one attack is limited, and reattack requirements are almost nonexistent. Either a LRCM-equipped bomber force or a LRCM-equipped naval force could address this role. However, a LRCM force procured for this role would constitute a small, specialized weapon buy, not a serious development and procurement effort. Table 2.4 summarizes the LRCM roles and forces discussion.

A force of several thousand LRCM weapons could, if deployed on heavy bomber platforms, be capable of performing each of the three roles discussed above. If deployed on naval platforms, such a LRCM force could perform either of the latter two roles discussed here. The rest of this document will therefore focus on potential benefits and risks of acquiring a force of several thousand LRCMs in the near term. This focus highlights important factors other than the platform tradeoffs discussed here. First, the volume and rate of attacks required for the Rapid Response role stress the operability of LRCM forces in terms of the information and planning required to support LRCM missions; later sections discuss this potential roadblock to successful operation of LRCMs in this role. Second, the need to acquire large numbers of LRCMs creates a focus on lowering the cost and complexity of LRCM weapon designs, abandoning the "silver bullet" approach to these weapons and trading off some individual performance for lowered costs.

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22 Note that even if only a thousand weapons are required for the Deep Attack role, the Navy will need to procure several times this number to address the availability of its forces in any one region of the world.
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<td>Punitive Attacks</td>
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<td>LRCM-equipped bomber, LRCM-equipped naval, B-2 bomber, F-117, F-111, F-15E, A-6, F/A-18</td>
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<td>Destroy high-value targets</td>
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**NOTE:** LRCMs are unique in that they eliminate the possibility of losses to enemy fire.
III. THE FUTURE OF TOMAHAWK

Section II focused on developing roles for a force of several thousand LRCM weapons. However, a force of several thousand Tomahawk conventional missiles is already projected for the Navy. This brings into focus several important questions:

- What is the future of this force, and is a new LRCM in fact needed for the Navy?
- In addition, could the Air Force utilize the Tomahawk as the LRCM for heavy bombers?

This section approaches these questions in two stages. First, the analytic framework described in App. A is utilized in subsequent appendixes to demonstrate some clear limitations to the effectiveness of the current Tomahawk. Second, an evaluation is made of the inherent differences between bomber and naval platforms and their effects on LRCM designs. Based upon this analysis, a LRCM designed for heavy bomber platforms is likely to differ markedly from the current Tomahawk. In contrast, an entirely new naval LRCM is probably not needed; instead, the enhancements to the current Tomahawk required by the Navy can probably be achieved with a block upgrade of the Tomahawk force.

THE TOMAHAWK LAND ATTACK MISSILE: TLAM-C/D

In terms of current and deployed technologies, the United States has only one land-attack system in its inventory that can be classified as an LRCM, the Tomahawk Land Attack Missile (TLAM). A large number of the unitary warhead TLAM version (TLAM-C) have been procured, and procurement is in the initial stages for the variant of Tomahawk that is equipped with a submunitions dispenser (TLAM-D). Both TLAM-C and TLAM-D are sea-launched cruise missiles, deployed on surface naval and submarine platforms.

The Tomahawk-class cruise missiles are an impressive mix of technologies. The airframes for all Tomahawks are circular and are built largely out of cored aluminum sections. The primary lift surfaces are two fixed-aspect, center-mounted wings, and control is accomplished by movable tail fins. Before and immediately after launch, the wings are folded

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1A note to the reader: This and subsequent sections rely heavily on analysis and discussion of LRCM technologies and effectiveness found in the technical appendixes accompanying this Note.

1The sources for physical descriptions of the Tomahawk missile are “Sea Launched Cruise Missile,” DMS Market Intelligence Report®, DMS Inc., 1987, and “Sea Launched Cruise Missile,” Briefing Presentation, General Dynamics Corporation, Convair Division.
into the center of the missile and the tail fins are folded flat against the missile; after launch, both the wings and the tail surfaces spring into position. In order to minimize potential center-of-gravity changes as fuel is depleted, the Tomahawk has a fairly sophisticated fuel-management system. In terms of airframe observability, selective application of radar absorbing material (RAM) is purported for TLAM in order to lower its radar cross section.2

TLAM-C and TLAM-D are powered by a Williams turbofan engine, the F107-WR-400, which combines the characteristics of low weight (roughly 140 pounds), compactness, fuel efficiency, and reasonable thrust (600 pounds). The turbofan engine uses an inlet on the underside of the airframe. Like the wings and tail surfaces, the inlet lies flush until after launch. In addition to the turbofan, TLAM is provided with a solid rocket booster, which boosts the missile up to speed, whereupon the turbofan engine takes over propulsion. The solid rocket booster is not a simple piece of equipment. It is designed to provide variable thrust levels at different distances from the launch platform. In addition, the booster includes thrust vector controls in order to change the pitch of the missile for different launch conditions.

The conventional TLAM variants both carry roughly 1000-pound payloads. The TLAM-C carries a unitary conventional warhead, the Bullpup. The Bullpup is an older warhead that was drawn out of inventory to put into TLAM. The TLAM-D carries a dispenser that dispenses clusters of Combined Effects Bomblet (CEB) submunitions. The dispenser system is a fairly complicated piece of equipment. It ejects submunitions, in up to three separate bursts, with an explosive gas ejection system. In addition, it maintains the TLAM's short-term flight capability by filling in ejected side panels with a fabric surface, enabling the TLAM-D to attack different targets with each burst of submunitions.3

Cruise missiles fly at subsonic speeds, a fact that results in some useful and some less than useful characteristics. One less than useful characteristic is that the Tomahawk's inertial guidance system has more time to generate position errors than would a faster-flying missile. Therefore, navigation to the target area for Tomahawk is provided by an inertial navigational unit (INU) aided with periodic positional updates utilizing the Terrain Contour Matching (TERCOM) system. TERCOM is a system that uses a radar altimeter to measure terrain features along its flight path and correlates these measurements with internally

3 "Sea Launched Cruise Missile," Briefing Presentation, General Dynamics Corporation, Convair Division.
stored digital maps. The system is in current use on both the TLAM and ALCM cruise missiles.

Given continuous terrain data and time to correlate it, TERCOM systems could resolve the missile position to within tens of meters. However, the system is not employed in this mode for two reasons: first, the amount of terrain data and computation required is beyond the TLAM or ALCM data-handling capabilities; second, not all terrain is useful for TERCOM. In particular, ocean scenes or scenes of flat or gently rolling ground can be difficult or impossible to match. Because of these limitations, current TERCOM navigation systems use preselected patches of terrain in which they perform the correlations and correct the missile heading. The missile is programmed to fly from patch to patch, utilizing the INU system for the navigation between scene-matchings. Using this procedure, TERCOM/INU systems can resolve the missile’s position to within tens of meters, with uncertainty as to position rising with the amount of time since the last update. The planning requirements for TERCOM are significant. Digital databases of terrain must be gathered using Defense Mapping Agency assets and analysis. These data must be prepared and loaded into the correct missiles at the correct time, along with planned flight routes incorporating them.

The conventional TLAM variants are equipped with terminal-area guidance, provided by a Digital Scene Matching Area Correlation (DSMAC) system. DSMAC updates the position of the missile by matching a stored visible-light image to a series of visible-light images sensed in flight. The DSMAC scenes are prepared from photographs of the area near the target. The greater resolution of the visual image allows for more accurate updates than those available from the coarser TERCOM, and the proximity of the scenes to the target does not allow navigator errors to rise to inordinate levels. Along with warhead type, the terminal-area DSMAC system is the main technical feature that distinguishes the conventional and nuclear TLAM variants.

The planning required for a DSMAC system is substantial. Overhead photographs of the target area are required, a complex process that involves security classification guidelines and may require digitizing of analog photographs, a time-consuming procedure. DSMAC also has some serious limitations, including diminished capability at night and little or no capability in bad weather. As with TERCOM, certain types of scenes are difficult to

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4 TERCOM-suitable terrain must have sufficient variation (roughness) to register on the altimeter. In addition, it must have the quality of “uniqueness”; that is, a missile flying over an area with a given initial error must be able to find a unique best-position correlation. It is the uniqueness requirement that makes TERCOM-suitable terrain relatively scarce. See Charles A. Baird and Mark R. Abramson, “A Comparison of Several Digital Map-Aided Navigation Techniques,” The Harris Corporation, IEEE Publication CH2110-5/84/0000-0280, IEEE, 1984.
match, and a scene might differ drastically between summer and winter, further complicating the planning process.

**Block III Tomahawk**

The Tomahawk system has been the subject of a consistent and planned block upgrade program. The next upgrade is Block III, which will feature some substantial changes in the missile. First, the Williams F107-WR-400 engine will be replaced by an upgraded Williams turbofan, the F107-WR-402. The F107-WR-402 will have higher thrust and a slightly lower specific fuel consumption than the F107-WR-400.

Both enroute navigation and terminal guidance will be upgraded. The current INU/TERCOM navigation system will be supplemented by the addition of a Global Positioning System (GPS) receiver. GPS is a system of satellites that broadcast a continuous positioning signal. Using the signals from several of these satellites, a vehicle can resolve its position to within roughly 15 meters. A GPS receiver is relatively inexpensive and is used only as a supplement, because of concern over potential jamming of the GPS signal. The current DSMAC terminal guidance system will be upgraded to DSMAC II. DSMAC II involves both a wider field-of-view optical sensor and a software upgrade that allows a wider range of terminal scenes to be utilized. The payload of the TLAM-C will be upgraded with a smaller reactive-casing warhead. The reactive warhead makes use of the fact that the casing material vaporizes and explodes, creating a bomb with more blast for any given weight. The new, smaller warhead will have similar blast to the current TLAM warhead, and its smaller size allows more fuel to be loaded on the missile. Even the booster will be upgraded, to allow submarine launches with full fuel payloads. Three versions of Tomahawk, nuclear, conventional, and Block III conventional are shown in Fig. 3.1.5

**Tomahawk Limitations**

**Lethality and Availability.** The discussion and analysis in Apps. A through E indicate some clear design shortfalls of current Tomahawk missiles. These stem from limitations of the current Tomahawk DSMAC guidance in two performance areas, accuracy and weather robustness. These two limitations have a fairly straightforward effect on LRCM lethality and availability. In particular, the current DSMAC sensor provides low lethality against small or hardened targets such as those shown in Fig. 3.2 (reproduced from App. D). These targets make up a significant portion of the political, military, and economic target

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Fig. 3.1—Schematic views of Tomahawk

Fig. 3.2—Projected lethality of Tomahawk
sets discussed in Sec. II. In addition, the capability of the DSMAC system is significantly degraded in rain or fog, owing to its visible-light sensor, and this affects Tomahawk's availability.

The solution to these lethality limitations is likely to be found in one of the target-looking sensors discussed in App. B. In addition, each of the sensor technologies discussed has a significantly better poor-weather capability than DSMAC, and each has much higher accuracy as well.

Range. A second major limitation of the TLAM from the point of view of the Navy is its range. There are several other reasons that the Navy desires a very long-range LRCM. First, the possibility of "malpositioning" discussed above drives the Navy to long-ranged LRCMs in order to ensure timely response. A naval vessel at top speed can travel at roughly 30 knots, or roughly 700 nautical miles per day, which means that a LRCM with 2000-mile range translates to two additional days of early response time over that of the current TLAM-C. As important, the major threat to U.S. naval forces is not other surface ships, but long-range bombers. This has been especially true in Soviet scenarios, where massed naval Backfire bombers are the major concern of naval commanders. The current TLAM-C missile, with a range of roughly 700 miles, places the naval forces well within the bomber's range envelope before TLAM attacks could begin.

A 2000-mile LRCM would vastly complicate such a bomber attack, both because it makes the naval force far more difficult to localize and because the Soviets would have to air-refuel the large force of bombers required for the anti-ship attack to be carried out. Although the importance of the Soviet war scenario has happily diminished of late, the magnitude of the potential threat from similar forces provides added incentive for increased naval LRCM range. The combination of these factors has caused the Navy to require a very long-ranged LRCM, with 2000 miles a candidate goal.6

In contrast, a heavy bomber is faced with a different set of constraints. For an air-launched LRCM, the possible LRCM launchpoints depend on international overflight rights and air defenses. The attack planner is free to use the set of launchpoints that do not violate neutral sovereignty and avoid attribution of launch aircraft by enemy air defenses, in contrast to sea-based LRCM launchpoints, which are limited to ocean areas. It seems intuitively obvious that the air-launched LRCM will have more flexibility, and hence a generally lower

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range requirement. This point is strengthened by the fact that all ocean areas are not routine operating areas for naval forces; the Persian Gulf is a prime example.

As discussed above, the bomber may launch from points denied to naval craft, but just as important, the threats faced by the bomber are of a different nature than those faced by naval forces. A bomber using standoff weapons will in general face fighter aircraft as its major threat; therefore, the points from which a bomber could safely launch are located beyond the point where the opponent's air defense can both detect the bombers and send fighter aircraft to intercept them. Fighter aircraft can be ground-launched or, more difficult to deal with, maintained on extended cover air patrol or CAP; in general, however, they will be located within their country's airspace or close to it. The Air Force has stated publicly its belief that 600 nautical miles is sufficient to meet its needs.  

The primary effect of these range arguments on LRCM designs is in the propulsion systems. Figure 3.3 is reproduced from App. D, and it shows the range/payload tradeoffs for several candidate propulsion systems. As can be readily seen, for weapons of the same general weight as TLAM, the Navy is driven to more advanced propulsion than the current Tomahawk turbofan. Although the turbofan is sufficient to meet the Air Force's stated range needs, the Air Force has some options that could result in use of the cheaper turbojet, which are discussed below.

Given these specific limitations in the capabilities of the Tomahawk, there is a clear impetus to make some changes. First, the discussion above points out the necessity for a new sensor and terminal guidance system for the next LRCM. Of the target-looking sensors discussed in the appendices, the passive IIR system is the least expensive and most technically mature system, since it is identical in most respects to sensors currently operational on U.S. weapons. Therefore, this analysis focuses on passive IIR as the primary sensor choice for any new LRCM. Note, however, that several alternate sensor systems exist that could be substituted for passive IIR sensor at some additional cost and technical risk. Each of these sensor systems will work in the simplest sense: if given a target scene and a

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8 It is important to note, however, that many of TLAM's performance areas are perfectly adequate. The Tomahawk airframe does not need to be radically redesigned for the roles envisioned for the next LRCM. The inherent observability characteristics of Tomahawk's airframe shape and size, coupled with standard low observability techniques, probably ensure sufficiently low observability for the scenarios discussed in Sec. II and detailed in App. C. The navigation systems discussed in App. A are either being incorporated into the Block III Tomahawk or constitute algorithmic variations on current navigation schemes. Likewise, the payload of the next LRCM is unlikely to change radically, especially if coupled with more accurate guidance.
point within that scene, they will guide the LRCM to that point. Second, new propulsion technologies may be desirable for both the sea-launched and the air-launched LRCM. Whether or not these changes are simple modifications or upgrades to the Tomahawk or constitute a new weapon development program depends critically on issues surrounding potential LRCM platforms.

**DESIGNING THE NEXT LRCM: BOMBERS VERSUS NAVAL PLATFORMS**

The Air Force LRCM platform of choice is a large heavy bomber such as the B-52 or B-1 aircraft. Navy LRCM platforms would most likely be the current TLAM platforms: surface ships and (possibly) submarines. In addition to their different range performance demands, discussed above, these different platforms will affect the design of the next LRCM through the inherent constraints they place on LRCM designs. The LRCM design components affected include vehicle size and shape, propulsion systems, and launch equipment requirements.
Platform Design Constraints

The constraints imposed on LRCMs by Navy and Air Force platforms primarily relate to the size of the missile. In addition, the different launch and transport environments associated with the different platforms provide additional constraints.

Size. The size constraints upon a heavy-bomber-launched weapon are related to both the physical capability of the aircraft to carry the weapons and the need to carry an operationally effective number of missiles. In practical terms, at least for the B-52 bomber, there is no real upper limit on either the size or the weight of a single weapon, as witnessed by the recent launch of the Pegasus space-launch vehicle from a B-52. The Pegasus vehicle weighed roughly 44,000 pounds, over ten times the weight of any reasonable LRCM design.

The true weapon size constraints, therefore, are derived from the requirement to carry a useful load of weapons to the launch area; these weapons can be carried externally on pylons or internally on launchers. In terms of external launch, constraints on missile dimensions are not very binding. In practice, the B-52 has been readily adapted to a number of wing pylon configurations, including Harpoon, Skybolt, Hornet Dog, SRAM, and ALCM carriage configurations. It would not be out of the ordinary to design yet another new pylon for a LRCM. If such a pylon were not developed, there are at least two options: the ALCM pylon and the Heavy Stores Beam.

The current ALCM pylon, which can accommodate six ALCMs, has room for a substantially wider missile, based on its ability to carry the Advanced Cruise Missile (ACM). For missiles up to 29 or 30 inches in diameter and up to 250 inches in length, the ALCM pylon should be able to carry six missiles per wing, for a total of twelve external LRCMs. If the ALCM pylon were unusable (perhaps for arms control reasons), the conventional Heavy Stores Beam can be adapted for LRCM launch. For short missiles, this beam could carry up to six weapons per wing, for a total of twelve missiles. Longer LRCMs, Tomahawk or ALCM length, could fit in quantities of three or four, for a total of six to eight external weapons. A new pylon or the Heavy Stores Beam option are perhaps the most likely solutions, since past arms control agreements have focused on externally and functionally related observable differences (EODs and FRODs) to distinguish bomber types. Use of the current (nuclear) ALCM pylon for conventional bombers could be difficult to negotiate, given this precedent.

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9 The ACM appears to be a substantially larger missile than ALCM. Compare the photographs of ACM in "Radical Design of Stealth ACM," Jane's Defence Weekly, March 10, 1989, with similar photos of ALCM available from a variety of sources. Clearly, the ACM is a wider missile than ALCM, based on the ACM’s close-packed configuration on the ALCM pylon compared to ALCM.
The B-52 bomber is considered a reliable workhorse; in contrast, the B-1B bomber has encountered a number of difficulties since its inception. One of these problems has been a questionable ability to carry cruise missiles externally. The B-1B carries cruise missiles on three rows of dual stations along its fuselage, giving it a nominal capability to carry twelve cruise missiles externally. For this purpose, the B-1 is equipped with the external hardpoints required for attaching weapon pylons. However, for arms control reasons these hardpoints have been covered in operational aircraft and will not likely be used in the near future. The B-1B is counted as a penetrating bomber under the START protocols currently being negotiated, and if external pylons were attached the non-ALCM designation would be in jeopardy.\(^\text{10}\)

The nonpolitical problems with B-1B external cruise missile carriage center on the acoustic levels to which the cruise missiles are subjected when carried externally. Noise and vibration, presumably related to the proximity of the engines, can reach higher than cruise missile design tolerances when the B-1B is at low altitudes. These problems are probably not of great concern; a 1988 CBO report characterized the problems as “minor,” and suggested that real concern would probably center on the two aft, outboard weapon stations. Avoidance of these two stations would reduce external LRCM carriage from twelve to ten missiles, two less than the B-52. The B-1 has also carried ACM externally, meaning that missiles of 29- to 30-inch diameter and up to 250-inch length are acceptable.\(^\text{11}\)

The internal carriage constraints of heavy bombers are less straightforward to calculate than outboard pylon constraints. Cruise missiles are generally carried on rotary launch systems when carried internally aboard bombers. These rotary launchers are cylinders around which the missiles are arrayed; the cylinder rotates, bringing each missile successively to its launch position and releasing it. Rotary launchers provide a greater overall launch reliability (since any one missile launch failure will not affect the launch of the other missiles), but they constrain and complicate the missile carriage capability of the bomber.

The missile carriage capability for a rotary launcher depends not only on the diameter and shape of the missile (affecting the number of missiles that can fit around the cylinder), but also on the combined width of the launcher and missiles in comparison to the bomb bay of

\(^\text{10}\) Penetrating bombers count for fewer weapons under the START treaty than do ALCM carriers. A change in the B-1 designation would have a major effect on U.S. treaty-compatible nuclear force structure.

the bomber. The B-52 has a single bomb bay, equipped with a rotary launcher capable of holding eight ALCM or TLAM-sized missiles. The B-1 normally has three shorter bomb bays (designed to hold SRAM missiles), but the bulkhead between two of these bays may be moved, allowing the installation of one longer rotary launcher. This launcher is similar to that carried on the B-52 and can also carry eight ALCM or TLAM-sized missiles. A wider missile (or one shaped differently) could cut down internal carriage from eight missiles to six or four missiles quite readily. For a B-52, the combination of internal and external carriage would allow for anywhere between 16 to 20 LRCMs; the B-1E could carry between 14 and 18 missiles. These LRCMs could be as long as the ALCM, roughly 250 inches, and somewhat wider than the ALCM, 29 or 30 inches. Figure 3.4 illustrates the three bomber LRCM carriage methods.

![Internal carriage: rotary launcher](image1) ![External carriage: wing pylons](image2) ![External carriage: fuselage pylons](image3)

Fig. 3.4—Air Force LRCM launch options

The Navy's launch options, both surface ship and submarine-based, are more constrained in terms of dimensions than the heavy bombers discussed above. The Tomahawk (BGM-109) class of missiles was designed for the most demanding Navy launch system, the submarine torpedo tube. The submarine torpedo launch system for Tomahawk is designated the Torpedo Capsule Launch System (CLS-T). However, the Navy is in the midst of equipping nearly all of its missile-capable surface ships with the Mk-41 Vertical Launch System (VLS). In addition, the newer Los Angeles-class attack submarines and all of the new Sea Wolf-class attack submarines will be equipped with the vertical submarine Capsule Launch System (CLS-V).\[12\] See Fig. 3.5 for a schematic representation of these three systems.

Both of the new vertical launch systems are designed as common carriers of several missile types. The shipborne VLS system consists of an array of modular launcher frames, each of which is a two-by-four array of launchers. VLS replaced the previous Armored Box Launcher (ABL) system and significantly increased ship missile-carrying capacities; it can carry a wide variety of missiles in customized cannisters, including Tomahawk, Harpoon, and Standard missiles. The VLS system serves as a stabilizing structure for the cannisters (which serve as the actual missile launch tubes), a mechanism to vent booster exhaust gases, and a maintenance and control platform.

For the Tomahawk missile, the VLS installation starts with three factory-assembled pieces: (1) the missile, (2) the missile capsule, and (3) the VLS cannister. All Tomahawk missiles are placed into a capsule, a close-fitting, sealed tube of aluminum roughly a quarter of an inch thick, which brings total missile diameter to 21 inches. The missile-capsule combination is then placed inside a square VLS cannister, which fits the square internal dimensions of the VLS tube. The cannisterized Tomahawk (often designated the "all-up round") is then shipped to the shipyard, where it and other missiles are placed into an eight-launcher VLS module; this module is then loaded by dock crane onto a ship. See Fig. 3.6 for a schematic depiction of the Tomahawk VLS system.

Each launch tube in a VLS module takes up 25 inches by 25 inches in total area, but the internal dimension of a VLS tube is only 22 inches by 22 inches square. The spacing area between the tubes is taken up by bracing and electrical and fluid connections. The bracing requirements are quite severe, since the structure must absorb launch energies from large missiles. In terms of missile diameter constraints, it should be noted that the capsule and cannister act as the launch tube for the missile; hence, the missile diameter is limited to
somewhat less than 22 inches along at least one axis. The overall depth of the VLS system is 265 inches, but some space is required at the bottom for exhaust and other systems, giving a maximum length of the missile plus the booster of roughly 250 inches. In addition, an overall

![Diagram](image)

**Fig. 3.6—Tomahawk VLS configuration**

weight limit for the missile, booster, capsule, and cannister of 4100 pounds is in effect, based both on static weight and dynamic thrust concerns.

A new Navy LRCM could presumably have a custom VLS module, with larger dimensions. This has several negative consequences from a total force perspective. First, it limits the number of LRCMs per ship, perhaps by as much as a factor of two; this number is already quite small, as is discussed below. Second and more important, it destroys the commonality that is one of the chief positive features of VLS. This option is an unlikely one.

The submarine CLS system has two variants, torpedo tube and vertical launch. The torpedo tube version (CLS-T) was the first system developed, since it was a straightforward extension of the standard submarine torpedo launching system. Unlike the shipborne VLS
system, the CLS-T uses only the standard Tomahawk capsule discussed above, with no launcher cannister.\textsuperscript{13} The Tomahawk-capsule combination is 21 inches in diameter, the standard size of every submarine-launched torpedo in the Navy's inventory. Tomahawks are loaded in the same weapon bay as torpedoes and are launched from the submarine in a manner similar to torpedoes. The missile capsule is designed to be watertight during storage aboard the submarine, but is not designed to withstand ocean depth pressures. At launch, the torpedo tube is flooded, and both the missile and the capsule are ejected. At a specified distance from the submarine, the missile booster ignites and boosts the missile out of its capsule. CLS-T can be used by all current attack submarines.

The CLS-T system has hard limits on missile dimensions. The torpedo tubes are round and 21 inches in diameter. Overall missile length is limited by the depth of the loading space behind the torpedo tubes. A practical limit is roughly 250 inches in length for the combination of missile and booster.

The vertical CLS system (CLS-V) has been installed on newer attack submarines. CLS-V is designed as an alternative missile launch system for attack submarines (alternative to torpedo tube launch) and consists of a vertical array of 12 launchers located outside the pressure hull. The separate launch tubes permit the submarine to launch cruise missiles while freeing its torpedo tubes for other uses. The CLS-V tubes carry the same encapsulated versions of Tomahawk and Harpoon missiles as are currently launched from torpedo tubes, and are essentially vertically emplaced torpedo tubes. Hence, the dimension constraints are roughly the same as torpedo launch. The missile and cannister cannot exceed 21 inches in diameter. Missile lengths longer than 250 inches may be allowable, but precise numbers are not available at this time.

Table 3.1 summarizes the constraints that potential Air Force and Navy platforms place on LRCM dimensions. In general, overall length limits are similar, with roughly 250 inches being the maximum allowed length in all launchers. However, Navy missiles require a rocket booster for launch, which imposes a 24-inch penalty on the maximum length of Navy LRCMs of Tomahawk size or larger. Maximum width is heavily constrained in all Navy launch systems. The shipborne VLS system has the potential to accommodate missiles of nearly 22 inches in diameter (with potential noncircular designs), but both submarine CLS systems are limited to 21 inches in circular diameter. In contrast, both Air Force platforms can accommodate up to 29-inch weapons. The third column shows the relative amount of volume available within the dimension constraints. Relative volume is a good rough

\textsuperscript{13} Both CLS systems are also capable of launching encapsulated Harpoon missiles.
Table 3.1
Comparison of LRCM Dimension Constraints

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<th>Launch Platform</th>
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<td>B-52</td>
<td>29&quot;</td>
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<tr>
<td>B-1B</td>
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</tr>
<tr>
<td>CLS-T</td>
<td>21&quot;</td>
<td>226&quot;</td>
<td>1.0</td>
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<tr>
<td>CLS-V</td>
<td>21&quot;</td>
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<td>1.0</td>
</tr>
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indicator of potential missile range for a given class of missiles, since it relates to fuel capacity for given payload and propulsion.\(^{14}\)

**Launch Conditions.** The discussion above makes the clear point that platform differences between the Navy and the Air Force result in very different constraints on missile dimensions. These platforms also create design constraints that are related to the conditions under which the LRPM will be transported and launched.

By far the most stringent transport and launch environment for a LRPM is submarine launch. Submarine-launched missiles have several difficult tasks they must face. First, they must be capable of withstanding severe lateral shocks brought about by depth charges (including potential nuclear depth charges). Second, they must be watertight and capable of withstanding rapid changes in pressure brought about by their transition from underwater launch to airborne flight. A final task is related to the rocket booster, which must boost the missile to flight speeds from underwater, and must be capable of orienting the missile to breach the surface.

This combination of tasks is directly related to the overall Tomahawk design. The Tomahawk airframe is constructed of several sections of aluminum, each of which is created from a cored aluminum block. This is essentially the same process used to create the space shuttle solid rocket boosters, and it gives the Tomahawk airframe considerable lateral strength and pressure resistance. The demands on the rocket booster are such that the

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\(^{14}\) The relationship is not perfect, since additional missile diameter will both increase drag and require a somewhat larger propulsion unit. These effects are not large relative to the magnitudes shown.
current Tomahawk is forced to offload fuel in order to lower its launch weight. This lower fuel amount accounts for the Tomahawk's lower range when launched from submarines.

Surface ships are far less stringent environments than submarines. First, the lateral shock requirements are considerably lessened from submarine launch. Second, the pressure differentials are minor, and third, the booster operates in the atmosphere throughout. The only significant demand on the missile (other than those faced by any missile in flight) is the initial boost period. During this period, the missile is subjected to its highest acceleration and vibration levels. Just how much design margin exists for the ship-launched Tomahawk is unclear, although the missile is fully fueled at launch.

Air launch has an entirely different set of launch condition constraints from either submarine or surface launch. Since there is no requirement for a booster, the launch conditions are relatively mild for air launch, and in general the dynamic shock environment is mild. However, long-range bombers cruise for long periods at altitudes above 30,000 feet, where air temperatures easily reach below minus fifty degrees Fahrenheit. In general, this requirement affects the propulsion and guidance components more than the missile airframe.

The launch condition differences between Navy and Air Force platforms could lead to quite different LRCM designs. In general, the Navy LRCM is forced to emphasize strength and rigidity in airframe designs to a greater extent than the Air Force. As a consequence, the Air Force may have more flexibility to explore different materials and production processes than would the Navy. These differences might be largely negated should the Navy choose to limit a future LRCM to surface ship launch alone. The Air Force has the additional requirement to withstand high-altitude temperature regimes.

The Next Naval LRCM: Tomahawk Block IV?

The design of the next naval LRCM will be confronted with design constraints that are roughly identical to those facing Tomahawk development. Naval launcher size constraints will remain constant, since their design is predicated on interoperability of several different missile systems from the same VLS and CLS launchers. A design change to VLS or CLS will either decrease interoperability or force changes to several different missile systems, an unlikely eventuality. The launch condition requirements of the next naval LRCM are also unlikely to differ significantly from the current Tomahawk, unless the Navy decides to drop the requirement for submarine launch, of which there has been no indication.

Given these design constraints, the airframe of the next naval LRCM cannot help but resemble that of Tomahawk in terms of roughly circular construction, maximum diameter, maximum length, maximum weight, and design strength.
The Tomahawk Block III upgrade already includes a GPS receiver for increased navigational accuracy. In addition, the radar altimeter and processor required for TERCOM or similar terrain reference systems is also included. In addition, TLAM Block III includes a munition upgrade to a smaller, high-blast reactive warhead.

This leaves only two major technology changes that could differentiate the next naval LRCM from Tomahawk, the terminal guidance system and the propulsion system. As discussed above, any new LRCM will have a target-looking sensor, and any near-term LRCM design is likely to use a passive IIR sensor as its terminal guidance system. In terms of propulsion, the Navy may be forced to move to different propulsion technologies to achieve its range goals within its design constraints. Figure 3.7 shows the propulsion choices confronting the next naval LRCM design and is based upon the methodology discussed in App. C. The baseline curve is an approximation of the current Tomahawk: roughly 2770 pounds, 42 percent structure fraction, and a current design turbofan engine. The other curves show, respectively, an advanced turbofan with a 10 percent lower specific fuel consumption and an advanced propfan engine with a 30 percent lower specific fuel consumption.

![Fig. 3.7—Naval LRCM propulsion tradeoffs](image-url)
In order to reach the 2000-mile range goal within current naval design constraints, it is clear that both an advanced propulsion system and the smaller reactive munition are required. The advanced propfan engine design is required if all demands and constraints are kept constant. An advanced turbofan design would require missile airframe weight decreases that are in all likelihood unachievable in order to reach the 2000-mile goal. The propfan engine design, a variant on current turbofan designs, is currently a developmental technology.

Figure 3.8 shows a schematic of the differences between the current Tomahawk, Tomahawk Block III, and the notional naval LRCM design. Although there are significant differences in the guidance and propulsion systems, there is a great deal of similarity between the missile designs, owing to the similarity in airframe, payload, and navigation. Moreover, the level of change from Tomahawk Block III to a new naval LRCM (i.e., a guidance system change and a propulsion change) is very similar to what will occur in the Tomahawk Block III upgrade. Therefore, instead of the “next naval LRCM,” a future naval LRCM could very well be considered as an upgrade to the basic Tomahawk design.

![Fig. 3.8—Comparison of Naval LRCM designs](image-url)
An Air Force LRCM Design

In contrast to the naval LRCM design, which faces the same constraints that drove Tomahawk design, the Air Force LRCM is relatively free to adjust several important design parameters. First, the airframe for an Air Force LRCM is far less dimensionally constrained than a naval LRCM. Second, the launch conditions for an Air Force LRCM are less structurally demanding than for a naval LRCM, and finally, the range requirements for an Air Force LRCM are less than those of the naval LRCM.

Figure 3.9 shows the range-payload tradeoffs facing an Air Force LRCM design. The upper curve is once again the Tomahawk curve for a missile with a turbofan engine, 42 percent structure fraction, and a total missile weight of 2770 pounds. The lowest curve shows the range payload capability if a cheaper turbojet engine is used instead of a turbofan, with all other variables held constant. Note that a missile with this range-payload tradeoff could probably reach the Air Force’s stated 600 nautical mile range requirement with a full 1000-pound payload. However, if 600 miles in fact proves insufficient, range can readily be traded off against increased missile weight and volume. This is demonstrated by the middle curve, which shows a LRCM 20 percent heavier than TLAM; this amount is well within the heavy bomber constraints discussed earlier. This tradeoff could also be used to increase payload for a given range, if necessary.

The weight and size design freedom for an Air Force LRCM would also eliminate some of the weight and shaping concerns that low-observables technologies create. As discussed in App. B and C, low-observables design considerations include radar absorbing materials, airframe shaping, and inlet and exhaust issues. In most instances, these design considerations will increase the size and weight of the vehicle. An LRCM designed for bomber platforms at the ranges discussed should not be significantly constrained by these considerations.

Figure 3.10 shows a schematic of a notional Air Force LRCM as compared to the Tomahawk and the notional naval LRCM. Although there are points of similarity, namely in the navigation and sensor areas, the airframe, propulsion, and munitions section differ substantially. The Air Force—particular design shown is roughly 3250 pounds, which is distributed in an airframe that is somewhat shorter and wider than the Tomahawk. The shape of the airframe (flat bottom and chine) and positioning of the wings (swept) suggests some of the low-observability characteristics of the ACM. A 1000-pound payload could be carried roughly 1000 miles in such a vehicle. The differences in platform, airframe, propulsion, sensor, and payload from the Block III Tomahawk would seem to justify a new missile design program to develop a design that integrates these changes.
Fig. 3.9—Air Force LRCM propulsion tradeoffs

Fig. 3.10—Air Force LRCM design comparison
IV. OPERATING THE NEXT LRCM: A POTENTIAL ROADBLOCK

Some of the primary features of LRCMs have both a positive and a negative side. Appendix D discusses how the lack of a human pilot has a dual effect on LRCM survivability issues; the LRCM's target-looking sensor and scene-matching capabilities have a similarly dual effect on LRCM operability and effectiveness. On one hand, these capabilities are central to the ability to attack targets autonomously with conventional munitions, the key task that defines a LRCM. Unfortunately, the autonomous nature of LRCMs and the technologies that make this autonomous attack possible are likely to strain our ability to gather and organize the information required to support them.

Appendix A lays out an analytic framework for linking the effect of individual LRCM technologies, employment options, and operating environments to an understanding of LRCM capabilities and effectiveness. This framework is explored in the remaining appendices. Throughout the discussion in the appendices of LRCM technologies, performance measures, and capabilities, a consistent element can be found: mission planning. Mission planning has a major effect, in multiple ways, on key LRCM capabilities, including LRCM lethality and survivability. The following pages discuss the nature of the mission planning process for the next LRCM, identify the types of information that will need to be gathered and processed, and raise questions about our capability to support the types of roles previously identified as useful for the next LRCM.

Figure 4.1 shows a schematic of the steps required to support a LRCM mission incorporating the technologies discussed above. Two major mission support processes are identified, the enroute planning process and the terminal area planning process. The functional divisions are based on both institutional structure and location. The first set of tasks are generally considered intelligence functions. They require either intelligence-collection assets or analysis of intelligence data. Some of this intelligence must obviously be gathered in the field, and the institutions generally charged with developing and gathering this type of information are distinct from the individual armed services. The second set of functions is the actual process of generating a LRCM mission profile, including the terminal target scene and the cruise missile route to the target area. Some tasks are hybrids and overlap between the first two functional categories. Because of the requirement to maintain large databases and support large computer operations, the mission preparation process would almost certainly be carried out in at most several centralized mission planning
centers. The mission support process ends when the information generated in the
preparation stage is transmitted to the operational command and loaded onto the missile.

This process has many elements in common with the mission planning process for the
current Tomahawk missile, especially in terms of enroute planning. As discussed earlier,
Tomahawk's guidance is provided by an inertial navigational unit (INU) aided with periodic
positional updates from the Terrain Contour Matching (TERCOM) system. TERCOM uses a
radar altimeter to measure terrain features along its flight path and correlates these
measurements with internally stored digital maps. TERCOM navigation systems use
preselected patches of terrain, produced by the Defense Mapping Agency (DMA), in which
they perform a positional correlation and correct the missile heading. The missile is
programmed to fly from patch to patch, calling upon the INU system for the navigation
between scene-matchings.

Between TERCOM patches, however, the path of the Tomahawk must be preplanned
so that it can both fly at low altitudes and avoid striking the ground. For this purpose, the
mission planning system requires digitized terrain elevation data (DTED) for the terrain
encountered enroute to the target. Fortunately, DTED has been in production for a number
of years, and it now covers most of the world. In addition to using terrain features, the
current Tomahawk planning system can display static databases of potential air defense
threats. The mission planner can then route the cruise missiles to avoid these threats. The
ease with which threat updates can be implemented in the current mission planning systems
is not clear, and this could be an important consideration for use of LRCMs in either quick-
response or rapidly changing environments.¹

Each of these elements of enroute mission planning is likely to be repeated for the next
LRCM. Although some of the navigation concepts discussed for the next LRCM could obviate
the use of TERCOM updates, nearly all will require the use of DTED data, which can be
stored and manipulated in current planning systems. Moreover, given LRCM's relative lack
of maneuverability and ability to see obstacles ahead, at least some preplanning of LRCM
routing will be required, a function for which current systems are well-suited. Nonetheless,
it is reasonable to assume that the planning systems and information flow that currently
exist for enroute mission planning could support the enroute planning requirements of the
next LRCM.

