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The Future of the U.S. Intercontinental Ballistic Missile Force

Lauren Caston, Robert S. Leonard, Christopher A. Mouton, Chad J. R. Ohlandt, S. Craig Moore, Raymond E. Conley, Glenn Buchan

RAND PROJECT AIR FORCE

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Preface

The most recent Nuclear Posture Review calls upon the Department of Defense, and therefore the U.S. Air Force, to initiate studies of the future intercontinental ballistic missile (ICBM) force with "the objective of defining a cost-effective approach that supports continued reductions in U.S. nuclear weapons, while promoting stable deterrence." In support of this work, the Air Force Assistant Chief of Staff for Strategic Deterrence and Nuclear Integration (AF/A10) and Air Force Global Strike Command (AFGSC) asked the RAND Corporation to examine future ICBM design, basing, and employment options for an ICBM fleet designed to meet evolving U.S. operational requirements. In this report, we present the analysis and findings of RAND's fiscal year (FY) 2011 study intended to lay the groundwork for the upcoming Analysis of Alternatives (AoA). It is the job of this AoA to evaluate alternatives based on technical feasibility, operational effectiveness, and cost. The potential development of a new ICBM poses important questions that demand comprehensive answers requiring objective assessment and rigorous analysis. It is important to start off on the right foot when thinking about this complex and vitally important issue. Considering the longevity of Minuteman, the decisions we make today will likely shape a central component of the U.S. strategic force for decades to come.

In this study, we examine ICBMs in the context of current and future national security challenges. We then identify criteria we believe to be important in carrying out an ICBM AoA.

The research was performed as part of a FY 2011 study, "Next-Generation ICBM: Maintaining Stability Using a New Land-Based Deterrent Force," which was conducted within the Force Modernization and Employment Program of RAND Project AIR FORCE.

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Summary

U.S. strategic nuclear forces may factor into a widening set of emerging security situations. Intercontinental ballistic missiles (ICBMs), in particular, may find new relevance in extending deterrence and assuring allies since they present a ready threat to newly emerged nuclear states that choose to base nuclear weapons and their means of delivery in the open or on alert. If these challenges demand more from the U.S. ICBM force than the Minuteman III (MM III) can deliver in a cost-effective way, a number of different classes of alternatives are worth consideration. The upcoming ICBM Analysis of Alternatives (AoA) will have to assess alternatives across a broad set of potential characteristics and situations weighed against the costs of those alternatives.

At the same time that the New Strategic Arms Reduction Treaty (New START) is pushing ICBM force levels to 420 or below, their lowest point in decades, the 2010 Nuclear Posture Review (NPR) identifies a variety of emerging situations in which strategic forces might play a role in deterring adversaries, stabilizing regions, and reassuring allies and partners. The United States' relationship with China is evolving, and with it our understanding of strategic nuclear stability. North Korea acts inconsistently with its assertions of intent to denuclearize the Korean peninsula, and Iran may be on the precipice of a realized nuclear weapon program. Meanwhile, the United States continues to support allies and partner nations with a "credible U.S. 'nuclear umbrella.'"[1] These situations are not independent, and how the United

[1] Department of Defense (DoD), *Nuclear Posture Review Report*, executive summary, April 2010, p. 12.

States may choose to shape or respond to any one of them may impact other relationships. The drive in the United States to continue to reduce force sizes may compound the problem of balancing these increasingly complex interactions and relationships. The ICBM may have to evolve to support these future situations.

Although the ongoing DoD Service Life Extension Programs (SLEPs) hope to enable the Minuteman III force, which has been in service since the 1970s, to serve until approximately 2030, it is important to begin thinking now about the necessary research, development, and testing of a new missile, as it could easily take a decade or more to field a new system. Procurement and fielding of complete systems can take equally as long. As called for in the NPR, policymakers should already be considering and assessing alternatives for the next-generation ICBM, understanding that adjustments to the U.S. nuclear force posture should be a deliberate policy choice rather than a consequence of budgetary pressures or aging machinery. Meanwhile, any future U.S. ICBM force must meet the twin goals outlined in the NPR of "maintaining strategic deterrence and stability at reduced force levels" and "maintaining a safe, secure and effective nuclear arsenal."

The Challenge

Air Force Global Strike Command (AFGSC) will soon begin a formal AoA for the next-generation ICBM. In fiscal year (FY) 2011, AFGSC began pre-AoA analyses with a Capabilities-Based Assessment and an Initial Capabilities Document (ICD) that will help guide the AoA. AFGSC and the Strategic Deterrence and Nuclear Integration Office, Headquarters U.S. Air Force (AF/A10), asked RAND to support these efforts by independently developing operational, organizational, and technological concepts for the future ICBM force. Specifically, RAND was asked to examine and assess possible ICBM alternatives against the current Minuteman III system, including cost drivers and cost parameters, to focus the scope of the AoA. In addition, AF/A10 asked RAND to provide insights into the potential impact of further force reductions on critical nuclear expertise and career fields.

Our Approach

To narrow the focus of the potentially large set of issues in play, we pursued three lines of research to shed light on the future of the U.S. ICBM:

- Using the current Minuteman III as a baseline, we developed a framework consisting of five categories—basing, propulsion, boost, reentry, and payload—to characterize alternative classes of ICBMs and assess the survivability and effectiveness of possible alternatives.
- Using existing cost analyses and cost data from historic ICBM programs, we derived likely cost bounds on alternative classes of ICBM systems.
- We developed force reduction scenarios and examined their impacts on several key nuclear specialty career fields to understand possible implications of reductions on the current organizational structure.

Our cost analysis is not meant to stand in for an AoA cost analysis. This is merely our attempt to make some broad characterizations about likely budget requirements for any ICBM follow-on.

While we did not identify or derive possible requirements—in fact, AFGSC specifically asked us not to do so—we were able to make some meaningful survivability and effects assessments of some ICBM alternatives. We examined several issues—survivable basing, range and overflight, and conventional strike—without holding to any specific number.

To examine the impact of force-size reductions on manpower, we compared sustainment and requirement profiles within the various reduction scenarios. This analysis should be most relevant to the Air Force because it highlights future organizational issues and decisions that need to be made if the ICBM force continues to shrink below New START levels.

Results and Findings

Options for ICBM Modernization

Our initial survey of options and costs suggests that incremental modernization and sustainment of the current Minuteman III force is a cost-effective alternative that should be considered within the AoA. The biggest hurdle currently standing in the way of continued SLEPs to sustain Minuteman III beyond 2030 is the declining number of missile bodies due to required test launches. If 420 Minuteman III missiles are retained for operations, the test inventory will be depleted by 2030. Maintaining a smaller force of 400 missiles would delay this milestone several years to 2035 by making more bodies available for tests; fielding even fewer missiles or reducing the number of annual test launches would proportionately extend the depletion date. Tests are critical to the longevity, readiness, and reliability of the system. While we did not explore whether the current testing requirements could be relaxed, caution should be exercised because reducing the number of tests could limit engineering-level assessments of the effects of aging and the effects of combining new parts with existing parts in any SLEP.

Sustaining Minuteman III through SLEPs and gradual upgrades is a relatively inexpensive way to retain current ICBM capabilities. The AoA should examine this option in more detail, to include expanding SLEPs to silos; nuclear command, control, and communications (NC3); and other support equipment. This report also outlines the operational and cost implications of future design options for ICBM basing, range, payload, and reentry vehicles. However, these options are only relevant if warfighting and deterrence demands push requirements for an ICBM system to beyond what an incrementally modernized Minuteman III can offer.

Options for Survivable Basing

In assessing basing alternatives against current baseline threats and possible future excursions from that baseline, we find that silo basing will likely continue to be the most cost-effective option for the foreseeable future. Today, only Russia is capable of attacking U.S. ICBMs, and, even in this situation, an attack would require a substantial fraction of Russian reentry vehicles (RVs) under the New START ceiling. Thus, the continuing vulnerability of U.S. ICBMs to a Russian preemptive strike may not be of nearly as much concern as it was during the Cold War, especially since the United States and Russia are no longer implacable enemies. Basing ICBMs in current silos is survivable against all other potential nuclear adversaries. In particular, China is now incapable of such an attack, and will likely remain so for the foreseeable future. The only thing that could move the United States away from its current silo basing is the future evolution of the threat in terms of either quality or quantity. Quantity, of course, has to do with the size of the potential attacking force relative to the total number of silos in the U.S. ICBM fields. Thus, unilateral reductions could affect the survivability of the residual U.S. ICBM force.

Options for Effectiveness and Lethality

While ICBM propulsion will likely continue to be based on solid fuels, boost, reentry, and payload options can add capability to hold a potentially larger class of targets at risk. We find that if overflight of Russia and China remains a dominant issue for ICBMs, the most cost-effective mitigation may be to add launch options to Vandenberg and Cape Canaveral, although this may not completely eliminate the risk. Overflight from current wing locations can be addressed by launching south or changing planes, but both options add significantly to missile size requirements. Because of this, systems other than the ICBM may be more effective in situations where overflight is a critical planning consideration; the flight paths of bombers and submarine-launched ballistic missiles (SLBMs), for example, are not as constrained as those of ICBMs. For payload options, we find that a conventional ICBM only holds at risk a narrowly defined set of targets—those characterized by being relatively stationary and relatively unhardened. The upcoming AoA should therefore focus on the nuclear capabilities necessary to deter attacks from established nuclear powers and to provide an effective counterforce capability against hostile emerging nuclear states in dangerous situations. An AoA could, however, consider conventional payloads as an option for some ICBM designs should the need arise.

The Impact of Further Force Reductions

Realistically, Congressional direction to significantly reduce the DoD budget over the next 12 years may make it difficult to significantly upgrade or replace the current silo-based Minuteman in the near term.[2] While budgetary constraints, along with other factors, could force further reductions of the current Minuteman force below the 400–420 level currently planned to meet the New START limit, only complete closure of an ICBM-only base would result in significant annual operation and support cost savings.

Moreover, of interest to Air Force personnel and career field managers, decreasing the force to or below 300 will impact key nuclear career fields. In the appendix, we show how, as the number of ICBMs decreases, mismatches within the 13S nuclear specialty career field will be exaggerated while mismatches in the 2M0 career field may arise if the Air Force continues current personnel policies. Air Force manpower policies will therefore need to adapt in the case of a decreasing force.

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[2] The Budget Control Act of 2011 contains automatic sequestrations if the Democrats and Republicans do not achieve other budget agreements.