¹"Sea Launched Cruise Missile," Briefing Presentation, General Dynamics Corporation, Convair
Division.
It is in the area of terminal area planning that the mission support process for Tomahawk and the next LRCM diverge radically. The conventional TLAM variants are equipped with terminal-area guidance, provided by a digital scene matching area correlation (DSMAC) system. DSMAC updates the position of the missile by matching a stored visible-light image to a series of visible-light images sensed in flight. The DSMAC scenes are prepared from photographs of the area near the target. The greater resolution of the visual image allows for more accurate updates than those available from the coarser TERCOM, and the proximity of the scenes to the target does not allow navigator errors to rise to inordinate levels.

The planning required for a DSMAC system is substantial. To generate the terminal portion of the Tomahawk flight, the operator obtains a photograph in the target area, generates one or more DSMAC scenes from it (a partially automated process), and includes the location of these scenes in his route planning. Of course, any number of complicating factors could arise (e.g., the photograph is not available, no DSMAC correlations occur near the target), but the basic process for generating the Tomahawk scene is simplified by (1) the fairly simple and tested DSMAC correlation algorithm, and (2) the use of a wide-area photographic asset that is likely to be available for most conceivable targets. Nonetheless, the gathering of the photography needed to support DSMAC has been an ongoing effort for years, and the overall planning time for a single TLAM mission can reportedly take up to several hours.²

In contrast to DSMAC, the target-looking sensors that provide much of the design incentive for the next LRCM require a much more specific set of target data and more difficult manipulation of that data. In particular, target-looking sensors require a photograph of the specific target scene tied to information about the absolute scale of the objects in the picture. Within this target scene, specific aimpoints for LRCMs must be identified if the accuracy of the target-looking sensor is to be exploited. The required degree of specificity about the terminal area and the target has some profound effects on the mission support requirement for the next LRCM. In particular, each LRCM target must first be a target of specific U.S. intelligence gathering activity. This statement implies that one of two eventualities must take place: (1) the United States is wise in its predictions of the future, and correctly preselects targets for which to develop LRCM support data, or (2) it will be

capable of both generating these data quickly and transferring the information efficiently to LRCM planners.

The timelines required for the planning process are a close function of the LRCM roles discussed in Sec. II. Of the three major roles discussed, only the Rapid Response role requires high-volume, sustained attacks in a timely manner. The Deep Attacks role requires a high volume of LRCM attacks, but the responsiveness of these attacks is not a major issue. In the Desert Storm air campaign, where Tomahawks played a Deep Attacks role, several months were used to plan the attacks. The Punitive Attack role requires neither large numbers of weapons nor rapid response. Given these facts, it seems clear that the general mission planning process utilized by the Navy for its Tomahawk system can address those LRCM roles for which the Navy is best suited, the Deep Attack and Punitive Attack roles.

The key question, therefore, is the capability of our current process (and particularly the Air Force) to handle the Rapid Response role. Given the volume and rate of attacks discussed in App. E, planning timelines must be measured in minutes rather than hours. The following discussion traces the terminal area planning process and examines how the various tasks involved might or might not be performed. The process is outlined once again in Fig. 4.2, along with notional timelines associated with each role. The shaded areas indicate the location and institutional control of the functional tasks. Heavy arrows indicate situations where large amounts of data, usually associated with digital terminal imagery, must be transmitted from one location to another.

TARGET IDENTIFICATION AND IMAGING

As can be seen in Fig. 4.2, the timelines for the Rapid Response role are stressing. The first step, gathering and analyzing intelligence, must take place in little more than hours. One method for accomplishing this, preselection of targets during peacetime, requires a faith in long-term U.S. military and political intelligence that is perhaps unjustified. In terms of selecting targets, the United States has many long-term “enemies” at whom it has never fired a shot, while some short-term or long-term “friends” have quickly turned into some of its most serious opponents. Confidence in an ability not only to identify future conflicts but also to identify the lucrative targets within them seems to be optimistic at the least. The counterpoint to this argument is that there are targets of obvious military importance (e.g., military airfields, strategic bridges, arms production) upon which U.S. military intelligence routinely turns a worldwide focus. These types of fixed installations are finite in number and could, perhaps, be photographed by process of elimination. Nonetheless, if wholly dependent
Fig. 4.3—Terminal area mission planning: timelines and information flow
on preselected targets, the operational flexibility of LRCMs could be severely limited in situations where foresight fails.

The needed flexibility would need to be provided by some real-time mission support capability. Target sets that are completely unidentified at the start of the process could probably not be addressed, but this is a very unlikely situation, given extensive U.S. military intelligence capabilities. A more likely possibility is that the targets have not been addressed in a manner useful for LRCM planning. If this is the case, several things must happen: (1) a photographic intelligence platform of some kind must make an image of the target, (2) this photograph must be processed for security classification reasons, often deleting information that may hint at sensor capabilities, (3) if it is an analog photograph, it must be digitized, and (4) this digital imagery must be transmitted to the mission planning center. It is difficult to see how this process, involving far-flung intelligence assets, security guidelines, and transference of information from one part of the government to another, can be accomplished in hours. At best, this can be done for a few targets, not many.

It seems, therefore, that the development of suitable target imagery for the Rapid Response role calls for a mixed strategy; obvious military targets could be identified before time of crisis and coupled with the capability to provide data on a few emerging targets in real-time. This would seem to fit in with the typical processes of a peacetime versus crisis-time military. However, even this mixed strategy for target selection and imaging calls for a high degree of understanding and cooperation between different bureaucratic institutions, the national intelligence agencies, and the military services. In terms of the roles discussed earlier for LRCMs, the Deep Attack and Punitive Attack roles could probably be supported with straightforward upgrades to the current Tomahawk planning process.

AIMPOINT SELECTION

Once targets are selected and photographic databases developed, these data must still be related to LRCM attacks rather than, for instance, F-15 attacks. This entails identification of the particular aimpoints that would yield an effective LRCM attack. Aimpoint selection is a mixed task, since it requires two distinct areas of knowledge. The planner must understand the target: its design characteristics and vulnerabilities; in addition, the planner must understand the operation of the LRCM: its capabilities and limitations. All of these elements go into the selection of effective aimpoints.\textsuperscript{3}

\textsuperscript{3} While this process might be complicated by the specificity of information needed for LRCM attacks, the same steps must be taken for any weapon system attacking the target. The issue is quality, not quantity, of the information and knowledge required.
For either the preselection case or the real-time case it is difficult to imagine this degree of knowledge in each planner. In all likelihood, the aimpoint selection function would be carried out in teams. However, it is important to note that this type of specialization has not existed to any great extent in the past. In order to use precision weapons such as LRCMs effectively, increased importance must be attached to the details of target vulnerability.

**IMAGE TRANSFORMATION AND VALIDATION**

All of the terminal sensor options discussed in App. A are based on energies other than visible light. For instance, the passive IIR terminal guidance system would use a series of contrast templates based upon elements of the target that have contrasting infrared emissivity. The basis for this template will almost certainly have to be a visible photograph of the target with sufficient resolution to identify and differentiate between separate target elements. Ideally, a far-field picture and a close-up picture are desired, in order to "nest" templates and further improve the probability of lock-on and accuracy.

Since the passive IIR sensor differentiates objects on the basis of differing infrared emission, while the visible light photograph is based upon differing visible light reflectivity, an operator must identify the types of surfaces and materials present in the photograph(s) and estimate (with the aid of a planning system) the expected contrast image of the scene. This will require a digitized photograph and an interactive workstation with image processing capabilities. Figure 4.3 shows a rough notion of this concept.

![Diagram](image)

**Fig. 4.3—Passive IIR prepared terminal image**

Note the main elements of the process described above: (1) a photograph of the target (not just the target area), (2) a process by which the photograph is transformed into a scene
comparable to that observed by the sensor, and (3) an operator knowledgeable in this process. Although the particular target characteristics to be matched will vary with sensors, these three requirements will remain constant for any of the target-looking sensors.

A reliable transformation algorithm is almost certainly achievable for any of the target-looking sensors with modern imaging and computational technology. However, the requirement for a skilled and knowledgeable operator to interactively oversee this process is a serious one. Preparation of the terminal scene template for any of these sensors will almost certainly not be as automatic as the DSMAC process. The operator must have enough understanding of the sensor's scene-matching algorithm to make judgements during the scene preparation process, acting iteratively with a validation procedure. This type of specialty is almost certainly absent in the military services today, since it has never been required before.

Depending on the complexity of the target scene, it is very likely that target scene preparation times could take some time, even with skilled operators. Times stretching to hours do not seem an unreasonable upper bound. However, the key issue is the development of these skilled operators.

SCENE TRANSMITTAL AND LOADING

The transmittal of the terminal scene information and loading are likely to pose little difficulty into the future. The terminal image scenes are not large in comparison to the data rate and bandwidth of current military communications systems, and flight path waypoint information is trivial in size. In all likelihood, this particular step (which interestingly enough is functionally equivalent to the often extensive aircraft pilot briefing) should take on the order of minutes.

LRM OPERABILITY: A NEED FOR INSTITUTIONAL CHANGE

Overall, this discussion points to some key difficulties with supporting the Rapid Response role for LRM. These difficulties point out two major changes that need to occur if the United States (particularly the Air Force) is to be able to operate the next LRM effectively in this role. First, institutional arrangements must be made for procuring and evaluating intelligence in support of LRM missions. LRM weapons will place unique pressures on our ability to gather the correct information, analyze it within the correct framework, and present it in the correct format. This process will require a high degree of cooperation between the intelligence community and the operational community. Even so,
LRCM targets will almost certainly be limited to a set of standard military targets supplemented by a small set of targets that emerge during crisis.

Second, and just as important, a new set of skills and specialties need to be developed in our military. This includes people who are versed in both target vulnerability and the capabilities of weapons such as LRCM; these two components of target attack are linked with unusual closeness by precision weapons like the LRCM. Also needed will be people who are capable of operating interactively with target imagery and autonomous sensor algorithmic processes, a new field in the armed services.

These conditions will not come about without some serious impetus for change. The military and national intelligence agencies are notoriously poor at sharing information; security classification guidelines differ between branches of the government and can act to prevent information from flowing freely. A process for understanding and expediting the intelligence information needed by LRCMs needs to be started now if the weapon is to be useful any time in the near future. In the Air Force, the path to promotion has always passed most quickly through the cockpit. Although this will in all likelihood remain the case, serious effort needs to be made now if the skills are to be available to exploit an LRCM capability.

The subcomponent technologies exist today to build the new LRCM (although they require integration and testing). The platforms for LRCM employment have already been bought and paid for. Nonetheless, institutional changes are necessary if the next LRCM is ever to become an operable weapon system for the Rapid Response role.
V. LRCM COSTS AND AFFORDABILITY

If the institutional changes advocated in the previous section take place, several of the questions asked in the introduction can be answered affirmatively. Useful roles for LRCM can be identified. LRCM designs can be developed that extend the effectiveness of the next LRCM beyond that of the Tomahawk and that incorporate mature technologies. We have heavy bomber platforms, such as the B-52, that could employ LRCMs effectively in the roles identified for them. This section addresses the costs and affordability of a LRCM weapon system.

Affordability has two aspects—economic and political—which are sometimes difficult to distinguish. For this section we will focus on economic affordability, in terms of U.S. capability to procure the LRCM in a fiscal sense in light of current military budgets. This will be investigated in a subjective way by comparing the cost of a notional LRCM procurement to different perspectives of the defense budget. Section VI will address the more difficult issue of LRCM affordability in a political sense.

Even under constrained budgets, it is extremely difficult to argue that the LRCMs are unaffordable in a fiscal sense; an Air Force LRCM would constitute a small fraction of the Air Force procurement budget, and a Navy LRCM program would simply constitute a continuing upgrade to the current Tomahawk. However, a closer reading of the Air Force budget demonstrates graphically the procurement competition faced by LRCM and foreshadows some of the political difficulties discussed later in this Note.

The economic affordability analysis proceeds in two steps. First, a reasonable estimate of LRCM unit costs is developed. Using this estimate and the analysis in App. E, an estimate is made of the total cost of the force. Projected over a multiyear procurement, LRCM’s impact on Air Force and Navy overall procurement budgets is identified.

LRCM UNIT COSTS

The unit costs facing the next LRCM designs are difficult to identify, for a number of reasons. In general, one would wish to use the existing cost data for the only operational LRCM designs, the conventional Tomahawk missiles, as a starting point. Unfortunately, such data are protected by proprietary restrictions and cannot be discussed in this open report. Moreover, it violates no proprietary arrangement to say that these data are often confusing, since the definitions of categories used for accounting for TLAM costs tend to shift from year to year. This analysis will not attempt any detailed costing of the TLAM system.
Instead, rounded and averaged data provided by contractors will be combined with the limited unclassified and nonproprietary data available to provide rough estimates of costs and the major variables affecting them. Using this range of estimates, the unit costs for the notional LRCMs discussed in Sec. IV are estimated.

This cost discussion makes a simple point: LRCM weapons bought in the quantities discussed here (roughly 4000 units) will almost certainly cost in the vicinity of a million dollars apiece, and perhaps somewhat more. Expectations of LRCM average unit cost of under a million are in all likelihood unrealistic.

**TLAM Costing**

The Tomahawk missile is a complex piece of equipment that has been bought under some fairly unique contract arrangements. These include arrangements for parts of the missile (most notably the DSMAC guidance set) to be included as government-furnished equipment (GFE), the concept of the all-up round, cross-system commonality, and leader-follower competitive procurement arrangements. Although these arrangements may or may not have resulted in a better acquisition program, they clearly made cost analysis of the TLAM-C more difficult. The maze of changing definitions of cost items, which alternately include and exclude different pieces of equipment, is not trod lightly. Moreover, a detailed discussion of this data would violate proprietary arrangements between contractors who are, in fact, competing for contracts.

Therefore, for this analysis nonproprietary LRCM cost variable estimates were utilized and compared (with allowances for different assumptions) for rough agreement with current TLAM data. The data are presented as a range of estimates which paint a fairly realistic picture of current TLAM costs to use as a baseline for this analysis. The sources for estimates and assumptions are listed below. Figure 5.1 shows the results of some of these calculations for a simple TLAM-C without external equipment (the booster, cannister, and

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A 90 percent learning curve is used, which tends to give good agreement with the actual Tomahawk cost relationship.

By examination of Fig. 5.1, one can see that the cumulative average unit cost for the unitary munition Tomahawk alone is in the range of $900,000 to $1 million for buy sizes in the low thousands. If the Air Force were to buy a TLAM-C for its next LRCM, this cost would be roughly applicable, with some inevitable minor additions. However, there are additional cost concerns for the Navy, including a booster and cannister for the TLAM. Figure 5.2 shows modifications to the baseline cost curves resulting from naval launch requirements. In general, the naval launch requirement will add roughly $100,000 to $150,000 to the unit cost.

The upper curves in Figs. 5.1 and 5.2 deal with the issue of dispensed submunitions. The equipped submunition dispenser for TLAM has an additional cost ranging from $300,000 to $500,000 (based on contractor estimates). A similar cost might accompany the BKEP-
equipped dispenser discussed earlier. Using the more optimistic estimate for dispenser costs, we arrive at the average unit costs for 4000 TLAM-like weapons found in Table 5.1. These numbers are rough, but they convey the essence of the current TLAM procurement.

Unit Costs for the Next LRCM

The Tomahawk-like systems discussed above each have costs in roughly the $1 million to $1.5 million range. The designs discussed above for the next LRCM call for a number of changes from the baseline Tomahawk, some of which would appear to increase LRCM costs and some of which have the potential to decrease them. The Air Force would build several thousand LRCMs to support the Rapid Response role discussed previously. Although fewer weapons are required for the Deep Attack and Punitive Attack roles, the Navy would also buy several thousand weapons in order to outfit its naval platforms and ensure LRCM availability.
Air Force LRCM. The Air Force LRCM incorporated the highest number of changes from the Tomahawk. Included were the propulsion system, airframe, and sensor system. The propulsion system proposed was the JCAE 372-11A turbojet engine. Turbojets are relatively less complex and therefore relatively less expensive than turbofan engines. If the turbojet engine cost much less than the turbofan, say 50 percent less, this could result in a cost drop of $80,000 to $100,000.

The modifications in the LRCM airframe yield uncertain cost benefits. Although the structural strength of the actual airframe could be much reduced for the Air Force LRCM, presumably lowering costs, much of the cost included under the airframe cost component includes elements that would not change, such as internal wiring and ducting, fuel management systems, and control and lift surfaces. Also, addition of low-observables technology might add to the airframe production costs. Therefore, we will treat airframe costs as a constant cost component.

Finally, the addition of an active sensor to the next LRCM may have a somewhat counterintuitive effect on LRCM costs. At least one Tomahawk contractor, General Dynamics, argues that the opportunity to redesign the guidance and control system for a new missile would enable it to integrate and simplify many elements by taking advantage of advances in processor, control, and inertial navigation technologies. Using these assumptions, the passive IIR terminal sensor and its accompanying navigational system are costed at $240,000 for 5000 units versus an estimate of $435,000 at 5000 units for the current Tomahawk sensor and navigation system.

\[ 3 \text{ The actual cost difference between a low-observable versus a nonstealthy design is uncertain, although some authorities argue that LO features add only 10 to 15 percent to the costs of the vehicle. See Benjamin F. Schemmer, "Will Stealth Backfire?" Armed Forces Journal International, January 1991.} \]

\[ 4 \text{ Advanced Sea-Launched Cruise Missile Terminal Sensor Concept Design Study, General Dynamics, Convair Division, Contract No. N60921-88-C-2822, February 1989.} \]
Figure 5.3 shows the effect of all these assumptions on the unit cost of the Air Force LRCM variants. At 4000 units, the cumulative average unit cost for the unitary warhead version is roughly $850,000, while the submunition dispenser version has a cumulative average unit cost of $950,000. The range areas indicate the fact that these estimates for terminal guidance and navigation packages were predevelopment estimates. As such they are very likely to rise, perhaps substantially. The upper bound of each area occurs under the assumption that any new terminal guidance and navigation system will have costs roughly equal to the estimates used for the current DSMAC system. Note, however, that even under the most optimistic of these assumptions, the average cost of an LRCM will be roughly $800,000 to $850,000. This is as a result of the use of submunitions in many of the LRCM attacks discussed in App. E. Roughly half of the force would be made up of the more expensive submunition weapons.\(^5\) Under less optimistic terminal guidance cost assumptions, the Air Force LRCM averages slightly more than $1 million apiece when the mix of unitary and submunition weapons is taken into account.

**Naval LRCM.** The naval LRCM costing is very similar to that discussed for the Air Force LRCM. The naval LRCM will have essentially the same airframe as Tomahawk, so little or no change in airframe cost could be expected. The propulsion system contemplated for the Naval LRCM is a developmental propfan system for which little or no open cost data exists. It is unlikely, however, that such an engine would be able to equal the cost of the current turbofan engines, since the propfan is generally considered to be a significantly more complicated engine. Therefore, a cost growth of 25 percent, or roughly $50,000, was assumed. The guidance set assumptions were equivalent to those used for the Air Force LRCM. In addition, the naval requirement for a booster and a cannister were included at a cost of roughly $150,000.

Figure 5.4 below shows the results of cost calculations using these assumptions. Naval LRCM costs will almost certainly be above those of an Air Force LRCM by several hundred thousand dollars because of booster, cannister, and propulsion differences. The integrated redesign of guidance and navigation has some potential for cancelling the increased propulsion costs of the propfan engine and lowering unit costs below that of the current Tomahawk (see Fig. 5.2). However, the unit costs of a naval launch-equipped LRCM will almost certainly hover in the million-dollar-plus range.

\(^5\) This is also roughly equivalent to the projected force mix between TLAM-C and TLAM-D.
Fig. 5.3—Air Force LRCM unit cost estimates

Fig. 5.4—Navy LRCM unit cost estimates
LRCM FISCAL AFFORDABILITY

Table 5.2 below summarizes the LRCM cost estimate figures above. The wide error bands on costs indicate the cost uncertainty associated with the new sensor technologies. In general, the lower bound of these variances should be viewed as a very optimistic lower bound, as they are based upon predevelopment cost estimates.\(^6\) The Air Force LRCM buy is entirely new procurement, and based upon a force mix incorporating 50 percent unitary and 50 percent submunition weapons, the change from present procurement funding brought about by Air Force LRCM missile procurement would account for anywhere from $3.2 to $4.0 billion.

<table>
<thead>
<tr>
<th>Service</th>
<th>Unitary Warhead per Unit ($M)</th>
<th>Dispenser per Unit ($M)</th>
<th>Procurement ($B)</th>
<th>Development &amp; Test ($B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Force</td>
<td>0.65 - 0.85</td>
<td>0.95 - 1.15</td>
<td>3.2 - 4.0</td>
<td>- 1.2</td>
</tr>
<tr>
<td>Navy</td>
<td>0.9 - 1.15</td>
<td>1.2 - 1.45</td>
<td>- 1.0</td>
<td>- 0.5</td>
</tr>
</tbody>
</table>

Added to this cost is the inevitable cost of developing the LRCM, including developmental test and evaluation (DT&E), and initial operational test and evaluation (IOT&E). The absolute size of these elements is difficult to assess. However, the Tomahawk program costs for development and testing ran on the rough order of $1.2 billion.\(^7\) This figure is used as a rough estimate of development and test costs for an Air Force LRCM.

The naval LRCM, however, can be funded as a block upgrade to the Tomahawk program. This means that later units in the Tomahawk buy could have the LRCM modifications as standard equipment, while previous units would be retrofitted. The change to projected procurement, therefore, would be unlikely to rise above a billion dollars. The development and testing of the sensor and propulsion units, however, could be substantial, since they will require integration into the existing airframe. A figure of $500 million for development and testing is used as a rough estimate for a Navy LRCM upgrade to

\(^6\) For instance, Tomahawk land attack missile cost estimates showed an increase in cost of 14 percent after the DSARC II acquisition milestone, marking beginning of full-scale Engineering development (see E. H. Conrow, G. K. Smith, and A. A. Barbour, The Joint Cruise Missiles Project: An Acquisition History—Appendixes., RAND, N-1989-JCMPO, August 1982). Most sources agree that cost estimates before FSED are subject to large variances.

\(^7\) Discussion with David Dreyfuss, RAND cost analyst, March 22, 1991. Based upon unclassified cost estimates in Tomahawk Selected Acquisition Reports and contractor data.
Tomahawk, based upon the proportion of costs associated with these elements in Tomahawk's original development.

By any estimate, the incremental cost discussed here should be affordable to the Navy if paid out over time. Likewise, development and test costs for the Air Force are not excessive. We will focus, therefore, on the ability of the Air Force to procure 4000 new LRCMs.

The program cost identified above for the Air Force LRCM is roughly $4 billion. This amount would not, of course, be spent at once. Instead, the LRCMs would be procured over an extended period. The discussion presented here assumes a ten-year program in which 400 missiles per year are acquired at a cost of $400 million per year. This is a somewhat simplistic approach, since missile quantities tend to "ramp up" to some value over the course of a procurement, but it serves to show the scope of LRCM procurement costs in relationship to the Air Force procurement budget.

In addition to the LRCM procurement expenses, a budget trend needs to be assumed. Figure 5.5 shows the overall effect on the defense budget of the 1990 five-year defense plan under the Bush Administration. This plan was presented in January 1990 and projected yearly cuts of roughly 2 percent in real terms over the next five years.

Where the actual budget is headed is an extremely slippery issue at this time, and predictions change rapidly. Nonetheless, the underlying budgetary issues that drove the January 1990 projections have not disappeared, and defense budgets will almost certainly decline in real terms for the near future. Therefore, this analysis assumes a real decrease in procurement budgets of 2 percent per year.

Given these assumptions, Fig. 5.6 shows the scale of the first five years of LRCM procurement in relation to a declining Air Force procurement budget.\(^8\) LRCM would constitute less than 2 percent of total Air Force procurement. When viewed in this manner, it is clear that the LRCM procurement program described here is not a "budget buster" in an absolute sense; an Air Force LRCM is economically affordable in an absolute sense.

However, Fig. 5.6 is not the only manner in which to view the situation; it is necessary to examine the Air Force procurement budget in more detail than previously. Figure 5.7 uses the same set of assumptions as Fig. 5.6 and breaks out the procurement elements in more

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Fig. 5.5—1990 Defense budget projection

Fig. 5.6—LRCM as a fraction of Air Force procurement
detail. This detail sheds a great deal of light on the problems faced by LRCMs in Air Force procurement battles. Roughly 70 percent of the FY 1990 Air Force procurement budget is devoted to aircraft procurement or procurement related to maintaining the aircraft fleet. This leaves 30 percent, or roughly $6.5 billion, for missile-related procurement. However, of this amount only 25 percent is used to procure known missile systems. The other 75 percent is directed to a series of other support activities, which include space launch and unspecified classified programs (at least some of which must be intelligence activities). This leaves roughly $2 billion for open procurement of missiles. Of this $2 billion, roughly 60 percent is aimed at strategic missiles such as MX, the ACM, and SRAM II. Of the tactical missile portion, the largest procurement is for AMRAAM missiles, which constitute $390 million of spending.

Given these breakdowns, it becomes fairly clear that a LRCM procurement would force some serious tradeoff within the Air Force. A LRCM procurement would make up a sizable fraction of missile procurement. If included in the 1990 budget, it would be the third largest missile procurement item, behind MX and AMRAAM. If the buy size were cut in half

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(without quantity-related cost penalties) LRCM would drop to number four, behind ACM. This situation would be exacerbated by the situation shown in Fig. 5.8, where the Air Force exercises its historical predilection to protect aircraft procurement at the expense of other components. Under these circumstances, LRCM would become an increasingly large portion of the missile procurement budget. Given the desire of the Air Force to procure the B-2, the ATF, and the C-17 in the future, Fig. 5.8 may be a mild case.

Several major points come out of this discussion. First, LRCM costs are likely to hover in the $1 million range, hopes for cheaper weapons to the contrary. Second, a Navy LRCM upgrade program to Tomahawk is likely to be a relatively inexpensive addition to current procurement plans. Third, although a new LRCM is clearly affordable to the Air Force in an absolute sense, in reality it is difficult to fit within constrained budgets. This outcome is but one of the motivating factors for the political discussion of the next section.

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**Fig. 5.8—LRCM procurement comparison II**
VI. THE POLITICS OF LRCM

There are two major political elements to the LRCM debate: (1) arms control limitations that could adversely affect U.S. ability to procure and employ new LRCMs, and (2) the perceived conflict between LRCMs and other politically important weapon systems.

Just as in the area of LRCM operability, the major roadblocks to LRCM development are political and institutional. As the previous section demonstrates, it is extremely difficult to argue that LRCMs are unaffordable in a fiscal sense; the next LRCM would constitute a small fraction of the Air Force procurement budget. Likewise, arms control regimes are discussed below that address LRCM issues. The greatest threat to development of an Air Force LRCM lies in the disinclination of the Air Force to procure it. The roots of this disinclination can be found in the discussion of the Air Force budget from the previous section, the history of Air Force involvement in standoff weapons in general, and in the debate over the B-2 penetrating bomber.

ARMS CONTROL AND THE NEXT LRCM*

LRCMs might pose serious arms control difficulties. The problems essentially arise from the fact that any LRCM capable of delivering a 1000-pound warhead over 700 miles could also carry a lighter nuclear warhead (a 250-kiloton nuclear warhead weighs roughly 250 pounds) to even greater ranges. This inherent problem has been complicated by the fact that the nuclear and conventional versions of the BGM-109 Tomahawk missile, the only deployed LRCM, are externally indistinguishable because they utilize the same airframe.

This discussion sidesteps the issue of sea-based LRCM arms control. The issue of controlling nuclear SLCMs has been handled in a manner fundamentally different from the other nuclear elements of U.S. forces, and to a large extent it remains unresolved.\(^1\) The discussion in this section presents a shortened version of the more complete arms control discussion found in App. F.

Traditionally, nuclear arms control treaties have controlled nuclear weapons by regulating the platforms—ballistic missiles or bombers—capable of carrying them, and the

*The discussion on arms control draws heavily on work performed jointly with RAND colleagues George Donohue and Robert Lempert.

\(^1\) Nonetheless, the general approach of separating nuclear and dedicated conventional cruise missile platforms, and employing different counting rules for these systems, is potentially applicable to the sea-launched weapons as well. See Robert Lempert, *Cruise Missile Arms Control*, RAND, R-3792-PP/RG, October 1989.
current START framework is following this pattern. However, because any bomber capable of carrying a large conventional cruise missile can carry a nuclear one as well, the treaty could force platforms for the former aircraft to be counted under its nuclear weapons ceilings. This would probably preclude the option of deploying a militarily significant number of bombers dedicated to carrying LRCMs, since a force of 30 to 70 bombers might be required to carry out many of the missions suggested for LRCMs. This discussion suggests some minor modifications to the current treaty framework that would allow such a dedicated conventional bomber force to be deployed under a START regime.

Range Limits: A Poor Solution

There are some ways not to ensure the capability to employ LRCMs on heavy bombers, and one such is range limits. Range limits refer to the process of distinguishing which aircraft do or do not count against the treaty's nuclear weapons ceilings by the range of the cruise missiles they carry. Range limits are not useful for preserving the option to deploy bombers carrying LRCMs. The range limit approach has, however, been suggested by many commentators, and is thus worth discussing in some detail.

The basic argument against range limits with respect to LRCMs is that any cruise missile that can carry a militarily useful conventional warhead 1500 km can carry a nuclear warhead nearly twice as far. Since a militarily useful long range conventional cruise missile needs a range 1500 km or greater, there is no range limit that will produce an identifiable external difference between large conventional cruise missiles and even longer-range nuclear cruise missiles. To determine the range of a large cruise missile, it is in fact necessary to know the payload it carries. But if the payload is known, there is no need for range limits to distinguish a nuclear from a conventional missile. This concept is easily seen in Fig. 6.1, which shows the range-payload tradeoffs facing several LRCMs. For any of the engine propulsion technologies shown, a missile that carries a conventional payload (800–1000 lbs) 700 nautical miles can carry a nuclear payload much further. The difference in range between the nuclear and conventional systems is due to the difference in warhead weight, which allows extra payload to be used for fuel.

Therefore, it is clear that if the United States wishes to preserve the option under START of deploying bombers capable of carrying LRCMs, where long range is on the order of 1500 km, range limits are not a useful way to proceed. As we argued above, any aircraft that can carry a conventional cruise missile with a range under the limit can also carry a nuclear cruise missile with a range over the limit, since the two weapons can have the same size and weight. It might be possible to add to the treaty regime procedures for inspecting the payload
of individual cruise missiles in order to determine their range. But if this is done, it is less complicated to base the treaty restrictions on the type of warhead, rather than the range, which is derived from the knowledge of the warhead. In the next subsection we will present an approach for preserving the option to deploy bombers carrying conventional cruise missiles under START that does not use range limits, but instead explicitly limits the types of missiles, conventional or nuclear, that certain types of bombers are allowed to carry.

**Bomber Classification: A Workable Alternative**

The second part of this discussion focuses on what we believe to be a more successful means to distinguish bombers carrying conventional and nuclear cruise missiles. The United States and Soviet Union have already agreed that the START treaty will implicitly recognize two classes of bombers distinguished by their ability, or lack thereof, to launch long-range cruise missiles. These two classes of bombers will count differently against the treaty ceilings. In order to allow the deployment of a bomber force carrying conventional cruise missiles, we propose that the treaty be modified to explicitly recognize four classes of
bombers, distinguished by their armament, nuclear or conventional, in addition to their capabilities regarding large cruise missiles. In this subsection we will define these four bomber classes and argue that using them, we can construct a robust treaty regime that will successfully allow the deployment of bombers armed with conventional cruise missiles while limiting the deployment of bombers armed with nuclear cruise missiles. These four classes are discussed below and summarized in Fig. 6.2.

I. Dedicated conventional bombers. These are heavy (long-range) aircraft which do not carry any nuclear or any long-range weapons. Often they are modified bombers used for maritime or reconnaissance roles. Types of aircraft in this class include the Bear D/E/Fs in the Soviet arsenal and the U.S. B-52G maritime craft. Such aircraft are not explicitly mentioned in the START proposals, and it is unclear how they would count under the treaty (they were not counted under SALT II).

II. Dedicated conventionally armed standoff bombers. These are heavy bombers which are capable of carrying large (conventional) cruise missiles but do not carry nuclear weapons. Such aircraft are not currently considered in the START proposals. There are no existing types of aircraft in this class, but the (presently nuclear) cruise missile carrying B-52Gs could be if, instead of being retired as planned, they were converted to dedicated conventional systems carrying LRCM weapons. We will recommend that a separate START sublimit cover these bombers and that they should not count otherwise toward the START ceilings. These bombers should be subject to inspection to verify they are not nuclear armed.

III. Nuclear armed penetrating bombers. These are heavy nuclear armed bombers which carry only short-range weapons, such as gravity bombs and SRAMs. Types of aircraft in this class are the planned U.S. B-2 Stealth bombers, the B-1Bs, and the B-52Hs that have not yet been converted to cruise missile carriers. The Soviet Blackjacks, if they

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3 Forty-seven of the remaining 69 B-52Gs that are not capable of launching long-range cruise missiles have been dedicated to a maritime role. The remaining 22 non-cruise missile carrying B-52Gs have been identified for retirement in the 1990s.

4 A bomber should fall into Class II depending on the range, weight, and/or volume of the cruise missiles it can carry (as is apparent from the discussion in Sec. II, these features are related). In light of the discussion in Sec. II, these limits should be set low, probably 600 km for range. Any bomber capable of carrying a cruise missile with characteristics above these thresholds would count as a standoff bomber. Also see the discussion in Sec. II, footnote 9.

5 CBO.

6 CBO.
do not carry cruise missiles, would also fall in this class, as do the Bear B/C/Gs. As we have seen, these bombers will count one against both the warhead and delivery vehicle ceilings under START. Some types of aircraft in this class may have to be inspected to verify they do not have the capability to launch cruise missiles.

IV. Nuclear armed standoff bombers. These are heavy nuclear armed bombers which are equipped and employed to carry large cruise missiles. Types of aircraft in this class include the U.S. AGM-86B-equipped B-52Hs and B-52Gs, and the Soviet Bear Hs and Blackjacks, if they are deployed with cruise missiles. Each of these bombers counts one against the treaty's delivery vehicle ceiling and some number (whose value will depend on how many cruise missiles are attributed to each bomber) against the weapons ceiling. These aircraft may be subject to an inspection scheme that will help verify the cruise missile carrying capacity of each type of bomber.

As can be seen from Fig. 6.2, these four bomber classes, with one important exception, are pure by type. That is, no currently deployed type of heavy bomber save one falls into two or more classes. This is important because bomber types can be easily distinguished, and the total number of aircraft of each type can be accurately counted by national technical means. Since each class carries different numbers and different types of cruise missiles (nuclear or conventional), the START treaty can restrict nuclear cruise missiles and allow conventional ones by appropriate counting of the four classes of bombers.

Our proposal is that upon entering into the treaty regime, each side declare to which of the four bomber classes each of its bomber types belongs. Each type of bomber must have external characteristics that make it distinguishable by national technical means (e.g., the different tail assemblies on B-52Hs and B-52Gs). Each class of bomber will have different counting rules under the treaty ceilings and sublimits. The treaty will specify a verification scheme, relying heavily on short-notice challenge inspections, which will certify that no bomber has military capabilities or associations that are inconsistent with its declared class.

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7 IISS.
8 CBO.
9 IISS.
10 The exception is the B-52G, which is currently configured as both a nuclear-armed cruise missile carrier and a conventional-armed maritime strike craft. The two variants are distinguishable, however, by the heavy weapons rails that can be carried under the wings of the former. Since our interest in bomber types owes to the fact that different types can be distinguished by national technical means, the two B-52G variants cause us no problems. In addition, if the nuclear-armed B-52Gs are converted into dedicated conventional systems, no bomber type will have both a nuclear and dedicated conventional variant.
<table>
<thead>
<tr>
<th>Class</th>
<th>Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Non-Strategic</td>
<td></td>
</tr>
<tr>
<td>Conventional bomber,</td>
<td>47 B-52G</td>
</tr>
<tr>
<td>short range weapons only</td>
<td>115 Bear D/F</td>
</tr>
<tr>
<td>(w/o heavy rails)</td>
<td></td>
</tr>
<tr>
<td>II. Conventional Standoff</td>
<td></td>
</tr>
<tr>
<td>Conventional bomber,</td>
<td>98 B-52G</td>
</tr>
<tr>
<td>can carry large cruise</td>
<td>(w heavy rails)</td>
</tr>
<tr>
<td>missiles</td>
<td></td>
</tr>
<tr>
<td>III. Nuclear Penetrator</td>
<td></td>
</tr>
<tr>
<td>Nuclear capable bomber,</td>
<td>100 B-1</td>
</tr>
<tr>
<td>short range weapons only</td>
<td>132 B-2</td>
</tr>
<tr>
<td></td>
<td>24 B-52H</td>
</tr>
<tr>
<td></td>
<td>(w/o heavy rails)</td>
</tr>
<tr>
<td></td>
<td>80 Bear G</td>
</tr>
<tr>
<td></td>
<td>Blackjack?</td>
</tr>
<tr>
<td>IV. Nuclear Standoff</td>
<td></td>
</tr>
<tr>
<td>Nuclear capable bomber,</td>
<td>98 B-52G</td>
</tr>
<tr>
<td>can carry large cruise</td>
<td>50 Bear H</td>
</tr>
<tr>
<td>missiles</td>
<td>(w heavy rails)</td>
</tr>
<tr>
<td></td>
<td>Blackjack?</td>
</tr>
<tr>
<td></td>
<td>72 B-52H</td>
</tr>
<tr>
<td></td>
<td>(w heavy rails)</td>
</tr>
</tbody>
</table>

Fig. 6.2—Bomber classifications

We will discuss such procedures below. The critical point is, however, that the problem of counting bombers carrying different types of cruise missiles has been reduced to the problems of (1) identifying and counting different types of bombers by national technical means, which is known to be possible, and (2) verifying by inspection that bombers of a particular type only carry and are only associated with those cruise missiles, if any, they are allowed to have. For instance, if B-52Gs were declared to be conventional standoff bombers, the discovery of one B-52G carrying nuclear cruise missiles (or nuclear weapons of any type) would be a treaty violation. Thus the problem of distinguishing and counting different types of cruise missiles, which would otherwise require complex schemes to identify and keep track of every such weapon in the other side's arsenal, has been replaced by a far simpler “zero option” problem.

To handle this verification problem, the treaty would specify a list of characteristics and associations forbidden to certain classes of bombers, and provide for short-notice challenge inspections to look for planes with the prohibited features. Figure 6.3 shows the two sets of capabilities that distinguish our four classes. An aircraft either can have the
ability to launch long-range weapons or it can carry short-range weapons only, and it can be either nuclear armed or conventionally armed.

<table>
<thead>
<tr>
<th></th>
<th>Dedicated Conventional</th>
<th>Nuclear Capable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Range Weapons</td>
<td>Class I</td>
<td>Class III</td>
</tr>
<tr>
<td>Only</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long Range Weapons</td>
<td>Class II</td>
<td>Class IV</td>
</tr>
<tr>
<td>Only</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

External pylons
internal launchers

Hard points on wings/
partitioned bomb bays

Association with nuclear weapons
(e.g., basing, weapons load)

Fig. 6.3—Distinguishing bomber classes

Mitigating the Effects of Breakout

We have been discussing the verification problem of preventing creepout: that is, determining that no bomber is covertly given capabilities that do not correspond to its declared class. There is a second, more difficult verification problem: guarding against a breakout. This is limiting the military utility to be gained by overtly breaking the treaty and rapidly converting bombers from one class to another. In terms of the capabilities listed in Fig. 6.2, a breakout would consist of converting Class I, Class II, or Class III bombers to Class IV bombers able to launch long-range nuclear cruise missiles, and/or converting Class I or II bombers to Class III or IV bombers able to carry nuclear weapons. Unfortunately, there is no way under the framework discussed here to eliminate the possibility of such a breakout.

However, it is possible to limit the total size, not the pace, of a potential breakout. If the treaty places a cap on the number of conventional standoff bombers, then the ultimate gain from breakout is limited. There is a rigid cap on the number of prohibited nuclear weapons that can be deployed, since the total force of conventional bombers has a finite capacity. The actual cap will be more severe, since any conventional bombers converted to nuclear cruise missile carriers during a crisis or conventional war will deplete a limited stock of conventionally armed aircraft which can perform useful tasks, and thus decrease the net military utility of the conversion. Four potential counting rules can be considered:
Option 1: no limits on Class II bombers. In this option, Class II dedicated conventional standoff bombers would not count in any way against the treaty ceilings or sublimits. This option places the least constraint on the conventional capability but provides the least control on the breakout potential.

Option 2: separate sublimits for Class II bombers. In this option, the treaty would have a separate sublimit on the number of allowed Class II bombers. These bombers would not otherwise count against the treaty ceilings. (Additional such bombers could always be deployed, but they would count against the treaty ceilings as if they were nuclear armed.) With an appropriate value for the sublimit, this option will protect against a large breakout potential and still allow a conventional capability. In contrast to the remaining options, deploying conventional standoff bombers within the sublimit does not require any sacrifice of strategic nuclear weapons capability.

Option 3: count Class II bombers as Class III bombers. In this option, Class II bombers which carry long-range cruise missiles count one against the treaty ceilings for warheads and delivery vehicles (i.e., Class II dedicated conventional standoff bombers are counted as if they were Class III nuclear penetrating bombers, but not as if they were Class IV nuclear standoff bombers). This option is similar to Option 2, except that it allows additional flexibility in choosing the number of conventional and nuclear bombers, at the expense of forcing a deployment of conventional bombers to slightly decrease the allowable number of nuclear weapons.

Option 4: no separate treatment for Class II bombers. In this option, there is no separate treatment under the treaty for conventional standoff bombers. All bombers carrying cruise missiles, whether nuclear or conventionally armed, would count under the treaty as if they were nuclear armed Class IV bombers. Thus, each side would only deploy conventionally armed heavy bombers that were dual-capable nuclear/conventional cruise missile carriers. Although this option removes the breakout potential because all the standoff bombers are already counted as nuclear, it severely constrains the conventional capability because exercising it involves subjecting strategic nuclear forces to reduced readiness while they carry out conventional attacks.

The effects of these counting rules can be considered for a notional START force such as that shown in Table 6.1. Most reasonable START-constrained forces reach warhead limits before they reach delivery vehicle limits. In Table 6.1, a force is constructed with an atypically large number of launchers, since it includes 486 single-warhead mobile ICBMs, all of which will certainly not be procured. Most foreseeable 6000-warhead forces would probably have even fewer delivery vehicles.
Table 6.1
A Notional U.S. START-Limited Force

<table>
<thead>
<tr>
<th></th>
<th>Nuclear Warheads</th>
<th>Nuclear Warheads</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Delivery Vehicles</td>
<td>(counted)</td>
</tr>
<tr>
<td>Nuclear</td>
<td>ICBM</td>
<td>686</td>
</tr>
<tr>
<td></td>
<td>SLBM</td>
<td>408</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1094</td>
</tr>
<tr>
<td>Bombers</td>
<td>B-2</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>B-1B</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>B-52H</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td></td>
<td>265</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1860</td>
</tr>
<tr>
<td>Conventional</td>
<td>B-52G</td>
<td>98</td>
</tr>
<tr>
<td>Counting Rules:</td>
<td>Option 1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Option 2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Option 3</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>Option 4</td>
<td>98</td>
</tr>
</tbody>
</table>

The best options appear to be Options 2 and 3. Both limit the breakout potential by controlling the allowed number of dedicated conventional standoff bombers. Option 2, which calls for a separate sublimit on conventional cruise missile carriers, places a direct cap on the number of these systems and thus provides a definite numerical limit on each side's breakout potential. For instance, a sublimit of 100 conventional standoff bombers would limit the breakout potential to no more than about 1200 deliverable nuclear cruise missiles (if each bomber could only carry 12 missiles), or about 12 percent of the 9392 U.S. warheads deployed in the notional force shown in Table 6.1.12 In addition, deploying a long-range conventional cruise missile capability under this option does not decrease the allowed number of strategic nuclear forces. A potential problem with Option 2 is that it requires the United States to argue for a special sublimit on a class of weapons that it has not yet deployed.

Option 3, which counts conventional standoff bombers as one against the nuclear weapons and delivery vehicle ceilings, provides more flexibility by allowing a tradeoff between nuclear and conventional systems. The main advantage is that the United States will not leave an allowed treaty category empty if it decides not to deploy a conventional standoff bomber force, as opposed to the case under Option 2. There are two main

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12 We have credited each bomber with 12 cruise missiles here because we are comparing to the total number of nuclear warheads, not only the START-accountable ones. The breakout potential faced by the United States would probably be less, since current Soviet bombers carry fewer cruise missiles than the B-52s.
disadvantages. First, deploying a force of dedicated conventional bombers under this option does decrease the allowed nuclear force by about 1 percent. Second, this option provides less breakout protection than Option 2, since there is no strict limit on the number of cruise missile carrying bombers. In the worst case, one side might forgo fielding any nuclear standoff bombers and deploy a large force of dedicated conventional standoff bombers. The breakout potential of the resulting force could be substantial, since each of these aircraft counts only one against the warhead limits, and several hundred could be deployed. For example, if all the slots allocated to bombers in the notional force shown in Table 6.1 were filled by conventional bombers, there would be 506 such aircraft. (The delivery vehicle ceiling would become the relevant constraint. See the discussion in the appendix on the treaty-imposed tradeoffs between standoff and penetrating bombers.) If each bomber could carry 12 cruise missiles, the breakout potential of this force would be about 6072 deliverable warheads, or two-thirds of the 9392 warheads shown in Table 6.1.

The choice between Option 2 and Option 3 depends on several factors. Among them are the number of bombers the United States really expects the Soviets might build, U.S. concerns about decreasing its strategic nuclear forces by 1 percent below the treaty ceilings, and the flexibility the United States desires in planning for its bomber force. We can only conclude here that while Option 2 seems better than Option 3, there are many situations in which the latter option would be sufficient, and sometimes preferable.

In conclusion, it appears possible to craft a START agreement that would allow the United States to deploy a militarily significant bomber force, most likely consisting of B-52Gs, dedicated to carrying LRCM weapons. This can be done by defining four classes of heavy bomber, each distinguished by its armament, nuclear or conventional, and its capability or lack thereof to carry long-range cruise missiles. The United States and Soviet Union would declare the class to which each of their bomber types belong and use national technical means to count the number of bombers in each class. On-site challenge inspections would verify that the capabilities of each bomber actually put it in its declared class. Such a treaty regime should allow each side to monitor with high confidence the nuclear and conventional cruise missile capacity deployed by the other. It does not, however, prevent a breakout that could be accomplished in a short time. This problem can be contained by limiting the number of allowed conventional cruise missile carrying bombers, either by implementing a separate weapons sublimit on them or by counting them as one weapon against the treaty warhead ceilings.

Finally, the reader should remember that LRCMs are of interest because they may be an effective tool for strengthening the United States' conventional capabilities around the
world. This fact should be weighed against the breakout potential posed by their separate treatment in a nuclear arms control regime. The signing or ratification of self-contained nuclear arms treaties has been linked in the past with events not directly related to the nuclear balance. The issue here is similar, but the linkage is within the treaty itself. It is the treaty provisions that must reflect the inherent tension between limiting nuclear standoff capability and allowing conventional standoff capability. In resolving this tension, it is well to remember that the purpose of strategic arms control agreements is to enhance the overall security of the United States, and not simply to address the nuclear aspect of that security. U.S. national security has both conventional and nuclear components, and in the case of long-range conventional capability and the START treaty, the two are intertwined. Where we set the balance clearly depends on how important we believe the long-range conventional capability to be. The framework that we have described may make it easier to set such a balance.

AIR FORCE INDIFFERENCE: THE LARGEST ROADBLOCK

Section V identified institutional roadblocks to creating an operable LRCM force. Perhaps the largest institutional roadblock comes from lack of interest in LRCMs among service sponsors, particularly the Air Force. This indifference on the part of the Air Force is based upon a number of factors and must be addressed squarely if the next LRCM is ever to become more than a technology development program.

The recently downgraded joint Navy-Air Force program to develop a weapon termed the long-range conventional standoff weapon (LRCSW) is a good example of the effects of service interests in development of LRCM weapons. This program was formed after both services generated statements of need for LRCMs. The Navy was the executive service for the development, and five contractors were selected for 18-month concept development studies, with funding totalling roughly $14 million in fiscal 1990.13 The fact that this program was "joint" obscured somewhat the fact that the Navy was the leading service in more ways than one. First, the Navy has a fielded LRCM and has invested money in the mission planning and support capabilities that such a system requires. More important, the Navy has articulated an institutional interest in LRCM systems,14 an interest that the Air Force consistently declined to articulate.

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13 The five companies are Boeing, General Dynamics, McDonnell Douglas, Martin Marietta, and Texas Instruments. Aviation Week and Space Technology, October 9, 1989.
However, with shrinking budgets, interest in the Navy for LRCSW dwindled.\textsuperscript{15} It is unclear whether the Air Force was ever interested in the first place.\textsuperscript{16} In December 1990, based upon lack of institutional support, the LRCSW program was downgraded to a "technology initiative."

The Air Force and Standoff Weapons

The Air Force has never fielded an LRCM and has historically shown little interest in actually fielding such a system. The reasons for this attitude are many and varied. First, LRCMs are viewed as programmatic threats to aircraft procurement. In this sense, the LRCM case is parallel to that of the ALCM nuclear cruise missile. The ALCM met severe resistance from the Air Force when it was proposed in the early 1970s, largely because of the perceived disincentive it created for further development of manned penetrating bombers.\textsuperscript{17}

In the conventional realm, LRCMs have been viewed as a competitor to both manned tactical aircraft (TACAIR) and penetrating bombers. In comparison to TACAIR, LRCMs operate in the same range regime, carry conventional payloads, and presumably could attack a similar set of targets. Commanders, seeing the potential competition between TACAIR and LRCMs, quite reasonably prefer TACAIR for the same reasons that their Navy counterparts prefer to have a carrier air wing: flexibility, responsiveness, and payload. The fact that TACAIR, either ground-based or sea-based, might be unavailable when needed seems to hold little weight.

One possible way out of this institutional difficulty might be to create a LRCM that could be carried by TACAIR. In this manner, a major group within the Air Force could be given an interest in the success of the program in much the same way that TLAM was made submarine-compatible by the Navy. Unfortunately, it has proven to be very difficult to design such a weapon. Carriage by tactical aircraft, specifically the F-16 fighter, imposes strict weight and size limits that LRCMs have been generally unable to meet. More fundamentally, the basic functions of the tactical ground-attack aircraft (i.e., human target identification, attack assessment, reconnaissance) are essentially negated by using the aircraft to fire a LRCM. Given their flexibility and fundamentally limited payload capability,

\textsuperscript{15} After all, as discussed in Sec. V, the Navy can pursue much of its LRCM development work under the rubric of Tomahawk upgrades rather than a new program.

\textsuperscript{16} "SAC Move to Undercut LRCSW Not Expected to Move JROC," \textit{Aerospace Daily}, March 27, 1990.

tactical aircraft are simply a less useful LRCM platform than bombers. A major interest
group within the Air Force, therefore, has little or no use for LRCM.

The group within the Air Force that would seem to have the greatest interest in
developing a LRCM is Strategic Air Command, which has command over the U.S. long-range
bomber force. A LRCM seems especially to complement the perceived strengths and
weaknesses of current U.S. heavy bombers, the B-52 and B-1. The strengths of these aircraft
include range, responsiveness, and heavy payload capability; the major perceived weakness
of the B-52 and B-1 is potential attrition when penetrating enemy air defenses. The
combination of the heavy bomber's range and payload capability with the LRCM's defense
standoff capability seems a particularly good match. This good match has been negated to
some extent, however, by the importance attached to the B-2 bomber, discussed below.

In addition, as discussed in the previous section, a LRCM procurement could take a
sizeable bite out of other weapon systems. It is under these circumstances that lack of strong
institutional sponsors within the Air Force leads to failure of LRCM systems to advance. The
tactical air force has little use for LRCMs, and focuses its advocacy on funding such systems
as AMRAAM and Maverick. SAC advocates a missile budget that has primarily been
directed toward prized nuclear capabilities such as MX and ACM. LRCMs have lacked any
strong voice within these budget debates.

The combination of interests described above has resulted in a long history of
interesting Air Force technology programs leading to canceled development programs and no
procurement programs. Two such development programs were the MRASM, discussed
above, and the more recent modular standoff weapon (MSOW). Significantly, the United
States withdrew from the MSOW program, a joint venture with NATO allies, because of an
inability to agree over the weight and range of the missile.18

LRCM and the B-2

The procurement tradeoff arguments above are essentially arguments about the
difficulty of changing the status quo. However, most of the weapon systems currently in the
budget had to fight their way through the inertia of prior budgets. Why has LRCM
consistently failed to do so? Essentially, the one potential institutional sponsor for LRCMs,
Strategic Air Command, has both a substantive and political position that does not allow it to
advocate LRCM weapons: support for the B-2 bomber.

Maintaining the capability of bombers to penetrate defenses and attack targets has been a major effort for the Air Force for the last 40 years. The B-2 bomber (and the heavy political and monetary investment made in it) indicates the depth of the Air Force's interest in this subject. The B-2 bomber has been prominently mentioned as a conventional bombing platform, and its eventual approval may well rest on its potential use in a conventional role. Congressional support for the B-2 can best be described as shaky, and given the determination of the Air Force (and SAC in particular) to support the B-2, potential competitors to it are not welcome.

Any standoff weapon of significant range can be viewed politically as decreasing the importance of a penetrating bomber platform. In addition, any weapon system that significantly enhances the effectiveness of the current bomber force can be viewed politically as diminishing the need for a new bomber. The LRCM is a standoff weapon that enhances the effectiveness of older platforms, and it is politically unsalable. Furthermore, if the LRCM truly is the death knell for the B-2, the Air Force is probably correct in its resistance. A manned, penetrating bomber platform has a great deal more flexibility than a standoff LRCM force. Although the B-1 versus MRASM decision appears to have gone badly in hindsight, choice of the B-2 over a LRCM force is not necessarily incorrect.

It may be, however, that the issue is framed poorly. Compared to the projected size of the B-2 procurement, the LRCM procurement is tiny, so it is not really money that places the LRCM in conflict with the B-2. Rather, it is a public relations matter. Although this Note has not investigated the use of a mixed force of LRCMs and penetrating bombers, it seems intuitively obvious that there would be many situations in which the mixed forces would complement each other. Whether or not this is the case is a subject for analysis, but such a mixed force approach is certainly not an obviously poor strategy. It is, after all, the strategy that the United States uses for its nuclear campaigns. The lack of interest in LRCMs is not fundamentally analytic, but political, in nature.

It is highly likely that the Air Force will maintain its priorities with respect to the B-2; too much time, money, and political capital have been invested in the B-2 up to this point. Therefore, the next LRCM will be built if and only if for some reason the availability of the B-2 for conventional missions is seriously in doubt, which could occur in several different ways, including (1) cancellation, (2) SIOP intervention, and (3) simple lack of desirability. Each is explored below.
The most obvious of these is cancellation of the B-2, which would obviously change the equation for the Air Force. The question of B-2 cancellation will, of course, be decided on much more global grounds than LRCM costs and benefits. Nonetheless, as the possibility of B-2 cancellation rises, Air Force interest in LRCM will increase.

Even if the B-2 is procured, there are open questions about the missions it will carry out. The driving mission behind the B-2’s development has been its use in the Single Integrated Operational Plan (SIOP), the United States’s nuclear attack plan. The B-2 was developed specifically with an eye to penetrating Soviet air defenses within the SIOP. In the past, forces involved in the SIOP were generally considered to be unavailable for conventional warfare, largely driven by a belief that such conflicts would involve confrontation and heightened tension between the United States and the Soviet Union. Given the current lessening of tensions and arms control advances between the two superpowers, two important differences emerge: (1) the central importance of the SIOP may diminish in the near future, and (2) conflicts are less likely to involve heightened U.S.-Soviet tensions. Hence, a dual-purpose nuclear/conventional bomber such as the B-2 may be viewed as a more certain option in conventional conflicts, especially by local theater commanders. To the extent that B-2s are viewed as nuclear-only or “conventional-rarely” aircraft, the Air Force’s view of LRCM will be more favorable.

In addition, B-2s could be unavailable because we can’t or don’t want to use them. The bomber equipment used for nuclear and conventional attacks differs considerably; if the B-2 is to be used for conventional attacks, the equipment (e.g., racks, bombs, test equipment, transporters, etc.) must be procured. This may seem a trivial expense compared to the overall cost of the B-2, but “for-want-of-a-nail” mistakes have ample historical precedent. In addition, one can imagine circumstances in which the United States simply wants no chance of attrition for either the aircraft or the pilots. As effective as the B-2 may be, bad luck and accidents can happen and could have extremely negative consequences if they happen over an opponent’s territory, most notably in the Punitive Attacks discussed in Sec. II.

Finally, we should reconsider the possibility that, contrary to appearances, the B-2 and LRCM may not be inherently in conflict with each other. LRCMs can act as a hedge against currently unexpected SIOP demands on the B-2. They can supplement what will be an extremely small bomber force in historical terms. Finally, LRCMs act as a hedge against the

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19 This discussion should not be construed as an argument for B-2 cancellation. It is simply a discussion of Air Force reactions to various eventualities.

20 The current Desert Shield operation in the Middle East is the most obvious example of this new phenomenon.
growing sophistication of worldwide air defenses, which could erode the viability of the conventional B-2 option over the long term. The current fiscal tightness obscures the fact that LRGM and B-2 are not necessarily in budgetary conflict. In short, there may be room for both.
VII. CONCLUSIONS AND RECOMMENDATIONS

In conclusion, let us recall how this Note started with a straightforward set of questions that must be answered affirmatively if the near-term LRCM is ever to be fully developed. They were:

- Are there useful roles for weapons with the characteristics of LRCMs?
- Are capabilities beyond those of Tomahawk needed for these roles?
- If so, are there technically and operationally feasible alternatives to Tomahawk?
- Finally, is the next LRCM affordable in both a fiscal and political sense?

Nearly all of these questions can be answered with a strong affirmative. Useful roles for LRCMs exist. In particular, LRCM-equipped long-range aircraft could play a role in countering aggression worldwide, assisting war termination, and conducting antiterrorist strikes. LRCM-equipped naval forces, because of their limitations on availability, could address the war termination and counterterrorist roles.

This Note developed a framework for evaluating LRCM technologies and their linkage to LRCM effectiveness. In the course of developing this linkage, two major limitations of the Tomahawk LRCM system become apparent: (1) accuracy and (2) availability due to weather. Coupled with launcher constraints for bomber and naval platforms, the design analysis for the next LRCM found that (1) a LRCM designed for bomber platforms would constitute a significant change from the current Tomahawk missile, while (2) a LRCM designed for naval platforms would share enough characteristics of Tomahawk that it might be considered an upgrade to that system.

There are no major technical obstacles to addressing the limitations of the Tomahawk systems. At least one sensor system constitutes mature technology. Likewise, employment of this LRCM on heavy bomber platforms or naval aircraft is an effective means of employment for the roles described. However, if LRCMs are ever to become operational for the Rapid Response role, the Air Force must develop a streamlined and tailored flow of intelligence and planning information and a set of specialist operators with skills that currently do not exist.

Finally, most reasonable budget analyses would agree that LRCMs are fiscally affordable, even in this time of shrinking budgets. Moreover, arms control regimes can be constructed that make LRCMs affordable in this sense. However, LRCMs have been unable
to find an institutional voice within the Air Force and therefore may be viewed as unaffordable in a political sense. The roots of the mismatch between the Air Force and LRCM lie in both objective budget and operational realities, subjective political realities, and perhaps most of all in the Air Force's own view of its role and interests.

Based upon the analysis and discussion in this report, the following policy recommendations are in order, generally aimed at the OSD decisionmaker.

- Because of clear technical and employment differences, development of LR
  airframes and propulsion should be a service, rather than joint, activity.
  Common airframes and propulsion are unlikely to meet either service's needs and
  will serve as a stumbling block to LR progress.
- The Air Force and Navy should jointly pursue development of target-looking
  sensor technologies and the intelligence and mission support equipment required
  to support them. As much commonality as possible in this area would minimize
  the strain on overburdened intelligence and planning assets.
- The terminal sensor technologies discussed in this document are a natural
  upgrade to Tomahawk's capabilities. Even in the absence of an Air Force LR
  program, the Navy should be encouraged to pursue an upgrade to the Tomahawk
  missile as an incremental step in developing and operating LR technologies.
- If the B-2 is not procured or bought in small numbers, the Air Force should be
  directed to develop a LR force along the lines described in this document. It is
  imperative, therefore, that employment options on other aircraft such as the B-52
  or B-1 not be forestalled prematurely by either arms control agreements or
  retirement of aircraft until the B-2 decision is made.
- If the B-2 is procured in numbers, the Air Force should refocus LR development
  efforts toward both longer-term and shorter-range technologies.
  Shorter-range technologies would address the occasional need or desire for the B-
  2 to stand off at short range from terminal defense areas. Longer-term
  technologies could include ongoing development of autonomous search-and-
  recognition technologies for a future in which the B-2 could become less
  survivable.

Some of these recommendations conflict with current reality. In particular, there
appears to be little coordination on these areas that require them most, terminal sensors and
mission planning. LR weapons have a great deal of promise under the circumstances
outlined in this Note. The ability to procure an effective LRCM force depends upon our ability to coordinate effort on a few key developmental and operational areas. Hard work in these areas could result in a substantial enhancement of U.S. military capabilities.
Appendix A

A FRAMEWORK FOR EXAMINING LRCM TECHNOLOGIES AND EFFECTIVENESS

The text of this Note dealt with the question of potential LRCM utility. Having discovered a potentially useful target set for LRCMs, the next major question confronting the LRCM development is technical: What are the technology tradeoffs facing the next LRCM? In the simplest sense, the conventional Tomahawk variants are an existing proof that construction of individual LRCM-type weapons is technically feasible. In this set of appendixes we shall identify the limitations on Tomahawk effectiveness, thus providing the incentive to investigate alternative technologies. These technologies will be identified and their effect on LRCM effectiveness quantified. This appendix describes the analytic framework used to support the discussion in the later appendixes.

Figure A.1 shows the analytic structure used to investigate the linkage between individual LRCM technology subcomponents on one hand and LRCM effectiveness on the other. Given the complexity of both the individual LRCM technologies and their many interactions, the linkage between individual technology components and overall LRCM effectiveness can be extremely difficult to make. Therefore, we shall use a structured approach to the problem, proceeding in several analytic steps from technologies to effectiveness. First, individual LRCM technology components are defined and various subcomponent technology options are described in App. B. These technologies are then combined with notional mission planning systems to generate a set of performance areas. These performance areas are defined and analyzed in App. C. Performance areas are then combined with a given set of operating environments and mission planning systems to generate capabilities, which are discussed in App. D. An understanding of LRCM capabilities leads to an understanding of overall LRCM effectiveness, in terms of force levels necessary to achieve different objectives, which are discussed in App. E.

Such a structure makes what could be an insurmountable analytic task manageable. Even so, the discussion here considerably simplifies the relationships between technologies and their performance measures; generally, only first-order relationships are followed. Whenever possible, footnotes will discuss second-order relationships and effects.

TECHNOLOGIES

The major technology subcomponents of any LCRM are (1) airframe, (2) propulsion,
Fig. A.1—Technologies to effectiveness: analytic framework

(3) terminal sensor, (4) enroute navigation, and (5) munitions. The airframe consists of the actual fuselage of the missile, fuel storage and control systems, and flight control surfaces. The propulsion unit consists of the engine and inlet mechanisms. Enroute navigation are those components of the LRCM’s guidance system devoted to guiding the missile to the target area. The terminal sensor is that portion of the guidance system which aims the missile accurately in the terminal target area. Munitions can consist of unitary warheads or submunitions and their dispensing mechanisms. The LRCM technology components are illustrated below in Fig. A.2. A detailed discussion of technology subcomponents options is found in App. B.

PERFORMANCE AREAS

Each of these technologies can be evaluated in terms of performance areas. As indicated in Fig. A.1, performance areas are an intermediate step between technologies and
Fig. A.2—LRCM technology components

capabilities. Performance areas are specific measurable characteristics that are (1) functions of the various technologies and (2) are direct drivers of LRCM higher-level capabilities. The connection between technologies and performance areas is sometimes clear and sometimes less so. The performance areas are described in Table A.1, and their relation to the five technology components is shown in Table A.2.

The airframe and its components have a clear connection to two performance areas. Through its structural and aerodynamic efficiency, the airframe is the dominant consideration for LRCM structure fraction. In addition, the airframe is a critical element in determining the vehicle's observability.\(^1\) The LRCM propulsion unit has as its major characteristic its thrust specific fuel consumption, a measure of fuel efficiency.\(^2\) The terminal sensor has a major effect on the accuracy of the LRCM. In addition, some types of sensors can be used to affect the flight altitude of the cruise missile. Finally, the terminal sensor is the component most susceptible to weather and other environmental effects.\(^3\) The major effect of enroute navigation is on the flight altitude of the cruise missile. Finally, the type of munition is the determinant of payload effects.

The key concept in examining the linkage between performance measures and technologies is the fact that individual technology components can have effects on several different performance areas. The motivation for approaching the technology effectiveness analysis in several steps is to make this linkage less complex for any one step.

\(^1\) In addition, the maneuverability inherent in the airframe design can affect the flight altitude of the cruise missile by limiting its ability to react to obstacles. In general, we will assume a relatively unmaneuverable airframe for this analysis.

\(^2\) The thrust generation ability of the engine can affect the flight altitude of the missile by limiting maneuverability in much the same way as the airframe. This effect is not considered here.

\(^3\) Some sensors emit radar energy. Others may need windows or optics that are strong reflectors of radar energy. These potential effects on the vehicle's observability are ignored here.
Table A.1
LRCM Performance Areas

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrust specific fuel consumption:</td>
<td>A measure of fuel efficiency of the LRCM propulsion. Pounds of fuel used per hour per pound of thrust.</td>
</tr>
<tr>
<td>Structure fraction:</td>
<td>A measure of the structural efficiency of the LRCM airframe. The fraction of total missile weight not devoted to payload and fuel.</td>
</tr>
<tr>
<td>Flight altitude:</td>
<td>The altitude at which the LRCM can fly enroute to the target area.</td>
</tr>
<tr>
<td>Weather resistance</td>
<td>The susceptibility of the terminal sensor to weather and other environmental factors.</td>
</tr>
<tr>
<td>Observability:</td>
<td>The visible, radar, and infrared signature of the LRCM.</td>
</tr>
<tr>
<td>Accuracy:</td>
<td>The “circular error probable” (CEP) of the LRCM, defined as the radius around the target within which the LRCM will land 50% of the time.</td>
</tr>
<tr>
<td>Payload effect:</td>
<td>The type and radius of effect of the LRCM's munition payload. This includes questions of the absolute size of the payload and the different effects unitary and submunition payloads.</td>
</tr>
</tbody>
</table>

Note also the important part that mission planning plays in generating in this structure. Although the mission planning function is not treated as an individual LRCM technology component, it has a critical effect on two important performance areas, flight altitude and accuracy. Mission planning is involved in the flight altitude of the cruise missile because some prior knowledge of the terrain enroute to the target is required for any low-flying LRCM. Mission planning is required to achieve high accuracy because an image of the target or the immediate target area is a necessary element for terminal sensor systems. Displaying and properly formatting terrain data and terminal image data are the two key functions of the mission planning systems at this point. LRCM performance measures are assessed in App. C.
Table A.2
LRCM Technologies and Related Performance Areas

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Performance Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airframe</td>
<td>Observability</td>
</tr>
<tr>
<td></td>
<td>Structure fraction</td>
</tr>
<tr>
<td></td>
<td>Specific fuel consumption</td>
</tr>
<tr>
<td>Propulsion</td>
<td></td>
</tr>
<tr>
<td>Terminal sensor</td>
<td>Accuracy$^a$</td>
</tr>
<tr>
<td></td>
<td>Flight altitude$^a$</td>
</tr>
<tr>
<td></td>
<td>Weather resistance$^a$</td>
</tr>
<tr>
<td>Enroute navigation</td>
<td>Flight altitude$^a$</td>
</tr>
<tr>
<td>Munition$^a$</td>
<td>Payload effect</td>
</tr>
</tbody>
</table>

$^a$ Depends additionally on mission planning.

CAPABILITIES

The performance measures discussed above are an analytic step between technologies and higher-order LRCM capabilities. There are five major LRCM capabilities: (1) range/payload, (2) availability, (3) reliability, (4) survivability, and (5) lethality. Any given LRCM will operate on a range/payload tradeoff curve; more payload implies less range. Availability is the likelihood that the LRCM will be available for a given mission, which will be determined by the availability of the platform carrying the LRCM and the ability of the LRCM to operate under prevailing conditions. Reliability is the likelihood that the LRCM will perform its mission without critical mechanical failures. Survivability is the likelihood that the LRCM will reach the target without being shot down. Lethality is the likelihood that the LRCM will destroy the target when it lands.

Capabilities are the level at which one can generally see a clear linkage to LRCM effectiveness, in that a serious failure of any one of them will clearly result in an ineffective LRCM. The LRCM's range/payload relationship defines those targets it is capable of attacking from any given launchpoint. Availability will determine how often a given set of missions can be feasibly performed. Reliability, survivability, and lethality will determine the likelihood that an individual LRCM will actually destroy the target when launched. Capabilities are dependent on a number of factors, only some of which are technical. The relationships between the performance areas discussed above and the five LRCM capabilities are summarized in Table A.3. Note that in addition to the performance areas noted above, other largely nontechnological factors help to determine LRCM capabilities. These factors are related to the operational environments discussed in previous sections. In fact,
capabilities can only really be measured in terms of a specific set of operating environments, such as those discussed in Sec. II. LRCM capabilities are analyzed in App. D.

<table>
<thead>
<tr>
<th>Capabilities</th>
<th>Performance Areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range/Payload(^a)</td>
<td>Specific fuel consumption</td>
</tr>
<tr>
<td></td>
<td>Structure fraction</td>
</tr>
<tr>
<td></td>
<td>Flight altitude</td>
</tr>
<tr>
<td>Availability(^a)</td>
<td>Weather resistance</td>
</tr>
<tr>
<td>Reliability</td>
<td></td>
</tr>
<tr>
<td>Survivability(^b)</td>
<td>Flight altitude</td>
</tr>
<tr>
<td></td>
<td>Observability</td>
</tr>
<tr>
<td>Lethality(^c)</td>
<td>Accuracy</td>
</tr>
<tr>
<td></td>
<td>Payload effects</td>
</tr>
</tbody>
</table>

\(^a\)Depends additionally on platform constraints.
\(^b\)Depends additionally on air defense environment and mission planning.
\(^c\)Depends additionally on target types.

MEASURES OF EFFECTIVENESS

The five capabilities can be combined to generate comparative measures of LRCM effectiveness. The foundation of these effectiveness measures is a model of successful attack on a target by a LRCM based upon an evaluation of the LRCM's capabilities. Two of the capabilities discussed above, range/payload capability and availability, essentially determine whether a given LRCM attack is feasible, and these capabilities revolve around a small set of sensor and platform availability issues. As such, these issues lead to essentially binary outcomes in any given situation: the platform is available or it isn't; the weather is suitable or it isn't. Therefore, platform availability and range/payload capability (which are heavily interdependent) are discussed separately, as is the issue of LRCM weather resistance and availability.

If one postulates a situation where the attack is feasible (i.e., the platform is available, the LRCM has sufficient range, and the launch conditions are suitable), the outcome of a given attack will depend on the reliability, survivability, and lethality of the individual missiles and the number of missiles delivered. The particular risk taxonomy for an individual missile is shown below in Fig. A.3. By nature these failure modes are generally
sequential and therefore conditional. As such, they can correctly be multiplied together to generate an overall probability of success, as shown in the figure.

\[ P_K = P_{\text{rel}} \cdot P_{\text{surv}} \cdot P_{\text{leth}} \]

Fig. A.3—Individual missile success probability

Given such a taxonomy of risk for a single missile, a formulation of the "successful" quantity for attack presents itself. It requires that a level of confidence or damage expectancy be fixed.\(^4\) The number of missiles needed to achieve this chosen damage expectancy can be designated as a "successful" quantity. The formula that describes such a quantity is given below in Fig. A.4. Such a formulation is an extremely common one and is easily derived.

The equation above allows one to examine the effect of differing weapon capabilities on total forces required to attack different types of targets and target sets. This LRCM effectiveness metric, \textit{weapons required per target destroyed}, can be used either as a comparative metric between LRCMs or as a means of generating a force size requirement at a given level of target damage confidence. It is clear, however, that there are some hidden assumptions that drive the formulation and the results of the equation. In terms of

\(^4\) This is so because the individual components of the denominator are less than one. A damage expectancy less than one must be chosen or the expression is meaningless (it yields an infinite number of weapons required).
\[ P_D = 1 - (1 - P_R)^{N_w} \]
\[ N_w = \frac{\ln(1 - P_D)}{\ln(1 - P_R)} = \frac{\ln(1 - P_D)}{\ln(P_F)} \]

where
\[ N_w = \text{Number of weapons required} \]
\[ P_D = \text{Desired probability of destruction} \]
\[ P_R = \text{Single-shot probability of destruction} \]
\[ P_F = \text{Single-shot probability of failure} \]

**Fig. A.4—A formula for successful attack**

assumptions, it is very clear that the choice of confidence level can seriously increase force requirements at some point. This conclusion derives from the fact that each marginal missile allocated to the target is facing a diminishing expectation, and very-high-confidence attacks can drive the allocation far down this diminishing curve. In terms of outputs, an implied but not immediately obvious result of the equation is that fractional missiles can be sent to a target. This occurs if the missile single-shot probability of destruction is higher than the desired damage expectation, or if the desired damage expectation is not some integer power of the single-shot probability of destruction. Such a result is clearly unreal: a “half order of LRCM” cannot be bought at the military supply counter.

Figure A.5 shows several different ways of viewing the formulation of successful attack shown above. The smooth curves show the simple outputs of the equation for three different single-shot probability of destruction levels. When graphed against a rising desired damage expectation, these curves are monotonic and bear a straightforward relation to one another. One result of such a formulation is that a missile with a higher individual probability of destruction will always require fewer weapons to achieve the desired damage expectation.

The bars in Fig. A.5 are based upon the same calculation, but in this instance the results have been integerized by rounding up to the next whole number of missiles. In this case, we see that the simple relationships between the curves have been destroyed. At low damage expectations, missiles with widely differing individual probability of destruction are identical in terms of their weapon requirements. At higher damage expectations, the differences depend largely upon edge effects in the calculations, with weapons requirements changing in leaps as the damage expectation passes a threshold value.

Finally, the arrowed line in Fig. A.5 represents a simple heuristic such as might be applied by a real commander. This “rule of thumb” causes the commander never to send fewer than two weapons to any one target. The basis for such a heuristic could be, for
example, an availability bias. The commander can easily imagine circumstances that would lead to the failure of one weapon, but has more difficulty envisioning the separate failure of two weapons. More charitably, the commander may simply be trying to lower the variance of his outcome. He can lower his standard deviation by roughly one-third by sending the second missile.