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Abbreviations

AoA	Analysis of Alternatives
ABM	anti-ballistic missile
ABRES	Advanced Ballistic Reentry System
AF/A1PF	Force Management Division, Directorate of Force Management Policy
AFB	Air Force base
AFGSC	Air Force Global Strike Command
AFNWC	Air Force Nuclear Weapons Center
AFS	Air Force Specialty
AFSC	Air Force Specialty Code
AIAA	American Institute of Aeronautics and Astronautics
AMaRV	Advanced Maneuverable Reentry Vehicle
APUC	Average Procurement Unit Cost
ASEE	American Society for Engineering Education
ASME	American Society of Mechanical Engineers
BDA	battle damage assessment
BMD	ballistic missile defense

BY12$	base-year dollars for fiscal year 2012
C3	command, control, and communications
CCR	cumulative continuation rate
CEP	circular error probable
CONUS	continental United States
CPGS	conventional prompt global strike
CVLSP	Common Vertical Lift Support Platform
DARPA	Defense Advanced Research Projects Agency
Δv	change in velocity
DoD	Department of Defense
DSP	Defense Support Program
EMD	engineering and manufacturing development
Falcon	Force Application and Launch from the Continental United States
FOBS	Fractional Bombardment System
FOC	full operational capability
FY	fiscal year
FYDP	Future Years Defense Program
GPS	Global Positioning System
GRP	Guidance Replacement Program
HDBT	hardened and deeply buried target
HE	high explosive
HGV	hypersonic glide vehicle
HML	hardened mobile launcher

HTV	hypersonic test vehicle
ICBM	intercontinental ballistic missile
IIM	indefinite incremental modernization
IMU	inertial measurement unit
INF	intermediate-range nuclear forces
IOC	initial operating capability
IR	infrared
ISR	intelligence, surveillance, and reconnaissance
LBSD	land-based strategic deterrent
LCC	launch control center
LE	life extension
LEP	life extension program
LoADS	Low-Altitude Defense System
LOW	launch on warning
LR	lethal radius
LUA	launch under attack
M&S	modeling and simulation
MAP	multiple aim point
MaRV	maneuvering reentry vehicle
MEECN	Minimum Essential Emergency Communications Network
MilCon	military construction
MilPers	military personnel
MIRV	multiple independently targetable reentry vehicle

MM III	Minuteman III ICBM
MM IV	Minuteman IV ICBM
MPS	mobile protective shelter
MT	megaton
NC3	nuclear command, control, and communications
New START	New Strategic Arms Reduction Treaty
NNSS	Nevada National Security Site
NPR	Nuclear Posture Review
O&M	operations and maintenance
O&S	operation and support
OTH	over the horizon
PAF	RAND Project AIR FORCE
penaids	penetration aids
PGRV	Precision-Guided Reentry Vehicle
P_k	probability of kill
POM	Program Objective Memorandum
PPI	Producer Price Index
PRP	Propulsion Replacement Program
PSI	pounds per square inch
RCS	Reaction Control System
R&D	research and development
RDT&E	research, development, test and evaluation
RSS	root-sum-squared
RV	reentry vehicle

SAE	Society of Automotive Engineers
SDR	System Design Review
SICBM	small intercontinental ballistic missile
SLBM	submarine-launched ballistic missile
SLEP	Service Life Extension Program
SPO	system program office
SRM	solid rocket motor
SSP_k	single-shot probability of kill
START	Strategic Arms Reduction Treaty
SUMS	Small (submarine) Undersea Mobile System
TAC	total annual cost
TEL	transporter erector launcher
TW	throw weight
TY$	then-year dollars
UN	United Nations
WMD	weapons of mass destruction
YOS	year of service

CHAPTER ONE

Roles of Strategic Nuclear Forces

The recent round of arms control negotiations between the United States and Russia and the subsequent ratification of the New Strategic Arms Reduction Treaty (New START) by the U.S. Senate may make it seem like an odd time to discuss the importance of modernizing America's intercontinental ballistic missile (ICBM) force. In fact, the discussion could not be timelier. At the same time that New START pushes ICBM force levels to their lowest point in decades, the 2010 Nuclear Posture Review (NPR) identifies a variety of emerging situations where strategic forces might play a role in deterring adversaries, stabilizing regions, and reassuring allies and partners. The United States' relationship with China is evolving, and with it our understanding of strategic nuclear stability. North Korea has likely emerged as a new nuclear state, while Iran may be on the precipice of a realized nuclear weapon program. The United States also continues to support allies and partner nations with a "credible U.S. 'nuclear umbrella.'"[1] These situations are not independent, and how the United States may choose to shape or respond to any one of them may impact other relationships, which may be compounded by the drive to continue to reduce force sizes. How the ICBM force evolves to support these situations is paramount to its future.

Ongoing DoD Service Life Extension Programs (SLEPs) hope to enable Minuteman III (MM III), in service since the 1970s, to serve until approximately 2030. If the United States is serious about a follow-

[1] Department of Defense (DoD), *Nuclear Posture Review Report*, April 2010, p. 12.

on system, it is important to begin necessary research, development, and testing processes in the very near future. Those steps could easily take a decade or more, while procurement and fielding of a complete system could take equally as long. As called for in the NPR, policymakers are already considering and assessing alternatives for the next-generation ICBM, understanding that adjustments to U.S. nuclear force posture should be a deliberate policy choice rather than a consequence of budgetary pressures or aging machinery. Meanwhile, the twin goals of "maintaining strategic deterrence and stability at reduced force levels" and preserving the U.S. commitment to "maintain a safe, secure and effective nuclear arsenal," as outlined in the NPR, warrant serious study of the roles, missions, and capabilities of the U.S. ICBM force.

Throughout the Cold War, U.S. policy argued that the purpose of strategic nuclear forces was to deter the Soviet Union from attacking the United States with nuclear weapons and to limit damage to the United States should deterrence fail. Although Russia still remains a competitor and continues to influence U.S. force planning, in the past decade a number of other states in myriad potential scenarios have emerged that complicate the strategic landscape.

Today, the NPR report focuses on several key objectives of our nuclear weapon policies and posture. These objectives range from preventing proliferation to extending deterrence.[2] We impute to the 2010 NPR "key objectives" the following four challenges relevant to U.S. nuclear forces:

1. Deterring nuclear use against the United States by a major nuclear power (for example, Russia) in the context of potentially fewer nuclear weapons
2. Preventing a nuclear arms race with a maturing nuclear power (for example, between the United States and China)
3. Maintaining appropriate counterforce and deterrence capabilities against states that have limited conventional militaries

[2] The full list and descriptions of challenges begins on page 2 of DoD, 2010.

but might possess nuclear weapons as well (for example, North Korea or potentially Iran)

4. Deterring nuclear use by regional powers (for example, India or Pakistan).

The United States extends deterrence to allies through membership in the North Atlantic Treaty Organization in Europe and through bilateral treaties with Australia, Japan, and South Korea in the Pacific region. More generally, the United States has security agreements with some states and offers at least negative security assurances to other states that are in compliance with their obligations under the Nuclear Non-Proliferation Treaty (NPT). Should such a state be attacked by a nuclear-armed state, the United Nations (UN) Security Council could seek the aid of UN members to protect and defend the victim of the attack. In terms of force posture and use, the NPR concludes that the United States should "continue to maintain and develop long-range strike capabilities that supplement U.S. forward military presence and strengthen regional deterrence."[3] In terms of force posture and use, extending deterrence amounts to challenges (3) and (4).

Deterring a Nuclear Attack on the United States

An enduring goal of strategic nuclear forces, in fact, one the United States inherits from its relationship with the former Soviet Union, is to deter a nuclear attack on the United States. Deterrence strategy requires that if one is not able to defeat or prevent such an attack directly, one can impose costs on the attacker that would outweigh any possible benefits by credibly threatening a devastating response. Thus, the idea is to convince a potential enemy that in any situation that might arise, launching a nuclear attack against the United States would always be its least attractive option. That, in turn, has historically required that the United States maintain nuclear forces capable of surviving any attack, no matter how large or clever, and retaliating by destroying whatever it

[3] DoD, 2010, p. xiii.

thinks the attacker values. This notion of a "survivable second strike" underpins what the United States has perceived to be a stable strategic nuclear relationship with Russia.

With the end of the Soviet Union, the intensity of the Cold War competition in strategic nuclear forces at the highest levels has diminished, and, although both Russia and the United States continue to maintain strategic forces that are much larger than those of other current nuclear powers, these numbers are greatly reduced from Cold War days. Both the United States and Russia have also continued to modernize their strategic forces, although much less aggressively than during the Cold War, while seeking to maintain a generally stable nuclear balance. They have also continued to reduce the overall size of their strategic forces through a series of nuclear arms control agreements aimed at maintaining the same overall stable balance between them at lower force levels.

As U.S. and Russian strategic nuclear levels come down, other issues are likely to become more important. Other nuclear powers might develop comparable capabilities; if so, they could affect U.S. decisions regarding its own strategic force structure. Still other nuclear powers have emerged since the end of the Cold War. Even those that cannot threaten the United States directly could complicate the U.S. calculus in terms of what it asks its strategic forces to do and what capabilities those forces require as a result.

In their primary deterrent role, U.S. strategic forces will still need all the same basic capabilities that they have always had. In general, they must be survivable and effective. ICBMs have to retain adequate retaliatory capability during and after a potential first strike. Historically, the main threat to ICBMs has always been other ICBMs. Basing its ICBMs in hardened silos has always been the U.S. response to this class of threat, although many other options have been considered. A robust, survivable command, control, and communications (C3) system is required. The U.S. solution to that has involved mobile, hardened, redundant, and diverse (land, air, and space) elements. In flight, the missiles may have to survive enemy defenses as well. To be considered reliable, the current and future ICBM system, including its launcher, flight vehicles, and warhead, must have insignificantly small testable failure rates. Last, the ICBM should produce the desired effects (e.g., damage expectancy [DE]) on all potential targets of interest. The ability to do so may include defeating anti-ballistic missile (ABM) systems, finding and destroying critical mobile targets, or defeating buried or terrain-masked targets. According to force posture statements made in the most recent NPR, the total U.S. strategic force, and in particular the ICBMs, should be on alert and ready to respond to emerging situations.

Preventing an Arms Race

One of the potential effects of the U.S. strategic force posture is to influence the weapon system and force structure choices of others. During the Cold War, "arms race stability" was the expression coined to address the idea that some kinds of weapon systems may be more likely than others to produce a dangerous response from an adversary. Cold War examples included highly accurate ballistic missiles, nationwide ABM systems, and—to some degree—multiple independently targetable reentry vehicles (MIRVs). All other things being equal, arms race stability argued that countries should try to avoid fielding such systems themselves and attempt to persuade others to do the same.

Arms race stability should be examined from both the U.S. perspective and that of potential adversaries in terms that address whether either side can affect the perception of the strategic balance by changing numbers or performance parameters of strategic force systems. The United States and Russia have found means to address some of these concerns in their formal arms control negotiations. Reducing force levels on both sides has caused some predictable problems. For example, by usual stability standards, it is a relatively "good" thing that the United States plans to de-MIRV its remaining ICBMs, particularly in an arms control environment that limits the total numbers of warheads.[4] De-MIRVing missiles does, however, create a potential stabil-

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[4] *De-MIRVing* refers to removing multiple warheads from each ICBM so that each ICBM only has a single warhead.

ity problem. In principle, existing "de-MIRVed" systems on both the U.S. and Russian sides could be rapidly reloaded with additional warheads in a crisis if the extra warheads were available. That could create a classic crisis instability problem. Fortunately, even beyond the routine intelligence collection that both Russia and the United States do, formal arms control has evolved enough to allow considerable intrusive inspection to make such a "breakout" very unlikely. It is much more of an issue for emerging and immature nuclear powers (e.g., China or Pakistan) that have every incentive to hide the details of their nuclear programs from the major powers.