Figure A.5 has several implications. First, given reasonable estimates of the reliability, survivability, and lethality for individual missiles, one can readily calculate the number of missiles required to achieve a given confidence of success for an attack against an individual target. However, the simple formulation of successful attack quantities cannot be applied directly to effectiveness. First, integer effects must be taken into account, which can destroy consistent relationships between missiles with differing individual effectiveness. Similarly, reasonable rules of thumb should be investigated to determine their effect on weapon requirements. These concepts are applied in App. E, which evaluates the LRCM force requirements versus a notional target set.
Appendix B
POTENTIAL LRCA TECHNOLOGIES

The analytic framework in App. A was discussed in some detail in order to give a
linkage from the discussion of LRCA technologies to capabilities and effectiveness. This
appendix will focus on the first element in this framework: potential subcomponent
technologies of the next LRCA. Figure B.1 shows the five major classes of LRCA
subcomponents: (1) airframe, (2) propulsion, (3) enroute navigation, (4) terminal sensor, and
(5) munitions. For each of these subcomponent classes, we will examine specific technical
options that have been proposed for use in LRCA designs. This includes a description of the
currently existing LRCA, the Tomahawk Land Attack Missile (TLAM).

![Diagram showing five LRCA technology classes: Terminal sensor, Munition, Airframe, Enroute navigation, Propulsion]

Fig. B.1—The five LRCA technology classes

THE TOMAHAWK LAND ATTACK MISSILE: TLAM-C/D

In terms of current and deployed technologies, the United States has only one land-
attack system in its inventory that can be classified as an LRCA, the Tomahawk Land
Attack Missile (TLAM). A large number of the unitary-warhead TLAM version (TLAM-C)
have been procured, and procurement is in the initial stages for the variant of Tomahawk
that is equipped with a submunitions dispenser (TLAM-D). Both TLAM-C and TLAM-D are
sea-launched cruise missiles, deployed on surface naval and submarine platforms.
The Tomahawk-class cruise missiles are an impressive mix of technologies.\(^1\) The airframes for all Tomahawks are circular and are built largely out of cored aluminum sections. The primary lift surfaces are two fixed-aspect, center-mounted wings, and control is accomplished by movable tail fins. Before and immediately after launch, the wings are folded into the center of the missile and the tail fins are folded flat against the missile; after launch, both the wings and the tail surfaces spring into position. In order to minimize potential center-of-gravity changes as fuel is depleted, the Tomahawk has a fairly sophisticated fuel-management system. In terms of airframe observability, selective application of radar absorbing material (RAM) is purported for TLAM in order to lower its radar cross section.\(^2\)

TLAM-C and TLAM-D are powered by a Williams turbofan engine, the F107-WR-400, which combines the characteristics of low weight (roughly 140 pounds), compactness, fuel efficiency, and reasonable thrust (600 pounds). The turbofan engine uses an inlet on the underside of the airframe. Like the wings and tail surfaces, the inlet lies flush until after launch. In addition to the turbofan, TLAM is provided with a solid rocket booster, which boosts the missile up to speed, whereupon the turbofan engine takes over propulsion. The solid rocket booster is not a simple piece of equipment. It is designed so as to provide variable thrust levels at different distances from the launch platform. In addition, the booster includes thrust vector controls in order to change the pitch of the missile for different launch conditions.

The conventional TLAM variants both carry roughly 1000-pound payloads. The TLAM-C carries a unitary conventional warhead, the Bullpup. The Bullpup is an older warhead that was drawn out of inventory to put into TLAM. The TLAM-D carries a dispenser that dispenses clusters of Combined Effects Bomblet (CEB) submunitions. The dispenser system is a fairly complicated piece of equipment. It ejects submunitions, in up to three separate bursts, with an explosive gas ejection system. In addition, it maintains the TLAM's short-term flight capability by filling in ejected side panels with a fabric surface, enabling the TLAM-D to attack different targets with each burst of submunitions.\(^3\)

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\(^1\)The sources for physical descriptions of the Tomahawk missile are "Sea Launched Cruise Missile," *DMS Market Intelligence Report*\(^\text{®}\), DMS Inc., 1987, and "Sea Launched Cruise Missile," Briefing Presentation 06036164, General Dynamics Corporation, Convair Division.
\(^3\)"Sea Launched Cruise Missile," Briefing Presentation 06036164, General Dynamics Corporation, Convair Division.
Cruise missiles fly at subsonic speeds, a fact that results in some useful and some less than useful characteristics. One less than useful characteristic is that the Tomahawk's inertial guidance system has more time to generate position errors than would a faster-flying missile. Therefore, navigation to the target area for Tomahawk is provided by an inertial navigational unit (INU) aided with periodic positional updates utilizing the Terrain Contour Matching (TERCOM) system. TERCOM is a system that uses a radar altimeter to measure terrain features along its flight path and correlates these measurements with internally stored digital maps. The system is in current use on both the TLAM and ALCM cruise missiles.

Given continuous terrain data and time to correlate it, TERCOM systems could resolve the missile position to within tens of meters. However, the system is not employed in this mode for two reasons: first, the amount of terrain data and computation required is beyond the TLAM or ALCM data-handling capabilities; second, not all terrain is useful for TERCOM. In particular, ocean scenes or scenes of flat or gently rolling ground can be difficult or impossible to match. Because of these limitations, current TERCOM navigation systems use preselected patches of terrain in which they perform the correlations and correct the missile heading. The missile is programmed to fly from patch to patch, utilizing the INU system for the navigation between scene-matchings. Using this procedure, TERCOM/INU systems can resolve the missile's position to within tens of meters, with uncertainty as to position rising with the amount of time since the last update. The planning requirements for TERCOM are significant. Digital databases of terrain must be gathered using Defense Mapping Agency assets and analysis. These data must be prepared and loaded into the correct missiles at the correct time, along with planned flight routes incorporating them.

The conventional TLAM variants are equipped with terminal-area guidance, provided by a Digital Scene Matching Area Correlation (DSMAC) system. DSMAC updates the position of the missile by matching a stored visible-light image to a series of visible-light images sensed in flight. The DSMAC scenes are prepared from photographs of the area near the target. The greater resolution of the visual image allows for more accurate updates than those available from the coarser TERCOM, and the proximity of the scenes to the target does not allow navigator errors to rise to inordinate levels. Along with warhead type, the

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4 TERCOM-compatible terrain must have sufficient variation (roughness) to register on the altimeter. In addition, it must have the quality of "uniqueness", that is, a missile flying over an area with a given initial error must be able to find a unique best position correlation. It is the uniqueness requirement that makes TERCOM-compatible terrain relatively scarce. See Charles A. Baird and Mark R. Abramson, A Comparison of Several Digital Map-Aided Navigation Techniques, The Harris Corporation, IEEE Publication CH2110-5/84/0000-0286, IEEE, 1984.
terminal-area DSMAC system is the main technical feature that distinguishes the conventional and nuclear TLAM variants.

The planning required for a DSMAC system is substantial. It requires photographs in the target area, which can be difficult to gather. Because it is a visible-light sensor, DSMAC has some serious limitations in bad weather. As with TERCOM, certain types of scenes will, because of statistical concerns, be difficult to match, further complicating the planning process.

Block III Tomahawk

The Tomahawk system has been the subject of a consistent and planned block upgrade program. The next upgrade is Block III, which will feature some substantial changes in the missile. First, the Williams F107-WR-400 engine will be replaced by an upgraded Williams turbofan, the F107-WR-402. The F107-WR-402 will have higher thrust and a slightly lower specific fuel consumption than the F107-WR-400.

Both enroute navigation and terminal guidance will be upgraded. The current TERCOM/INU navigation system will be supplemented by the addition of a Global Positioning System (GPS) receiver. GPS is a system of satellites that broadcast a continuous positioning signal. Using signals from several of these satellites, a vehicle can resolve its position to within roughly 15 meters. A GPS receiver is relatively inexpensive and is used only as a supplement because of concern over potential jamming of the GPS signal. The current DSMAC terminal guidance system will be upgraded to DSMAC II. DSMAC II involves both a wider field-of-view optical sensor and a software upgrade that allows a wider range of terminal scenes to be utilized. Even the payload of the TLAM-C will be upgraded with a smaller reactive-casing warhead. The reactive warhead makes use of the fact that the casing material vaporizes and explodes, creating a bomb with more blast for any given weight. In this analysis, we assume that the new, smaller warhead will have similar blast to the current TLAM warhead, and that its smaller size allows more fuel to be loaded on the missile. Three versions of Tomahawk—nuclear, conventional, and Block III conventional—are shown in Fig. B.2.5

AIRFRAME TECHNOLOGIES

The Tomahawk class of cruise missiles was developed with the requirements of submarine launch in mind. Submarine launch requirements place an unusually high

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amount of stress on airframe design, due both to differential underwater pressures and lateral shock requirements placed on all submarine ordnance. As a result, the airframe of each Tomahawk missile is constructed from cored aluminum sections, comparable in design to the space shuttle solid rocket boosters. In addition, the TLAM missile was developed in the 1970s and reached initial production in the early 1980s, before the advent of serious application of low-observables technologies. The advanced cruise missile (ACM) design clearly incorporates elements of signature reduction that are lacking in the TLAM and its time-counterpart, the air launched cruise missile (ALCM). The two obvious differences from Tomahawk that the next LRCM could exhibit are a lighter airframe and/or application of low-observables technologies. Each is discussed below.

Lighter Airframe

The first basic alteration to the airframe of the next LRCM could be an attempt to lighten the airframe. Two basic approaches present themselves: (1) lessening of airframe
strength constraints while utilizing standard airframe materials, and (2) maintaining current strength constraints while utilizing new materials. Lowering overall airframe strength constraints would eliminate the possibility of submarine launch and limit the next LRCM to air or surface launch.

Alternatively, lighter high-strength composite materials could be utilized in the design of the airframe without relaxing the airframe strength requirements. Application of composite material technologies to cruise missile design is a reasonable step; composite materials are used increasingly in aircraft design. However, an airframe utilizing composite materials would be unlikely to prove less expensive than the current Tomahawk design and could be significantly more expensive. As indicated in Fig. A.1, a change to a lighter airframe could alter the potential range-payload capability of the LRCM by way of increasing structure fraction performance.

**Stealthy Airframe**

The Tomahawk airframe is, by its very nature, a fairly small and difficult target for air defenses to shoot down. In addition, some measures have been taken to lower the Tomahawk's radar cross section (RCS), such as the application of radar absorbing materials. However, a simple comparison of the Tomahawk airframe and the ACM airframe makes it clear that the Tomahawk does not incorporate all possible measures to reduce its observability. The next LRCM could take advantage of advances in the design of low-observable missiles.

The application of stealth technologies to LRCMs will probably result in a higher airframe weight, conflicting with the lighter airframe option discussed above. The most straightforward approach to stealth, application of radar absorbing materials (RAM) to the outer surface of the airframe, has been widely associated with aerodynamic weight penalties. In addition, many of the airframe-shaping techniques used to lower cross section (e.g., the chines along the length of the ACM, masked engine inlets and outlets) would reasonably result in a higher airframe weight. In addition, low-observable technologies as applied to ACM have been associated with significantly higher missile unit costs. The costs associated with all technology subcomponents are discussed in the main text.

**PROPULSION TECHNOLOGIES**

The current Tomahawk cruise missiles use the Williams F 107-WR-400 turbofan engine. The turbofan engine draws air into the engine through an inlet and splits the airflow into two separate components. The first and smaller part is compressed with a series
of high-compression turbines. The highly compressed air is then mixed with fuel and burned to generate energy. Part of the generated energy is exhausted through a nozzle in the rear of the engine, producing some thrust. The rest of the energy is used to turn a series of low-compression turbines, the largest of which is termed the "fan." The fan and its associated compressors direct the larger part of the airflow around the engine through bypass ducts. In this sense, these lower-pressure turbines act like an internal propeller. A propeller is a more efficient method of propulsion than simple burning and exhaust of the gases, and in general, the higher the fraction of air that passes through the bypass ducts, the higher the propulsive efficiency. The F 107-WR-401, scheduled for use in the Tomahawk Block III, is an upgrade to the F 107-WR-400, with similar TSFC and slightly more thrust. There are two potential directions for LRCM technology to take: a cheaper, less efficient engine or a more expensive, more efficient engine.

**Turbojet Propulsion**

Less complex and less fuel efficient than the turbofan, the turbojet differs from the turbofan in that it lacks the bypass fan and its associated ducting and nozzles. Therefore, all of the air drawn into the turbojet passes through the combustion chamber and is burned with fuel. These differences, in general, will make the turbojet a less fuel-efficient engine than the turbofan but should also make it somewhat less expensive (based on lower complexity). The JCAE 372-11A (built by Teledyne CAE) is an existing turbojet design with comparable weight and diameter to the turbofans above.

**Propfan Propulsion**

At the other end of the scale, a more complex and more fuel-efficient engine design is the propfan. The propfan differs from the turbofan in that the propulsive mechanism is a series of exterior propellers. The air drawn into the engine is burned to supply energy to power turbines, which in turn power the propellers. The propfan is more fuel efficient, as it is essentially an extension of the turbofan. Since the propellers are in the airstream outside the missile, the propfan is essentially a much higher bypass or unducted turbofan.

Propfan designs are generally more complex than turbofans in that they require linkages to propellers and often require the propeller blades to fold flat for storage and launch. Current small propfan designs are in the initial stages of testing and evaluation, and their development and production costs would be higher than either the turbofan or turbojet engines. Figure B.3 gives schematic views of the three types of engines and their differences.
ENROUTE NAVIGATION TECHNOLOGIES

Cruise missiles such as the next LRCM have times of flight on the order of hours. This poses a problem for navigation enroute to the target. Use of an inertial navigation system alone is not possible, and LRCMs must supplement such a system with other navigational methods. The navigation system can potentially affect the survivability of the cruise missile through the flight altitude performance of the LRCM.

Inertial Navigation Systems

Inertial navigation systems (often termed inertial measurement units, or IMUs) are among the most mature of navigation technologies. They constitute the basic navigation system for most advanced weaponry, including ships, planes, submarines, and intercontinental missiles. Their application to cruise missile navigation was, therefore, a natural step. INS systems operate through use of gyroscopes and accelerometers, measuring turn rate and speed by the differential effects on these subsystems. Use of laser measurement techniques and high-precision gyros has enabled INS systems to become much more accurate over time.

The precision of an INS is characterized by its drift rate over time. An INS, even one that is carefully calibrated, will show some drift in its assumed position from its real position over time as small errors in measurement, anomalies in spin, and distortions in earth gravity and magnetism make themselves felt. A subsonic, cruise missile LRCM will have a flight duration anywhere from one half hour to several hours. A reasonably accurate IMU will have a drift rate corresponding to 0.1 degree per hour. An extremely accurate IMU will have a drift rate of 0.01 degrees per hour at a substantial cost penalty.

Terrain Contour Matching

Terrain Contour Matching (TERCOM) is a system that uses a radar altimeter to measure terrain features along its flight path and correlates these measurements with
internally stored digital maps (see Fig. B.4 for an illustration of this concept). The system is in current use on both the TLAM and ALCM cruise missiles.

Given continuous terrain data and time to correlate it, TERCOM systems could resolve the missile position to within tens of feet. (Such a system is discussed below: see the subsection on Terrain Referenced Navigation.) However, the system is not currently employed in this mode for several reasons: First, the TERCOM set of algorithms were the first explored and utilized. Second, the amount of data storage and processing required is beyond TLAM or ALCM data-handling capabilities. Finally, not all terrain is useful for TERCOM. In particular, ocean scenes or scenes of flat or gently rolling ground can be difficult or impossible to match with the TERCOM algorithm.

Because of these limitations, current TERCOM navigation systems use preselected patches of terrain in which they perform the correlations and correct the missile heading. The missile is programmed to fly from patch to patch, utilizing the IMU system for the navigation between scene matchings. Using this procedure, TERCOM/INU systems can resolve the missile’s position to within tens of meters, with uncertainty as to position rising with the amount of time since the last update. The planning requirements for TERCOM are significant. Digital databases of terrain must be gathered using Defense Mapping Agency assets and analysis. These data must be prepared and loaded into the correct missiles at the correct time, along with planned flight routes incorporating them.

**Terrain Referenced Navigation**

Terrain referenced navigation (TRN) is essentially the logical extension of the TERCOM navigation system. TRN systems attempt to update the position of the cruise missile nearly continuously with reference to the terrain underneath it, as opposed to the patch-to-patch TERCOM method. In addition, TRN algorithms are generally somewhat different from TERCOM in their specific approach to the update problem. In addition, TRN systems attempt to avoid the terrain preparation and validation procedures currently in use for TERCOM; instead, TRN uses basic digitized terrain elevation data (DTED), which is more widely available than TERCOM maps. Aside from algorithm and software differences, the equipment used for TRN is little different from TERCOM. Both methods use a radar altimeter and some processing as their primary hardware components.

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Global Positioning System

The Global Positioning System (GPS) is currently in the final stages of implementation. It consists of a constellation of satellites that emit a continuous time signal.\(^7\) An antenna receiver on the cruise missile picks up the signals of several satellites, and the signals are used to calculate position and velocity. Currently, the projected position accuracy of a GPS-equipped system is roughly 15 meters. GPS is a planned upgrade for the Tomahawk missile in its Block III modification. Given the relatively inexpensive antenna required for GPS, it will almost certainly be included on any new LCM.

The primary concern for GPS navigation is its susceptibility to line-of-sight noise jamming of the GPS receiver. The GPS satellite signal is roughly 6 db in the native noise when it reaches the receiver, so the receiver must do a significant amount of processing to receive the normal GPS signal. If the noise is significantly increased with a jammer, the signal may become indistinguishable, in which case a backup IMU system must take over. This jamming, if present, is likely to be intermittent, but the possibility of it requires the presence of a reasonably accurate IMU.

TERMINAL SENSOR TECHNOLOGIES

Terminal sensor choices can affect many different areas of LRCM capabilities. The lethality of the missile is affected through terminal accuracy performance. Survivability may be affected through flight altitude performance, and availability can be affected through weather robustness performance. In addition, terminal guidance and sensors are traditionally a high fraction of the total cost of conventional missiles. The choice of a sensor, therefore, could be critical for the next LRCM. The DSMAC guidance system used on the Tomahawk missile is described above; the other sensor choices discussed here are (1) a passive imaging infrared (IIR) system, (2) a CO2 laser radar (LADAR) system, and (3) a synthetic aperture radar (SAR) system.

Passive IIR Terminal Sensor

Passive IIR sensors utilize the infrared (heat) energy emitted from targets as their detection mechanism. Imaging infrared sensors differ from simple infrared sensors in that they build up a pixelated image of the scene. This is generally accomplished by rapidly sweeping a small row of infrared detectors across the field of view angle of the sensor. With each sweep of the sensor array, an image is built of the scene. Imaging infrared sensors are currently deployed on several missiles, including the Maverick anti-tank system.

The primary difference for LRCM applications of passive IIR is that the terminal guidance must be autonomous. The Maverick missile, for instance, displays the infrared image to a human operator, who identifies the target and locks the missile onto it. For LRCMs, the passive IIR terminal guidance system would use a series of contrast templates to match the target scene. These templates would be based upon elements of the target that have contrasting infrared emissivity. The degree of contrast (above a sensitivity threshold) need not be known beforehand, but the fact that a contrast is likely to exist should be known. The basis for this template will almost certainly have to be a photograph of the target that has sufficient resolution to identify and differentiate between separate target elements. Ideally, a far-field picture and a close-up picture are desired, in order to "nest" templates and further improve the probability of lock-on and accuracy.

Since the passive IIR sensor differentiates objects on the basis of differing infrared emissivity, while the photograph is based upon differing reflectivity of visible light, an operator must identify the types of surfaces and materials present in the photograph(s) and estimate (with the aid of a planning system) the expected contrast image of the scene. This will require a digitized photograph and an interactive workstation with image processing capabilities. Figure B.5 shows an example of a notional passive IIR contrast template.
Passive IIR technologies are widely considered to be the terminal imaging system with the lowest cost and associated risk. This is based upon the fact that similar systems are currently in flight on existing missile platforms.

![Actual scene](image1.png) ![Passive IIR contrast template](image2.png)

**Fig. B.5—Passive IIR prepared terminal image**

**CO₂ Laser Radar Terminal Sensor**

A CO₂ laser radar (LADAR) sensor operates by scanning a coherent laser beam over the target area, building a three-dimensional image of the scene using the reflected energy. The CO₂ laser emits energy at 10.6 microns, which is in the same infrared regime as the passive IIR system discussed previously. The LADAR beam is scanned through the use of a gimballed mirror, and the detection of reflected beam is done in much the same manner as the passive IIR system. However, the additional range information provided by the LADAR system means that the processing and scene-matching algorithms are much different.

Since the LADAR provides a three-dimensional image of the target area, the reference scene that it matches to must also be three-dimensional. This is accomplished through the use of image workstations, which allows an operator to draw pseudo three-dimensional outlines of the major target objects. Figure B.6 shows an example of a notional LADAR template.

The LADAR system described here has been under development for a number of years in the Air Force's Cruise Missile Advanced Guidance (CMAG) program. Recently, it had

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become a part of the Advanced Terminal Laser Seeker (ATLAS) program. Although it uses some of the same infrared optics and detectors as the passive IIR system, the LADAR is expected to be quite a bit more expensive, based upon the cost of the laser and the power and cooling it requires. In addition, the LADAR is generally considered the least mature (in technical terms) of the seeker options discussed here, since it has not been utilized in any form in any operational system to date. However, the LADAR has some distinct advantages in terms of the predictability and stability of the three-dimensional terminal scene.

![Actual scene](image1) ![LADAR 3-D template](image2)

Fig. B.6—LADAR prepared terminal image

**Synthetic Aperture Radar Terminal Sensor**

Synthetic Aperture Radar (SAR) is an established method by which a high-frequency radar can be used to generate a high-resolution image of an area. This is accomplished by means of both the waveform of the radar and processing of the reflected radar signal. The SAR generates an image that is not a picture of the scene in the same sense as passive IIR and LADAR images; instead, the SAR produces outputs that give intensity as a function of range and the Doppler shift of the returned signal. This essentially translates to an “overhead view” on a SAR template. The basic principles upon which SAR is based also

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prevent one from viewing SAR images directly in front of the missile. The "squint" angle off the nose of the missile would cause a missile to fly a curved path toward the target.

The reflection of radar energy off a target is significantly different from that of visible or infrared energy. The SAR energy coming from the target would tend to be strongest from edges and from objects that act as reflectors or "glitter points." Hence, the template generated for a SAR sensor could look significantly different from that generated for either of the other sensors. A major difficulty for SAR is that significant radar scatterers are not always readily apparent in the visible image. Given this, the transformation process from a photograph to the SAR image is conceptually far more difficult than the transformation from a visible photograph to a passive IIR or LADAR template.\footnote{See Guidance Sensor Technology Options, The Analytic Sciences Corporation, SP-5175-14, December 1988.} Figure B.7 shows a notional SAR terminal template.

![Actual scene vs. SAR template](image)

**Fig. B.7—SAR prepared terminal image**

SARs have been flying in aircraft for some time, but they have not been demonstrated in a constrained-size vehicle such as a LRCM. For this reason, they are less mature than passive IIR but somewhat more mature than LADAR technology. Their major advantage is all-weather capability, while major potential drawbacks are the scene-preparation discussed above and potential observability problems from the active SAR radar beam.

**MUNITIONS TECHNOLOGIES**

The munitions technologies for the next LRCM break down into two basic categories: unitary payloads and submunition payloads. Unitary payloads derive most of their effect
from blast damage. If other effects are desired, a tailored submunition payload is almost always the desired option.

Unitary Payloads

There are three major unitary payloads investigated in this Note: (1) standard high-explosive (HE) warheads, (2) more advanced reactive warheads, and (3) fuel-air explosive (FAE) warheads. The effects of these warheads are discussed in Sec. V; what follows is a short description of the technologies involved.

Ordinary high-explosive warheads are the staple of our armed forces. The Tomahawk uses an older bomb, the Bullpup, which was taken from inventory for use as the warhead in the TLAM-C missile. The Bullpup is a good example of the general class of high-explosive bombs. It weighs roughly 1000 pounds, of which 50 percent is high explosive and 50 percent is casing and fuzes. The fuzes for normal HE warheads can be set for contact fusing or short delays. The casing for the Bullpup is not hardened for penetration of hard surfaces, such as bridge piers, but such hardening involves a relatively straightforward tradeoff between casing and explosive weight and careful placement of fuzes.

Reactive-casing warheads utilize the explosive nature of some vaporized metals to add to the overall blast of the high-explosive warhead. The warhead detonates in the same manner as a normal HE warhead, but a secondary explosion occurs when the casing vaporizes and detonates. In the case of the Tomahawk Block III warhead, the casing will be made of titanium, although vaporized aluminum also exhibits explosive properties. The negative effects for such a weapon lie in the strength of the warhead for penetrating hard surfaces and in any potential fragment effects that the warhead might have had. In the case of the Tomahawk Block III upgrade, a 1000-pound Bullpup is being replaced with a roughly 700-pound reactive warhead, allowing additional space for fuel carriage.

Finally, fuel-air explosive warheads have recently been in the news, with interest generated by potential Iraqi FAE weapons. Indeed, FAE warheads have long been studied for use as weapons. FAEs work by first dispersing a cloud of liquid vapor from the warhead and then detonating it with a secondary "burst" charge. The advantages of FAE warheads are twofold. First, the explosive fuel in the warhead need not contain its own oxygen; instead, the oxygen is gained from the mixture of air with the fuel when the fuel is

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13 The process is quite complex. The secondary charge is generally equipped with a high-drag casing and ejected from the weapon shortly before the cloud is dispersed. The secondary charge then flies into the cloud as it is dispersing and detonates it. See Louis Lavoie, "Fuel Air Explosives, Weapons, and Effects," Military Technology, No. 9/89, September 1989, pp. 64-70.
vaporized and spread in a cloud. This, combined with the lower warhead casing strength requirements, constitutes a savings in weight of roughly 50 percent over conventional explosives, which must contain their oxygen within their chemical structure. Second and more important, FAEs detonate roughly simultaneously over a large area, allowing more explosive impulse to be transferred to targets in the area. These effects are discussed at length in Sec. V.

Unfortunately, FAE warheads have a number of significant weaponization difficulties, generally related to the proper formation and detonation of the fuel cloud. FAE fuels are by definition unable to detonate in their initial state, since they do not contain internal molecular oxygen. When detonation occurs, the source of oxygen is the air that has mixed with a vaporized cloud of fuel. If too little oxygen is present (the cloud is too small), deflagration can take place instead of detonation, greatly lowering the amount of blast energy generated. If too much oxygen is present (the cloud is too large), incomplete detonation can occur, again lowering the blast energy generated. This places a great deal of importance on the timing of the secondary burster charge and the proper dispersal of the cloud with the initial charge. The dispersal of the cloud from an irregularly shaped cruise missile moving at roughly 500 miles per hour is not well-understood. The outcome can be affected by winds and humidity. Overall, while FAE warheads will almost certainly continue to be investigated, high explosives will almost certainly continue to be used for the next LRCM unitary payload.

Submunition Payloads

When specialized or wide-area effects are required, submunition payloads are generally required. The Tomahawk missile is capable of carrying a submunition dispenser that dispenses up to 220 fragmentation bomblets in three separate releases. The dispenser system is very complicated. It ejects submunitions in up to three separate bursts by an explosive gas ejection system. In addition, it maintains the missile’s short-term flight capability by filling in ejected side panels with a balloon surface, enabling the TLAM-D to attack different targets with each burst of submunitions. This entire process requires precise packaging, precise measurement of ejection charges, and precise timing, all of which can be quite expensive.

The submunition payload in the TLAM-D is the Combined Effects Bomblet, a small cylindrical munition that combines a shaped charge with fragment and incendiary effects.
Figure B.8 shows a cross section of the CEB. Upon release of the CEB, the retarding air chute pops free to orient the bomblet downward. When the bomblet strikes, the detonation of the explosive simultaneously fires the shaped charge jet downward and the preformed fragments outward. The magnesium incendiary with the explosive provides an additional incendiary effect.

Fig. B.8—Combined effects bomblet

In addition to fragmenting submunitions such as the CEB, a specialized airfield attack submunition has long been advocated for LRCM weapons, the Boosted Kinetic Energy Penetrator (BKEP). BKEPs are submunitions designed to crater airfield runways and taxiways. Their particular design is based upon the difficulties one faces when attacking the flat, hardened surface of an airfield runway. If the angle of the weapon as it strikes the surface of the runway is too shallow, the weapon tends to either ricochet off the surface or

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14 Based on diagram from “Sea Launched Cruise Missile,” Briefing Presentation, General Dynamics Corporation, Convair Division.
"broach," which involves a short flight underground followed by reemergence. These effects can be counteracted to some extent by slowing the weapon down and tipping it over somewhat. But if the weapon is released from low altitude, such as might be the case for a cruise missile delivery, it can be extremely difficult to slow and tip the weapon enough to avoid ricochet and simultaneously maintain enough speed to breach the surface of the runway.

The BKEP overcomes these problems with two distinct steps. When it is dispensed, the BKEP deploys a parachute from the rear, which acts to brake it and tip it over to a steep angle. When a preset angle has been reached, a rocket booster accelerates the BKEP into the runway, whereupon an explosive charge detonates and creates a crater. This process avoids ricochet, maintains enough speed to breach the runway, and creates a crater that is difficult to repair because the blast source is underneath the runway's concrete surface. Figure B.9 shows a diagram of this process.

1. Dispense BKEPs

2. Deploy parachute

3. Tip to firing position

4. Release parachute; fire booster

5. Penetrate runway; detonate

Fig. B.9—BKEP operation
Appendix C
ANALYSIS OF LRCM PERFORMANCE MEASURES

This appendix presents analysis on the technologies and performance areas discussed previously. The performance measures cover a broad range of LRCM performance issues, and this analysis utilizes a mix of methodologies. Figure C.1 shows the linkage between technologies and performance areas.

For existing systems such as TLAM, we can cite some current performance measures. These include accuracy, thrust-specific fuel consumption, structure fraction, and weather capability. Other performance measures, including payload effect and flight altitude, we will analyze from first principles. Finally, observability will be analyzed parametrically because of classification limits on such information.

For new technologies, the same set of methodologies will prevail, with the addition that alternative structure fractions and different observabilities will be considered as modifications from the baseline TLAM value.

THRUST-SPECIFIC FUEL CONSUMPTION

Thrust-specific fuel consumption (TSFC) is a performance measure that relates only to LRCM propulsion technology choices. The thrust-specific fuel consumption of an engine is defined as the rate at which it burns fuel per unit thrust. For our purposes, this will be measured as pounds of fuel per hour per pound of thrust. Thrust-specific fuel consumption varies with altitude for airbreathing engines. Higher-altitude flight is more fuel efficient for cruise missiles, since the density of the atmosphere is lower. This clearly results in lower drag on the airframe, but it also allows the engine to operate at a higher propulsive efficiency.1 Since cruise missiles spend a significant fraction of time at low altitude, the sea-level TSFC will be used throughout this discussion.

The current Tomahawk cruise missiles use the Williams F 107-WR-400 turbofan engine. The turbofan engine draws air into the engine through an inlet and splits the airflow into two separate components. The first and smaller part is compressed by a series of high-compression turbines. The highly compressed air is then mixed with fuel and burned to

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1 For an airbreathing engine, there is an optimal velocity ratio between the speed of incoming airflow and the speed of the exhaust gases. At higher altitudes, the amount of fuel required to generate this ratio is lower, since the density of the incoming air is lower, requiring a lower amount of fuel for stochiometric burning. See, for example, Hosny's *Propulsion Systems*, University of South Carolina Press, 1974.
generate energy. Part of the generated energy is exhausted through a nozzle in the rear of the engine, producing some thrust. The rest of the energy is used to turn a series of low-compression turbines, the largest of which is termed the "fan." The fan and its associated compressors direct the larger part of the airflow around the engine through bypass ducts. In this sense, these lower-pressure turbines act like an internal propeller. A propeller is a more efficient method of propulsion than simple burning and exhaust of the gases, and in general, the higher the fraction of air that passes through the bypass ducts, the higher the propulsive efficiency. Hence, efficient turbofan engines are often referred to as high-bypass turbofans. For the Tomahawk missile, the bypass ratio is limited by the dimension constraints on the missile. However, the design of small efficient engines was one of the major success stories of the Tomahawk development program. The F 107-WR-400 engine has a sea-level TSPC of roughly 0.95 lbs/sec/lb.²

Other small turbofan engines also exist. The F 107-WR-101 engine, which powers the AGM-86B (ALCM) cruise missile, is essentially a minor modification of the F 107-WR-400 and has similar characteristics. The F 107-WR-401 is an upgrade to the F 107-WR-400 with similar TSFC and slightly more thrust.\(^3\) In general, small turbofan engines will have thrust-specific fuel consumption in the range of 1.0 to 0.9 lbs/hour/lb.

A less complex and less fuel-efficient engine type is the turbojet. The turbojet differs from the turbofan in that it lacks the bypass fan and its associated ducting and nozzles. Therefore, all of the air drawn into the turbojet passes through the combustion chamber and is burned with fuel. These differences, in general, will make the turbojet a less fuel-efficient engine than the turbofan but should also make it somewhat less expensive (based on lower complexity). The JCAE 372-11A (built by Teledyne CAE) is an existing turbojet design with comparable weight and diameter to the turbofans above. It has a quoted thrust-specific fuel consumption of 1.2 lbs/hour/lb.\(^4\) This is roughly 20 to 30 percent less efficient than the turbofan designs.

At the other end of the scale, a more complex and more fuel-efficient engine design is the propfan. The propfan differs from the turbofan in that the propulsive mechanism is a series of exterior propellers. The air drawn into the engine is burned and supplies energy to power turbines, which in turn power the propellers. The propfan is more fuel efficient, as it is essentially an extension of the turbofan. Since the propellers are in the airstream outside the missile, the propfan is essentially a much higher bypass or unducted turbofan. Propfan designs are generally more complex than turbofans in that they require linkages to propellers and often require the propeller blades to fold flat for storage and launch. Recent propfan designs based on current turbofan engines promise thrust-specific fuel consumption on the order of 0.6 to 0.7 lbs/hour/lb. This is an increase of 20 to 30 percent in fuel efficiency from current turbofan designs. Table C.1 summarizes the thrust-specific fuel consumption associated with the various LRCM propulsion choices.

**STRUCTURE FRACTION**

The structure fraction performance measure is associated with LRCM airframe technology. Structure fraction is defined as that proportion of the total weight of the missile that is not devoted to fuel or payload. As such, the structure fraction includes the airframe and associated control surfaces, guidance systems, and the propulsion unit. The structure

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\(^3\) "Williams International Overview," briefing given to RAND, April 26, 1988.

Table C.1

<table>
<thead>
<tr>
<th>Engine Type</th>
<th>TSFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbofan</td>
<td></td>
</tr>
<tr>
<td>F 107-WR-400 (TLAM)</td>
<td>0.95</td>
</tr>
<tr>
<td>F 107-WR-401 (TLAM Blk. III)</td>
<td>0.90</td>
</tr>
<tr>
<td>Turbojet</td>
<td></td>
</tr>
<tr>
<td>TCAE 372-11A</td>
<td>1.2</td>
</tr>
<tr>
<td>Propfan</td>
<td></td>
</tr>
<tr>
<td>Advanced design</td>
<td>0.65</td>
</tr>
</tbody>
</table>

fraction is, within limits, a comparative measure of the structural efficiency of the airframe. The major limit is that the missiles should be in the same general total weight class. Various elements of the structure fraction, including the engine, guidance, and control elements would appear to be relatively insensitive to changes in the gross weight of the vehicle. Other elements, including the airframe and fuel control systems, would seem to be heavily correlated with total vehicle weight. Parametric use of the structure fraction requires the assumption that guidance and propulsion units maintain a relatively constant fraction of LRCM weight. As a practical matter, the guidance and propulsion units of modern cruise missiles are a fairly small fraction of total vehicle weight and are of similar weight across systems of similar total weight. Therefore, the errors brought about by this formulation of structure fraction should not greatly affect this analysis.

The Tomahawk conventional cruise missile has a total weight of 2770 pounds fully fueled. Of this weight, roughly 1000 pounds is made up of payload and roughly 600 pounds is made up of fuel. This results in a structure fraction of:

\[
\frac{2770 - 1000 - 600}{2770} = 42\%
\]

This value will be considered as a standard reference for cruise missiles in its weight class carrying a 1000-pound payload.

How might this structure fraction be altered? First, it is clear that the design of the Tomahawk was constrained by the demands of submarine launch. The Tomahawk airframe is constructed from cored aluminum sections, designed to withstand the lateral strain of depth charges and the pressures of underwater launch. If some of these strength constraints could be relaxed, some of the weight of the airframe might be lessened. This possibility arises for air-launched or surface-launched LRCMs. Alternatively, some new composite

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5 "Sea Launched Cruise Missile," Briefing Presentation 06036164, General Dynamics Corporation, Convair Division.
materials might be utilized in LRCM construction. These materials combine high strength with light weight, although it should be noted that their use for cruise missile construction is unproven and their potential expense is high. For this analysis, we will consider either of these two approaches to generate a savings of 10 percent of total structure weight (an ambitious goal) from the TLAM baseline. This results in a change in structure fraction from 42 percent to 38 percent.

Alternatively, the application of stealth technologies to LRCMs will probably result in a missile with a higher structure fraction. The most straightforward approach to stealth, application of radar absorbing materials (RAM) to the outer surface of the airframe has been widely associated with aerodynamic weight penalties.\(^6\) RAM is, by all accounts, efficient in terms of radar absorption but fairly heavy. In addition, many of the airframe-shaping techniques used to lower cross section (e.g., the chines along the length of the ACM, masked engine inlets and outlets) would reasonably result in a higher airframe weight. For this analysis, the effects of significant application of stealth technologies will be an increase of 10 percent in airframe weight, corresponding to an increase in structure fraction from 42 percent to 46 percent. Table C.2 shows the structure fraction performance cases.

### Table C.2

<table>
<thead>
<tr>
<th>Airframe Type</th>
<th>Structure Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current Tomahawk</td>
<td>42%</td>
</tr>
<tr>
<td>New lighter airframe</td>
<td></td>
</tr>
<tr>
<td>Air/surface launch only</td>
<td>38%</td>
</tr>
<tr>
<td>Composites</td>
<td>38%</td>
</tr>
<tr>
<td>New heavier airframe</td>
<td></td>
</tr>
<tr>
<td>Stealth</td>
<td>46%</td>
</tr>
</tbody>
</table>

**FLIGHT ALTITUDE**

The flight altitude of a LRCM enroute to its target is a function of the missile's navigation system and terminal sensor as well as the quality of terrain information available to the mission planner. We will utilize a model incorporating models of inertial navigators.

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\(^6\) Knott, et al., *Radar Cross Section*, Artech House, 1985. Note that the current TLAM missile antedates the heavy development of stealth technologies in the mid-to-late 1980s, although TLAM reportedly incorporates some low-observables technologies and is inherently difficult to observe based on its size and overall shape.
terrain data, and cruise missile flight characteristics to determine reasonable flight altitude assumptions for various technology combinations.

Current cruise missile flights are preprogrammed into the missile before launch as a series of location, speed, and altitude waypoints through which the cruise missile flies. The feasible flight altitude of a LRCM is driven, in general, by the desire of the mission planner to avoid driving the cruise missile into the ground. There are several possible scenarios for this process, depending on the level of information available to the planner and the level of technology available on the missile.

If the mission planner has little or no information on terrain elevations enroute to the target, he or she would be forced to fly the cruise missile above some “sure-safe” altitude, likely the highest known elevation along the flight path. This outcome would be relatively unaffected by any of the LRCM technical characteristics.

However, digital elevation information for the entire world is steadily being gathered into DTED (Digital Terrain Elevation Data) databases by the Defense Mapping Agency; much of the globe is already covered to some level of detail. Therefore, the mission planner will in all likelihood have altitude information for the area of interest. Under these circumstances, the mission planner must decide how close to the ground he or she can reasonably plan for the cruise missile to fly. Here, the technology on the cruise missile becomes very relevant. The flight altitude will depend on (1) the accuracy of the navigation system over time, and (2) the existence or nonexistence of a forward-looking, ranging sensor on the missile.

The accuracy of the navigation system will determine the feasible flight altitude up to a point: the point where objects not in the terrain database become significant. Below a given altitude, the chance of hitting one of these objects can become unacceptably high. Objects that are not included in the terrain data include such items as trees, buildings, power lines, or storage facilities. Discussions with mission planning personnel have indicated that a reasonable cut-off altitude for significant “vertical obstructions” is 200 feet, or 60 meters.

In order to plan for flights below 60 meters, therefore, we will require the existence of a forward-looking, ranging sensor; such a sensor is required to avoid unexpected obstacles. The sensor must be forward-looking (in contrast to the downward-looking DSMAC sensor on TLAM-C) in order to observe an obstacle’s approach; the sensor must be able to determine the range to the obstacle in order to calculate the maneuver required to avoid it. With such a sensor, we will assume that a vehicle will be capable of very low flight, down to 50 feet or 15 meters. At very low altitudes, the maneuverability of the airframe and thrust of the engine
can become important concerns. These effects are handled in this analysis by imposing climb and turn rate limits on the cruise missile.

A sensor such as the one described will still require a reasonably accurate navigator. Since both the range of the sensor and the climb rate of the LRCM are limited, the ability of the LRCM to compensate for any extremely large, unexpected feature (such as a mountain) is also limited. A reasonably good navigator is required to avoid gross deviations from the preplanned waypoints. Therefore, two scenarios will be examined: (1) navigator alone and (2) navigator with forward-looking sensor.

**Navigator Alone**

**Inertial Navigation.** Inertial navigation systems (often termed inertial measurement units, or IMUs) are among the most mature of navigation technologies. They constitute the basic navigation system for most advanced weaponry, including ships, planes, submarines, and intercontinental missiles. Their application to cruise missile navigation was, therefore, a natural step. INS systems operate through use of gyroscopes and accelerometers, measuring acceleration and its direction by the differential effects on these subsystems. Use of laser measurement techniques and high-precision gyro has enabled INS systems to become much more accurate over time. The precision of an INS is characterized by its drift rate over time. An INS, even one that is carefully calibrated, will show some drift in its assumed position from its real position over time as small errors in measurement, anomalies in spin, and distortions in earth gravity and magnetism make themselves felt. A subsonic, cruise missile LRCM will have a flight duration anywhere from one half hour to several hours. Figure C.2 shows the growth of lateral position errors for several different IMUs, ranging from highly accurate to relatively inaccurate. A reasonably accurate IMU will have a drift rate corresponding to 1 degree per hour; an extremely accurate IMU will have a drift rate of 0.1 degrees per hour.

It is clear that over these time periods, drift from reasonable IMUs is unacceptable from many standpoints. First, drifts on the order of thousands of meters result in unacceptable position errors for the enroute portion of the flight. Second, and more critical, errors of this order place unacceptable demands on any terminal sensor considered, in terms of both sensor field of view and sensor range. This is not to say that an accurate IMU is without utility; although use of an IMU alone for cruise missile navigation is unacceptable, the IMU is useful in combination with other navigation systems.
TERCOM. As discussed earlier, TERCOM is a system that uses a radar altimeter to measure terrain features along its flight path and correlates these measurements with internally stored digital maps. The system is in current use on both the TLAM and ALCM cruise missiles.

The TERCOM navigation systems use preselected patches of terrain in which to perform the correlation and correct the missile heading. The missile is programmed to fly from patch to patch, utilizing the IMU system for the navigation between scene matchings. The terrain element sizing of the DMA data is roughly 100 meters by 100 meters, implying that the overall position error of the TERCOM navigation system is roughly 50 meters plus the INS drift rate since the last TERCOM scene-match. Figure C.3 shows how sensitive the TERCOM system is to the frequency of updates and the time since the last TERCOM fix. The difference from the nonupdated IMU drift is significant. With a TERCOM update every half hour (roughly 500 kilometers of flight), the navigation errors never rise above 1000 meters. Smaller spacings (every fifteen minutes, or 250 kilometers) result in maximum errors on the order of hundreds of meters.
**Terrain Referenced Navigation.** As discussed previously, terrain referenced navigation systems attempt to update the position of the cruise missile nearly continuously with reference to the terrain underneath it, as opposed to the patch-to-patch TERCOM method. TRN algorithms also utilize basic Digitized Terrain Elevation Data (DTED), which is more widely available than TERCOM maps.

Given that they operate nearly continuously, TRN systems have an even lower position error than TERCOM, as shown in Fig. C.4. Overall, TRN is an attempt both to generate lower position errors and to increase the flexibility of mission planning. Use of DTED elevation data and freedom from the requirement to fly over prespecified TERCOM patches should considerably lessen route-planning demands.

**GPS.** As discussed previously, the Global Positioning System (GPS) consists of a constellation of satellites that emit a continuous position signal. An antenna receiver on the cruise missile picks up the signals of several satellites and uses them to calculate its position and heading.

Currently, the projected position accuracy of a GPS-equipped system is roughly 15 meters. However, one cannot assume that GPS will operate effectively all the way to the
target, since it is susceptible to line-of-sight noise jamming of the GPS receiver. If the noise is significantly increased with a jammer, the signal may become indistinguishable, in which case a backup IMU system must take over.

In the case of jamming, the overall position error grows from roughly 15 meters at the IMU drift rate after the point where the receiver is jammed. If the threat is a terminal one based at the target, the jamming begins at the radar horizon around the target (roughly 25 to 30 miles, or a 0.1-hour flight for a low-flying LRCM). The growth in position error can be drawn from Fig. C.2 for a 0.1-hour flight, indicating an error growth of at most tens of meters for a standard IMU. An airborne jamming system presents a more difficult problem for the GPS receiver, but also for the jammer. The line-of-sight for the radar jammer is increased, but its power is likely to be decreased on an airborne platform. However, a somewhat more sophisticated GPS receiver, perhaps one with planned antenna nulls, might deal with an airborne jammer. Figure C.5 shows the continuously low position errors associated with GPS navigation.

Although GPS does not utilize any terrain data for correlation and matching, the mission-planning requirements for a GPS navigational system are unlikely to be much below
those of TRN. If the cruise missile attempts to fly low routes to the target (as is the case at present), the terrain data and flight-planning equipment must still be procured and utilized in preplanning the missile flight.

![Position error vs. time graph](image)

**Fig. C.5—GPS position errors over time**

**Flight Altitude Using Navigator Alone.** Based upon the above discussion, how low can the LRCM fly using these different types of navigation, bearing in mind the 60-meter vertical obstruction buffer? The analysis presented in this section utilizes a series of models. The central analytic tool is a 14-state Kalman filter model of an inertial navigator. This model simulates in great detail the generation and propagation of errors in such a navigator and can generate either an error covariance matrix or a Monte Carlo series of flight path deviations. Various types of navigator updates are allowed. Outputs of this model were utilized in Figs. C.2 through C.5. This model was linked with Digitized Terrain Elevation Data and simple aerodynamic flight models through the use of the Cartographic Information System (CAGIS), an integrated system of models and data storage developed at RAND.7

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7 The model of an inertial navigator was developed jointly by RAND researchers David Vaughn and Harry Evans. The CAGIS analytic tool was developed at RAND by researcher Al Zobrist. I am indebted to all three individuals for the development of this unique analytic capability and their advice in its use.
A standard procedure was followed in order to generate comparative cases. First, inputs for the navigator model were developed, including initial errors, accelerometer biases and drift rates, and update points. These inputs were utilized by the inertial navigator model to generate an error covariance matrix over time in the form of error standard deviations in the vertical, lateral, and longitudinal directions. At this point, this error covariance was utilized to develop a "clobber-limited" flight path over DTED data. The route of the cruise missile over a given piece of terrain was selected, and a simple box was defined with the dimensions of a given number of error standard deviations around the cruise missile. The height of the missile was then adjusted to keep all portions of the standard deviation box above the surface of the ground. This concept is illustrated in Fig. C.6 below.

![Diagram of clobber-limited path generation]

**Fig. C.6—Clobber-limited path generation**

The effect of this procedure is to raise the missile’s flight path when errors are large and lower it when errors are small. Errors in the vertical direction will clearly have this effect, but longitudinal and lateral errors (often larger) will also drive missile height higher if the missile is approaching or passing by a rise in terrain.
At this point, a "clobber-limited" flight path has been generated, a path the altitude of which is based upon the chance of striking the ground. This path is not necessarily a feasible path for a cruise missile. In particular, it could violate the aerodynamic climb rate and gee-limit constraints of the missile. Therefore, a test is made against a simple aerodynamic model incorporating these limits. If a violation of the limits occurs, the path is adjusted (smoothed) with the constraint that the resulting path cannot ever lie below the clobber-limited path. The resulting flight path is termed the "planned path." The gee limit used in this analysis was 2 gees, and the climb rate limit used was 30 meters per second (corresponding to a flight angle of 6 degrees). These parameters were selected based upon the relative lack of agility of current cruise missiles.

At this point a series of Monte Carlo runs are made using the navigation model. Instead of a covariance matrix, these runs generate a correlated series of deviations which simulate the errors that would occur on a single cruise missile flight. Using the planned path as a central line, these deviations are subtracted (or added) to the path to generate a simulation of the flight of a single missile along the planned path, termed the "actual path." If at any point the actual path strikes the ground, the path has clobbered for that particular Monte Carlo run. Over a number of Monte Carlo runs, the overall probability of clobber is simply that fraction of runs that clobber at any point.

The Monte Carlo approach is clearly unwieldy, especially if one desires to analyze a number of different cases. In practice, we have found that for flight paths of lengths of greater than an hour, a box of dimensions equal to four standard deviations gives a very low probability of clobber, whereas three standard deviations gives unacceptable clobber results. An examination of probabilities associated with these sigma values indicates that this outcome is quite reasonable; the probability associated with values outside of four standard deviations is roughly 100 times less than that of three standard deviations. Given that the clobber problem is a sequential set of conditional probabilities, it is very likely that this difference is significant over the flight times indicated. All results discussed here are based upon the four-sigma heuristic.

Notional flight paths were investigated with the procedure described above for each of the four navigation systems. The terrain elevation data used was unclassified DTED data of Southwest Asia provided by the Defense Mapping Agency. This region encompasses areas of high terrain relief as well as relatively flat areas. Based upon these analyses, the four technologies were found to be capable of supporting the flight altitudes in the neighborhood of those shown below in Table C.3. These are averaged values, but they provide a good comparison of technology performance. The Global Positioning System analysis results in an
actual altitude capability of 40 meters; however, the vertical obstruction buffer means that this result is functionally equivalent to 60 meters, the same as is achieved by TRN. The TERCOM results indicate how sensitive TERCOM navigation is to the frequency of updates; TRN could be considered to be the asymptote of increased TERCOM update frequencies.

Table C.3

<table>
<thead>
<tr>
<th>Navigation System</th>
<th>Flight Altitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TERCOM 1/2 hour updates</td>
<td>220</td>
</tr>
<tr>
<td>1/4 hour updates</td>
<td>150</td>
</tr>
<tr>
<td>Terrain reference navigation</td>
<td>60</td>
</tr>
<tr>
<td>Global positioning system*</td>
<td>40*</td>
</tr>
</tbody>
</table>

Navigator With Forward-Looking Sensor

The analysis of a minimum altitude for a navigation system with a forward-looking, imaging sensor is based upon a rather simpler model. Given that the navigator has fixed the position of the missile to a reasonable accuracy, an accuracy at which the positions of large terrain features are reasonably well characterized, the job of the forward-looking sensor is to avoid smaller obstacles it encounters at low altitudes. In order to perform this task, the sensor must look ahead from the position of the missile and establish both the range and height of approaching obstacles. In order to do so, the sensor must in general be an active sensor, one that emits energy and analyzes it upon its reflection and return. In addition, it must be an imaging sensor, on that gains some picture of the scene before it. Active sensors can generate range information by analyzing the delay between transmission and reflection, and imaging sensors can gain information about the height of the object being viewed.

Once we postulate such a sensor—a forward-looking, active, imaging sensor—the calculation for flight altitude capability is a combination of seeker range, obstacle height, and the maneuverability of the cruise missile. Figure C.7 shows an analysis of the amount of altitude gained over distance for a cruise missile limited to both 2 gees of acceleration and a maximum climb rate of 30 meters per second. Figure C.8 indicates that a fairly sluggish cruise missile can gain roughly 100 meters of altitude over the first kilometer of distance traveled after it begins its ascent. This would indicate that a 60-meter obstacle, at the vertical obstruction limit, could be avoided if sensed in time to initiate action 800 meters
away. In general, the active imaging sensors discussed for use in LRCMs have ranges of over a kilometer. It would seem that they would be capable of flying at very low altitudes.

In fact, however, the obverse of the curves in Fig. C.7 is also in effect; the cruise missile takes some time to return to low altitude once it has pulled up to avoid an obstacle. Overall, when tested against the same set of paths discussed above, this time with zero position errors, the cruise missile averaged roughly 30 meters in altitude. This value, roughly half that of the vertical obstruction limit placed on systems operating on navigator alone, will be utilized for systems equipped with forward-looking, active, imaging sensors.

OBSERVABILITY

For several reasons, observability is the most problematic of the performance measures discussed here. First, observability is not a single quantity; it is several. Strictly speaking, optical, infrared, and radar observability should all be considered, since major air defense systems exist that utilize one or some combination of these detection methods. This discussion, however, will focus on radar observability alone; based upon the greater range of radar systems, they can reasonably be assumed to be the greater threat to cruise missiles.
Second, unlike the fuel consumption and structural information discussed above, radar observability data for current and projected systems are classified. Therefore, we will discuss cruise missile observability in general terms from the point of view of vehicle shape and generic measures one can take to reduce cross sections.

Radar observability is often discussed in terms of radar cross section (RCS) with respect to a perfectly reflecting sphere with a presented cross section of 1 square meter. However, cruise missiles are generally cylindrical in shape and have many irregularly shaped surfaces attached to them (e.g., inlets, lift and control surfaces.) It is reasonable to expect, therefore, that the cruise missile RCS will not be uniform. Specifically, analyses in Knott et al.\(^8\) and Skolnik\(^9\) indicate that the radar cross section of a cylindrical object will bloom on the side, based upon specular returns from the cylinder’s major axis.

Given this basic starting point, what potential modifications to the missile could one reasonably expect in order to reduce the RCS? As discussed in Knott, et al., there are four generic means of reducing the cross section of an object: shaping, radar absorbing materials, passive cancellation, and active cancellation. Passive and active cancellation use different methods to produce an out-of-phase signal that cancels out the incoming radar pulse. For a variety of reasons, these methods have proved less than useful for practical signature reduction.\(^10\) Shaping, however, is a clear option for a cruise missile. Here, the Advanced Cruise Missile (ACM) is indicative of the types of shaping that could be utilized. First, the nose and tail both taper to half-cone shapes with sharp points and chine-like fairings along their longitudinal edge.\(^11\) These shapes would tend to lower returns from near the nose, but the side-on cross section due to the cylindrical shape of the body would be unlikely to be affected by this shaping. RAM materials could also be used, which could lower vehicle cross section somewhat at the cost of additional weight. Finally, wings, control surfaces, inlets, and antennae will all contribute somewhat to the cross section of the vehicle. Some responses to these issues would be some of the design features seen on the ACM, including swept wings with curved surfaces and flush inlets.

A LRCM vehicle incorporating features such as these would entail little additional effort to design if the vehicle is being designed from scratch and, with somewhat more effort, could likely be applied to existing vehicles such as the Tomahawk.

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The overall effect of these design possibilities is a vehicle with a lower forward-aspect cross section than side-on cross section—not a bad strategy, since the geometry of most engagements with defenses at least begins with the cruise missile flying toward the defense. Lowering the nose-on cross section limits the detection range of the defenses and thus moves the engagement to side-on and tail-chase geometries, less favorable to the defense.  

As a matter of technical interest, it is clear that RCS reductions to cruise missiles are currently limited by their fundamentally cylindrical shape. A radical redesign of cruise missiles, perhaps to a flat wing shape, could result in substantially lower RCS, especially at angles near perpendicular to the line of flight. However, such a design would encounter significant incompatibilities with any current or projected launch platform and is not considered in this analysis.

**ACCURACY**

The accuracy of a weapon is measured by its circular error probable (CEP). The CEP of a weapon is the circular contour within which the missile will land 50 percent of the time. The distribution of weapon miss distances is assumed to be an unbiased, normal (Gaussian) distribution, with variance a function of the CEP. The Tomahawk cruise missile has a stated CEP of 7.6 meters when equipped with the DSMAC guidance system.

The DSMAC guidance system uses a position fix near the target, and therefore the position error when it reaches the target is presumably based upon three factors: (1) the absolute accuracy of the position update, (2) the relative accuracy of the target with respect to the DSMAC update image, and (3) the drift of the inertial measurement unit between the update and the target. Based upon the IMU analysis above, much of the error must be related to either the first or the second factor, since the drift of a reasonable IMU does not reach 25 feet for an appreciable time after an update. Given that mission planners attempt to locate the DSMAC update image on the same photo as the target, very little error would be generated by the relative target to update image errors.

By process of elimination, therefore, the main source of error for DSMAC guidance should be the resolution of the DSMAC fix itself. The DSMAC II system (a Block III upgrade

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12 Defense encounter difficulties when attempting to engage low-altitude cruise missiles from the side or behind because of the methods they use to deal with radar ground clutter. A full discussion of these effects can be found in the next appendix.

13 As will be discussed later, the CEP is the simplest measure of accuracy, since it assumes equal errors in all directions. In fact, the downrange and crossrange portions of the error are not always equal.

to Tomahawk) is reportedly equipped with the ability to utilize a larger internally-stored DSMAC scene. This larger internal scene could be used to match against a larger imaged area, which would lead to no increase in resolution and hence no increase in terminal accuracy. Alternatively, the larger internal scene could be used to match against the current-size imaged area, which would necessarily lead to some increase in accuracy.

In contrast to DSMAC, all of the other sensors discussed utilize a target-looking sensor. Although the different sensors employ different mechanisms and wavelengths, each has the ability to resolve the target with extreme accuracy, on the order of one meter. However, the ability to fly a cruise missile-sized body to a point depends on much more than the resolution of the sensor. The response of the airframe, the geometry of the terminal target area, and even such factors as wind can play a role in determining the final miss distance. Therefore, we will parameterize the accuracy of the target-looking sensors as having CEPs between 1 and 3 meters. These values are shown in Table C.4 below.

It would appear from Table C.4 that the target-looking sensors are roughly equal in achievable accuracy. However, one necessary component of this accuracy (as discussed in App. B) is mission planning. In terms of mission planning required, these sensors have some very different requirements. The DSMAC sensors utilize currently available photographs. The mission planning procedure requires that these photos be passed through a series of image processing algorithms, which identify areas of the photograph that are acceptable as DSMAC scenes. The scenes are then selected by the planner and processed into DSMAC images. The system is fairly well automated, but it requires some operator supervision.15

<table>
<thead>
<tr>
<th>Terminal Guidance System</th>
<th>Terminal Accuracy (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSMAC</td>
<td>7–8</td>
</tr>
<tr>
<td>Passive IIR</td>
<td>1–3</td>
</tr>
<tr>
<td>SAR</td>
<td>1–3</td>
</tr>
<tr>
<td>C02 Ladar</td>
<td>1–3</td>
</tr>
</tbody>
</table>

The target-looking sensors, however, will have additional mission planning requirements that are significantly higher than for current DSMAC systems. For example,

the passive IIR sensor utilizes a series of contrast templates to match the target scene. The basis for this template will almost certainly have to be a photograph of the target with sufficient resolution to identify and differentiate between separate target elements. Ideally, a far-field picture and a close-up picture are desired, in order to "nest" templates and further improve the probability of lock-on and accuracy. The operator would then identify the types of surfaces and materials present in the photograph(s), and the planning system would develop an expected contrast image of the scene.

Note the two main elements of the process described above: (1) a photograph of the target (not just the target area), and (2) a process by which the photograph is transformed into a scene comparable to that observed by the sensor. These requirements will remain constant for the target-looking sensors. A timely, digitized photograph of the target is a significant intelligence and communications requirement for these missiles. The time it takes to generate, communicate, and manipulate these images constitutes the major reason why LRCMs will, in general, be restricted to relatively fixed targets.

The second process, transformation, will vary between the sensors, and constitutes one means of differentiation between them. The passive IIR process described above, while demanding, is fairly well understood. The intensity of contrast between objects is not required, only some contrast. The SAR transformation process, however, is less well-behaved. In a SAR image, the primary features are edges and glitter points of objects within the scene, which are not always readily apparent in the visible image. Given this, the transformation process from a photograph to this SAR image is conceptually far more difficult than the transformation from a visible photograph to passive IIR. On the other hand, the CO2 LADAR sensor utilizes a laser radar beam to image the target set, enabling it to generate a three-dimensional image of the target scene. The transformation process for a LADAR therefore involves creating a series of three-dimensional "stick images" of the target scene, which would seem no more or less difficult than the process required for passive IIR.

Overall, however, this discussion makes clear the importance of mission planning. Such a system for a target-looking sensor requires generation of a digital image of the exact target scene, a transformation process by which this specific visible-light photograph is altered to fit the sensor's capabilities, and finally, a knowledgeable operator to oversee the entire process.

WEATHER RESISTANCE

Weather resistance is a second critical performance measure for the sensors discussed in this Note. Since each of the sensors relies on a different form of energy to operate, one
would expect their ability to operate under different conditions to vary quite widely. The DSMAC system depends on visible light, which makes it very susceptible to obscuration by rain and fog and other weather effects.

Infrared systems, such as the passive imaging infrared system and the CO₂ LADAR system, are more robust to fog and rain than are visible-light sensors, since infrared light is absorbed less strongly by water than visible wavelengths. Differences in weather capability between the active and passive IIR systems are marginal, although the energy that the passive system receives travels only one way. Heavy rain or fog can still obscure the target for the passive IIR system, while rainfall or fog that is somewhat lighter, but still fairly heavy, will obscure the target from the active LADAR system.

The passive IIR system has another potential problem, related to the day-night (diurnal) cycle. The passive IIR system relies on contrasts in infrared emissivity between different portions of the target area. As the day progresses, a certain material (Material A) will absorb energy more efficiently than another adjoining it (Material B). This will cause Material A to rise in temperature faster than Material B. After the sun has set, Material A may also emit heat more rapidly than Material B and cool down to a lower temperature. This cycle will begin anew the next day. A diagram of the heat contrast between Material A and Material B will pass through two phases where there is no contrast: one when the temperature of Material A is rising past Material B, and one when the temperature of Material A is dropping past Material B. This diurnal "greying out" of the IIR contrast is of concern in midmorning and at dusk.

Of the sensors we will discuss, the synthetic aperture radar system is the most resistant to weather. Since it is an active radar system, very little of its energy is absorbed by water in the atmosphere. Hence, the SAR system can operate under most conceivable weather conditions. The robustness of the sensors to different types of weather is summarized in Table C.5 below.¹⁶

PAYLOAD EFFECTS

The performance of actual U.S. conventional weapons is classified. Therefore, in order to develop a model of LRCM payload effects it is necessary to begin with first principles.

Table C.5
Weather Robustness Performance

<table>
<thead>
<tr>
<th>Terminal Guidance System</th>
<th>Weather Problems</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSMAC</td>
<td>Rain, fog, snow</td>
</tr>
<tr>
<td>Passive IIR</td>
<td>Heavy rain, heavy fog, diurnal</td>
</tr>
<tr>
<td>CO2 LADAR</td>
<td>Heavy rain, heavy fog</td>
</tr>
<tr>
<td>SAR</td>
<td>Unaffected</td>
</tr>
</tbody>
</table>

There are two major effects that conventional weapons can display: blast effects and fragmentation effects. Fortunately, a good body of unclassified literature allows us to generate reasonable estimates of the likely effects of LRCM payloads.

Unitary Warheads

The unitary warhead currently carried on Tomahawk, the Bullpup, is an example of an LRCM payload that relies on blast to achieve its ends. The Bullpup is an older warhead that was put to a new use as the TLAM-C payload. It weighs approximately 1000 pounds, approximately 500 pounds of which is explosive. The blast-distance relationships for such a weapon are fairly well understood. Based upon theoretical scaling relationships for high explosives, an overpressure-impulse relationship such as the one shown in Fig. C.8 can be developed.\(^{17}\) The ordinate expresses peak overpressure generated in *bars*, a metric unit equal to one atmosphere or 14 pounds per square inch. The abscissa expresses impulse per unit area in *bar-milliseconds*. Impulse is essentially the integral of overpressure over the duration of positive overpressure and is related to the amount of force exerted by a blast wave.

As a blast wave propagates over time and distance, both the overpressure and the impulse drop rapidly. Overpressure drops more rapidly than impulse over portions of the curve, since the blast duration (which affects impulse through the integral) behaves

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\(^{17}\) See Gilbert F. Kinney and Kenneth J. Graham, *Explosive Shocks in Air*, Springer-Verlag, 1985. The curve is based upon a 1000-pound charge of H-6, a common military explosive which yields slightly more blast energy than standard TNT.
nonmonotonically. The overpressure-impulse curve is created by plotting the overpressure and impulse values for various distances from the center of the blast, and some distances are shown in Fig. C.8.

The overpressure-impulse curve is useful because it has been used to relate blast effects to target vulnerabilities. Side-on overpressure, such as might occur from a conventional explosion, acts on a target by creating a condition of differential pressure on the
structure. High pressure exists on the side closest to the explosion, while low pressure exists on the back side of the target. This creates a condition of “drag” on the structure; if acute enough, this drag effect can cause the structure to move, which causes failure in many structures. Impulse damage, however, can be concisely described as “crushing.” Impulse measures the amount of force applied over time to the object; if a sufficient amount of impulse is translated to the target, failure of the structure can occur without any relation to drag effects.18

Targets can be destroyed either through overpressure or impulse effects, but the effects of one damage mechanism are limited by considerations of the other. An extremely high overpressure can be generated, but without a sufficient duration of the overpressure there is insufficient time for the drag effects to work on the structure. Likewise, a high impulse can be generated by a long-duration, low-overpressure blast (the limiting case is a strong wind). So, a sufficiently high overpressure is required in order for impulse to be an effective damage mechanism. Based upon these considerations, the shaded areas in Fig. C.8 show one notion of hard, medium, and soft targets. Remembering that the scales are logarithmic, a hard target requires both high peak overpressure and high impulse to effect damage. Softer targets have much lower peak overpressure and impulse requirements, with medium targets falling somewhat closer to hard targets in terms of overpressure requirements and softer targets in terms of impulse.19

Figure C.9 shows the effect of changing the warhead to a 2000-pound-class bomb, of which roughly 1000 pounds is explosive. As one can see, the overpressure-impulse curves are slightly different, based upon both scaling and on the different absolute sizes of the charges. More important, the distances corresponding to points on the 2000-pound curve are shifted upward along the curve. For any given distance, both overpressure and impulse are higher than for the 1000-pound warhead.

There has been much recent discussion of fuel-air explosive (FAE) warheads. FAEs work by dispersing from the warhead a cloud of liquid vapor, which is then detonated by a secondary “burst” charge. The advantages of FAE warheads are twofold. First, the explosive fuel in the warhead need not contain its own oxygen; instead, the oxygen is gained from the mixture of air with the fuel when the fuel is vaporized and spread in a cloud. This, combined with the lower warhead casing strength requirements, constitutes a savings in

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18 This discussion is simplified but conveys the main differences between overpressure and impulse damage mechanisms. See Kinney and Graham, op cit.

Fig. C.9—Overpressure-impulse comparison: 1000-lb versus 2000-lb warhead

weight of roughly 50 percent over conventional explosives, which must contain their oxygen within their chemical structure. Second and more important, FAEs can transfer significantly more impulse to the target than can normal explosives. This is as a result of the fuel detonating simultaneously over a large volume. This additional impulse is a very significant improvement over conventional explosives, but there is no free lunch. The additional area of the initial explosion also serves to limit the peak overpressure of the explosion. The effects of
a 1000-pound ordinary high explosive and a 1000-pound FAE warhead are compared in Fig. C.10.

As one can see from Fig. C.10, the impulse resulting from a FAE explosive is orders of magnitude higher than that available from ordinary high explosives of roughly the same weight. In fact, for a standard 1-kiloton explosion, FAE warheads outperform nuclear

Fig. C.10—Overpressure-impulse comparison: HE versus FAE warhead
weapons in terms of impulse. However, extending this result directly to actual weapons ignores the fact that a 1-kiloton FAE warhead weighs one thousand tons, whereas a 1-kiloton nuclear weapon weighs at most several hundred pounds. Clearly, FAE warheads would be much more effective against soft or medium targets than high explosive warheads. However, FAE warheads lack the high peak overpressures needed to damage hard targets. Overall, FAE warheads have a number of significant weaponization difficulties, generally related to the proper formation and detonation of the fuel cloud. Overall, while FAE warheads will almost certainly continue to be investigated, high explosives will almost certainly continue to be used for the next LRCM unitary payload.

Finally, the Tomahawk Block III modernization calls for a smaller, reactive-casing warhead. Reactive-casing warheads utilize the explosive nature of some vaporized metals to add to the overall blast of the high explosive warhead. In the case of the Tomahawk Block III warhead, the casing will be made of titanium, although vaporized aluminum also exhibits explosive properties. The tradeoff made for such a weapon is in the strength of the warhead for penetrating hard surfaces and in any potential fragment effects of the warhead. The calculation of the additional blast effect from such a weapon is not straightforward, and the empirical tests have not been made public. Therefore, for the reactive-casing option we will assume that the roughly 700-pound reactive-casing warhead being used in the Tomahawk upgrade will generate a blast equivalent to that of the 1000-pound Bullpup warhead currently being used.

Submunition Payloads

In addition to unitary blast warheads, the Tomahawk cruise missile is also capable of carrying a submunition dispenser. The particular submunition carried in Tomahawk is the Combined Effects Bomblet (CEB), a small bomblet that combines a shaped charge with fragment and incendiary effects. Figure C.11 shows a cross section of the CEB. When the weapon is released, its retarding air chute pops free to orient the bomblet downward. When the bomblet strikes, the detonation of the explosive simultaneously fires the shaped charge.

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jet downward and the preformed fragments outward. The magnesium incendiary with the explosive provides an additional incendiary effect.\textsuperscript{22}

\begin{center}
\includegraphics[width=0.5\textwidth]{figure.png}
\end{center}

Fig. C.11—Combined effects bomblet

The TLAM-D version of the Tomahawk is capable of carrying 166 CEBs, which it can disperse in up to three separate locations. The shaped charge will have a drastic effect on any object that the CEB actually strikes, but the primary wide-area effect of the CEB comes from the dispersal of roughly 300 preformed fragments. Evaluation of incendiary effects is notoriously difficult, and the magnesium filler in CEBs must generally be considered either a side or nuisance effect.

Analysis of behavior of fragmenting warhead cases is a bit more complex than that for warhead blast effects, but systems of analysis exist. The following discussion is based upon a

\textsuperscript{22} "Sea Launched Cruise Missile," Briefing Presentation 06036164, General Dynamics Corporation, Convair Division.
Gurney analysis of fragment initial velocities combined with a model of drag affecting irregularly shaped fragments and a model of fragment penetration into typical targets.\textsuperscript{23}

The Gurney analysis of fragment initial velocities develops an empirical relationship between the qualities of the explosive, the energy it imparts to the casing upon explosion, and the portion of this energy that is translated to the velocity of the ejected fragments. This analysis is widely known and is discussed in nearly all major ballistics and explosives texts. For this analysis, H-6 was the explosive used throughout.

After the explosion, the fragments are assumed to be nonaerodynamic objects moving through the air. Assuming a given shape (in this analysis, a cubic was assumed), one can calculate the deceleration of the fragment due to both supersonic and subsonic drag. Drag curves for these objects are cited in the terminal ballistics references noted below.

Finally, the analysis of the penetration of fragments into the target is based upon target ballistic limits. The ballistic limit is defined as that velocity below which no fragment penetration takes place. This limit is theoretically explained by the plastic and nonplastic behavior of the target material. At very high velocities, a fragment striking a sheet of metal (such as the skin of an aircraft or the wall of a radar van) will essentially punch out a section of the sheet equal to the cross-section of the fragment, a phenomenon known as plugging. As the speed of the fragment decreases, however, the additional time that it takes to penetrate the target allows for the target to undergo plastic deformation, a process of stretching that absorbs far more energy than the simple momentum transfer of plugging. Below a given velocity, the ballistic limit, a reasonably sized fragment is simply unable to penetrate the target. For the analysis discussed here, the target is assumed to be a thin sheet of steel, with a ballistic limit equal to 500 meters per second.

The CEB is modeled as a bomblet weighing approximately 2.5 kilograms, of which 60 percent by weight is explosive and the rest concentrated in the casing. Upon detonation, 300 fragments are dispersed uniformly outward with an initial velocity (from the Gurney equation) of 2040 meters per second. Given the relatively small individual weights of the individual fragments and their high-drag shape, the fragments are rapidly decelerated, reaching the target ballistic limit of 500 meters per second at a distance of seven meters from the center of the explosion. Therefore, seven meters is the baseline radius of effect for a CEB submunition.

\textsuperscript{23} See Kinney and Graham, op. cit. Also see Marvin E. Backman, \textit{Terminal Ballistics}, Naval Weapons Center-China Lake, 1976.
The result is relatively insensitive to the exact choice of target ballistic limit. If a ballistic limit of 700 meters per second is chosen, the radius of effect is six meters; if 300 meters per second is chosen, the radius is ten meters. For the baseline case, an analysis of fragment trajectories indicates that (1) the majority of fragments are still in flight at seven meters, and (2) a significant number of fragments can be expected to strike reasonably sized targets. For a target 10 meters wide by 5 meters high, roughly three fragments can be expected to strike the target; roughly four fragments will strike a target 10 meters wide by 10 meters high, and roughly eight fragments will strike a 20 by 10 meter target. Figure C.12 shows the area affected by an optimal pattern of 77 CEBs in the baseline case.

![Diagram of optimal CEB area of effectiveness](image)

Fig. C.12—Optimal CEB area of effectiveness

Clearly, the CEB pattern shown in Fig. C.12 cannot be implemented by any actual LRCM system. The dispenser will be unable to deliver the CEBs as precisely as shown, nor will the CEBs fly perfectly to their detonation points. However, it is interesting to note the advantages of fragmenting submunitions over unitary munitions when they are used against targets that are susceptible to fragment damage. Similar calculations performed for a unitary warhead yield at most a 30-meter radius of effect, with less than half the area of effect. Therefore, the CEB pattern shown can move quite far from its optimal structure.
before it falls below the utility of a unitary warhead, and the pattern shown is for only one of three CEB patterns per missile.

Table C.6 summarizes the payload effects discussion. For unitary payloads, blast effects are shown for hard, medium, and soft targets that are primarily susceptible to blast. In later discussions, specific targets will be assigned to these categories. For submunition payloads, the effectiveness measure is related to the mechanism of the specific submunitions.

<table>
<thead>
<tr>
<th>Payload</th>
<th>Unitary Measures</th>
<th>Submunition Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hard</td>
<td>Medium</td>
</tr>
<tr>
<td>Unitary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000-lb HE</td>
<td>1.5 m</td>
<td>5 m</td>
</tr>
<tr>
<td>2000-lb HE</td>
<td>2.5 m</td>
<td>7.5 m</td>
</tr>
<tr>
<td>1000-lb FAE</td>
<td>0 m</td>
<td>12 m</td>
</tr>
<tr>
<td>700-lb reactive</td>
<td>1.5 m</td>
<td>5 m</td>
</tr>
<tr>
<td>Submunition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CEB</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>BKEP</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

In addition to fragmenting submunitions such as the CEB, a specialized airfield attack submunition has long been advocated for LRCM weapons, the Boosted Kinetic Energy Penetrator (BKEP). BKEPs are submunitions designed to crater airfield runways and taxiways. Their particular design is based upon the difficulties one faces when attacking the flat, hardened surface of an airfield runway. If the angle of the weapon as it strikes the surface of the runway is too shallow, the weapon tends to either ricochet off the surface or "breach," which involves a short flight underground followed by reemergence. These effects can be counteracted to some extent by slowing the weapon down and tipping it over somewhat. However, if the weapon is released from low altitude, such as might be the case for a cruise missile delivery, it can be extremely difficult to slow and tip the weapon enough to avoid ricochet and simultaneously maintain enough speed to breach the surface of the runway.
The BKEP overcomes these problems with two distinct steps. When it is deployed, the BKEP deploys a parachute from the rear, which acts to brake and tip it over to a steep angle. When a preset angle has been reached, a rocket booster accelerates the BKEP into the runway, whereupon an explosive charge detonates and creates a crater. This process avoids ricochet, maintains enough speed to breach the runway, and creates a crater that is difficult to repair because the blast source is underneath the runway's concrete surface.