None of this should pose any particular problems for a future U.S. ICBM force because the United States is certainly capable of taking actions that will make clear to others the size and basic capabilities of any future ICBM force. Production, testing, and fielding of an ICBM force would be difficult to conceal under any circumstances, and the United States has no reason to be unduly secretive about such a future ICBM force.

Compatibility with Future Arms Control Agreements

While arms control is only one factor in evaluating future strategic force options, it is nevertheless important to identify any particular potentially dangerous missteps that a particular future ICBM proposal might contain. Fortunately, the United States has considerable experience with accommodating ICBMs in arms control agreements. First, the United States and Russia have a history of using national technical means (i.e., overhead reconnaissance and other forms of intelligence collection) to establish and verify the critical characteristics of ICBM systems and the overall force levels once those systems were deployed. During the days of the MX basing controversy, the United States developed elaborate methods to allow the Soviets to determine the overall size of the deployed U.S. ICBM force in spite of deceptive basing methods designed to enhance the survivability of the missiles. Similarly, the United States routinely monitored force levels of Soviet mobile ICBMs once those systems were fielded. Moreover, with the signing of the Intermediate-Range Nuclear Forces (INF) Treaty, the United States and the Soviet Union established procedures for onsite inspection of not only operational sites but also production facilities, among other things. Since the INF Treaty took the unprecedented step of actually eliminating entire classes of weapons, the verification procedures used to monitor dismantling and destroying those weapons certainly provide useful experience for establishing future protocols for deep reduction or elimination of strategic forces, including ICBMs.

Maintaining Warfighting Capabilities

The principal role of U.S. strategic nuclear forces has been to deter "high end" nuclear-armed adversaries from attacking the United States by fear of retaliation. In principle, it would be preferable to do better. Specifically, it would be much more satisfactory if the United States could find a way to actually protect itself against such an attack. So far, that has proved to be impossible, and there is no reason to believe that will change in the foreseeable future. However, that sort of limitation does not necessarily apply to dealing with lesser nuclear powers. Against these potential adversaries, it may be that the United States can find more direct ways to prevent others from achieving that same level of capability.

Sufficiently effective counterforce capabilities might be able to prevent an enemy from successfully attacking others (e.g., the United States or its neighbors) rather than having to depend solely on being able to deter an enemy by threats of retaliation. Deciding how aggressively the United States should pursue this sort of "damage-limiting" capability was at the heart of the Cold War debate over U.S. ICBM development, in particular.

The situation is quite different now. The flexibility to target a wide array of targets—for example, to potentially include deeply buried or mobile threats—may be necessary, as may a force that can quickly respond to emerging situations. For the United States to maintain regional influence, assure allies, and extend deterrence to NPTcompliant states, U.S. strategic forces are counted on to to attack a range of potential adversaries and destroy a range of targets.

Deterring Regional Nuclear Powers

Whereas deterring a major nuclear power emphasizes the direct relationship between the United States and that state, the relationship of the United States and regional powers considers the role of the U.S. nuclear force to deter nuclear use and other actions by certain states against each other, third parties, or American interests abroad. This may affect the way in which the United States communicates a credible threat and has been an issue since the beginning of the nuclear age.

During the Cold War, the United States worked very hard to convince the Soviet Union, as well as its own European allies, that it would defend its allies with nuclear weapons if necessary. It took a number of operational actions aimed at convincing its European allies that its pledges to protect them were genuine. Mainly, the United States integrated its nuclear plans so thoroughly into alliance war planning that it would have been difficult either to deceive the Europeans, who participated in the planning process, or to overcome the momentum that the joint plans involved. Although both the Soviet Union and the United States took risks on occasion, for the most part, all concerned behaved cautiously most of the time; "extended deterrence" likely contributed to discouraging a Soviet attack on Western Europe.

The track record of extended deterrence elsewhere has been more mixed. In Asia, in the early days, the U.S. nuclear monopoly in the region may have been a factor in stopping the Chinese shelling of Quemoy and Matsu islands; it may have also helped prevent a Chinese invasion of Formosa. However, the American monopoly on the bomb obviously did not prevent the North Korean invasion of South Korea or the Chinese entry into the war on the North's side, though it might have been a factor in the North's eventual acceptance of a ceasefire. Results are similarly mixed in assessing what effects, if any, U.S. extended deterrence has had in the Middle East. If anything, the situation is much more complex than in Europe. There was, of course, the famous U.S. nuclear alert during the 1973 Yom Kippur war between Israel and various Arab states. The Soviets threatened to introduce troops into the region, and the United States increased the defense readiness condition (DEFCON) level of its nuclear forces. According to observers on the scene, Soviet leadership was alarmed over the U.S. actions, even asking visiting American scholars how to interpret U.S. actions.

Extended deterrence is, in many ways, more complex than traditional bilateral deterrence. There are several key questions:

1. Under what conditions would U.S. nuclear threats appear credible to a regional power or to a major nuclear power with a regional client?
2. Against whom would the United States threaten to use force? The regional power? Its nuclear-armed sponsor? Both?
3. Would or could the United States credibly threaten to use its nuclear forces not to deter a regional nuclear power, but actually to defeat it?
4. What kind of forces, both nuclear and conventional, would be required to "win" a war against a regional nuclear power?
5. What exactly would those forces have to be able to do to be effective in that role?
6. What does that say about the characteristics of the U.S. forces necessary to perform the required missions?

Credibility of extended deterrence is a central issue. What does it take to make an adversary believe that the United States would really carry out threats to use nuclear weapons in situations where its own existence is not being threatened directly and the risks might exceed the benefits? Moreover, under what conditions would such a use of nuclear weapons be acceptable to the United States itself?

The traditional view of extended deterrence may not completely capture how to assess future directions for U.S. nuclear forces. Instead, a distinct possibility is that U.S. nuclear forces will be asked to perform two very distinct functions. One might be the traditional role of deterring attacks by major nuclear powers by threatening devastating nuclear retaliation. The second might actually be to defeat emerging nuclear powers in regional conflicts or, for that matter, in attempts to attack the United States directly. Addressing those two sets of possibly diverging sets of force requirements, and even political attitudes, is likely to be central to designing future U.S. nuclear force postures.

As the number of situations that resemble extended deterrence cases expands, the value of long-range and standoff weapons and systems becomes increasingly important for both the deterrence and the defeat missions. Inasmuch as emerging nuclear states put their own nuclear weapons on ballistic missiles, the zones in which the United States can safely operate and base nuclear assets will be pushed farther and farther from likely targets. In the Pacific region, moreover, the relative paucity of basing options could also place a premium on standoff and long-range platforms. ICBMs, in particular, may be newly relevant because they can compel emerging nuclear states to conceal or bury their nuclear weapons and their means of delivery so that they are not available on a day-to-day basis.

An ICBM for a New Generation of Challenges

At the crux of forthcoming decisions is the question of what capabilities are necessary to achieve U.S. goals within these emerging challenges. A central tension has emerged in the discussion over the potential implications of developing a more "credible" ICBM. Improvements in guidance technologies, lower explosive yields (with less collateral damage), and other developments may enable the ICBM to be an effective military capability option against a larger class of targets than the current Minuteman missile. However, choices made to provide broader capability, especially against lesser nuclear powers, may prove destabilizing in the context of relations with more powerful states like Russia and China. Technical attributes that offer greater flexibility or enhance the adaptability of the ICBM may seriously affect these relationships. In a world where the United States and Russia have significantly reduced their arsenals, qualitative improvements in weapon systems could prove more threatening, spurring either potential breakout or a more hair-trigger posture by others. One focal point we examine in this report is whether conventional ICBMs can be viewed as an alternative to nuclear ICBMs in some situations. The 2001 NPR explicitly considered the development of conventional strategic systems to provide greater flexibility to decisionmakers and to more effectively address the perceived threats of the post–Cold War era. The 2010 NPR reiterates this interest in the context of reducing our total nuclear force.

Budgetary pressures will undoubtedly influence upcoming ICBM modernization decisions. Further force reductions are coming, most notably the urgent need to cut $400 billion from the DoD budget over the next 12 years and perhaps even more over that same timeline under the Budget Control Act of 2011.[5] While some ICBM reduction scenarios may be examined with an eye toward saving money, only the closure of an ICBM wing and base would realize significant savings. Because total annual operation and support (O&S) costs are less than $1.5 billion annually, an upper bound on closing a single wing would be one-third of this total. The actual annual cost of each ICBM base is even lower, so annual savings may be more in the $200 million range.[6] Instead of relatively small near-term savings, current and projected future budget constraints might compel the Air Force to choose among many upcoming replacement or modernization program decisions. It is not yet clear where a new or modernized ICBM might fit into any ranking of such programs. Further reductions based on New START will impact the ICBM force and could necessitate reorganization decisions. Reducing to 300, 150, or even fewer missiles will pose organizational decisions to close wings and consolidate commands. The U.S. Air Force special nuclear expertise core may be affected as the number of field-level officers and senior enlisted personnel positions

[5] The Secretary of Defense is to reduce accounts directly under his charge within DoD. The language of the Budget Control Act mandates that reductions from the Congressional Budget Office baseline include defense-related expenditures within the Department of Energy, such as additional accounts and programs for modernizing nuclear weapons and the nuclear weapon production infrastructure.

[6] According to the Air Force Total Ownership Cost (AFTOC) database, O&S costs of Warren Air Force Base (AFB) in fiscal year (FY) 2009 dollars were $179 million; O&S costs for Malmstrom AFB were a reported $183 million.

changes and the supply of company-level officers and junior enlisted personnel shrinks.

At the same time, reductions that occur via arms control agreements have positive effects, such as raising the relative cost to attack ICBM silos. Historically, a particular strength of the ICBMs was that they offered a cost-effective way of maintaining a large number of warheads at the ready. At the height of the Cold War, however, this proved to be a liability because issues of silo-based vulnerability, especially if populated by ICBMs with MIRVs, introduced what was a serious balance and stability concern at the time: The side that struck first might have an advantage.[7] With the deactivation of Peacekeeper and the almost complete de-MIRVing of the remaining Minuteman missiles, the resulting U.S. force is probably less destabilizing. With New START's warhead limits, the Minuteman launch facilities and alert facilities represent close to 500 discrete targets that the Russians would have to attack. If the Russians were to consider using the traditional conservative approach of targeting two reentry vehicles (RVs) on each silo and launch control center (LCC) to compound damage and to reduce uncertainties over accuracy and reliability, they might view the cost of such an attack under the New START force limits to be excessive. If so, this particular "window of vulnerability" may be less important than in the past. Arms control agreements with Russia have somewhat mitigated the need for a survivable ICBM basing alternative, a quest that the nation unsuccessfully pursued for several decades during Minuteman's tenure.