A vehicle roughly the size of Tomahawk might carry up to 15 BKEPs, limited mainly by volume rather than weight. If dispensed in three separate groups of five, such a missile could expect to make three runway "cuts," enough to limit an 8000-foot runway to four 2000-foot sections. Although there have been developmental difficulties with BKEP, we will utilize them as a potential submunition payload for the next LRCM.
Appendix D

ASSESSING LRCM CAPABILITIES

The previous two appendixes have outlined LRCM technologies and the performance measures that can be derived from them. This appendix addresses the next step in a technical analysis of LRCSs: the analysis of various LRCS capabilities. Recalling Fig. 3.7, there are five major LRCS capabilities: (1) range/payload, (2) survivability, (3) lethality, (4) reliability, and (5) availability. Figure D.1 details the relationships between performance measures and capabilities.

LRCS RANGE/PAYLOAD CAPABILITY

LRCS range/payload capability is based upon three of the performance measures discussed previously: structure fraction, thrust-specific fuel consumption, and flight altitude. Given a baseline range/payload tradeoff curve, the LRCS is limited in its absolute range only by the constraints and limitations of its launch vehicle. The three major launch platforms for the LRCS are (1) heavy bombers such as the B-52 bomber, (2) surface naval vessels, and (3) submarines. A comparison of these launch platforms is made in Secs. II and III.

LRCSs will in general attempt to fly at low altitudes for purposes of survivability, and according to App. C, any of the navigation systems chosen for LRCS are capable of achieving low flight altitudes in an absolute sense. Therefore, we will discuss LRCS range performance in terms of range at near sea-level altitude. This brings the range/payload tradeoff discussion down to one involving thrust-specific fuel consumption, structure fraction, and weight of the missile.

Range/Payload Methodology*

The governing equation used to approximate the range of aircraft in level flight with constant velocity is known as the Breguet range equation. Although the intent of the Breguet range equation is often associated with the prediction of the maximum range attainable by aircraft, it may be used to predict the range of aircraft confined to a given operating environment. In particular, cruise missiles are likely, due to mission requirements, to operate out of their maximum range environment. That is, cruise missiles are powered by gas turbines that reach an optimum efficiency at high altitudes (around

* The cruise missile range methodology discussed here closely reflects unpublished work performed by RAND colleagues John Matsumura and Robert Lempert.
30,000 feet). The operation of cruise missiles at such altitudes may, however, defeat their intended purpose, since cruise missiles typically depend on low-altitude flight for survivability. The end result is a sacrifice of maximum efficiency for increased survivability. Additionally, cruise missiles may be confined to operate at nearly constant altitude throughout flight, maintaining a nearly constant velocity. Finally, they may have abnormally high fuel-to-total-weight percentages in comparison to manned aircraft.

Referring to the Breguet range equation, all of these deviations from the norm can be accounted for by making modifications to the parameters used in the equation. The Breguet range equation for aircraft with gas turbine engines is given by the following relationship:

\[ R = \frac{V}{\text{TSFC}} \times \frac{L}{D} \times \ln \left( \frac{M_{\text{init}}}{M_{\text{final}}} \right) \]

where \( R \) is range, \( V \) is velocity, TSFC is thrust-specific fuel consumption, \( L \) is lift, \( D \) is drag, \( M_{\text{init}} \) is initial aircraft mass, and \( M_{\text{final}} \) is final aircraft mass.
As a general rule, the optimum range for many gas turbines is seen to increase with altitude, being inversely proportional to the square root of the density ratio. In the analysis of the gas turbine engines, this translates into a lower TSFC value with higher altitude, where TSFC is defined as the ratio of pounds of fuel burned per hour to pound of thrust provided. Using an altitude-corresponding value of TSFC, which for the sea level case will inevitably be higher than the values attainable at higher altitudes, will accordingly decrease the maximum achievable range.

The increase in TSFC may not be the only cause for decreased range at low altitudes. Like most aircraft, cruise missiles may suffer a decrease in lift-to-drag ratio associated with low-altitude flight. This decrease in the L/D ratio with altitude can be attributed to several causes, which may ultimately relate back to the choices made in the design of the cruise missile. Specifically, the design requirement may be to develop a cruise missile that can accomplish a comprehensive set of tasks. In satisfying the requirement, the use of a "multipurpose" airframe may be the solution to maintaining mission robustness. In some cases, very-high-altitude flight may be necessary to accomplish some missions. By designing an airframe to optimize flight at low altitudes, high-altitude flight may not be possible. In conclusion, a decrease in range may be a small penalty to pay for an extension in cruise missile mission versatility. In any case, it should be emphasized that using an altitude-corresponding value for the the L/D ratio in the Breguet range equation can refine the overall range analysis. Furthermore, operating a cruise missile at low altitudes decreases the maximum achievable range.

Unfortunately, the L/D ratio for cruise missiles may not be constant throughout flight; hence, further analysis is necessary to properly evaluate the L/D ratio. Unlike most manned aircraft, which can make adjustments to optimize range in cruise, cruise missiles may not have such a liberty. Due to strict mission requirements, cruise missiles may be confined to fly at a fixed altitude (as opposed to a fixed throttle setting where range can be increased, referred to as cruise-climb). Also, cruise missiles may have a relatively high fuel-to-total-weight percentage compared to manned aircraft. These deviations must be weighed into the Breguet range equation. In ordinary Breguet range equation analysis, the L/D ratio is assumed to be a constant value, often the L/D ratio that corresponds to maximum range at the operating altitude. For cruise missiles that operate at a set altitude and velocity, and which also have a relatively high fuel-to-total-weight percentage, the L/D ratio cannot be

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1 B. W. McCormick, Aerodynamics, Aeronautics, and Flight Mechanics, John Wiley & Sons, 1979, (see the discussion on turbojets, p. 443).
considered a maximum value throughout flight. Substantial changes in the L/D ratio can occur. To further explain this, an example involving the analysis of the aerodynamic parameters of a typical cruise missile will be useful. The restrictions imposed on this example will be a constant flight velocity (Mach 0.7) and a constant flight altitude (sea level), with no maneuvering.

In considering a typical cruise missile, one approach to account for the varying L/D ratio is to substitute an average value for the L/D ratio into the Breguet range equation.\textsuperscript{2} This average L/D ratio can be determined by the lift and drag coefficients, which are given by

\[
C_L = \frac{L}{Q S_{ref}} \quad C_D = \frac{D}{Q S_{ref}}
\]

where \(L\) and \(D\) are respectively aircraft lift and drag, \(Q\) is the dynamic pressure of the free air stream, and \(S_{ref}\) is the wing total planform area.

The following can be used to approximate the drag coefficient relative to the lift coefficient (at moderate values of \(C_L\)) for an aircraft with an uncambered wing:

\[
C_D = C_{D0} + K (C_L)^2
\]

where \(C_{D0}\) is the zero lift drag coefficient and \(K\) is the drag due to lift factor.\textsuperscript{3} The zero lift drag coefficient is estimated to be 0.035 for a subsonic cruise missile, and the drag due to lift factor is approximated for a cruise missile with uncambered wings, with no sweep and having an aspect ratio of 6, to be 0.059. These values were obtained from a paper describing cruise missile preliminary sizing techniques and were applied to a discussion on the Tomahawk sea launched cruise missile.\textsuperscript{4}

By knowing the missile’s weight (where weight is equal to lift) at initiation of cruise and at end of cruise, corresponding values for the lift and drag coefficients can be determined. These coefficients can be expressed in ratio form to produce the upper and lower bounds for the L/D ratio throughout flight, where the average value can be used in the Breguet range equation for an initial approximation.

This methodology can be applied directly to a notional Tomahawk-like cruise missile with the following parameters: the wing planform area can be approximated to be 12 sq ft (1.11 sq m) and the dynamic pressure to be 725 lbs per sq ft (34.7 KPa). The cruise missile

\textsuperscript{2} L. M. Nicolai, paper presented at the Aircraft Design Short Course, Dayton, Ohio, July 1987.


\textsuperscript{4} L. M. Nicolai, paper presented at the Aircraft Design Short Course, Dayton, Ohio, July 1987.
weight at initiation of cruise is approximated to be 2770 lbs. Using the equations above, the
lift and drag coefficients can be calculated. In doing so, the lift and drag coefficients at
initiation of cruise are determined to be 0.30 and 0.040, respectively. This produces an initial
L/D ratio of 7.5.

The structural weight, weight of the propulsion system, and the amount of payload in
the form of munitions and guidance will determine the missile weight at end of cruise. As a
conceptual lower bound, if a final weight of 880 lbs is chosen, the lift and drag coefficients are
determined to be 0.10 and 0.036, respectively. This produces a final L/D ratio of 2.8. Hence,
the L/D ratio throughout a constant-velocity flight, for this notional cruise missile, varies
from 7.5 to 2.8. The average value for the L/D ratio, 5.2, can then be substituted into the
Breguet equation. For an actual Tomahawk structure and payload, the degree of change in
the lift-to-drag ratio is not as extreme, changing from approximately 7.5 to 6.2, for an
average of approximately 6.8.

As an aside, note that even at initiation of cruise, the lift coefficient is not at the value
which corresponds to maximum range. The lift coefficient for maximum range can be
evaluated for the case of constant altitude by using the following expression:

\[
C_{L_{\text{max}}} = \left[ \frac{C_{\text{Do}}}{3K} \right]^{1/2}
\]

where \( C_{L_{\text{max}}} \) is an ideal value of \( C_L \) corresponding to maximum range. For the conditions
discussed above, \( C_{L_{\text{max}}} \) has a value of 0.44. Hence, even at initiation of cruise the lift
coefficient (evaluated above as 0.30) is not at the value corresponding to maximum range.
This is primarily a design choice which allows for greater cruise missile maneuverability.

For the range/payload analysis discussed here, spreadsheet models of the Breguet
equation (modified by the use of an average L/D value) were developed for the various missile
options discussed. The values for parameters were as discussed in this section.\(^5\)

The analytic approach should give reasonable approximations of the range of cruise
missile derivatives. The overall range calculation can be further refined by using a more
descriptive evaluation of the actual flight mechanics and a more accurate determination of
the aerodynamic parameters. For example, the incorporation of the trim drag associated
with maintaining level flight could improve accuracy of the range calculation. Additionally,
the use of precise values for the zero lift drag coefficient and the drag due to lift factor (the

\(^5\) Further work by Matsumura and Lempert developed a "quasi-exact" solution to the problem of
changing L/D ratios during flight. These solutions essentially involved piecewise integration of the
aerodynamic changes over the course of the flight. However, for the cases examined in this Note, the
average L/D approach gives good agreement with this more exact procedure.
values used in the example corresponded to a generic cruise missile) could further enhance the accuracy of the range calculation.

With the restrictions imposed on the cruise missile examined here, it is obvious that the cruise missile is not operating in its maximum range environment. One method to increase overall cruise range would be to allow the missile to fly at high altitudes. Another method would be to allow the missile to operate at a lift coefficient that corresponds to maximum range (referring to equation 4 and Fig. D.2). This could be done by either reducing the wing size (decreasing maneuverability, which is a component of survivability) and/or allowing the velocity to decrease as the weight of the cruise missile decreases throughout flight (decreasing survivability and timeliness). These methods could be easily implemented, but might seriously degrade overall mission performance.

In the typical cruise missile, a certain level of performance must be maintained, which is often determined by the mission requirements. As a result, the cruise missile may be constrained to fly within a particular environment. In this analysis, the cruise missile was constrained to flight at a low altitude and at constant velocity. In any case, a relationship between the actual flyout range and the actual mission range exists, and this relationship can be found for a specific mission, given the mission flight profile. The result, of course, will be an approximation, which is inherent upon any preliminary application of the Breguet range equation, whether the case be a "normal" manned aircraft or an unmanned cruise missile. For a calculation beyond an approximation, elaborate computer programs exist which produce more accurate results.

Range/Payload Results

Figure D.2 shows the basic effects of the three candidate engine types discussed in Apps. B and C. The propfan engine with its significantly lower TSFC has a far higher range/payload capability than either the turbofan or turbojet, which has the lowest range/payload capability. Each of these curves was obtained for a vehicle similar to the Tomahawk both in its structural design (gross weight and structure fraction) and its aerodynamic capabilities (wing area).

An increased or decreased airframe structure fraction has a relatively minor effect on the range/payload capability of the basic Tomahawk design shown in Fig. D.3. In these calculations, the Tomahawk turbofan engine and total weight of 2770 pounds were used as the baseline. A similar percentage effect occurs if the structure fraction modifications are made to the turbojet or propfan designs in Fig. D.2.
Fig. D.2—Range/payload comparison of engine types

Fig. D.3—Range/payload comparison of structural designs
Finally, the total weight of the airframe can have an effect on range/payload capability. Figure D.4 shows the effect of a roughly 20 percent change in missile weight on the baseline Tomahawk design. The structure fraction is constant, as is the turbofan engine design.\(^6\)

![Diagram showing range/payload comparison of airframe weights](image)

**Fig. D.4—Range/payload comparison of airframe weights**

**LRCM SURVIVABILITY**

Any aircraft is susceptible to being shot down by defenses, and LRCMs are no exception. Among airbreathing vehicles, however, cruise missiles have some unique characteristics, and it follows that LRCM survivability and the factors affecting that survivability will have some unique features. What follows is a general discussion of key

\(^6\) Note that the range equations used to generate these curves are based upon ratios of starting and ending weights. With a fixed structure fraction and no payload, these ratios will be constant for any missile weight.
determinants of LRCM survivability, and an application of the discussion that compares survivability for several notional missions for LRCMs.

**Cruise Missiles and Manned Aircraft**

Cruise missiles are, after all, a subclass of airbreathing vehicles. The most obvious difference between cruise missiles and most other aircraft is their lack of a pilot, with all of the technological adjustments that this requires. But cruise missiles and manned aircraft differ in a number of other aspects, and before beginning a discussion of LRCM survivability alone it is useful to highlight the contrasts between cruise missiles and manned aircraft. These differences have some profound effects on both LRCM survivability techniques and on the criticality of absolute levels of LRCM survival.

The average LRCM and the average performance aircraft differ in five extremely important respects: human pilot control, maneuverability, ECM capability, observability, and acceptable attrition. When a manned aircraft encounters a SAM or AAM, one of its most important counters is the pilot's ability to react to the situation and to avoid threats. Pilots are trained specifically for these contingencies, and in fact the record seems to indicate that most planes are shot down under conditions when the pilot did not realize the aircraft was engaging defenses.

At the risk of sounding mechanistic, we may think of the pilot as providing a flexible and sophisticated threat battle management or avoidance system: detect the threat and take appropriate situation-dependent action. The current LRCM is at a severe disadvantage in these situations. The LRCM clearly has no pilot for threat identification or battle management. Even if the required sensors, software, and processing were provided for the LRCM (a difficult undertaking), its minimal maneuver capability (approximately 1.5 G versus up to 9 G for fighter aircraft) would make acting on the threat information in any meaningful way very difficult.

Likewise, the current cruise missiles have nothing like the impressive ECM suites found on high-performance manned aircraft. When faced with air- or ground-based threat, fighter aircraft employ a variety of sophisticated countermeasures, including jamming, chaff, flares, and decoys. Although some consideration is being given to employment of these measures for cruise missiles, the LRCM will always be power, weight, and volume limited in these areas, compared to typical manned aircraft.

In each of the three areas discussed above, the LRCM is at a significant disadvantage versus a fighter aircraft. The LRCM essentially flies along its flight path “fat, dumb, and
Fortunately, the LRCM has some characteristics that counteract these disadvantages, and the first among them is observability. A normal LRCM could have a nose-on radar cross section (RCS) well below that of a fighter aircraft, along with a significantly lower infrared (IR) signature. This difference arises from (1) the size and shape of the airframes and control surfaces, (2) the large inlets and outlets of current high-performance fighter engines, and (3) the smaller downward-looking antenna area of cruise missiles. For reasons of classification, the discussion of LRCM observability in App. C did not deal with the RCS issue specifically; it is clear, however, that low cross sections can substantially increase the difficulty of detecting and engaging cruise missiles. The implications of low RCS and RCS reductions will be extremely important considerations for LRCM survivability.

Second, the lack of a human pilot, heretofore discussed as a disadvantage, also has some positive aspects. Although the lack of a pilot’s ability to detect and avoid threats will have some negative effect on LRCM survivability, it is also likely to render far less important the absolute level of LRCM attrition. During a sustained war effort, the most crucial asset for our air forces will be trained crewmen and the limited number of combat aircraft available at the start of a conflict. Both these aircrews and aircraft must fly repeated sorties over a course of weeks or months. Faced with the demands of a sustained campaign, force planners routinely place an “unacceptable” label on missions involving aircraft attrition rates above 3 percent, purely on force conservation grounds.

In contrast, there is no a priori reason to believe that LRCM attrition must be kept at these low levels. A LRCM has no aircrew to place at risk and, in any event, is not a reusable asset, as are manned aircraft. A distinction must be drawn here between peacetime planning on one hand, and wartime requirements on the other. During peacetime evaluation, cost-effectiveness arguments might drive one to choose a LRCM system promising lower attrition over a higher-attrition LRCM system; in this respect, cruise missiles and manned aircraft are identical. However, the treatment of LRCM attrition by war planners can and should differ significantly from manned aircraft. The only practical absolute limit placed upon LRCM attrition should be the total number of LRCMs available and, to some extent, the level

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Note: The disadvantages discussed relate to current cruise missile systems. Threat detection and avoidance sensors and processing could be designed for later cruise missile systems. Likewise, the current unwieldy “flying pencil” design of cruise missile airframes and control surfaces could be changed to a more maneuverable configuration. The key point, however, is that one will always be laboring at a relative disadvantage to fighter aircraft in terms of the difficulty of these endeavors and their expected payoff.
beyond which the planner loses confidence in the ability to plan a successful mission. This attrition level, while probably less than 50 percent, is just as certainly not 3 percent.

Two major points on LRCM survivability can be derived from the discussion above. First, cruise missiles are at a distinct disadvantage to manned aircraft in a number of areas related to survivability. In contrast with manned aircraft, the current LRCM that is detected and tracked by defenses has very little chance of survival. Given this fact, it follows that the primary aim of LRCM survivability measures will be to significantly reduce the probability of being detected and engaged by enemy defenses. The factors discussed below all essentially affect the ability of any given LRCM to decrease encounters with enemy defenses.

Finally, and just as important, the absolute level of attrition is far less critical for cruise missiles than for manned aircraft. We do not need and probably should not aim for the creation of a perfectly survivable LRCM. Rather, we should seek a combination of missile characteristics and employment strategies that will result in an acceptable level of LRCM survivability. The discussion below points out some of the major determinants of our capability to achieve these acceptable levels.

Key Determinants of LRCM Survivability

There are five key determinants of LRCM survivability: (1) the threat environment, (2) the altitude at which the LRCM flies, (3) the observability of the LRCM, (4) the degree to which LRCMs can saturate defenses, and (5) intelligence and mission-planning capabilities. These factors and their importance are interdependent and in many cases synergistic (e.g., a low-RCS LRCM will also gain benefits from flying lower). Although these factors and results related to them will be presented separately, it is important to recognize this synergistic relationship.

Threat Environment. Any LRCM survival capability must be defined in relation to the level of threat it will be flying against. Any analysis of LRCM survivability must therefore define specific threat scenarios. Across the range of currently existing threat environments, we can identify four major types of air defense threats: (1) strategic air defenses, (2) dense tactical air defenses, (3) air-to-air plus terminal air defenses, and (4) terminal defenses only.

Strategic Air Defense. The first threat environment, strategic air defense, is the most stressing. It consists of layered, netted defense elements intended to provide integrated air

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8 This loss of confidence would be based upon an inability to reach some desired confidence level of mission success because of a low confidence in any one missile's success. It implies some upper limit on the number of missiles that can be used for any one mission.
defense of a large area. This could include airborne warning aircraft (AWACS), ground-based EW and GCI radars, look-down, shoot-down fighters, mobile SAM areas, fixed terminal SAMs and guns, and the command and communications structure to integrate them.

At present, only the Soviet Union can be said to have a true strategic air defense, which extends only to the Soviet Union itself and not the other Warsaw Pact countries. Hence, this type of defense would be faced only when attacking targets deep in the Soviet Union. This contingency is both an unlikely mission for LRCMs and a highly stressing one. A notional strategic air defense is shown in Fig. D.5. Note that the major elements of the air defense are layered and connected.

Depending on the locations of targets and the axis of attack, LRCMs attempting to penetrate the Soviet strategic defenses could encounter any combination of the defense elements giving the defense multiple opportunities for detection and intercept. Airborne warning assets enable the defense to vector fighter aircraft while maintaining continuous radar coverage of the LRCMs. Dense GCI coverage can supplement areas that are uncovered by airborne warning assets. Ground-based defenses have a good chance of being warned of the approach of the LRCMs because of the existence of the command and control network, and have two possible phases, enroute and terminal, to make an intercept. The capability of the radars and SAM systems is likely to be very high, with the Soviet Tall King warning radar and SA-10 SAM system being examples of extremely capable air defense systems possessed by the Soviets.⁹

_Dense Tactical Air Defenses._ NATO and the Warsaw Pact have many of the individual elements of strategic air defenses, but not the command and communications structure required to integrate them. The command structures for NATO and the Warsaw Pact in the event of a major conflict are what cause us to term this threat environment a “dense tactical” threat. Although the warning, ground-based, and air-based threats of a strategic defense are all present, the command and control net are structured to support ground force actions. Mobile assets deploy with troops and are charged with defending force concentrations or headquarters. Fixed assets such as EW and GCI radar and fighter bases are charged with sector, rather than integrated, defense.

Figure D.6 shows an example of a dense tactical threat environment. In comparison to the strategic defense, the tactical threat environment has less depth and more fragmented

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information flow. Although terminal defenses exist, there is the potential for delayed or nonexistent warning to specific terminal sites. Nonetheless, this environment is still an extremely difficult one for LRMs. Many defense assets are highly mobile, resulting in the possibility of unexpectedly encountering masses of ground forces and their defense assets enroute to the target. Whether cued or uncued, terminal defenses are likely to be substantial. Currently, this threat environment would be encountered only in portions of Europe and Korea during a major conventional conflict, or during some other established conventional conflicts involving large numbers of Soviet forces.
Air-to-air plus Terminal Air Defenses. The third type of threat environment we have termed a "air-to-air plus terminal" threat. This defense environment also exhibits terminal defenses, but its major elements are dense radar coverage, aircraft vectoring capability, and LDSD fighter aircraft. Intercept vectoring can be accomplished with dense low-altitude ground-based radars or airborne warning and control aircraft. An LDSD fighter capability requires advanced fighter aircraft, meaning the latest generation American, Soviet, or French fighter aircraft with advanced avionics, and well-trained pilots. This combination of capabilities currently resides only with members of NATO, the Warsaw Pact, Israel, Iraq, Syria, and Korea. The radar and control technologies currently exist, but are very expensive to implement over a large area. Given U.S., Soviet, and French production rates for LDSD aircraft, it seems inevitable that the fighter technologies will spread further.

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Figure D.7 shows an example of an air-to-air plus terminal defenses with GCI radars providing the vectoring information for fighter aircraft. This threat environment lacks the mobile and area ground-to-air defenses exhibited by the previous defense environments, but it contains air-to-air assets, warning, and command and control.

![Diagram of air-to-air plus terminal threat environment](image)

**Fig. D.7—Air-to-air plus terminal threat environment**

An integrated countrywide fighter air defense implies a sophisticated opponent. This threat environment would constitute the upper end of threat environment for almost all areas of the world outside of Korea, Europe, and the Soviet Union. It is worth noting that the Iraqis made a serious attempt to develop a countrywide air-to-air defense system and largely failed.

*Terminal Only Air Defenses.* The final type of threat environment consists only of terminal defenses, either SAMs or guns. This threat environment holds over the vast majority of the world, where countries have neither the resources nor the expertise to set up integrated air defense and warning systems. These countries are generally sold less than
top-of-the-line defense systems, which they procure in small numbers and deploy around important military and government sites.

The terminal defense systems, generally older Soviet SAMs or guns, have a far lower capability against LRCMs than newer systems, which have so far trickled out only in small numbers. The older SAMs are often limited in their minimum altitude, offering the possibility of "underflying" the SAM systems, and they have longer command and communications delays and slower processing systems, making saturation easier. Gun systems will generally be effective only if cued for target azimuth, a small possibility in most countries, and are also susceptible to saturation.

Figure D.8 shows a schematic example of a terminal only defense. The radar coverage that exists is generally associated with radars designed for observation of high-altitude commercial air traffic, also termed "air sovereignty." Such defenses can be easily avoided by routing and low-altitude flight. The ground-based defenses are located only in the terminal area.
Given the extreme expense of extending defenses countrywide, very few countries that currently have terminal only defenses are likely to develop extended area defenses. Instead, they are likely to upgrade their air defenses with increasingly able terminal defenses.

In terms of where terminal only defenses are likely to be encountered, note that a wide-area air defense is very expensive item. The fact that a country does not have a very sophisticated air defense system does not imply that its armed forces are unsophisticated in general. Terminal only defenses could therefore be faced in many types of conflicts. In fact, the Iraqi air defense swiftly became a sporadic terminal-only defense, despite Iraq's possession of the world's fourth-largest army.

In the past, the United States has generally tended to design its systems in response to the threat environments in Central Europe or the Soviet Union, since systems designed to meet these challenging conditions are generally capable of operating anywhere else in the world. Although this approach has had its merits in the past, it should be clear from the discussion above that it results in systems that are significantly "overbuilt" for other areas of the world. Given the LRCM roles discussed in Sec. II, the primary focus of this survivability discussion will be the "air-to-air plus terminal" air threat environment. This environment is the most stressing of the threat environments one is likely to face throughout most of the world. Figure D.9 shows the current air defense threat environments around the world.

**Flight Altitude.** During the enroute portion of its flight, the LRCM has two possible flight profiles, high or low. These two flight profiles have different risks and benefits. High flight allows the missile to ignore ground obstacles and fly straight and level; this decreases the stress on the airframe, eliminates the risk of ground "clobber," and results in better fuel efficiency and range. The drawback of this altitude mode is that the high flight increases the radar horizon for ground defenses with a correspondingly greater chance of encountering defense assets and longer vulnerable time once they are encountered. Low flight (below 200 meters) has as disadvantages all of the advantages of high flight: the requirement for a means of avoiding terrain, increased airframe stress, chance of clobber, and possible degraded fuel efficiency. Low-altitude flight has the advantage of making the job for defense significantly, perhaps even vastly, more difficult. First, low-altitude flight increases the chances of being able to avoid enroute defenses by routing and utilizing terrain masking. Second, low flight delays detection of the incoming LRCM(s) and lowers the amount of time spent in the SAM defense envelope. This, combined with the effects of terrain masking, may delay the detection time to the point where defense systems cannot respond in time to effect an intercept. Finally, uncertainty exists about the ability of many SAM systems to operate at very low altitude. The uncertainty revolves around (1) the ability of radar to perform
Fig. D.9—Worldwide Threat Environments
clutter rejection, an extremely important consideration given the low RCS of LRCMs and probable low altitude clutter, and (2) the fusing capabilities of surface-to-air missiles versus small, low-altitude targets. Hence, low-altitude flight presents the difficulties we have discussed above but may also yield very large gains in survivability. The radar clutter rejection problem is discussed the following section on observability.

With these caveats, most would agree that SAM systems (which make up a large fraction of the non-NATO, non-Soviet defenses worldwide) can probably be "flown under" by today's LRCMs. Such is not the case, however, with modern SAM systems such as the U.S. Hawk, the French Roland, and the Soviet SA-10. These systems supposedly work down to extremely low altitudes. If modern clutter rejection and fusing systems are in fact effective, some means besides low altitude must be used to defeat these ground-based systems as well as air-to-air threats.

However, a "cue ball earth" is not an accurate representation of the environment of LRCM flight. In reality, the SAM system must track a LRCM over terrain. Depending on the terrain roughness and the capability of the SAM system to exploit terrain features for masking, the job for SAM systems could be made significantly more difficult. Figure D.10 shows a radar line-of-sight plot for a relatively flat area on the north German plain along the coast of East Germany, along with a representative LRCM heading. The low-altitude masking allows the LRCM to approach much closer to the SAM than the radar horizon, which would reduce the SAM's time to react and therefore degrade the number of available shot opportunities. Such an example does not carry weight in an absolute sense (i.e., the radars might not be located in these positions, the terrain may be atypical, etc.), but they are provocative. Clearly, there are additional possible benefits to low-altitude flight when terrain effects are considered. These effects could be further compounded by the clutter effects discussed previously and route planning that seeks to explicitly take advantage of the cover the terrain offers.

**Observability.** Cruise missiles have significantly less radar, optical, and infrared signature than other aircraft. This lower observability of current LRCM designs makes the job for defensive systems significantly more difficult, and may have reached the point where it (1) negates older SAM and warning systems, and (2) severely stresses the capability of modern SAMs.

The effects of low observability are not straightforward. The first major effect is on the absolute detection range of the radar. As discussed above, LRCMs will in all likelihood fly at low altitudes; therefore, in order for low observability to have a positive impact on LRCM survivability, it must be capable of lowering radar detection ranges to ranges less than the
low altitude radar line-of-sight horizon. Figure D.11 shows one way of viewing the relationship between radar cross section and altitude for several potential radars.¹¹

Figure D.11 can be interpreted in a very straightforward manner. The curves describe the locus of points where the detection range limited by radar cross section is exactly equal to the range limited by the radar line-of-sight horizon. Points to the left of the curves are conditions where the detection is limited by the radar cross section; points to the right of a curve are limited by the radar line of sight. The curves describe radars which differ in terms of their free-space detection range versus a one square meter target.

Both of these results are very sensitive to the specific capabilities of the individual radars. Two tradeoff points are shown for the central curve in Fig. D.11. The first corresponds to -20 dBsm and the second corresponds to -30 dBsm, both of which are

¹¹ I am indebted to RAND colleague William Dean for this method of presenting the observability-altitude tradeoff.
extremely low RCS levels. Note that a radar with 100 nautical mile range attempting to
detect a -20 dBsm vehicle is not RCS-limited until the flight altitude rises above 140 meters.
Most of the navigation systems discussed in Apps. B and C achieved flight altitudes well
below this altitude. The situation is different for the -30 dBsm vehicle; a 100 nautical mile
radar will be RCS-limited above roughly 30 meters, an altitude that corresponds to the most
optimistic flight altitude profile discussed in App. C.\textsuperscript{12}

The three radars shown in Fig. D.11 differ by a factor of four in their range capability,
and this variance in system performance is one that exists in the real world. The baseline
range capability of radars is dependent on size and power limitations on the design and the
design function of the system. Various sources list different warning and SAM radars with
ranges between 20 and 300 miles.\textsuperscript{13} As can be seen from Fig. D.11, changes in baseline
detection range can have a drastic effect on the altitude-RCS tradeoff, a manifestation of the
fact that radar range and RCS are related through a fourth-root function. This variance
indicates that the simple range-limitation benefits of lower observability exist, but will be
situation dependent.

For the LRCM, some of these difficulties are alleviated by the existence of ground
clutter.\textsuperscript{14} Against low-altitude targets, a portion of a defense radar’s main beam
and sidelobes intersect the ground. The reflected energy that returns to the radar is an
unwanted form of radar noise generally termed “clutter.” Although clutter energy is
returned to and received by the radar, there are a number of processing schemes that can
attempt to filter out the clutter once it is received. Chief among these techniques is doppler
processing. This technique is based upon the well-known principle of doppler shift; when
radar energy is reflected off a moving target, the frequency of the energy is shifted by an
amount proportional to the radial velocity of the target to the radar. Since most objects on
the ground (e.g., trees, houses, etc.) are moving slowly if at all, the clutter returns should be
perfectly differentiable by means of their doppler shift from objects such as LRCMs which
move at speeds of roughly 500 miles per hour.

In fact, however, the differentiation is not perfect. Although doppler techniques differ
in their details based upon the specific characteristics of the radar employing them, all
encounter a phenomenon termed the doppler notch. The doppler notch occurs when the

\textsuperscript{12} These radar cross section values are entirely notional and are suggested by the discussion in


\textsuperscript{14} Much of this simplified discussion of clutter processing is based upon \textit{Principles of Air Defense
and Air Vehicle Penetration} by Frank Heileman, CEBPress Books, George Washington University,
1986.
target reaches very low radial velocities with respect to the radar, as when the radar line-of-sight is roughly perpendicular to the flight path of the LRCM. At these low radial velocities, the doppler shift from the target becomes indistinguishable from that of ground objects, and the target signal is filtered out with the ground clutter. Many radars use a simple velocity
cutoff, treating objects with radial velocities less than a given velocity as clutter and all other velocities as targets. This method is shown in Figure D.12 for a velocity of 100 knots.\textsuperscript{15}

The doppler notch explains in part why the potential for large side-on radar cross section is less of a concern than it might be. The side-on RCS bloom is largely negated by the clutter filtering process. Of course, more sophisticated radars may be able to narrow this notch with greater processing power and more stable radar elements, but a notch will exist under all circumstances.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{target_radial_velocity_versus_aspect.png}
\caption{Target radial velocity versus aspect}
\end{figure}

The doppler notch is a well-understood problem for radars, but the degree to which the clutter can be reduced when the target is not within the notch is also subject to real-world limitations. As an example, Table D.1 below shows the case of the ASR-9, a modern early-warning radar.\textsuperscript{16} The free-space range of the ASR-9 against a one square meter (0 dBsm) target is given as 62.6 nautical miles. With lower radar cross section, this range is lowered according to the fourth-root law. However, with lowered RCS comes an increasing requirement to diminish clutter-generated noise, as measured by sub-clutter visibility (SCV)

\textsuperscript{15} This velocity was suggested as a commonly used value by the previous source.

requirement. The reference notes that the actual SCV of the ASR-9 is roughly 50 dB. So, although the free-space calculation for the ASR-9 gives it a nonnegligible capability against even -40 dBsm targets, the ASR-9 is clutter-limited to targets with -20 dBsm radar cross sections. The upper limit of sub-clutter visibility for an actual (as opposed to theoretical) radar is on the rough order of 60 to 70 dB, which can be expected only from the more advanced (and expensive) modern radars.

The two footnotes in Table D.1 indicate a final problem facing a radar attempting to detect objects with very small cross sections, the false target problem. Systems attempting to find very low observable targets must be capable of considering and discounting large number of false detections. This problem is exacerbated by attempts to narrow the doppler notch as discussed above.

<table>
<thead>
<tr>
<th>RCS (dBsm)</th>
<th>Free-Space Range (nm)</th>
<th>SCV (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>62.6</td>
<td>32.7</td>
</tr>
<tr>
<td>-10</td>
<td>35.2</td>
<td>42.7</td>
</tr>
<tr>
<td>-20</td>
<td>19.8</td>
<td>52.7</td>
</tr>
<tr>
<td>-30\textsuperscript{a}</td>
<td>11.1</td>
<td>62.7</td>
</tr>
<tr>
<td>-40\textsuperscript{b}</td>
<td>6.2</td>
<td>72.7</td>
</tr>
</tbody>
</table>

\textsuperscript{a} RCS of birds.

\textsuperscript{b} RCS of insects.

The relatively lower optical and IR observability and small vulnerable area of LRCMs should yield some significant payoffs versus hand-held SAM systems and guns. These defensive systems are short range relative to SAMs (approximately 0.5 to 2 miles operational radius). Although we have not undertaken any detailed modeling of these systems, it is clear that they will require accurate cueing information on target heading and azimuth if they are to observe and fire upon LRCMs in time. Further, the small total area of the LRCM will pose problems for gun systems (which rely on volume of fire), and the lower IR signature of small turbine engines will present lock and homing difficulties for IR systems. In short, without the detection and cueing assets that generally accompany only sophisticated defense systems (which presumably contain the longer-range, more capable radar SAM systems), guns and IR systems probably pose a small threat.
Overall, the discussion above seems to indicate that low LRCM observability will seriously strain modern radars, but not necessarily negate them entirely. On the other hand, the small cross section of LRCM vehicles could be a decisive aid to LRCM survivability in those threat environments that lack the latest, most sophisticated radar equipment. Luckily, these environments currently encompass most of the world.

The only countries equipped with radars that can match the requirements discussed above (i.e., high power, high clutter rejection capability, and good false target rejection) currently reside with the United States, the Soviet Union, and their major military allies. Inevitably, over time these capabilities will spread, but such radars, the command and control equipment, and the personnel required to run them are costly to obtain and maintain. LRCM observability is likely to prove a decisive advantage in the mid-scale to low-scale conflicts.

Defense Saturation. Aside from attempting to limit the capability of defense systems against individual missiles, one can attempt to overcome defenses by saturating them with a number of missiles. Any defense system, whether airborne or ground-based, must spend time detecting, acquiring, tracking and destroying a target. Saturation works by exploiting this defense turn-around time. If enough LRCMs are sent into the defensive envelope, some will inevitably remain unattacked; the defensive system will simply be overwhelmed.

The nature of a saturation attack changes with the type of defenses. If the primary threat is from airborne fighters, one would wish to spread the LRCMs over a large area, along a number of different flight paths. This helps to ensure that any intercepts made by an aircraft will be low-payoff ones; the aircraft will be forced to acquire, track, and destroy individual targets in sequence, eventually exhausting its fuel. If, on the other hand, the primary threat is from a ground-based concentration of defenders, one takes a different tactic: as opposed to air-based threats which can follow the LRCM, ground-based defenses have a fixed and limited time in which to fire. Under these conditions, one wishes to bunch a large number of LRCMs into a small volume in order to overwhelm the individual SAM sites by presenting too many targets for their limited action time.

The preferred saturation tactics, therefore, seem to be to (1) bunch LRCMs when they are forced to pass through or into areas that present a heavy ground threat, and (2) spread the missiles out when ground defenses are expected to be less heavy. A heavy ground threat could exist through portions of the enroute phase in the strategic and dense tactical threat environments and in the terminal area in all threat environments. One might expect the “ground defense” and “air-to-air defense” portions of the route to be roughly differentiated
based on friend or foe considerations. The simplest way to avoid shooting down one's own defense aircraft is to establish "free fire" zones for either ground defenses or aircraft but not both.

Given a sufficient number of LRCMs in an attack, saturating an air-to-air defense region should be a rather simple operational matter, given the inherent flight time limitations faced by fighter aircraft. The LRCMs should fly as far apart as possible, within the constraints of (1) bunching to saturate unavoidable ground defenses, and (2) simultaneous target arrival. This tactic will be successful if one can force the fighter engagement to be sequential, which will depend both on the absolute spacing of the LRCMs and the type of surveillance aircraft present (i.e., airborne warning versus fighters on CAP). However, if successful this saturation tactic should hold encounters to some small fraction of any given sortie. Given a combination of low observability, sufficient spacing, and a reasonable number of LRCMs fired, air-to-air threats to LRCM should be largely negated by saturation tactics.

The key element for effective ground defense saturation is having some control over the time of arrival for the LRCMs. For ground defenses, the LRCMs must arrive roughly together in order to bunch effectively for ground defense saturation. In addition, LRCMs will gain some benefit from the fact that the terminal ground defenses will be located near the target. Since the LRCM will not need to egress the target area, the amount of time that terminal defenses have to fire upon the LRCM will be limited.

Saturation tactics can have a potentially dramatic effect on SAM systems that lack multitarget track and fire capability. Although the latest generation of U.S. and Soviet SAM systems have such a capability, the majority of systems deployed around the world do not. Given enough LRCMs, any system can be saturated, and this saturation is made easier by the effects of low-altitude flight and lowered observability. The effects of saturation are heightened by the lower observability of the vehicle through its effect on the reaction time and effective radius of the SAM. By nature, the effects of saturation are slight until some critical number of LRCMs is reached.

Saturation capability is primarily an economic issue. Given either an unlimited budget or a costless LRCM, saturation would always be the simplest single defense penetration option. However, neither of these two conditions ever appears in reality, and cost effectiveness arguments will dictate the degree to which one can rely purely on saturation for LRCM air defense penetration. However, it is an operational tactic that should be used no matter the final configuration of the LRCM, given its obvious effectiveness. One can conceive of very few LRCM attacks where only one missile is required to arrive on
the target(s). Given this fact, it makes sense to take advantage of the LRCM raid size to degrade the opponent’s air defense effectiveness, bearing in mind that LRCMs are by their nature expendable items, and saturation will enhance the effectiveness of each individual LRCM.

**Intelligence/Mission Planning.** It is clear that to take advantage of some of the factors discussed above (e.g., routing, terrain masking, low-altitude flight and defense saturation) a large amount of varied information must gathered and synthesized. For survivability purposes, the capability must exist to (1) locate and identify threats in real time, and (2) generate LRCM mission plans and profiles quickly enough to exploit this intelligence information. The current LRCM mission planning systems are capable of storing terrain data and threat information and generating missile flight paths taking advantage of these over periods of time ranging from of tens of hours to days. In most areas of the world, this planning turnaround time is probably sufficient, but it is probably inadequate to deal with the mobility of a Soviet-style strategic air defense or the rapidly changing face of a major conventional conflict.

Plan generation times can probably be shortened significantly in upcoming mission planning upgrades, but a mission plan is only as good as the information that it is based upon. The intelligence/mission planning cycle emerges as perhaps the most critical issue for continued LRCM survivability. During the next few years and for any fixed defense deployment, a successful LRCM mission plan that utilizes the techniques discussed above can be generated. This careful planning, however, can come to naught if the threat information is outdated and in error. Of crucial importance could be the integration of the mission planning systems with real-time threat intelligence capabilities such as JSTARS and COMPASS CALL. By exploiting the information that we have available in a timely manner, effective LRCM survivability can be ensured.

**Ensuring LRCM Survivability: An Example**

The following is an application of the concepts discussed above to a notional mission for LRCMs. This mission involves attack of several targets within a secondary theater conflict involving an air-to-air plus terminal defense environment. The discussion serves to illustrate the points made above and to emphasize the importance of tactics and mission planning to the development of a survivable LRCM mission.

Figure D.13 shows an example of the types of tactics and effects that are likely to ensure high LRCM survivability in the air-to-air plus terminal threat environment. The first major point is that a large number of LRCMs are used in the attack. This makes it possible
to utilize saturation tactics against the ground-based and air-based defenses. If only a small
number of LRCMs were utilized, the capability to saturate defenses would clearly be
diminished. This argues for attacks in volume, and bolsters the argument for LRCM use in
mid-level conflicts, where a large number of potential targets can be expected. Bomber
aircraft are shown launching this particular attack, but it might have been launched by a
naval force.

The saturation tactics include a large number of routes through the air-to-air fighter
defense zone, forcing the fighter aircraft to intercept LRCMs on an individual basis. The
routes converge on the terminal target area roughly simultaneously.

The effects of flight altitude and observability are shown by reduction of the radar
coverage below the radar horizon and the effect of the doppler notch.

Overall, the effects of saturation, low-altitude flight, observability, and routing should
ensure high LRCM survivability in this threat environment. Each of these individual
components had some positive effect on the survivability of the LRCM, and their effects
compound synergistically. Given reasonably low LRCM RCS, a capability for low-altitude
flight (60 meters), time of arrival control for defense saturation, and a responsive mission
planning system, LRCM attrition rates should be low even in the more dense air threat
environments over the next few years, and the lower threat environments pose almost no
threat to effective LRCM use.

LRCM LETHALITY

Lethality is defined as the ability of the LRCM to destroy a target given its
availability, reliability, and survivability. For any given target, LRCM lethality can in
general be broken down into two components: target vulnerability and accuracy. Target
vulnerability to a LRCM is determined by a combination of the physical extent of the target
(its size), the intrinsic nature of the target's structure (its hardness), and the munition effects
of the LRCM payload; the combination of these three factors generally results in target
vulnerable dimensions, the area within which a LRCM impact will result in target
destruction. This vulnerable dimension may be larger than the actual LRCM munition
effects, indicating that more than one LRCM will be required to fully destroy the target.
Finally, LRCM accuracy will drive the capability of the LRCM to land in the target
vulnerable area. In combination, target vulnerability and LRCM accuracy combine to give a measure of the ability of an individual LRCM to damage a given target.
Notional LRCM Targets

A number of possible targets have been proposed for LRCMs by a number of sources. Table D.2 below indicates some of the many that have been discussed. These target sets include a broad range of military, political, and economic targets. In addition, some of these targets have different elements that need to be addressed separately.

<table>
<thead>
<tr>
<th>Target Type</th>
<th>Targets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Military</td>
<td>Highway bridges</td>
</tr>
<tr>
<td></td>
<td>Railroad bridges</td>
</tr>
<tr>
<td></td>
<td>Airfields</td>
</tr>
<tr>
<td></td>
<td>Command posts</td>
</tr>
<tr>
<td></td>
<td>Bunkers</td>
</tr>
<tr>
<td></td>
<td>Radar/SAM sites</td>
</tr>
<tr>
<td>Economic</td>
<td>Power plants</td>
</tr>
<tr>
<td></td>
<td>Oil refineries</td>
</tr>
<tr>
<td>Political</td>
<td>Terrorist camps</td>
</tr>
<tr>
<td></td>
<td>Government buildings</td>
</tr>
</tbody>
</table>

Bridge Targets. Bridges of any type are perhaps the most difficult of all targets to attack, as evidenced by a great deal of anecdotal evidence from World War II, Korea, and Vietnam. The primary purpose of an attack on a bridge is to stop its use for a period of time. In almost any situation, if the bridge is truly critical, attempts to repair it will be made, and reattack of the bridge may be necessary. Two criteria for successful attack on a bridge exist. The first is the easier of the two and consists of dropping at least one span of the bridge. This would force a repair crew to replace the span with either a temporary span or a more permanent replacement. The second criterion is more difficult and consists of destroying the pier of the bridge; the damaged pier must be replaced or shored before spans can be replaced, making a much more difficult job for the repair crew. We will confine our discussion to the simpler and better understood task of dropping a span. In areas lacking extensive bridging equipment (i.e., most areas outside of Europe and Korea), dropping a span may well be a sufficient requirement.

Although all bridges are difficult targets, railroad bridges are generally considered to be more difficult to destroy than highway bridges. This is because railroad bridges are generally more open, flexible structures than highway bridges and are shock-loaded to take the rapid increase in stress associated with the advent of a large, swiftly moving train. Both
types of bridges may require a hardened high explosive warhead to avoid failure of the warhead casing when it strikes the hard deck or pier of the bridge.

Bridges are often extremely large structures, but the actual target extent of a bridge is small, generally consisting of small areas above and immediately surrounding the piers of the bridge. A LRCM striking in this region will detach the span from the pier and drop it. Weapons that land further from the piers are likely to punch an easily repaired hole in the decking or rails. Bridges in this analysis will be assumed to be 30 meters wide, which will constitute the length of the target area, and the pier width will be considered to be roughly one meter. The additional width of the target area beyond the pier width is determined by the effectiveness of the LRCM payload. Figure D.14 illustrates this concept.

![Diagram of a bridge showing top and side views with labels for span, pier, and target area.](image)

Fig. D.14—Bridge targets

**Airfield Targets.** For this analysis, airfields can be considered as two distinct target elements. The first of these are the runway and taxiway surfaces that aircraft could use for takeoff. In the common usage, the attacker attempts to limit the usable (uncratered) segments of runway or taxiway to lengths less than the minimum takeoff distance for the aircraft using them. We will utilize a standard notional airfield for this analysis consisting of one primary runway 2400 meters long by 50 meters wide, one secondary runway 1800 meters long by 30 meters wide, and one connecting taxiway 1200 meters long by 25 meters wide. The goal of attacks will be to limit usable runway segments to below 750 meters (roughly 2500 feet) in length. This will require three cuts on the main runway, two cuts on the secondary runway, and one cut on the connecting taxiway. An illustration of these targets is shown in Figure D.15.

None of the airfield takeoff surfaces is realistically susceptible to attack by a unitary-munition LRCM. In Apps. B and C we discussed the use of Boosted Kinetic Energy
Penetrator (BKEP) submunitions for runway attack, and we will assume that each LRCM will be capable of making three separate cuts with BKEP submunitions.

The second set of airfield targets comprises parked aircraft. These aircraft can either be parked in the open or revetted. Revetted aircraft are parked with roughly circular open earthen berms designed to protect them from near-miss bombs. Such a revetment would probably measure 30 meters in internal diameter. Revetments would also be attacked with submunitions, in this case the Combined Effects Bomblet (CEB) discussed earlier. The LRCM should be capable of dispensing three sets of CEBs, and therefore attacking three different revetments. For the standard airfield, we will assume that the revetments contain a squadron of aircraft in eighteen revetments.

![Diagram of airfield targets]

**Fig. D.15—Airfield targets**

**Command Post and Bunker Targets.** A command post or bunker can be considered as a generic small, hardened target. Since there is obviously no standard size for a military command post or weapons storage bunker, we will assume a small, 10 meter square structure that would fit into the hard target category discussed in App. C. Such a structure could be made out of reinforced concrete or semi-buried wood and concrete. It would generally require a hardened case warhead to carry out the attack.
Radar/SAM Site Targets. SAM and radar sites share similar characteristics. They are generally made up of a number of individual equipment elements, a number of which are very susceptible to fragment damage. These include radar antennae, power generation, and command structures. For military systems, these elements are often deployed on trucks or vans. These different elements can be collocated or slightly dispersed. Figure D.16 shows a schematic of a notional SAM site used for this analysis. It consists of a SAM launcher/track radar combination, an early warning radar, and a control van. These elements are located within a 50 meter by 100 meter area (roughly the size of a football field). The vulnerable elements of this site are highlighted, and consist of the two radar antennae and the control equipment located within the van. The best munition to use against radar and SAM sites would be the CEB submunition payload. In this case, all of the payload would be dispensed in one release, instead of three.

![Schematic diagram](image)

**Fig. D.16—SAM targets**

Power Plants. Thermal electric power plants have a number of potentially vulnerable elements, including the generator turbines, boiler rooms, transformer farms, and control rooms. For this analysis, we will examine one potential set of targets, the turbines located in the power plant generator hall. These turbines consist of several large metal objects spaced down the length of a building. Although they are heavy metal, the turbines are spinning at high speed. A sufficiently large shock can unbalance the turbine and swiftly lead to significant damage as the kinetic energy of the turbine is used against itself. The turbine will therefore be considered as a medium hard target in the parlance of App. C. Each
power plant will be assumed to have four 5 meter by 5 meter turbines spaced sufficiently far apart that they may be considered individual targets. Figure D.17 shows a schematic of the power plant target.

![Turbines](image)

**Fig. D.17—Power plant targets**

**Refinery Targets.** Oil refineries are extremely extensive and complex targets. The two major approaches to attacking them are (1) attack important key refining elements, such as cracking or distillation towers, and (2) attack key control centers, which are essential for directing and monitoring the refining processes. Other elements of a refinery can generally be bypassed or repaired with more ease than the two elements identified.

There can be a large number (dozens) of process towers associated with any given refinery, whereas the control centers are limited in number to a primary center and, perhaps, one or two secondary control centers. However, it is generally easier to identify cracking and distillation towers in a photograph than to identify control centers, and control center locations may require some other type of intelligence information in addition to the photography.

Finally, destruction of the control center, while disabling the refinery for an extended period, is the more limited attack. Destruction of process towers would generally be accompanied by secondary damage and explosions brought about by combustion of the volatile chemicals found in the refining process. Although some additional damage to the facility is likely in an attack on the control centers, it is not likely to require the massive repair and replacement that a process tower attack might cause.
Therefore, for this analysis we will parameterize between the two types of attack. A process tower attack will include attack on ten separate tower elements, while a control center attack will require attack on three separate control structures, each of which must be destroyed in order to halt the refinery's production. The towers will be considered as 5 meter square targets of medium hardness. The control buildings will be considered to be 10 meter square targets of medium hardness. Figure D.18 shows a schematic of the standard refinery target.

![Diagram](image)

**Fig. D.18—Refinery targets**

**Political Targets.** Finally, political targets can come in all shapes and sizes. As an assumption, they will be considered to be normal frame buildings, and therefore soft targets. The size of the building area that one might wish to destroy can of course be highly variable, and we will generate parametric curves for this type of target. Table D.3 summarizes the sizes and classes of all the various target types identified in the discussion above.

**Evaluating Target Vulnerable Dimensions**

The discussion of target vulnerable dimensions (for those targets where this metric is appropriate) relies in part on the munitions effects discussion developed earlier. Table D.4 summarizes the munition effectiveness radii of the various LRCM munitions developed in the discussion of LRCM performance.

Given Table D.4 and the discussion above, two possible outcomes can evolve for target vulnerable dimensions. First, for targets whose vulnerable area is on the same order as the
Table D.3  
Summary of LRCM Target Descriptions

<table>
<thead>
<tr>
<th>Targets</th>
<th>Target Size</th>
<th>Target Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway bridges</td>
<td>30 m x Variable</td>
<td>Hard</td>
</tr>
<tr>
<td>Railroad bridges</td>
<td>30 m x Variable</td>
<td>Hard</td>
</tr>
<tr>
<td>Airfields</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runways</td>
<td>Six total cuts</td>
<td>BKEP</td>
</tr>
<tr>
<td>Revetments</td>
<td>20 revetments</td>
<td>CEB</td>
</tr>
<tr>
<td>Command posts</td>
<td>10 by 10 meters</td>
<td>Hard</td>
</tr>
<tr>
<td>Bunkers</td>
<td>10 by 10 meters</td>
<td>Hard</td>
</tr>
<tr>
<td>Radar/SAM sites</td>
<td>150 x 50 meters</td>
<td>CEB</td>
</tr>
<tr>
<td>Power plants</td>
<td>4 turbines: 5 x 5 m</td>
<td>Medium</td>
</tr>
<tr>
<td>Oil refineries</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process towers</td>
<td>10 towers: 5 x 5 m</td>
<td>Medium</td>
</tr>
<tr>
<td>Control rooms</td>
<td>3 structures: 10 x 10 m</td>
<td>Medium</td>
</tr>
<tr>
<td>Political targets</td>
<td>Variable</td>
<td>Soft</td>
</tr>
</tbody>
</table>

LRCM munition effects radius, we can generate a set of target dimensions within which a single LRCM must land for damage to occur. Alternatively, for targets with vulnerable areas that are much larger than the LRCM munition effects, we can develop the number of individual LRCM attacks required to cover the target.

**Bridge Targets.** As noted above, bridge targets will be considered to be long, thin targets whose width is primarily determined by the effectiveness of the LRCM munition effectiveness against hard targets. By examining Table D.4, one can find that the effective radius of the different munitions against hard targets (note that fuel-air explosives are ineffective). Combining these figures with the physical dimensions of the target yields the following target vulnerable areas for bridges: (1) 30 meters by 4 meters for 1000-lb HE or 750-lb reactive warheads, and (2) 30 meters by 6 meters for 2000-lb HE warheads. The results arrived at through this methodology give good agreement to experimental data.17

**Airfield Targets.** Lacking any sufficiently detailed methodology to approach the analysis of BKEP cuts against runways, we assume that a survivable, reliable LRCM capable of BKEP carriage would be able to make three runway cuts.

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Table D.4
Summary Of LRCM Munition Effects

<table>
<thead>
<tr>
<th>Payload</th>
<th>Unitary Measures</th>
<th>Submunition Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hard</td>
<td>Medium</td>
</tr>
<tr>
<td>Unitary</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000-lb HE</td>
<td>1.5 m</td>
<td>5 m</td>
</tr>
<tr>
<td>2000-lb HE</td>
<td>2.5 m</td>
<td>7.5 m</td>
</tr>
<tr>
<td>1000-lb FAE</td>
<td>0 m</td>
<td>12 m</td>
</tr>
<tr>
<td>700-lb Reactive</td>
<td>1.5 m</td>
<td>5 m</td>
</tr>
<tr>
<td>Submunition</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CEB</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BKEP</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Revvetted aircraft targets would be attacked by roughly 70 CEB bomblets in a 75 meter by 75 meter pattern. This pattern would almost certainly cover the 30 by 30 meter revetment position. If the pattern does in fact cover the revetment, roughly 12 bomblets could be expected to land within its confines. In all likelihood, the fragment effects and potential damage caused by the shaped-charge portion of the CEB will destroy any aircraft within the revetment.

**Command Posts and Bunker Targets.** A command post or bunker is a hard target to warheads detonating outside of the confines of the target. However, if the LRCM strikes the command post or bunker or lands close enough to it, failure of the structure should result in its destruction. Therefore, the vulnerable dimensions of the command post or bunker target are simply the physical extent of the target (10 by 10 meters) plus the additional area outside of the target equal to the LRCM munition effective radius. For the 1000-lb HE warhead or the 750-lb reactive warhead this results in a 13 by 13 meter vulnerable dimension, and for the 2000-lb HE warhead this results in a 15 by 15 meter vulnerable dimension.

**Radar and SAM Targets.** The vulnerable dimension analysis for radar and SAM targets is more complicated than that of the previous targets. As noted above, the notional SAM deployment is made up of three vulnerable elements in a 50 by 150 meter area. It is clear that the LRCM should be able to to cover this area with the roughly 220 bomblets at its disposal in a pattern of roughly 75 by 225 feet. For the accuracies discussed here, this
pattern should almost always completely overlay the site. The issue, therefore, is the likelihood that fragments from the CEB bomblets will strike the various target elements. For a 75 by 225 meter area, 220 bomblets in a perfect pattern will equate to one bomblet roughly every 9 meters, leaving a maximum distance from any one bomblet of roughly 4.5 meters. This distance is well within the maximum effective distance of 7 meters discussed earlier for CEBs.

Utilizing a model of fragment density versus distance, roughly four fragments could be expected to strike the vulnerable portion of the control van identified in Figure D.15. The early warning radar would receive an expected six fragment hits, and the track radar, the smallest target, could expect on average one hit.

The dispersal of bomblets from the LRCM would certainly not be perfect, but the density and velocity of fragments is certainly on the order necessary to attack this type of target. In all likelihood, two reliable, survivable LRCMs would be desired in order to gain increased confidence of successful attack.

**Power Plant Targets.** Power plant turbines can be treated in the same manner as command posts and bunkers, with the distinction that turbines are considered to be medium targets. Therefore, their vulnerable dimension for 1000-lb HE or 750-lb reactive warheads will be 15 meters by 15 meters (5 meter extent plus twice the 5 meter munition effectiveness) and 20 meters by 20 meters for the 2000-lb HE explosive.

Turbines present a difficulty when one attempts to target fuel-air explosive warheads. Although turbines are of medium hardness, and therefore susceptible to FAE blast, they are located within a structure. For HE warheads this presents little difficulty, since fuzing for this type of attack is relatively straightforward. For FAE warheads, however, the most feasible attack would have to be against the plant as a whole, since the charge must be detonated in the open air. This may destroy the plant walls or ceiling, but it is unclear that this actually damages the turbines. Therefore, we will assume that FAE warhead cannot be used for this type of power plant attack.

**Oil Refinery Targets.** The two types of targets for an oil refinery attack are similar to power plant turbines. The process towers are assumed to be 5 by 5 meter medium targets. Therefore their vulnerable area is identical to the turbines for HE warheads: 15 meters by 15 meters for 1000-lb HE or 750-lb reactive warheads, and 20 meters by 20 meters for the 2000-lb HE explosive. In this case, however, FAE warheads might be utilized, since the attacks take place in the open. The process towers would have a vulnerable area equal to 29 by 29 meters for FAE warheads.
The control room is a slightly larger but similar target. For 1000-lb HE or 750-lb reactive warheads its vulnerable area would be 20 by 20 meters, for the 2000-lb HE warhead 25 by 25 meters, and for the FAE warhead 34 by 34 meters.

**Political/Large Building Targets.** Frame buildings can generally be classed as soft targets, meaning that all of the unitary munitions discussed here have extensive effective radii against them. However, such buildings often combine their soft structure with extensive area. Figure D.19 shows the relationship between the size of the building in terms of floorspace and the number of each type of payload required to roughly cover the area.

![Graph showing the relationship between target dimensions and weapons required for different warhead types.](image)

**Fig. D.19—Coverage of large soft targets**

As one can see, the numbers of LRCMs required for either high explosive payload swiftly becomes very large indeed; in all likelihood a LRCM attack with HE warheads aimed at complete destruction of a building would be limited to buildings of 1600 to 3600 square meter area. For extensive soft targets such as these, the FAE warhead is used to most effect. In fact, the effectiveness of both warhead types may be underestimated somewhat for soft
targets. High explosives detonating within a building could be expected to gain some
destructive benefit from the containment that the walls of the building provide. This
containment ensures that more of the blast energy is transferred to the target; moreover,
buildings are rarely designed to contain large internal overpressures. The FAE warhead
effect could be significantly greater if the extent of the FAE cloud is larger than we have
suggested.

Based upon the discussion above, Table D.5 summarizes the target vulnerable
dimensions by target type.

**Table D.5**

<table>
<thead>
<tr>
<th>Summary of LRCM Target Vulnerable Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Targets</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Highway bridges</td>
</tr>
<tr>
<td>Railroad bridges</td>
</tr>
<tr>
<td>Airfields</td>
</tr>
<tr>
<td>Runways&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Revetments&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Command posts</td>
</tr>
<tr>
<td>Bunkers</td>
</tr>
<tr>
<td>Radar/SAM sites&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Power plants</td>
</tr>
<tr>
<td>Oil refineries</td>
</tr>
<tr>
<td>Process towers</td>
</tr>
<tr>
<td>Control rooms</td>
</tr>
<tr>
<td>Political targets</td>
</tr>
</tbody>
</table>

<sup>a</sup> BKEP target.
<sup>b</sup> CEB target.

**Expected LRCM Lethality**

Given the results in Table D.4, LRCM lethality versus these targets depends on the
accuracy with which the LRCM can be aimed. LRCM accuracy, as discussed earlier, is
measured by Circular Error Probable (CEP), defined as the radius normal to the flight of the
missile within which 50 percent of weapons will be contained. If the impact of the weapon is
normal to the surface of the target, the weapon impacts are distributed in a circular,
Gaussian distribution around the aimpoint. If the weapon strikes the target at an angle, the
CEP in the target plane breaks into two components, a Range Error Probable (REP) and a Deflection Error Probable (DEP). The DEP is the side-to-side error, which is unaffected by the incident angle and is therefore equal to the CEP. The REP is the uprange-downrange error and is related to the CEP by the relationship $\text{REP} = \text{CEP} + \sin(I)$, where $I$ is the incident angle. This concept is illustrated in Figure D.20.

For the cases considered, the LRCM will be assumed to attack from a 60 degree dive angle. A dive capability has been demonstrated on the Tomahawk missile; in fact, it was a critical test milestone for the Tomahawk. It is clear from Fig. D.20 that the 60 degree attack angle pays very little penalty from the point of view of extension of the REP. In addition, the REP is fairly insensitive to the exact attack angle at angles above 45 degrees (as one would expect from the sin relationship).

Fig. D.20—Range and deflection error probable for various impact angles

Figures D.21–23 show the lethality of the various munitions against the targets we have discussed when plotted against a range of LRCM normal CEPs. Also plotted are (1) the
Fig. D.21—Lethality of 1000-lb HE and 750-lb reactive warheads

Fig. D.22—Lethality of 2000-lb HE warhead
relationship between submunition lethality and accuracy (weak for the cases discussed), and (2) the largest soft building that can be completely attacked with a single weapon. These three figures demonstrate several important concepts which are carried through other portions of this analysis.

First, it is clear that the accuracy of the DSMAC guidance systems yields limited single-shot probabilities of destruction against small medium or hardened targets; this is especially evident from the small, hard bridge targets. In contrast, the target-looking sensors yield uniformly high single-shot destruction probabilities with the exception of bridge targets at the high end of the accuracy uncertainty range.

Second, the combination of target-looking sensor and 1000-lb HE or 750-lb reactive warhead yields very high individual lethality against all targets except the aforementioned bridge targets and soft targets greater than 20 by 20 meters. For target-looking sensors, there is only a marginal advantage in the 2000-lb HE warhead for small, hard targets. The FAE warhead would yield a marginal advantage against very large soft targets, but is
ineffective against the harder target sets and some medium targets. Therefore, if a target-
looking sensor is chosen as the LRCM guidance set, the 1000-lb HE warhead or 750-lb
reactive warhead are the most reasonable baseline unitary payloads. Only if DSMAC or a
similar terminal guidance system is used would the larger HE or FAE warheads be a very
useful option.

LRCM RELIABILITY AND AVAILABILITY

Reliability

As previously discussed, reliability emerges as a problematic LRCM capability since its
relationship to individual technologies is so unclear. By definition, most individual
unreliable elements of a weapon system can be identified and repaired. This is the purpose
of developmental testing and operational testing. There is every indication that this
procedure can be done well. The difficulty in obtaining an estimate of the reliability of a
weapon system \textit{a priori} is that much of the inherent reliability of complex systems derives
from problems of integration. The interconnection of individually reliable components can
generate unexpected and difficult-to-diagnose failures. Such has been at least part of the
reliability history of the Tomahawk missile system, which has at different times experienced
transient missile integration failures.\textsuperscript{18}

Nonetheless, Tomahawk and many other complex weapon systems have achieved high
reliability in tests. For this analysis, reliability will be treated as an exogenous factor, and in
general, the reliability will be assumed to be quite high.

Availability

Availability has a different flavor than either lethality, survivability, or reliability. Each of these three latter characteristics is related to individual missile capability to reach
the target and destroy it once it is reached. Availability, on the other hand, will determine
whether any missiles will be launched at all; it is an all-or-nothing proposition.

In general, the availability of the LRCMs to launch any given attack will be depend on
two major factors: (1) the time at which the LRCM platforms reach appropriate
launchpoints, and (2) prevailing weather conditions. A portion of the discussion in this Note
deals with comparisons and tradeoffs between different LRCM launch platforms. In general,
long-range bomber platforms based in the United States can, with appropriate tanker

\textsuperscript{18} Conversations with Dr. Myron Hurw, member of the RAND technical staff, former Project
Manager, Tomahawk Missile Program.
support, reach most of the world in hours. In contrast, inherently slower naval platforms are often based far from U.S. shores. Although naval forces have the potential for malpositioning, they can generally buy back the availability of their LRCM forces by extending the LRCM range. In general, correct platform versus LRCM design tradeoffs should ensure that platform constraints do not significantly affect LRCM availability.

This leaves the weather resistance of the LRCM terminal sensor as the key determinant of LRCM availability. As previously discussed, the current Tomahawk DSMAC system suffers from some important weather limitations due to its visible light sensor. These include susceptibility to fog and rain, along with potential seasonal variations of the terminal scene. Imaging infrared systems have more effectiveness in fog and rain, but they can still be defeated by heavy rain or snow. In addition, passive IIR can suffer from washout at specific times of day. The SAR radar works in virtually all weather.

Obviously, one key question is how often the conditions would preclude use of these various sensors. Unfortunately, this question is very difficult to answer. Some areas of the world, most notably Europe and the northern Soviet Union, have extremely poor weather much of the time, while other areas, such as the Persian Gulf, are less likely to have precipitation over large periods of the year. The acceptable level of weather-related availability is a subjective judgment. For this analysis, we will in general assume that use of at least an IIR sensor will result in acceptable LRCM availability.
Appendix E
NOTIONAL LRCM TARGET SETS AND FORCE SIZES

This appendix discusses a completely notional target set for LRCMs that might be encountered in regional conflicts such as those discussed in Sec. II. Although the exact size of a LRCM force cannot be derived from this analysis, it becomes clear that military use of the weapon would require several thousand LRCMs with the ability both to attack in volume and to sustain such an attack.

Any conflict could be expected to have a mixture of military, economic, and political targets. The discussions of Desert Storm targets that have appeared in a number of newspapers in recent months indicate that such a mix was in fact attacked. However, analysis of any given target set swiftly leads to the conclusion that military target sets will drive the force size requirements. This is because of the capability and incentive for enemy forces to repair battle damage to military targets such as bridges and airfields, necessitating reattack of these targets. Table E.1 shows a notional target set incorporating a mix of military, economic, and political targets, along with their reattack requirements.

Table E.1
Notional LRCM Target Set

<table>
<thead>
<tr>
<th>Targets</th>
<th>Target Size</th>
<th>Reattack?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bridges</td>
<td>20</td>
<td>Each 3 days</td>
</tr>
<tr>
<td>Airfields</td>
<td>10 Total</td>
<td></td>
</tr>
<tr>
<td>Runway cuts</td>
<td>60</td>
<td>Each day</td>
</tr>
<tr>
<td>Revetments</td>
<td>180</td>
<td>No</td>
</tr>
<tr>
<td>Command posts</td>
<td>10</td>
<td>No</td>
</tr>
<tr>
<td>Bunkers</td>
<td>10</td>
<td>No</td>
</tr>
<tr>
<td>Radar/SAM sites</td>
<td>10</td>
<td>No</td>
</tr>
<tr>
<td>Power plants</td>
<td>10</td>
<td>No</td>
</tr>
<tr>
<td>Oil refineries</td>
<td>10 Total</td>
<td></td>
</tr>
<tr>
<td>Process towers</td>
<td>100</td>
<td>No</td>
</tr>
<tr>
<td>Control rooms</td>
<td>30</td>
<td>No</td>
</tr>
<tr>
<td>Political targets</td>
<td>10</td>
<td>No</td>
</tr>
</tbody>
</table>
Figure E.1 indicates the attack requirements for individual targets described in App. D with LRRCMs utilizing 1000-lb HE explosive weapons and target-looking sensors capable of 3-meter accuracy. Based upon the discussion in App. D, the reliability and survivability of the LRRCMs are each set at a high value, 90 percent, with the lethality based upon the lethality curves found in App. D. In all cases, the desired confidence of destruction for the target is 90 percent.

![Chart showing weapons required per target for different targets.]

Reliability = 0.9  
Survivability = 0.9  
Lethality = Fig. D.21

Fig. E.1—Single target attack requirements

Force requirements will be driven both by single-attack requirements and by reattack needs. Although the number of targets of each type are roughly equal, some targets will require repeated reattacks. Figure E.2 shows a particular scenario for attack of these targets.
targets. All targets are attacked on the first day of a twenty-day conflict. After the first day, only bridge and airfield runway targets are reattacked in order to prevent them from being reopened for use.

![Graph](image)

**Figure E.2**—LRCM force requirements 1

Figure E.2 has several important features. First, the number of weapons required to address the high-value and defense targets, those addressed in the Deep Attack role, is under a thousand weapons. Second, the total number of LRCMs required to address the whole
target set is predicated largely upon the attack requirements against the repairable military target set, mainly bridges and airfields.

Figures E.3 and E.4 show the force size if less favorable assumptions are made on LRCM reliability and survivability, which are set at 0.7 and 0.8 respectively. The actual sizing of a LRCM force will depend on detailed (and in all likelihood classified) analysis of potential scenarios for LRCM use worldwide. However, the analysis discussed here indicates that the size of the LRCM force is likely to be quite large even for relatively small numbers of military targets, simply based upon the requirements to periodically reattack these facilities.

Fig. E.3—Single target attack requirements II
Twenty day conflict
Reliability = 0.7
Survivability = 0.8
Lethality = Fig. D.21

Fig. E.4—LRCM force requirements II
Appendix F
ARMS CONTROL FOR AIR-LAUNCHED LRCMs

LRCMs pose serious arms control difficulties. Currently, the nuclear and conventional versions of the BGM-109 Tomahawk are externally indistinguishable because the same airframe is used for both. More generally, any cruise missile capable of delivering a 500-kg warhead over 1500 km can also carry a lighter nuclear warhead (a 250-kiloton nuclear warhead weighs roughly 125 kg) to even greater range. Traditionally, nuclear arms control treaties have controlled nuclear weapons by regulating the platforms—ballistic missiles or bombers—capable of carrying them. The current START framework is following this pattern, but because any bomber capable of carrying a large conventional cruise missile can carry a nuclear one as well, the treaty could force platforms for the former aircraft to be counted under its nuclear weapons ceilings. This would probably preclude the option of deploying a militarily significant number of bombers dedicated to carrying large conventional cruise missiles, since a force of 30 to 70 bombers might be required to carry out many of the suggested missions. This discussion suggests some minor modifications to the current treaty framework that would allow such a dedicated conventional bomber force to be deployed under a START regime.

There are some ways not to ensure the capability to employ LRCMs on heavy bombers. The first part of this appendix argues that range limits, by which we mean distinguishing the aircraft which do or do not count against the treaty’s nuclear weapons ceilings by the range of the cruise missiles they carry, are not useful for preserving the option to deploy bombers carrying long range conventional cruise missiles. The range limit approach has, however, been suggested by many commentators, and is thus worth discussing in some detail.

Our basic argument is that any cruise missile that can carry a militarily useful conventional warhead 1500 km can carry a nuclear warhead nearly twice as far. Since a militarily useful long range conventional cruise missile needs a range of 1500 km or greater, there is no range limit that will produce an identifiable external difference between large conventional cruise missiles and even longer-range nuclear cruise missiles. To determine the range of a large cruise missile, it is in fact necessary to know the payload it carries. But if the payload is known, there is no need for range limits to distinguish a nuclear from a conventional missile.

The second part of this discussion focuses on what we believe to be a more successful means to distinguish bombers carrying conventional and nuclear cruise missiles. The current
START framework would control nuclear air-launched cruise missiles by regulating the aircraft that carry them. We suggest expanding on this approach by allowing each side to deploy under the treaty two separate classes of cruise missile carrying bombers—one that carries nuclear weapons and another dedicated to conventional weapons. The two classes of bombers would count differently towards the treaty ceilings. Each class would be distinguishable by national technical means, while onsite challenge inspections would be used to verify than none of the dedicated conventional bombers carry or are associated with nuclear weapons. Note that while this approach is conceptually similar to those found in previous arms control regimes, it is the onsite inspection procedures, which have recently gained political credibility under the INF treaty, that make the current plan workable.

LRCMs can potentially pose serious arms control difficulties. These problems essentially arise from the fact that any LRCM capable of delivering a 1000-pound warhead over 700 miles can also carry a lighter nuclear warhead (a 250 kiloton nuclear warhead weighs roughly 250 pounds) to even greater ranges. This inherent problem has been complicated by the fact that the nuclear and conventional versions of the BGM-109 Tomahawk missile, the only deployed LRCM, are externally indistinguishable since they utilize the same airframe.

This discussion sidesteps the issue of sea-based LRCM arms control. The issue of controlling nuclear SLCMs has been handled in a fundamentally different manner than the other nuclear elements of U.S. forces and to a large extent remains unresolved. Nonetheless, we believe that our general approach of separating nuclear and dedicated conventional cruise missile platforms, and employing different counting rules for these systems, is potentially applicable to the sea-launched weapons as well.¹

In suggesting modifications to the current START framework, we suggest what we believe are only minor modifications of the current proposals relating to air-launched cruise missiles. For instance, we have not considered options that rely on counting all the cruise missile airframes and distinguishing which are nuclear and which are conventional, or that rely on counting all the nuclear warheads in either side's inventory. While such provisions might be more effective than the ones we consider here, they are quite far afield from the treaty that is currently being negotiated.² Finally, we have not considered the Soviets' views on the desirability of these conventional weapons, and how they might be enticed to make room for them within START.