Purpose and Organization of This Report

Capabilities and costs motivate alternatives. The decision to acquire a new system or modernize an existing one is only as attractive as the potential for cost savings it presents or the new or added capabilities

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7 We do not want to overstate this point, however. The advantage was hardly certain: For example, consider the potential for launching under attack if U.S. and Russian ICBMs passed each other in flight.

it offers. Without an explicit characterization of the requirements for a follow-on ICBM, it is impossible to evaluate any list of contending alternatives. How could we decide whether a new booster, for example, is worth the added investment if we do not first know what the range and payload requirements might be? However, it is possible—and good due diligence—to examine the universe of ICBM possibilities to understand basic differences, physical constraints, and associated cost drivers in order to appropriately focus any future Analysis of Alternatives.

The purpose of this report is to identify issues that should be considered in the design of future ICBM systems and to help focus the scope of the ICBM AoA. In Chapter Two, we construct a framework for ICBM design options and alternatives. We use this framework in Chapters Three and Four to examine and assess the survivability and effectiveness of different classes of alternatives. We then derive costs for alternative classes of ICBM systems in Chapter Five.

No matter what ICBM system the United States fields in the future, further force reductions will affect how the Air Force organizes this force. In the appendix, we examine several reduction scenarios to highlight potential issues the Air Force will have to address if force size continues to decline. We also make several excursions to provide possible alternatives to address the issues raised.

ICBMs have been a cornerstone of the U.S. nuclear force posture since the 1960s when the United States fielded the first Minuteman missile. In the chapters to follow, we discuss the issues involved in maintaining a future force that has to be cost-conscious and numbers-conscious and that must help the United States meet diverse and evolving security challenges. In doing so, we start to paint a picture of what the U.S. ICBM force may look like in the coming decades.

CHAPTER TWO

A Framework for ICBM Design Decisions

To begin thinking about the many different systems and subsystems that could make up an ICBM, we develop a framework consisting of five categories for classifying alternatives: basing,[1] propulsion, boost, reentry, and payload. This framework accounts for steps in delivering a weapon from the continental United States (CONUS) to intercontinental distances. This five-category approach will help us differentiate and examine ICBM alternatives. We find it helpful to focus on key design parameters and potential capability trade-offs without being overly constraining. The one underlying assumption we do make is that a U.S. ICBM will be CONUS-based and deliver a payload at intercontinental distances.

As Figure 2.1 depicts, we divide each of the five categories—basing, propulsion, boost, reentry, and payload—into two subcategories: one that is based on the current Minuteman III system and the other that acknowledges potential variations. For example, ICBMs can be based in fixed locations—Minuteman III resides in hardened and dispersed silos—or in variable locations, which require some mobility. To propel an ICBM, the missile may be powered by solid fuels or by other types of fuels such as liquids and hybrids. Once an ICBM is

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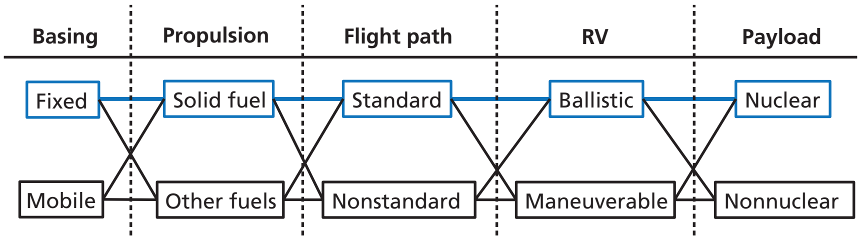
1 *Basing* encompasses a set of issues ranging from warning dependence to nuclear command, control, and communications (NC3). While we address warning and concepts of operations in our discussion of alternative basing schemes, our primary focus is on survivability, and we do not explicitly address NC3 systems or issues in this study. NC3 played a principal role in the 2006 "Land-Based Strategic Deterrent Analysis of Alternatives," and we direct the reader there for details.

Figure 2.1
ICBM Alternatives



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launched, it can follow a ballistic great-circle trajectory to maximize range; it can also be lofted or depressed to achieve different reentry angles, or it can change great-circle planes midflight, which is what we mean by "nontraditional" boost. In terms of RVs, the currently deployed Mark-21 and Mark-12 RVs are nonmaneuvering, but the United States has explored and developed maneuvering RVs (MaRVs) as a potential solution for defense penetration, terrain penetration, and even accuracy improvement.[2] MaRVs may also include current developmental glide vehicle concepts such as the Defense Advanced Research Projects Agency's (DARPA's) hypersonic test vehicle (HTV), which we discuss in Chapter Five. U.S. ICBMs have historically existed solely to deliver nuclear weapons; however, the current debate about which systems ought to constitute conventional long-range strike (LRS) platforms has nominated ICBMs, and this is a natural analytic excursion to make. Of course, each of the five categories may be subdivided further—for example, alternative basing schemes include deception and missile defense overlays as well as hybrid approaches; however, we find that it is sufficient to start with this as a basic categorical overview for designing an ICBM.

This breakdown of ICBM variations identifies 32 possible basic design alternatives. The blue line across the top row in Figure 2.1 depicts

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[2] One such example is the ABRES (Advanced Ballistic Re-Entry System) program, established in 1963. For a detailed description and discussion, see Robert Aldridge, *First Strike! The Pentagon's Strategy for Nuclear War*, Boston, Mass.: South End Press, 1983.

both the current Minuteman III system and the silo-based Peacekeeper missile, whereas the rail-mobile version of Peacekeeper would indicate a move away from the first row at the "basing" first column. Some combinations within these 32 basic ICBM variations constitute qualitatively different systems—for example, if a nuclear payload is compared to a nonnuclear one. Other combinations may lead to very costly systems.

Throw weight can be considered an additional variable and is proportional to the size of the missile. Because weight will be determined by choices made in the outlined categories, we do not explicitly include it in the framework. In fact, once range and payload are fixed, the rocket equation gives a mass requirement. Sizing an ICBM above this requirement would give options for adding throw weight. Theoretically, achieving intercontinental ranges puts a lower limit on size at approximately 30,000 lb. While we do not derive a theoretical upper bound, we note that the largest solid-fueled ICBM the United States has fielded is the Peacekeeper missile at 190,000 lb., which is about as large a missile as can be fired from a Minuteman III silo.[3] Figure 2.2 illustrates the spectrum of weight classes with a few examples: The minimum extremum is exemplified by a U.S.-designed "Small ICBM" (SICBM, or "Midgetman," as it is still sometimes referred to); the maximum extremum is represented by Peacekeeper. The U.S. Minuteman III missile is just about in the middle, the Russian Topol-M weighs in slightly above

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[3] The "MX Missile Basing" report (John D. Gibbons, *MX Missile Basing*, Washington, D.C.: Office of Technology Assessment, September 1981) describes the cold launch process:

> The use of a gas generator to build up steam pressure inside a canister housing a ballistic missile which forces the missile out of the canister prior to the ignition of the first stage rocket motor. The temperature of the steam used to eject the missile from the canister is quite hot; however it is substantially less than the many thousand degrees F. of the rocket motor exhaust.

Cold launch was developed for the Peacekeeper so that it could be deployed in Minuteman silos that were designed for a missile a third of its size. To prevent Peacekeeper from burning up upon launch, cold launch allows the first stage to ignite once the missile is outside the silo. The canister used for cold launch also protected the Peacekeeper from damage and minimized damage to the silo after launch so that the silo could be reloaded and reused more rapidly.

Figure 2.2
ICBM Sizes

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this at approximately 105,000 lb., and the Israeli Jericho III comes in slightly below the Minuteman at 65,000 lb.

Some concepts for ICBM-like systems may alter the traditional payload range equation given for solid rocket motors (SRMs). Aside from liquid- fueled alternatives, which generally offer higher specific impulses than solid rocket fuel, the U.S. Air Force is conducting ongoing research and development on hypersonic glide vehicles (HGVs) that may be launched to altitude and given a push onward by more traditional rockets, such as the Minotaur. We describe this in some more detail later (see Chapter Four) and mention it here because the relationship between throw weight and launch weight of these systems may not follow as linear a relationship as a solid fuel rocket.

Variations in weight class can lead to ICBM systems that differ in significant ways and have different strategic implications. Returning to Figure 2.1, Minuteman III is therefore characterized by the top line (in blue) at 80,000 lb. The United States has studied and developed similar systems at different weights. The silo-based Midgetman and Peacekeeper would be recent examples. Changing just the weight class of a design characterized by our framework could already be a significant departure from Minuteman III. Midgetman (the Small ICBM) was designed to carry a single RV and warhead, whereas Peacekeeper could accommodate up to ten RVs.

More important is the impact of throw weight on effectiveness. Once a set propulsion and boost design has established a range-payload trade-off, to add more or heavier RVs as well as penetrating aids (penaids) without sacrificing range of a particular system requires a larger missile.[4] The addition of penaids or a MaRV could add defense or terrain-penetrating capabilities, thereby broadening the set of potential targets. Increasing the number of RVs could add to the targeting potential of the missile by allowing for multiple RVs on a single target or by targeting multiple objects.

Effectiveness is further addressed in the last four categories: propulsion, boost, reentry, and payload. In the following sections, we describe a set of problems that variations within each category can address. We also construct physical or feasible bounds on the ability of these variations to address those problems. For propulsion, we examine alternatives to solid rocket fuels. For boost, we examine, in particular, "overflight," which we define as the extent to which a great-circle route from the three current ICBM wings intersects Russia or China on the way to other potential targets of interest. For RVs, we derive efficiency bounds on guidance and control systems to improve overall accuracy. And for payload, we describe classes of targets potentially held at risk by conventional high explosive (HE) warheads. We do not discuss battle damage assessment (BDA) in this report, even though BDA could be included in assessments of effectiveness. Devices that can obtain and transmit information on a failed launch or failed warhead separation are feasible additions to an ICBM system. They may add some relatively small amount of weight but could enhance the effective delivery of nuclear warheads, which could be particularly useful in a security environment where a large exchange is less likely than a situation involving limited numbers.

Survivability assessments are made from a chosen basing scheme. In the next chapter, we assess the survivability of the current silo-based Minuteman force according to current and possible future threats. We

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[4] When Minuteman III was de-MIRVed, its range increased; another way to characterize this change would be to say that the current single-RV Minuteman would accrue a range penalty by uploading additional RVs.

then synthesize more than 40 years of ICBM basing analyses to identify alternative approaches and to screen various options for feasible candidates. We assess mobile basing candidates and derive associated cost estimates as part of our overall ICBM cost analysis.

CHAPTER THREE
ICBM Basing

The quest to find suitable ICBM basing modes began more than 50 years ago with the development of the Minuteman system. The objective was to set the survivability of the U.S. ICBM force to some "acceptable" level, that is, to make the cost of attacking the ICBM force "prohibitive" to an attacker. Though survivability and the notion of stability—disincentivizing first use—are inextricably linked, our assessment of ICBM basing is focused on survivability. While a non-survivable system is unstable because it gives an attacker incentive to strike first, the converse is not necessarily true. Making a survivable system does not ensure that it is a stable one, as stability has to account for a bilateral relationship in which the other player's, or actor's, behaviors can only be assumed or guessed. Therefore, in this section, the measure we find most helpful when comparing basing alternatives is survivability in terms of the cost imposed on an enemy to attack U.S. ICBMs.

Initially, using rail cars on the commercial railroad system was a seriously considered option prior to the decision to base Minuteman in dispersed and hardened underground silos.[1] Through the end of the Cold War, the increasing vulnerability of these silos to the growth in

[1] In *Politics and Force Levels: The Strategic Missile Program of the Kennedy Administration* (Berkeley, Calif.: University of California Press, 1980), Desmond Ball describes a Weapons System Evaluation Group study (WSEG No. 50) that encompasses one of the original examinations of Minuteman basing. The study "favored the mobile over the silo-based version," though from a cost-effective perspective, there was a "cross-over point" at about "900 missiles." Above that level, "the advantage passed to fixed Minuteman ICBMs in silos" against the Soviet threat of the time.

the size, improved accuracy, and increased yield of the Russian missile force added renewed urgency to finding acceptable alternatives; countless schemes have been seriously analyzed by generations of engineers. In several cases, these analyses turned into development programs. Unfortunately, none of the analyses and development efforts resulted in an acceptable alternative to the current silos. The most recent efforts in the 1980s focused on finding a survivable basing scheme for the MX/Peacekeeper missile, which was significantly larger than the Minuteman III (190,000 lb. versus 80,000 lb.). Since Peacekeeper's size exacerbated most non-silo basing challenges, the United States chose to pursue development of a new SICBM, or Midgetman, at 35,000 lb. In the end, Peacekeeper was deployed in modified Minuteman silos (the right-hand side of Figure 2.2 depicts a cold-launched Peacekeeper from a modified Minuteman III silo) with a promise to continue the search for a follow-on, more survivable mode, such as a rail-mobile mode, when SICBM was canceled.

In this chapter, we examine and provide answers to two critical issues: (1) Who could attack the current silo-based force and what would an attack entail? (2) What are the constraints and costs of potential alternatives? The motivation for alternative basing schemes remains threat-driven: Are current silos survivable against plausible attacks in the sense that the cost imposed on an attacker is adequately high? We believe that the Air Force should consider moving away from the current Minuteman silos if added survivability against the perceived threat outweighs the cost of moving to another basing mode. This chapter develops how to think about the survivability of different classes of ICBM basing and their associated survivability metrics. We synthesize more than 40 years of ICBM basing research to identify feasible alternatives and quantify certain characteristics of those alternatives to directly compare them to current silo basing.

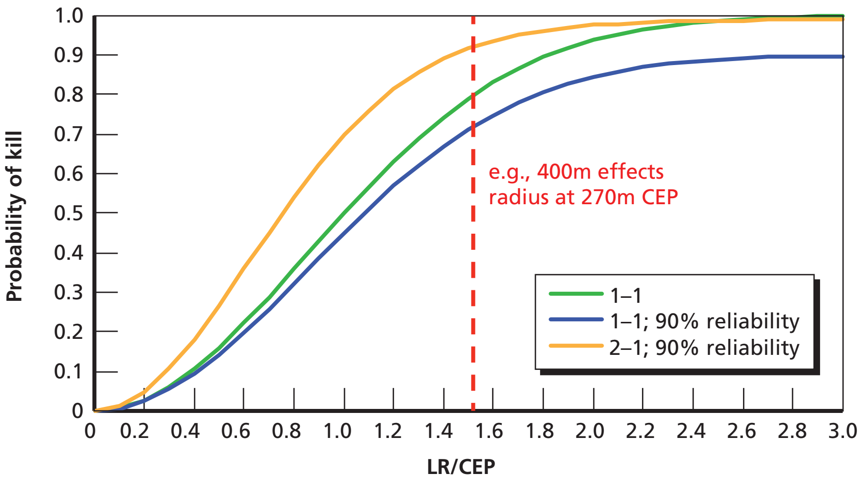
Survivability of the Current Silo-Based Force

Because current Minuteman silos are in well-known and fixed locations, they can be targeted. Although the silos have been hardened against nuclear attack and spaced miles apart to ensure that an attacker cannot destroy several silos with one high-yield weapon, no system can survive a near-direct hit with a nuclear weapon. For this reason, silos have long been theoretically vulnerable to preemptive attack. This is especially true of an attacker with a large number of weapons who can potentially target each silo with multiple warheads to offset reliability and accuracy uncertainty. See, for example, Figure 3.1, which indicates that a two-on-one attack of missiles with 90-percent reliability and certain assumptions about its effects size and accuracy could attain a likelihood of destroying a fixed target of over 90 percent. At the height of the Cold War, when the Soviet Union had thousands of ICBM RVs, this was a particular concern.

Increased Accuracy

What has changed over the years is not only the impact of arms control agreements on Russian force numbers but how near the weapons

Figure 3.1
Vulnerability of Fixed Point Targets



NOTE: The x-axis, LR/CEP, represents the ratio of the effects radius of the weapon (or the "lethal radius," *LR*) and a measure of accuracy (the "circular error probable," or *CEP*), that is, the size of the radius of the circle that represents the weapon having a 50 percent chance of landing inside.

RAND *MG1210-3.1*

can get and their explosive yields. Accuracy is typically specified in terms of the missile's CEP, which, in simplified terms, is the radius of a circle in which 50 percent of the weapons targeted at its center will, on average, land. In the earliest days of ICBMs, CEPs were measured in miles, whereas today's ICBMs can attain CEPs of several hundreds of feet using inertial guidance alone. Future systems that might employ external aids, such as Global Positioning System (GPS) for midcourse and terminal updates with a MaRV to take out reentry errors due to weather, could do significantly better.[2] In quantitative terms, the probability of destroying a silo, P_k (for probability of kill), depends on the ratio of the attacking weapon's *LR* and its *CEP*. "Lethal radius," of course, depends on the silo's hardness and the weapon's yield as well as the height-of-burst and other complicating factors we ignore in this simple characteristic equation, on which we base the curves in Figure 3.1:

$$P_k = 1 - \left(\frac{1}{2}\right)^{\left(\frac{LR}{CEP}\right)^2}.$$

Factoring in reliability, *R*, we get the single-shot P_k, SSP_k:

$$SSP_k = R \times P_k.$$

For n-on-one, or n:1, attacks, we then get:

$$P_k(n) = 1 - \left(1 - SSP_k\right)^n.$$

Figure 3.1 depicts $P_k(n)$ for $n = 1,2$ for varying missile reliabilities. Because accuracy improves with a fixed-effects radius, the right-hand side of the figure shows just how effective targeting fixed silos can be.

2 Dependence on an external system such as GPS, however, can negatively affect readiness and availability and add operational risk. The reality that GPS can be jammed, spoofed, or otherwise negated creates a trade-off between improved accuracy and that increased risk.

Multiple Independently Targetable Reentry Vehicles

Fixed silos can become vulnerable to technical improvements in some threat factors we cannot control, such as CEP or yield, and to other factors we might be able to control—namely, the number of attacking weapons. When both the United States and the Soviet Union had comparably large forces of heavily MIRVed silo-based ICBMs, a single ICBM, say a 10-RV Peacekeeper or 10-RV SS-18, could theoretically attack up to five adversary silos 2-on-1. If P_k were high enough, this would provide an exchange ratio of several-to-one in favor of the attacker. This vulnerability to a preemptive attack in which the attacker could, in theory, destroy nearly all of the adversary's ICBM forces while holding a large fraction of its own in reserve (or use them for attacks on other target classes) was a serious concern.

Launch Under Attack

Thus, the logic of increasing the effectiveness and efficiency of a missile by arming it with multiple warheads came at a cost in terms of strategic stability. As warheads became smaller and missiles became more accurate—and, therefore, more effective—the destabilizing effects of MIRVs became more acute, especially if both sides placed MIRVs on vulnerable missiles.

In the case of the United States and the Soviet Union during the Cold War days, the imbalance in size between U.S. and Soviet ICBMs beginning in the 1960s exacerbated the stability problem still further. For a variety of technical, operational, institutional, and even cultural reasons, the two sides chose different ICBM development paths. A key difference was that, with Minuteman, the United States moved toward smaller ICBMs, while the Soviet Union continued to emphasize large ICBMs. The advent of MIRVs meant that the Soviet Union had at least a theoretical advantage, depending on how accurate its warheads were, in an exchange of vulnerable ICBMs with the United States. That apparent imbalance in warheads on theoretically vulnerable ICBMs was at the heart of decades of contentious debate within the U.S. defense community for decades. The United States tried, largely unsuccessfully, to eliminate the MIRV imbalance through arms control. Eventually, the United States succeeded in including a ban on

MIRVed ICBMs in the Strategic Arms Reduction Treaty (START II), which the United States and Russia signed in 1993. However, Russia withdrew from the treaty in 2002, and subsequent arms control treaties have not included a MIRV ban.

An even more contentious approach to eliminating the destabilizing effects of maintaining theoretically vulnerable ICBM forces has been the idea of launching them on warning of an impending attack. Launch on warning (LOW), launch under attack (LUA), launch on nuclear detonations, and several other variants have been the subject of intense debate in public and, presumably, at the highest levels of government for half a century. The public debates have been massively documented.[3] Until recently, the policy-level debates inside government have been both highly classified and very closely held. However, recently, enough of the classified history of launch under attack—by whatever name—has been declassified to provide some revealing insights into what senior U.S. policymakers were thinking about launch under attack during critical periods of the Cold War.[4] Undoubtedly, the most important revelation to date is that, during at least some periods of the Cold War, *the United States really planned to do it*. Launch under attack was an official policy option:

> (U) . . . LUA for Minuteman ICBM (implemented in SIOP 5D). . . . ICBM only LUA against low collateral military and leadership subsets.[5]

Although the conceptual attraction of launch under attack in eliminating some of the more intractable sources of theoretical strate-

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[3] See, for example, Bruce G. Blair, *The Logic of Accidental Nuclear War*, Washington, D.C.: Brookings Institution, 1993, pp. 168–218.

[4] William Burr, ed., "Launch on Warning: The Development of U.S. Capabilities, 1959–1979," *National Security Archive Electronic Briefing Book No. 43*, Washington, D.C.: National Security Archive, George Washington University, April 2001.