² However, such provisions might enter the treaty in order to control sea launched cruise missiles or mobile ICBMs.
THE TROUBLE WITH RANGE LIMITS

Before proceeding with our main discussion, it is useful to mention what is wrong with the commonly suggested approach of range limits, that is, distinguishing nuclear and conventionally armed bombers by the range of the cruise missiles they carry. Many commentators have argued that for the purposes of the START treaty, any aircraft equipped to carry a cruise missile with a range of greater than 1500 km should count against the treaty ceilings as a nuclear cruise missile carrying bomber, while an aircraft equipped to carry cruise missiles of lesser range would not count as such a bomber. This formulation is similar to that of the SALT II treaty, which only counts an aircraft against its ceilings on multiple warhead platforms if that aircraft has the capability to carry cruise missiles with a range greater than 600 km.

However, such a 1500 km range limit would not be very helpful in distinguishing between aircraft capable of carrying nuclear armed cruise missiles and those capable of carrying long-range conventional cruise missiles. In brief, this is because a militarily useful, long-range cruise missile would be likely to have a range of at least 1500 km; thus, a range limit that distinguished such missiles from nuclear armed cruise missiles (whose range is on the order of 2400 km) must be at least this high. However, a 1500 km conventionally armed cruise missile will be large, on the order of 3000 pounds, to be able to carry an effective payload to the desired range. Any cruise missile this size can carry a nuclear warhead much further than 1500 km, since the nuclear warhead will be in general be lighter than the conventional one. Thus, any aircraft capable of carrying the treaty-allowed large conventional cruise missile will be able to carry the treaty-limited nuclear one as well. Range limits are clearly not a useful way for the treaty to restrict the nuclear armed bombers without also restricting those which are conventionally armed.

The fact that any cruise missile capable of carrying a 500 kg conventional warhead 1500 km can carry a lighter nuclear warhead about twice as far is probably not surprising in light of the respective ranges of the nuclear and conventionally armed variants of the BGM-109 (1200 nm and 700 nm, respectively). Nonetheless it is worthwhile to make this point in general, as is done in Fig. F.1, repeated from App. C. For any of the engine propulsion technologies shown, a missile that carries a conventional payload (800-1000 lbs) 700 nautical
miles can carry a nuclear payload much further. The difference in range between the nuclear and conventional systems is due to the difference in warhead weight, which allows extra payload to be used for fuel.

![Graph](image)

**Fig. F.1—Range/payload tradeoffs for LRCMs**

Therefore, it is clear that if the United States wishes to preserve the option under START of deploying bombers capable of carrying LRCMS, where "long range" is on the order of 1500 km, range limits are not a useful way to proceed. As we argued above, any aircraft that can carry a conventional cruise missile with a range under the limit can also carry a nuclear cruise missile with a range over the limit, since the two weapons can have the same size and weight. It might be possible to add to the treaty regime procedures for inspecting the payload of individual cruise missiles in order to determine their range. But if this is done, it is less complicated to base the treaty restrictions on the type of warhead rather than the range, which is derived from the knowledge of the warhead. In the next section, we will present an approach for preserving the option to deploy conventional cruise missile carrying
bombers under START that does not use range limits, but in fact explicitly limits the types of missiles, conventional or nuclear, that certain types of bombers are allowed to carry.

**BOMBER CLASSIFICATION: A WORKABLE ALTERNATIVE**

There are two fundamentally different ways to embrace cruise missiles, or for that matter any other weapon, in an arms control regime. The first is by controlling the weapons themselves and the second is by controlling the vehicles needed to deliver them. To date, all treaties limiting offensive nuclear arms have used the latter route. As we shall see below, the current START framework continues in this pattern in its treatment of ballistic missiles and air-launched cruise missiles. (How the treaty will treat sea-launched cruise missiles is still very much an open question.) For instance, while the START framework includes ceilings for both nuclear warheads and strategic nuclear delivery vehicles, individual ballistic missile reentry vehicles (RVs) are not counted against the treaty ceilings. Instead, the total number of deployed ballistic missile warheads charged against the treaty ceilings is the sum of the number of boosters times the number of RVs each booster is presumed to carry. The current framework governs air-launched cruise missiles in a similar fashion. Bombers are considered to be delivery vehicles and cruise missiles are considered to be warheads. The total number of deployed cruise missiles charged against the treaty ceilings is the sum of the number of bombers times the number of cruise missiles each bomber is presumed to carry.

Thus, the current START framework focuses not on the nuclear weapons themselves, but on the capacity to deliver these weapons. Our proposal for modifying this framework to allow the option to deploy conventional cruise missile carrying bombers merely extends this idea. Instead of attempting to distinguish between nuclear and conventionally armed cruise missiles, the treaty should, we argue, distinguish between bombers that carry nuclear armed cruise missiles and those that are dedicated to carrying conventional missiles. Different counting rules can then be employed for these two classes of platforms. In this section we will first review the START framework as it stands at the time of this writing. We will then present our proposal for distinguishing conventional and nuclear cruise missile carrying bombers and discuss how it can be verified, address the breakout problem, and finally suggest options for ceilings and sublimits on the conventional cruise missile carrying platforms.

**Current START Framework**

Our first step is to understand the outlines of the proposed treaty as it relates to weapons and weapon counting, which are a matter of public record. The main features are
ceilings of 6000 on deployed nuclear warheads, 1600 on strategic nuclear delivery vehicles, and 4900 on ballistic missile warheads. The former include warheads on ICBMs, SLBMs, as well as air-launched cruise missiles and non-cruise missile carrying heavy bombers. Note that this last category of bombers, no matter how many weapons they carry, only count as one against the warhead limits. This counting rule for non-cruise missile carrying bombers is presumably based upon the effects of Soviet air defenses on penetrating bombers. The delivery vehicle category includes ICBMs, SLBMs, and heavy bombers. The ballistic warhead limits affect ICBM and SLBM warheads.

While delivery vehicles are counted directly, the warheads are tallied via counting rules on the platforms that deliver them. As discussed above, the total number of deployed ballistic missile RVs and air-launched cruise missiles charged against the treaty's warhead ceiling is the sum of the number of boosters/bombers times the number of RVs/cruise missiles each booster/bomber, respectively, is presumed to carry. For the ballistic missiles, each side has agreed to declare how many RVs each of its types carries with the provision that the other side will verify these numbers by direct inspections of randomly chosen missiles.\footnote{The Reagan-Gorbachev joint communique in 1987 lists the US MX as carrying 10 warheads, the Minuteman III with 3, the Minuteman II with 1, the Trident I with 8, the Trident II with 8, and the Poseidon with 10. It lists the Soviet SS-17 as carrying 4 warheads, the SS-19 with 6, the SS-18 with 10, the SS-24 with 10, the SS-25 with 1, the SS-11 with 1, the SS-13 with 1, the SS-N-6 with 1, the SS-N-8 with 1, the SS-N-17 with 1, the SS-N-18 with 7, the SS-N-20 with 10, and the SS-N-23 with 4.}  

Each side will similarly declare the number of cruise missiles carried by each of its bomber types. However, the United States has proposed that this declared capacity not be the actual capacity but some smaller number, since these aircraft rarely fly with their full complement of cruise missiles. Finally, it should be noted that a long-range cruise missile is currently defined as a pilotless aircraft with a range greater than some value, yet to be determined. The United States has suggested the value of 1500 km, but the Soviets have not accepted this figure.

In addition to the overall ceilings on warheads and delivery vehicles, there are a number of agreed and proposed sublimits relating to ballistic missiles. The United States and Soviet Union have agreed to an overall ceiling of 4900 on these warheads. They have also agreed to a 1540 ceiling on heavy ICBM warheads and a 154 ceiling on heavy or heavily fractionated ballistic missiles. (A heavily fractionated ballistic missile is one carrying seven or more warheads.) Thus, the Soviets have agreed to cut their SS-18 force, the limitation of which has long been a U.S. objective, in half. Note that one effect of the 4900 sublimit on countable ballistic missile warheads is that in order to field their full allotment of countable
warheads, both sides must deploy some combination of cruise missile and non-cruise missile carrying bombers which account for a total of at least 1100 countable warheads.

Four Classes of Long Range Bombers

The United States and Soviet Union have already agreed that the START treaty will implicitly recognize two classes of bombers distinguished by their ability, or lack thereof, to launch long-range cruise missiles. As we have seen, these two classes of bombers will count differently against the treaty ceilings. In order to allow the deployment of a bomber force carrying conventional cruise missiles, we propose that the treaty be modified to explicitly recognize four classes of bombers, distinguished by their armament, nuclear or conventional, in addition to their capabilities regarding large cruise missiles. In this subsection we will define these four bomber classes and argue that we can use them to construct a robust treaty regime that will successfully allow the deployment of bombers armed with conventional cruise missiles while limiting the deployment of bombers armed with nuclear cruise missiles.

Our four proposed bomber classes, shown in Figure F.2, are defined as follows:

I. Dedicated Conventional Bombers. These are heavy (long range) aircraft which do not carry any nuclear or any long range weapons. Often they are modified bombers used for maritime or reconnaissance roles. Types of aircraft in this class include the Bear D/E/F's in the Soviet arsenal and the U.S. B-52G maritime craft. Such aircraft are not explicitly mentioned in the START proposals, and it is unclear how they would count under the treaty (they were not counted under SALT II).

II. Dedicated Conventionally Armed Standoff Bombers. These are heavy bombers which are capable of carrying large (conventional) cruise missiles, but do not carry nuclear weapons. Such aircraft are not currently considered in the START proposals. There are no existing types of aircraft in this class, but the (presently nuclear) cruise missile carrying B-52Gs could be, if instead of being retired as planned, they were converted to

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7 Forty-seven of the remaining 69 B-52Gs that are not capable of launching long-range cruise missiles have been dedicated to a maritime role. The remaining 22 non-cruise missile carrying B-52Gs have been identified for retirement in the 1990s.

8 A bomber should fall into Class II depending on the range, weight, and/or volume of the cruise missiles it can carry (as is apparent from the discussion in Sec. II, these features are related). In light of the discussion in Sec. II, these limits should be set low, probably 600 km for range. Any bomber capable of carrying a cruise missile with characteristics above these thresholds would count as a standoff bomber. Also see the discussion in Sec. II, footnote 9.

9 CBO, ibid.
dedicated conventional systems carrying LRCM weapons. We will recommend that a separate START sublimit cover these bombers and that they should not count otherwise towards the START ceilings. These bombers should be subject to inspection to verify they are not nuclear armed.

III. Nuclear Armed Penetrating Bombers. These are heavy nuclear armed bombers which carry only short-range weapons, such as gravity bombs and SRAMs. Types of aircraft in this class are the planned U.S. B-2 Stealth bombers, the B-1Bs, and the B-52Hs, which have not yet been converted to cruise missile carriers.\(^{10}\) The Soviet Blackjacks, if they do not carry cruise missiles, would also fall in this class, as do the Bear B/C/Gs.\(^{11}\) As we have seen, these bombers will count one against both the warhead and delivery vehicle ceilings under START. Some types of aircraft in this class may have to be inspected to verify they do not have the capability to launch cruise missiles.

IV. Nuclear Armed Standoff Bombers. These are heavy nuclear armed bombers which are equipped and employed to carry large cruise missiles. Types of aircraft in this class include the U.S. AGM-86B equipped B-52Hs and B-52Gs,\(^ {12}\) and the Soviet Bear Hs and Blackjacks, if they are deployed with cruise missiles.\(^ {13}\) Each of these bombers counts one against the treaty's delivery vehicle ceiling and some number (whose value will depend on how many cruise missiles are attributed to each bomber) against the weapons ceiling. These aircraft may be subject to an inspection scheme which will help verify the cruise missile carrying capacity of each type of bomber.

As can be seen from Figure F.2, these four bomber classes, with one important exception, are pure by type. That is, no currently deployed type of heavy bomber save one falls into two or more classes.\(^ {14}\) This is important because bomber types can be easily distinguished and the total number of aircraft of each type can be accurately counted by

\(^{10}\) CBO, ibid.
\(^{11}\) IISS, ibid.
\(^{12}\) CBO, ibid.
\(^{13}\) IISS, ibid.
\(^{14}\) The exception is the B-52Gs, which are currently configured as both nuclear armed cruise missile carriers and conventional armed maritime strike craft. These two variants are distinguishable, however, by the heavy weapons rails that can be carried under the wings of the former. Since our interest in bomber types owes to the fact that different types can be distinguished by national technical means, the two B-52G variants cause us no problems. In addition, if the nuclear armed B-52Gs are converted into dedicated conventional systems, no bomber type will have both a nuclear and dedicated conventional variant.
# Bomber Classifications

<table>
<thead>
<tr>
<th>Class</th>
<th>Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Non-Strategic</td>
<td>B-52G (w/o heavy rails)</td>
</tr>
<tr>
<td>Conventional Bomber</td>
<td>Bear D/F</td>
</tr>
<tr>
<td>short range weapons</td>
<td></td>
</tr>
<tr>
<td>only</td>
<td></td>
</tr>
<tr>
<td>II. Conventional Standoff</td>
<td>B-52G (w heavy rails)</td>
</tr>
<tr>
<td>Conventional Bomber</td>
<td></td>
</tr>
<tr>
<td>can carry large cruise</td>
<td></td>
</tr>
<tr>
<td>missiles</td>
<td></td>
</tr>
<tr>
<td>III. Nuclear Penetrator</td>
<td>B-1</td>
</tr>
<tr>
<td>Nuclear Capable Bomber</td>
<td>Bear G Blackjack?</td>
</tr>
<tr>
<td>short range weapons</td>
<td>B-2</td>
</tr>
<tr>
<td>only</td>
<td>B-52H (w/o heavy rails)</td>
</tr>
<tr>
<td>IV. Nuclear Standoff</td>
<td>B-52G (w heavy rails)</td>
</tr>
<tr>
<td>Nuclear Capable Bomber</td>
<td>Bear H Blackjack?</td>
</tr>
<tr>
<td>can carry large cruise</td>
<td>B-52H (w heavy rails)</td>
</tr>
<tr>
<td>missiles</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. F.2—Bomber classifications**

Since each class carries different numbers and different types of cruise missiles (nuclear or conventional), the START treaty can restrict nuclear cruise missiles and allow conventional ones by appropriate counting of the four classes of bombers.

Our proposal is that upon entering into the treaty regime, each side declare to which of the four bomber classes each of its bomber types belongs. Each type of bomber must have external characteristics that make it distinguishable by national technical means (e.g., the different tail assemblies on B-52Hs and B-52Gs). Each class of bomber will have different counting rules under the treaty ceilings and sublimits. The treaty will specify a verification scheme, relying heavily on short notice challenge inspections, which will certify that no bomber has military capabilities or associations that are inconsistent with its declared class. We will discuss such procedures below. The critical point is, however, that the problem of counting bombers carrying different types of cruise missiles has been reduced to the problems

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of (1) identifying and counting different types of bombers by national technical means, which is known to be possible, and (2) verifying by inspection that bombers of a particular type only carry and are only associated with those cruise missiles, if any, they are allowed to have. For instance, if B-52Gs were declared to be conventional standoff bombers, the discovery of one B-52G carrying nuclear cruise missiles (or nuclear weapons of any type) would be a treaty violation. Thus the problem of distinguishing and counting different types of cruise missiles, which would otherwise require complex schemes to identify and keep track of every such weapon in the other side's arsenal, has been replaced by a far simpler "zero option" problem.

To handle this verification problem, the treaty would specify a list of characteristics and associations forbidden to certain classes of bombers, and provide for short-notice challenge inspections to look for planes with the prohibited features. Figure F.3 shows the two sets of capabilities that distinguish our four classes. An aircraft can either have the ability to launch long-range weapons or it can carry short-range weapons only, and it can be nuclear or conventionally armed.

<table>
<thead>
<tr>
<th></th>
<th>Dedicated Conventional</th>
<th>Nuclear Capable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short Range Weapons Only</td>
<td>Class I</td>
<td>Class III</td>
</tr>
<tr>
<td>Long Range Weapons Only</td>
<td>Class II</td>
<td>Class IV</td>
</tr>
</tbody>
</table>

Association with Nuclear Weapons (e.g. basing, weapons load)

External Pylons
Internal Launchers

Hard Points on Wings/Partitioned Bomb Bays

**Fig. F.3—Distinguishing bomber classes**

U.S. bombers can currently carry long-range cruise missiles inside their bomb bays on rotary launchers or under their wings on pylons. Soviet bombers have similar capabilities. The U.S. AGM-86B can only be launched from distinctive equipment, externally from the ACM External Launch Pylons and internally from the Common Strategic Rotary Launcher. In normal operations, the pylons and launchers are first loaded with cruise missiles and then mated to the bomber. This latter process takes about an hour. The treaty might prevent a Class I (nonstrategic) or Class III (nuclear penetrating) bomber from carrying cruise missiles.
by prohibiting it from ever being mated with a pylon or internal launcher of a type capable of carrying cruise missiles, and perhaps in addition, prohibiting it from ever being stationed at a base where such items are stored. While these provisions could be verified with high confidence by national technical means and short-notice challenge inspections, they do not provide robust impediments to cheating.

If a higher degree of confidence in treaty compliance is desired, the treaty could prohibit Class I and Class III bombers from having the capability to carry cruise missile pylons or internal launchers. Even though this equipment is readily detachable, it normally leaves permanent indications of its presence, in particular the special fairing on which the pylons are mounted and the structural modifications that must be made to the bomb bay before the rotary launcher will fit inside. Nonetheless, it is in principle easy to design new launch equipment that would fit onto a bomber which had none of these telltale signs. Thus, to prohibit a bomber from having the capability to launch cruise missiles from external wing pylons, the treaty could dictate that the aircraft can not have hard points capable of supporting the weight of a loaded cruise missile rack. Knowledgeable inspectors should be able to verify the absence of such hard points, though they might need to x-ray the wings to make their judgement. Because a bomb bay must necessarily have hard points to carry any weapons at all, the only way to verifiably prohibit a bomber from having the capability to launch cruise missiles from internal launchers is for the treaty to require all Class I and Class III bombers to have their bomb bays permanently partitioned into segments shorter than the length of a cruise missile (about three to four meters). Such partitioning could clearly be verified by inspectors.

Unfortunately, it does not seem possible to construct a treaty that would verifiably restrict the capability of a bomber to carry nuclear weapons, since there are no identifiable characteristics which would unambiguously reveal such a capability. For instance, the equipment required for safe and arm systems can easily be submerged in the offensive avionics that would be necessary to launch highly accurate conventional weapons. However, it is possible to verify that a bomber is nonnuclear in the sense that it is never associated with nuclear weapons on a day-by-day basis. (The obvious breakout problems

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16 The U.S. maritime B-52Gs could physically carry BGM-109s, but lack the avionics to employ them. At present, it would be in the U.S. interest to count these bombers as Class I aircraft, as the corresponding long-range Soviet maritime aircraft do not seem to have a cruise missile carrying capability. However, such counting of the maritime B-52Gs would set a weaker verification standard for the treaty than counting them as Class II, and would make potential Soviet violations easier.

17 Alternatively, any electronics related solely to nuclear operations could be mounted in the nuclear cruise missile carrying pylons or internal launchers, so that it was present only on a bomber actually loaded with nuclear cruise missiles.
associated with this type of restriction are discussed in the next section.) The START treaty could prohibit a Class I (conventional) or Class II (conventional standoff) bomber from ever visiting an airbase that stores nuclear weapons or ever being loaded with nuclear weapons. National technical means should be able to detect significant infractions of the first provision, and short-notice challenge inspections of bombers at their bases by inspectors carrying radiation detectors could detect infractions of the latter.\textsuperscript{18} These inspections would only apply to types of bombers declared to be conventional. The only need to inspect bombers declared to be nuclear would be to ensure that Class III penetrating bombers did not have the capability to carry cruise missiles.\textsuperscript{19} Provisions banning any nuclear association for the dedicated conventional bombers clearly do not provide as robust an impediment against cheating as do the provisions banning the capability to carry cruise missiles. But at a minimum, these former provisions do make it more difficult to operate the dedicated conventional bombers as a nuclear force, since they make nuclear mission training more difficult and provide pressure to assign these aircraft to conventional duties, which would make them unavailable for breakout, in time of crisis or war.

Limiting the Breakout Potential

We have been discussing the verification problem of preventing breakout, that is, determining that no bomber is covertly given capabilities that do not correspond to its declared class. There is a second, more difficult verification problem, guarding against a breakout. This is limiting the military utility to be gained by overtly breaking the treaty and rapidly converting bombers from one class to another. In terms of the capabilities listed in Fig. F.2, a breakout would consist of converting Class I, Class II, or Class III bombers to Class IV bombers able to launch long-range nuclear cruise missiles, and/or converting Class I or II bombers to Class III or IV bombers able to carry nuclear weapons.

For two reasons, the path that is of most concern is conversion of Class II conventional standoff bombers to Class IV nuclear standoff bombers. First, we are proposing that the category of Class II conventional standoff bombers be included in the START treaty. The main breakout danger posed by placing aircraft in Class II that would otherwise be in Class IV is the conventional to nuclear cruise missile carrier conversion. Second, it would take

\textsuperscript{18} Since cruise missiles can be offloaded from a bomber in about an hour, it might be necessary to implant radiation-sensitive badges in the bomb bays and under the wings of conventional bombers to ensure that any nuclear weapons mounted on these craft could not be removed without leaving evidence of their presence.

\textsuperscript{19} It would probably be desirable to exempt from such inspections all types of Class III penetrating bombers, such as the B-2, which had never been tested launching cruise missiles.
about a month to modify a Class I dedicated conventional bomber or a Class III nuclear penetrating bomber so that it could launch large cruise missiles; but, as is apparent from the above discussion, it could take as little as a few hours to convert a Class II conventional standoff bomber into a Class IV nuclear cruise missile carrier, if nuclear cruise missiles on compatible pylons and launchers have been covertly stockpiled. Thus, converting the Class II conventional standoff bombers to nuclear cruise missile carriers can have a much shorter lead time than converting Class I and Class III bombers carrying short-range weapons to the same task. We will only specifically address restrictions on this former path, although some of our comments will have relevance for the others as well.

There are two generic ways the United States or Soviet Union could give their conventional standoff bombers the ability to launch nuclear armed cruise missiles. The first is to change the warheads on the conventional cruise missiles to nuclear ones, and the second is to stockpile nuclear cruise missiles that can be mounted on the conventional bombers. The most robust way to protect against breakout would be to control the inventory of nuclear cruise missiles and require that conventional cruise missiles be of such a design that their warheads can not easily be changed. Controlling the cruise missile inventory is perhaps possible, although it would require a far more extensive inspection scheme than is otherwise necessary to control the capacity to deliver air-launched cruise missiles. (It is quite possible, however, that a regime of cruise missile inventory controls, which might include air launched missiles, will be necessary to limit sea-launched cruise missiles.) Such a scheme might require each side to tag all currently existing cruise missiles, and all those produced during the life of the treaty; declare each of their cruise missiles to be conventional or nuclear; and specify where these missiles will be stored. Inspectors using short notice challenge inspections at the missile storage areas could then ask to see randomly chosen missiles to certify that there are no covert stockpiles of nuclear cruise missiles ready to mount on conventional bombers.

Even if such inventory controls could be verified without an intolerably intrusive inspection scheme (which is unlikely), they are unlikely to ensure more than a few weeks warming of a breakout. Even under the best of circumstances it should take no more than that amount of time to convert any allowed stockpile of conventional cruise missiles to nuclear ones. Under normal operating procedures, replacing the conventional warhead on the existing BGM-109 takes on the order of a few weeks if compatible nuclear warhead

\[20\] While we do not expect that the United States would ever be able to cheat on a START treaty, it is interesting to note that having a large stockpile of conventional cruise missiles that could be converted to nuclear systems could make it easier to respond to or deter any Soviet treaty violations.
sections have been previously manufactured. It is not known what the relevant conversion times are for the Soviet systems.\textsuperscript{21} The U.S. systems were not built to enhance nuclear/conventional incompatibility, but even if new cruise missiles were designed with this goal in mind, it is probably not possible to build a conventional cruise missile that takes much longer than a few weeks to mate with a nuclear warhead, particularly during a period of crisis. Thus, no matter how good the inventory controls, the breakout warning time will be at least this short.

Fortunately, there is another means to protect against breakout, if this short warning time is viewed as unacceptable. This is to limit the size, not the pace, of a potential breakout. If the treaty places a cap on the number of conventional standoff bombers, then the ultimate gain from breakout is limited. There is a rigid cap on the number of prohibited nuclear weapons that can be deployed, since the total force of conventional bombers has a finite capacity. The actual cap will be more severe, since any conventional bombers converted to nuclear cruise missile carriers during a crisis or conventional war will deplete a limited stock of conventionally armed aircraft which can perform useful tasks, and thus decrease the net military utility of the conversion. In the next section, we will describe a number of options for sublimits and ceilings on conventional bombers and assess their effect on the breakout potential.

**Sublimits and Ceilings on Conventional Standoff Bombers**

Each of the four options for counting rules for conventional standoff bombers we will present in this subsection is a balance between two factors—the effect the option has on each side's ability to deploy bombers carrying conventional cruise missiles, and the extent it limits the breakout potential. The more tightly controlled the number of conventional standoff bombers, the more limited the breakout potential but the less capable the resulting conventional force. In addition, two of the options include the conventional bombers under the START nuclear ceilings, and thus offer a tradeoff between the number of deployed conventional standoff bombers and the number of strategic nuclear weapons allowed. We will present our options, show how they affect the breakout potential and the allowed number of strategic nuclear weapons, and then suggest which options seem most promising.

\textsuperscript{21} An additional problem is that it is unclear how each side could convince the other that these conversions really take as long as they do without allowing them such detailed access to the missiles that their military effectiveness is compromised.
Option 1: No Limits on Class II Bombers. In this option, Class II dedicated conventional standoff bombers would not count in any way against the treaty ceilings or sublimits. This option places the least constraint on the conventional capability, but provides the least control on the breakout potential.

Option 2: Separate Sublimits for Class II Bombers. In this option, the treaty would have a separate sublimit on the number of allowed Class II bombers. These bombers would not otherwise count against the treaty ceilings. (Additional such bombers could always be deployed, but they would count against the treaty ceilings as if they were nuclear armed.) With an appropriate value for the sublimit this option will protect against a large breakout potential and still allow a conventional capability. In contrast to the remaining options, deploying conventional standoff bombers within the sublimit does not require any sacrifice of strategic nuclear weapons capability.

Option 3: Count Class II Bombers as Class III Bombers. In this option, Class II bombers that carry long range cruise missiles count one against the treaty ceilings for warheads and delivery vehicles (i.e., Class II dedicated conventional standoff bombers are counted as if they were Class III nuclear penetrating bombers, but not as if they were Class IV nuclear standoff bombers). This option is similar to Option 2, except that it allows additional flexibility in choosing the number of conventional and nuclear bombers, at the expense of forcing a deployment of conventional bombers to slightly decrease the allowable number of nuclear weapons.

Option 4: No Separate Treatment for Class II Bombers. In this option, there is no separate treatment under the treaty for conventional standoff bombers. All cruise missile carrying bombers, whether nuclear or conventionally armed, would count under the treaty as if they were nuclear armed Class IV bombers. Thus, each side would only deploy conventionally armed heavy bombers that were dual capable nuclear/conventional cruise missile carriers. While this option removes the breakout potential because all the standoff bombers are already counted as nuclear, it severely constrains the conventional capability because exercising it involves subjecting strategic nuclear forces to reduced readiness while they carry out conventional attacks.

To show the effect of using each of these counting rules on the breakout potential and the allowed number of deployable nuclear weapons, it is useful to present a national START-constrained U.S. strategic nuclear force. This is shown in Table F.1, assuming a base year of 1985. We assumed that the United States will deploy 17 Trident submarines, each carrying 24 D-5 missiles with 8 warheads each. The remaining ballistic missile warheads are carried
by 50 silo-based MX, 150 Minuteman III, and 486 mobile small ICBMs.\textsuperscript{22} The remaining warhead slots allowed under the 6000 ceiling are allotted to the air-breathing leg. These are filled by 75 B-2s and 97 B-1Bs serving as penetrating bombers, each carrying 16 short-range weapons (SRAMs and gravity bombs), respectively, and 94 B-52Hs, each declared to carry 12 AGM-86s or 12 ACMs, serving as standoff bombers. (This figure of 12 is consistent with the U.S. position that the full cruise missile capacity of a bomber not be counted against the treaty ceilings.) This gives a total of 1360 delivery vehicles, 6000 counted warheads, and 9392 total actual warheads, since the short-range weapons on penetrating bombers are not counted one for one under the START rules. Note that the warhead and not the delivery vehicle ceiling is the critical limit, since the MIRV ratio in this force is higher than the 3.75 warheads/delivery vehicle ratio implied by the respective 6000 and 1600 warhead and delivery vehicle ceilings. We have in fact constructed a force with an atypically large number of launchers, since it includes 486 single warhead mobile ICBMs. Most foreseeable 6000 warhead forces would probably have even fewer delivery vehicles.

We would like to add to this nuclear force a robust conventional standoff bomber force and look at the effect under the four counting rule options. Such a conventional force might consist of anywhere between 50 to 100 platforms. Currently, the 98 AGM-86-carrying B-52Gs could be equipped to carry 12 LARCM weapons each and could be used in this role. Note first the reason that it is necessary to create a separate set of counting rules for conventional, as opposed to nuclear, standoff bombers. If these conventional bombers were counted against the treaty ceilings as if they were nuclear armed, it would be difficult to deploy them as a dedicated conventional force. Under such a counting rule these aircraft could count 686 against the warhead ceilings\textsuperscript{23} as shown in Table F.1, and deploying them would require a 7 percent reduction in the 9392 deployed nuclear weapons. It is unlikely that the United States would field conventional cruise missiles at such a cost to its strategic nuclear forces.

Under the rules of Option 1, all conventional bombers excluded, and Option 2, separate sublimits for conventional bombers, the conventional bombers shown in Table F.1 would not count at all against the treaty ceilings. Thus they would have no effect on the number of nuclear systems that could be deployed. Under the Option 3 rules, in which each conventional cruise missile carrying bomber counts one nuclear warhead and one delivery

\textsuperscript{22} We have assumed that the U.S. is not successful in banning mobile ICBMs in START.

\textsuperscript{23} The 686 figure assumes that the B-52Gs which carry 12 cruise missiles are counted as carrying 7 cruise missiles. This is the same discount ratio as we used for the B-52Hs which carry 20 cruise missiles but we counted as carrying as carrying 12. If B-52Gs were declared to carry a different number of cruise missiles, the 686 figure would of course change.
Table F.1
A Notional U.S. START-Limited Force

<table>
<thead>
<tr>
<th>Delivery Vehicles</th>
<th>Nuclear Warheads (counted)</th>
<th>Nuclear Warheads (potential)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nuclear</strong></td>
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<td></td>
</tr>
<tr>
<td>ICBM</td>
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<td>1436</td>
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<tr>
<td>SLBM</td>
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<td>3264</td>
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<tr>
<td>1094</td>
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<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>B-1B</td>
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<td>97</td>
</tr>
<tr>
<td>B-52H</td>
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<td>1128</td>
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<tr>
<td>266</td>
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<tr>
<td>1380</td>
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<td>6000</td>
</tr>
<tr>
<td><strong>Conventional</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>B-52G</td>
<td></td>
<td></td>
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<tr>
<td>If counted as nuclear</td>
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</tr>
<tr>
<td>Counting Rules:</td>
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<td></td>
</tr>
<tr>
<td>Option 1</td>
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<td>686</td>
</tr>
<tr>
<td>Option 2</td>
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<tr>
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<td>98</td>
</tr>
<tr>
<td>Option 4</td>
<td>98</td>
<td>686</td>
</tr>
</tbody>
</table>

vehicle, such a force would count as 98 warheads and 98 vehicles against the respective treaty ceilings, as shown in Table F.1. This poses no constraint at all against the delivery vehicle ceiling. For this force to be deployed, it would, however, require a 1 percent reduction in the number of deployed, accountable nuclear warheads. For instance, this might be 33 Minuteman III missiles or 9 B-52Hs. If the United States desired to deploy a conventional cruise missile capability, such a sacrifice in the nuclear arsenal might be acceptable. Finally, Option 4, which does not have separate counting rules for conventional and nuclear standoff bombers, returns to the problems discussed in the preceding paragraph.

The breakout potential allowed by each option is, not surprisingly, inversely favorable to the degree to which it constrains the conventional capability. Under Option 4, which provides for dual-capable nuclear and conventional systems, there is no breakout potential, since any standoff bomber is counted as nuclear under the treaty. The main drawback of this option is that it calls for portions of the strategic nuclear bomber force to conduct conventional operations. In many scenarios these operations may be concurrent with the time the United States would want its strategic forces at maximum readiness levels. If, using for an example the forces shown in Table F.1, the 94 cruise missile carrying B-52Hs (assumed for this example to be dual capable and each able to carry 20 conventionally armed cruise missiles) were employed in a conventional mission, the readiness of 20 percent of the total U.S. force of 9392 nuclear warheads would be reduced. This seems unacceptable, and it
is likely that Option 4 would result in a greatly constrained conventional standoff capability. This option would probably allow operations that either were small (such as strikes against Soviet space launch pads) or were required under circumstances where the nuclear bomber force was not at a high-level alert (such as many strikes against terrorist-associated targets).

In contrast, Option 1, which excludes conventional standoff bombers from the treaty, places no limit on the allowed number of U.S. conventional cruise missile carrying bombers, so that the deployment of such aircraft would not affect the allowed nuclear forces. However, in placing no limits on the number of allowed conventional bombers, this option provides no cap on the breakout potential. This option would only be acceptable if the United States was not concerned about the capabilities the Soviets might gain by breaking out or did not believe the Soviets would build large numbers of conventionally armed bombers in the absence of a treaty ceiling.

The best options appear to be Options 2 and 3. Both limit the breakout potential by controlling the allowed number of dedicated conventional standoff bombers. Option 2, which calls for a separate sublimit on conventional cruise missile carriers, places a direct cap on the number of these systems and thus provides a definite numerical limit on each side's breakout potential. For instance, a sublimit of 100 conventional standoff bombers would limit the breakout potential to no more than about 1200 deliverable nuclear cruise missiles (if each bomber could only carry 12 missiles), or about 12 percent of the 9392 U.S. warheads deployed in the notional force shown in Table F.1.24 In addition, deploying a long range conventional cruise missile capability under this option does not decrease the allowed number of strategic nuclear forces. A potential problem with Option 2 is that it requires the United States to argue for a special sublimit on a class of weapons that it has not yet deployed.

Option 3, which counts conventional standoff bombers as one against the nuclear weapons and delivery vehicle ceilings, provides more flexibility by allowing a tradeoff between nuclear and conventional systems. The main advantage is that the United States will not leave an allowed treaty category empty if it decides not to deploy a conventional standoff bomber force, as opposed to the case under Option 2. There are two main disadvantages. First, deploying a force of dedicated conventional bombers under this option does decrease the allowed nuclear force by about 1 percent. Second, this option provides less breakout protection than Option 2 since there is no strict limit on the number of cruise

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24 We have credited each bomber with 12 cruise missiles here because we are comparing to the total number of nuclear warheads, not only the START accountable ones. The breakout potential faced by the United States would probably be less, since current Soviet bombers carry fewer cruise missiles than the B-52s.
missile carrying bombers. In the worst case, one side might forgo fielding any nuclear standoff bombers and deploy a large force of dedicated conventional standoff bombers. The breakout potential of the resulting force could be substantial, since each of these aircraft counts only one against the warhead limits, and several hundred could be deployed. For example, if all the slots allocated to bombers in the notional force shown in Table F.1 were filled by conventional bombers, there would be 506 such aircraft. If each bomber could carry 12 cruise missiles, the breakout potential of this force would be about 6072 deliverable warheads, or two-thirds of the 9392 warheads shown in Table F.1.

The choice between Option 2 and Option 3 depends on several factors. Among them are the number of bombers the United States really expects the Soviets might build, U.S. concerns about decreasing its strategic nuclear forces by 1 percent below the treaty ceilings, and the flexibility the United States desires in planning for its bomber force. We can only conclude here that while Option 2 seems better than Option 3, there are many situations in which the latter option would be sufficient, and sometimes preferable.

CONCLUSIONS

It appears possible to craft a START agreement that would allow the United States to deploy a militarily significant bomber force, most likely consisting of B-52Gs, dedicated to carrying large conventionally armed cruise missiles. This can be done by defining four classes of heavy bomber, each distinguished by its armament, nuclear or conventional, and its capability or lack thereof to carry long range cruise missiles. The United States and Soviet Union would declare the class to which each of their bomber types belongs and use national technical means to count the number of bombers in each class. On-site challenge inspections would verify that the capabilities of each bomber actually put it in its declared class. Such a treaty regime should allow each side to monitor with high confidence the nuclear and conventional cruise missile capacity deployed by the other. It does not, however, prevent a breakout that could be accomplished in a short time. This problem can be contained by limiting the number of allowed conventional cruise missile carrying bombers, either by implementing a separate weapons sublimit on them or by counting them as one weapon against the treaty warhead ceilings.

Range limits, by which we mean distinguishing the aircraft which do or do not count against the treaty's nuclear weapons ceilings by the range of the cruise missiles they carry, are not useful for preserving the option to deploy bombers carrying long range conventional cruise missiles. This is because any cruise missile that can carry a militarily useful conventional warhead 1500 km can carry a nuclear warhead nearly twice as far, and a
militarily useful long range conventional cruise missile needs a range 1500 km or greater. Thus there is no range limit that will produce an identifiable external difference between large conventional cruise missiles and even longer range nuclear cruise missiles.

Finally, the reader should remember that these large, conventional cruise missiles are of interest because they may be an effective tool for strengthening the United States' conventional capabilities around the world. This fact should be weighed against the breakout potential posed by their separate treatment in a nuclear arms control regime. The signing or ratification of self-contained nuclear arms treaties has been linked in the past with events not directly related to the nuclear balance. The issue here is similar, but the linkage is within the treaty itself. It is the treaty provisions that must reflect the inherent tension between limiting nuclear standoff capability and allowing conventional standoff capability. In resolving this tension, it is well to remember that the purpose of strategic arms control agreements is to enhance the overall security of the United States, and not simply to address the nuclear aspect of that security. U.S. national security has both conventional and nuclear components, and in the case of long range conventional capability and the START treaty, the two are intertwined. Where we set the balance clearly depends on how important we believe the long range conventional capability to be. The framework that we have described may make it easier to set such a balance.