[5] Col Kearl and Lt Col Locke, *Current US Strategic Targeting Doctrine*, U.S. Strategic Air Command, HQ SAC/XOK/XPS, December 3, 1979. Document 20, "Launch on Warning: The Development of U.S. Capabilities, 1959–1979," *National Security Archive Electronic Briefing Book No. 43*, Washington, D.C.: National Security Archive, George Washington University, April 2001. Unclassified, redacted version.

gic instability is obvious, so are the risks and the practical difficulties. For example, at a minimum, implementing a successful launch-under-attack policy for ICBMs would require at least the following:

- missiles at a high-enough level of warning that they could be launched successfully in the amount of time available following warning that an attack was in progress
- a means of providing warning that an attack was actually in progress and characterizing it well enough for policymakers to make an informed decision about launch under attack
- a command and control system that was fast, reliable, secure, and effective enough to allow high-level authorities to actually make and implement an informed launch-under-attack decision under the most stressful conditions imaginable.

None of those things is easy, and all are fraught with risks. Ironically, the Cold War adversaries, the United States and the Soviet Union, at least had geography on their side. They were about as far apart geographically as adversaries could be on planet earth. As a result, ICBM flight times would have been about as great as the earth would allow. Translating that into effective warning time is a nontrivial matter, but at least there was room to "proceed to the next step" in the calculation. *Note that newly emerging nuclear powers may not be so fortunate*, and that could make their situations critically different from those of the original nuclear powers.

Even at intercontinental ranges, ballistic missile flight times are on the order of half an hour.[6] That is not much time to work with. In the early days of ICBMs, that would not have been enough. However, the advent of large-scale solid propellant and storable liquid rocket engines at least eliminated fueling time as an issue for launching missiles on warning. However, even assuming that little or no preparation (e.g., spinning up gyros) is required to launch the missiles themselves,

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[6] Francis J. Hale, *Introduction to Space Flight*, Englewood Cliffs, N.J.: Prentice Hall, 1994, pp. 285–292, for example.

a lot still has to happen in the half hour or so before the attacking missiles arrive.

The first problem is getting some kind of timely warning that an attack is under way. Ideally, one would want to do that at the earliest possible moment, which means as soon after the missile launches as possible. In principle, there are a number of possibilities. For example, the Soviets initially chose over-the-horizon (OTH) radar based in the Soviet Union to try to detect U.S. ICBMs as soon as they were launched. OTH radar operates at low frequency, which allows the beam to bounce off the ionosphere one or more times, thereby potentially extending its detection range well beyond the radar's normal line of sight. Unfortunately for the Soviets, OTH propagation over the North Pole can be unreliable or even impossible, which could have made reliance on OTH radar to provide early detection of a U.S. ICBM launch very risky.

The United States chose another path. It developed space-based infrared (IR) sensors to try to detect ICBM boosters early in flight when they were burning brightly.[7] If all worked as it is supposed to, that should provide the earliest possible warning that an attack was in progress and perhaps some initial estimates of the size and nature of the attack. Specifically, even the earliest Defense Support Program (DSP) early-warning IR satellite would be capable of providing "roughly 30 minutes of warning of approaching intercontinental missiles."[8] The DSP satellites proved to be capable of providing a variety of other important capabilities as well. Overall, DSP succeeded spectacularly, exceeding the expectations of even champions, as well as skeptics. Its successors have not fared as well, although the first of the Space-Based Infrared System satellites has been launched and is operating successfully, while DSP has operated effectively much longer than its design lifetime. As a result, there has so far been no loss in missile warning

[7] Jeffrey T. Richelson, *America's Space Sentinels: DSP Satellites and National Security*, Lawrence, Kan.: University Press of Kansas, 1999; Jeffrey T. Richelson, *America's Space Sentinels: The History of DSP and the SBIRS Satellite Systems*, 2nd ed., expanded, Lawrence, Kan.: University Press of Kansas, 2012.

[8] Richelson, 1999, p. 65.

capability.[9] Following the success of the U.S. program, the Russians eventually followed suit with an IR early-warning satellite system of their own. Thus, both countries depend on space-based IR systems to provide the earliest warning of ICBM and submarine-launched ballistic missile (SLBM) attacks.

The IR systems are not without their problems, however. From the very beginning, false alarms have been a cause for concern, and, indeed, well-publicized, potentially catastrophic incidents resulting from IR system false alarms have occurred. Accordingly, both sides have, from the very early days of the Cold War, maintained networks of long-range early-warning radars to provide warning of ICBM, and later SLBM, attacks. The radar warnings would have come later in the flight of the missiles and would, therefore, have provided less warning time. On the other hand, some of the radar systems were capable of providing additional information about the nature of the attack (e.g., a more accurate raid count, more refined impact point prediction for the incoming warheads) that could have been of use to decisionmakers in selecting an appropriate response. They also provided what became known as "dual phenomenology" (i.e., IR and radar) warning of attack. Because the two types of sensor systems involved different kinds of physical phenomena, it seemed unlikely that both could be subject to the same kinds of false alarms. Thus, requiring dual phenomenology as a prerequisite for an LOW or LUA was intended to provide some measure of assurance that warning of an attack was real. In fact, the Soviets eventually made dual phenomenology a formal prerequisite for launching missiles under attack.[10]

The last piece of the LOW/LUA package is C3. All the pieces have to be wired together in such a way that decisionmakers can get the information that they need to reflect as much as they have to and then make a decision in time to actually launch missiles before they can be destroyed. The problems are technical, organizational, and operational and are, as one would expect, quite severe.

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[9] Richelson, 2012, p. 274.

[10] Blair, 1993, p. 215.

For all these reasons, having to depend on launching missiles under attack has never been a popular solution to the ICBM vulnerability problem. However, it has been on the table as a technical option on both sides for decades and will probably continue to be as long as ICBMs remain vulnerable and policymakers actually care about their potential vulnerability.

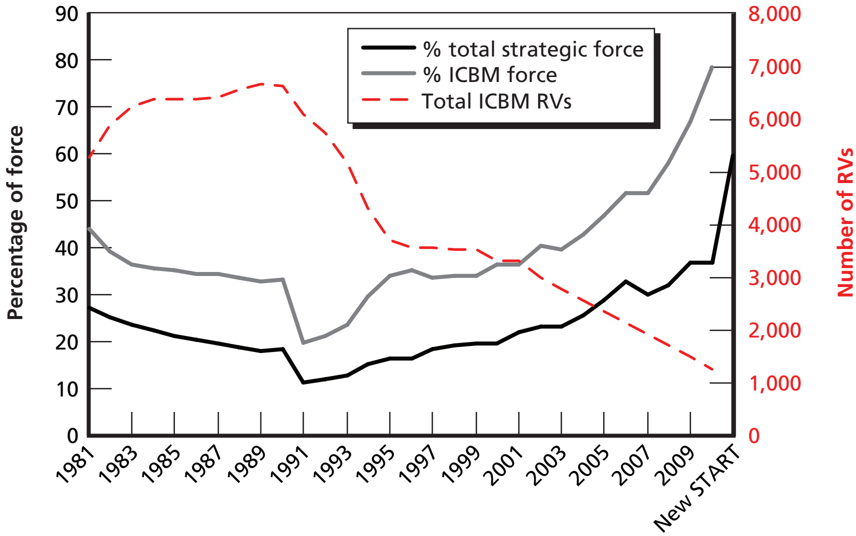
Although the United States has had a technical capability to launch under attack, policy direction has been to posture forces so as not to rely on it. Robert Bell, senior director for defense policy and arms control at the National Security Council, made this explicit in 1997: "Our policy is to confirm that we are under nuclear attack with actual detonations before retaliating."[11]

The Impact of Arms Control

Most important, in the more than two decades since the end of the Cold War, the number of strategic warheads in the hands of the Russians has dropped significantly, as Figure 3.2 depicts. Moreover, no state other than Russia—or the United States itself—has even close to this inventory. Both nations maintain large strategic nuclear forces, but New START marks a change in the old arms control approach in that it is less prescriptive on matters such as force mixes and MIRVing, and more focused on reducing the overall numbers of accountable strategic nuclear weapons. This means that the U.S. and Russian ICBM forces are becoming essentially balanced and strategically offsetting. Even though the United States will likely draw down its ICBM force from its current 450 silos to 420 or fewer (down from over 1,000 silos at the peak of the Cold War), Russia is also reducing its ICBM forces. This, coupled with de-MIRVing of Minuteman, presents the Russians with a less favorable exchange ratio than during the Cold War. Figure 3.2 shows that while Russia has drawn down its forces, the percentage of its force it must expend to attack U.S. ICBM silos has steadily increased, most recently making even larger jumps upward. Although, at the

[11] Bell was correcting some reporting that President Clinton's new Presidential Directive (PDD-60) retained launch under attack. See "Clinton Issues New Guidelines on U.S. Nuclear Weapons Doctrine," *Arms Control Today*, November–December 1997.

Figure 3.2
Percentage of Russian Strategic Nuclear Force Required for 2:1 Attack of U.S. ICBMs, from 1981 to Present



RAND *MG1210-3.2*

height of the Cold War, the Soviet Union would have had to expend less than 20 percent of its forces in an attack, today Russia would have to expend much more than 50 percent. The black and grey curves in Figure 3.2 assume a 2:1 attack on U.S. ICBM silos only (i.e., we did not include the additional missiles needed to simultaneously attack LCCs); we derive inventories for both the United States and Russia from a variety of sources.[12]

Although the Russians retain the potential to destroy most of the U.S. ICBM force with their strategic forces, it now costs them most of their force to do so. Likewise, the silo-based "window of vulnerability" has not been closed, but its destabilizing effects have been mitigated by the threat drawdown. The New START ceiling will reduce numbers even further. Under New START, the United States and Russia will

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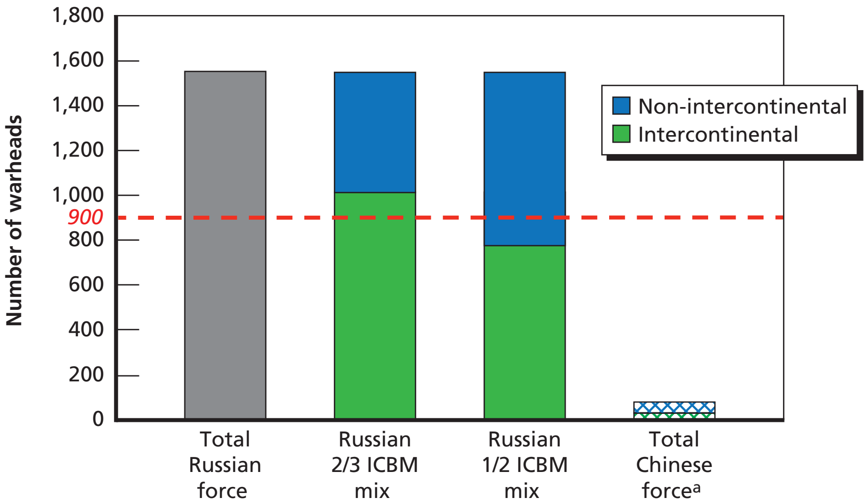
[12] Specifically, we used the following sources: Pavel Podvig, ed., *Russian Strategic Nuclear Forces*, Cambridge, Mass.: MIT Press, 2004; Natural Resources Defense Council, Archive of Nuclear Data Program, undated.

agree to a ceiling of 1,550 warheads. If we now assume a 2:1 attack against U.S. ICBMs on both silos and LCCs, more than 900 RVs are required of an attacker. This is almost 60 percent of the post–New START total. Measuring ICBMs purely against ICBMs, if Russia allotted half of its warhead total to its ICBM force, it would not have enough to commit a 2:1 attack, as seen in Figure 3.3. Russia has historically allocated between one-half and two-thirds of its warhead total to ICBMs. Figure 3.3 also shows just how far off China is in this calculation. China currently fields only a fraction of the number of nuclear weapons that the United States and Russia do under New START, only some of which are mated to ICBMs or other strategic systems.

There are two challenges to the assumptions we use in our calculations: (1) the improving quality of future Russian or Chinese missiles or intelligence, surveillance, and reconnaissance (ISR) systems could

Figure 3.3
Russian and Chinese Strategic Forces



[a] Hans Kristensen and Robert Norris, in "Chinese Nuclear Forces, 2011" (*Bulletin of the Atomic Scientists*, Vol. 67, No. 6, November–December 2011, pp. 81–87), put some bounds on China's nuclear forces. While they do not give an exact number of strategic delivery systems, they indicate that it is very likely significantly less than U.S. or Russian strategic nuclear forces. They also report a currently nonoperational Chinese ballistic missile submarine force.

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convince those actors of the feasibility of a 1:1 attack; and (2) a significant shift in force sizes, for example via U.S. unilateral reductions. In the first case, moving away from a 2:1 attack means the attacker convincing himself that the reliability and accuracy of his systems have improved or that he has a "look" opportunity to retarget what he may have missed in a first barrage. In Figure 3.4, the orange line is a baseline 2:1 attack with 90 percent reliability. The solid red line is a 1:1 attack with the same 90 percent reliability. To push the solid red curve down toward the orange curve requires either moving toward 100 percent reliability—the first dashed red curve—which intersects the baseline case at higher levels of accuracy (assuming a constant yield) or having a "look" opportunity—the second dashed red curve overlying the baseline orange curve—which produces the same effects as 2:1, but with fewer weapons.[13] At high reliability and accuracy, a 1:1 attack is more feasible and halves the number of attacking missiles required. A "look" opportunity also allows an attacker to use fewer missiles, up to, but no lower than, half of the amount required in a 2:1 attack.

Nevertheless, deriving numbers requirements from a 2:1 attack will probably be the most attacker-optimistic assumption for the foreseeable future. High degrees of accuracy—in the less-than-100-m range—requires sophisticated guidance updates or a MaRV (we examine this in more detail in Chapter Four). A high level of reliability is likely only achievable with significant investments in testing and maintenance programs. Even then, confidence in having near-perfect reliability may be infeasible. A "look" opportunity could theoretically be afforded by high-resolution real-time ISR for BDA; however, the attacker has to shoot again before the attacked can launch survivors. Sensing requirements for BDA alone after a nuclear attack are incredibly challenging. Adding quick shooters and linking them in real time to the sensors significantly compounds the challenge.

Because a large effects size can offset inaccuracy (and conversely, a very accurate weapon can offset the blast effects size), these variables

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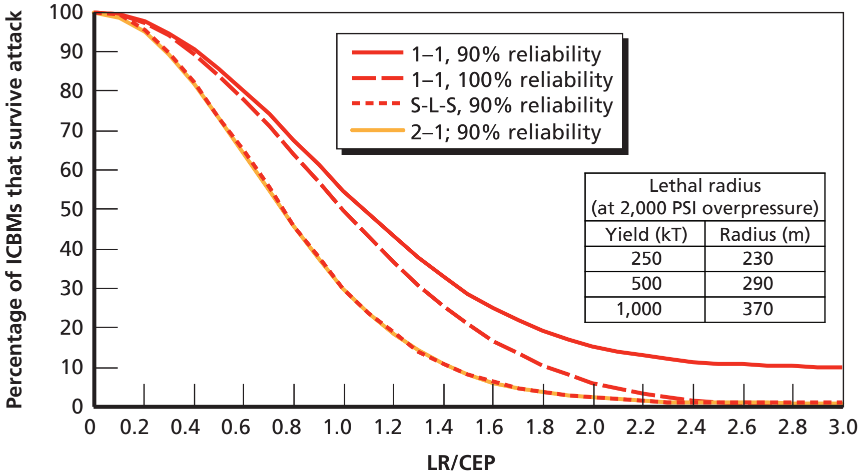
[13] Fewer weapons are required in this case because in no instance is a target being hit or "killed" twice. In the 2:1 scenario, some nonzero fraction of targets will be hit by both attacking missiles.

Figure 3.4
Notional Attacks on U.S. ICBMs



NOTE: PSI = pounds per square inch. 1–1 = one warhead attacks one target. S-L-S = shoot, look, shoot (one uses a second warhead on the targets that survive the first attack). 2–1 = two warheads are assigned to each target at the outset.

RAND *MG1210-3.4*

are treated as a ratio that acts as an overall measure of the weapon's effectiveness. The same outcome may be achieved—that is, fewer attacking missiles may be required—if the United States takes unilateral action to reduce the size of its ICBM force. For example, if the United States were to reduce the number of its ICBM silos to 150, 330 missiles would be required in a 2:1 attack on U.S. ICBMs and their LCCs. That is 20 percent of the New START ceiling, but it is still probably at least three times the current Chinese inventory of strategic nuclear warheads.

A more survivable ICBM is no longer as important as it was during the Cold War. The tolerance for alternatives that cost more or that raise public interface issues[14] may therefore be lower. To be

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[14] *Public interface issues* encompass risks to and from public proximity to the ICBM system and is a term of art used in ICBM literature. See, for example, Barry E. Fridling and John R. Harvey, "On the Wrong Track? An Assessment of MX Rail Garrison Basing," *International Security*, Vol. 13, No. 3, Winter 1988–1989, pp. 113–141, which describes the potential

selected as a viable alternative basing candidate for the next-generation ICBM system, any silo alternative will have to offer benefits that are cost-effective relative to continued silo basing. The bad news is that these assessments will likely be as difficult and contentious as they have been in the past. The good news is that continuing to base in silos is a more comfortable fallback option if acceptable alternatives continue to elude us.

In the next section, we identify alternative approaches to ICBM basing and screen various options. We then assess a particular class of feasible candidates—those based on some mobile concept—against the silo baselines we identify here. All of these concepts have analytic precedent, and many were given serious consideration by U.S. strategic planners during the Cold War. The March 2006 *Report of the Defense Science Board Task Force on Future Strategic Strike Skills* gives a concise history of the U.S. ICBM basing concepts that were funded or programmed.[15]

Options for Basing Alternatives

Options to enhance survivability span a spectrum of mobile and hardened schemes. We identify three categories to characterize this spectrum: hardened (fixed), mobile, or deceptive. Overlays, including missile defenses, possible tactical responses, and hybrid or combination approaches are additional issues to consider for any basing scheme. Table 3.1 provides a summary of these categories and overlays as well as some initial applications and specific examples. To the right of hardening, we list several survivability modes introduced during the Cold War, including attempts to complicate an attack by enforcing a standoff distance between the weapons and the hardened structures or by intro-

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dangers to the public and to MX by the public. Dangers to the public include the routine transportation of explosive propellant and nuclear material; dangers by the public include all security issues such as sabotage, theft, terrorism, etc.

[15] Defense Science Board, Washington, D.C.: Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics.

ducing fratricide problems.[16] The main assumption made about mobile systems is that an attacker could not target these systems directly since he could not know exact locations. That would force him to barrage the entire potential deployment area.[17] The area an attacker can barrage scales with the hardness (e.g., is measured in PSI of overpressure or dynamic pressure) of the targets and the yield, *Y*, of his weapons. In general, for a MIRVed missile, its throw weight (TW) is a constant measure of the barrage potential, regardless of fractionation, *N*. Fractionation details are unimportant for area targets, but fractionation does play a role in the systems that are made up of proliferated, discrete aim points, such as the various MAP systems, also referred to as mobile protective shelter (MPS) systems. In this case, breaking the payload up into as many RVs as possible increases effectiveness and forces the survivable basing system to proliferate shelters, which can be a costly proposition. Moving to overlays, active defenses are sensitive to saturation attacks: If the number of attacking weapons can be reduced, the defense's job becomes easier. Finally, as a tactical response, even LOW and LUA are sensitive to threat size: In a "pin-down" scenario, nuclear weapons with short flight times, say SLBMs, can be repeatedly deto-

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[16] For example, deep underground systems sought to provide standoff by virtue of hundreds to a few thousand feet of overburden. Effects at depth are proportional to the number and yield of the attacking force for a given underground system. A smaller threat could be countered with a smaller, shallower (and therefore less expensive and less technically and operationally risky) underground system. Basing on the south side of mesas was originally proposed to stress the ability of an attacker to detonate weapons near the hardened sites, since a typical ICBM reenters at about 20–24 degrees, which would make it difficult for a ballistic RV to hit a target beneath a 60-degree mesa slope. (However, a MaRV executing a "tuck" maneuver should be able to target south-facing sites.) Finally, the "dense pack" concept proposed to use superhard silos spaced so close together that timing errors in the laydown of the attacking weapons could lead to fratricide (either due to debris from earlier weapons, or due to pre-initiation caused by prompt radiation from nearby detonations), especially if the attacker was forced to use ground bursts to "dig out" the silos due to their extreme hardness.

[17] Excursion threat analyses could examine the potential for the attacker's surveillance systems (either on or off the attacking weapons) to search the deployment areas in real time and to use these data to home in on these mobile systems after the attacking missiles were launched. Although weapon technology is moving in this direction, as evidenced by various classes of smart or even "brilliant" tactical systems, there were never any successful strategic systems developed with this potential (although the B-2 was, at one point, thought to be a good platform with which to hunt for and attack Soviet rail-mobile ICBMs).

Table 3.1
ICBM Basing Classes and Overlays

	Generic Approaches	Specific Applications	Examples (Systems/Programs)
Options	Hardening	• Current or upgraded silos • Superhardened silos • Deep underground basing • Special configurations	• Current silo program • "Dense Pack" • Mesa basing
Options	Mobility	• Ground mobile • Air mobile • Sea mobile	• Road-mobile Minuteman • SICBM • Rail-garrison MX • Cargo aircraft/airship • SUMS
Options	Deception/ concealment	• MAPs • Concealed launch points	• MAPs • Hard Trench
Overlays	Defenses	• BMD	• LoADS
Overlays	Tactical responses	• LUA • LOW	• LUA • LOW
Overlays	Combinations	• Hardening + mobility	• Hardened mobile launcher

NOTE: The taxonomy of ICBM basing is derived from a synthesis of the relevant literature, most notably from the 11 possible basing modes discussed in Gibbons, 1981, and the basing alternatives discussed in Art Hobson, "The ICBM Basing Question," *Science and Global Security*, Vol. 2, 1991, pp. 153–198. SUMS = Small (submarine) Undersea Mobile System. MAP = multiple aim point. BMD = ballistic missile defense. LoADS = Low-Altitude Defense System.

nated above the Minuteman wings so that any in-flight missiles will be subjected to lethal x-ray effects. The hardness of ICBMs in flight, and the throw weight (e.g., number and yield) of the attacking SLBMs determine the effectiveness of this attack scenario.

Decades of exploration and analyses have uncovered many types of basing approaches. Here, we synthesize conclusions over the feasibility of those approaches. As shown in Table 3.2, none of the basing options studied in the past was accepted for a variety of reasons, most notably, cost, land requirements, and, perhaps mostly due to the first two reasons, political feasibility. In other cases, greater scrutiny paid by U.S. scientists to alternative schemes revealed doubts over the claimed increases in survivability due in part to possible counters by an attacker.

Table 3.2
Forty Years of Basing Options

	Description	Features	Advantages	Disadvantages
Fixed	Current silo basing	Retain missiles in current silos	Cheap; familiar	Vulnerable to high-end opponent
	LUA	Launch missiles on attack assessment	Cheap; survivable	False alarms: potential disaster; targeting
	Superhard silos	Less vulnerable	Minimal operational impact	Cost; still vulnerable
	Deep Underground Basing	"Bury" missiles in tunnels or caverns	Probably survivable	Very costly; not responsive
Mobile	Random road mobile	Randomly move on roads	Difficult to target; not dependent on tactical warning; very high price to attack	More costly than silos or garrisons; "public interface;" smaller missiles; potential for operational risk
	Road/off-road/rail garrison	Dash on tactical warning *or* deploy on strategic warning	Less costly than random movement	Tactical warning, quick decision, hardening needed; potential for operational risk
	Carry Hard	Only missile canister itself is hardened	Reduces costs by reducing extent of hardening	Still not cheap
Deception	MPS	Combines mobility, hardening, and deception	Greatly increases cost to attack	Expensive and extensive; deception may fail
	MPS/LoADS	Adds defense	Added defensive layer increases the cost to attack	More expensive and complex
Hybrid	Hard Trench	Mobile missile concealed in hardened trench	Increases cost to attack	Expensive
	SUMS	Missiles carried by small submarines	Does not use United States as "RV sink"	Complex; not cheap; time required to develop

NOTE: The following citations are specific examples relevant to topics in this table. For Super-hard silos: Hobson, 1991; for Deep Underground, random mobile, garrison mobile, MPS, LoADS, Hard Trench, and SUMS: Gibbons, 1981; for Carry Hard: John R. Harvey, *Carry Hard ICBM Basing: A Technical Assessment*, Livermore, Calif.: Lawrence Livermore National Laboratory, 1989.

Because the driving constraints endure, in no case do we believe that these historical results are sensitive enough to technological improvements, force-size reductions, or assumptions over the size of the threat to change these findings. To demonstrate this observation, we next assess the two other basic classes of basing schemes—that is, other than fixed-silo basing—in quantitative detail: (1) mobile either from garrison or continuously mobile, and (2) deceptive. Whereas mobile systems survive by forcing the attacker to blindly barrage the operating area, deceptive schemes work by proliferating the number of aim points an attacker would have to target.

Garrison mobile concepts involve colocating ICBMs on a day-to-day basis and dispersing those missiles on vehicles upon warning. Therefore, in addition to having warning requirements or dependencies, garrison mobile systems require speed, land area, and hardness. We assess these schemes by comparing various measures of speed, land area, and hardness with the baseline case of 900 RVs required to attack current silos at 2:1. The effectiveness of a barrage attack depends on the dispersal area that needs to be covered, A, and the total lethal area the attacking weapons can create, L. Then P_k (or the probability that the barraged area encompasses the mobile system), is

$$P_k = \frac{L}{A}$$

for $L < A$ and $P_k = 1$ otherwise. Area, A, depends on the number, N, and yield, Y, of the weapons:

$$A = C \times N \times Y^{2/3},$$

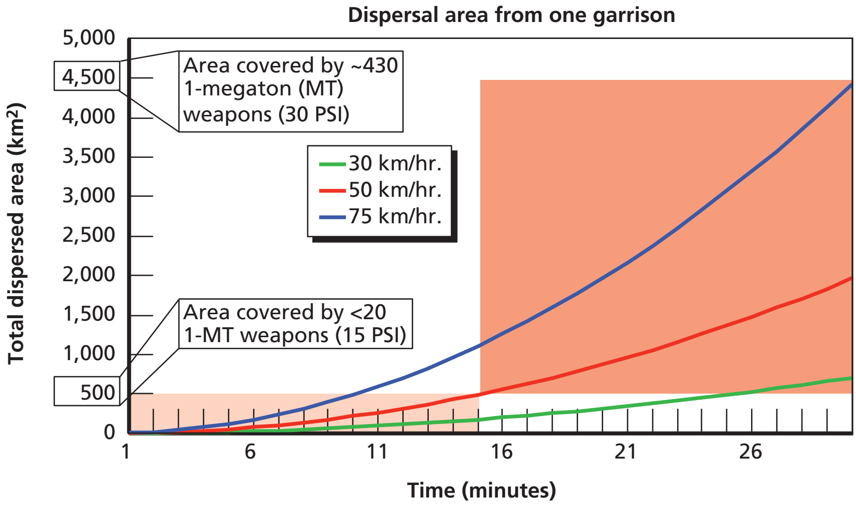
where C is a scale factor determined by the vulnerability of the targets—for example, as measured in PSI of overpressure or dynamic pressure (most unhardened large trucks are quite susceptible to the dynamic pressure created by nuclear weapons). Because the deployment area, A, is limited at least by the area into which the mobile systems can disperse on strategic or tactical warning, the survivability of the mobile ICBMs depends on making the most out of whatever area can be generated. There is a premium on how hard the vehicle can be made to nuclear effects and how quickly it can generate an area the attacker must barrage. For this reason, in Figure 3.5 we look at various hardness levels up to 30 PSI.[18]

The curves in Figure 3.5 show the areas that can be generated around a single garrison with the simplifying assumption that area grows such that

$$A = \pi(V \times t)^2,$$

where V is the average speed (e.g., 50 km/hr.) and t is the time from when dispersion starts from garrison to finish. The small pink rectangle shows the area that can be barraged under various speed and time (translated from warning) assumptions. These curves show that

Figure 3.5
The Garrison-Mobile Concept



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18 Various hardened mobile launcher (HML) concepts were investigated for SICBM development in the 1980s. We note that hardened vehicles needed to park and "hunker down" to achieve the stated hardness levels and that, while they were moving, they were relatively soft. Time to disperse from a garrison had to include the warning and command decision time delay, missile flight time, and the time to achieve the hardened state.

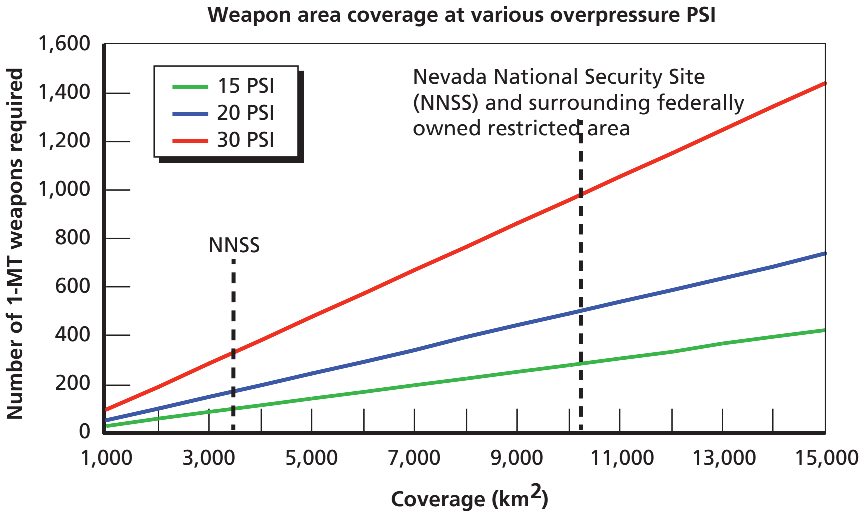
system survivability is dependent on response time, average speed, and hardness. We can design the system to achieve a prescribed speed and hardness and response time, but the adversary can also design an attack to reduce our dispersal time to 10–15 minutes, as could be the case with forward-launched SLBMs). Confidently achievable survivability levels will be highly uncertain, given real-world operational challenges to achieve the desired speed (for example, 50 km/hr. in all weather and road or off-road conditions) and hardness (30 PSI is notably challenging, and may require prepared pads on which to hunker down, which starts to turn the mobile system into an MPS system—see below). Figure 3.5 shows that with 30 minutes of warning, which—as we noted earlier—corresponds to only the earliest tactical warning, superhard mobile launchers could generate about 4,500 km^2 of area, or enough to require approximately 430 1-MT nuclear missiles in a barrage attack to destroy (see area-to-weapons required calculus below). With 15 minutes of tactical warning, the dispersal area could be barraged by fewer than 20 weapons, which means that even one close-in ballistic missile submarine can be a big threat to the entire ICBM force. This implies that, to achieve survivability levels at or beyond current silos, either strategic warning or multiple garrisons are required.

A continuously mobile scheme would make the system more robust against short-warning attacks compared with garrison mobile, but potentially at the cost of greater public interface, safety, and security concerns. Even these "continuously mobile" systems could not be, for practical reasons, in continuous random movement over the entire theoretically achievable deployment area all the time. Their actual operating area and move frequency would probably be situationally dependent, meaning that the exchange ratio at one threat extreme could be as low as one attacking RV per transporter erector launcher (TEL) destroyed (assuming they were not so densely deployed that several could be destroyed by a single weapon) to several tens of weapons per TEL destroyed in a blind barrage. To derive land requirements for a continuously mobile system to impose a cost to attack as high as current silos, we calculated the number of 1-MT weapons required to barrage a range of areas with various hardness assumptions of the mobile unit. In these calculations, we assume a hexagonal weapons pattern with a weapon aim point at the center of each hexagon to ensure that the entire area has at least the overpressure stated. The area of each hexagon is given by

$$A = \frac{3\sqrt{3}}{2}t^2.$$

The dimension of the hexagon, *t*, is the blast radius for a 1-MT weapon with the stated overpressure. We assume optimal height of burst to achieve the maximum blast radius of each of the stated overpressures. For a pattern of accurate weapons, the overpressure reaches the stated value at the vertices of each hexagon. All other points in the grid pattern have a higher overpressure. The total number of weapons per area is then the total area divided by the number of 1-MT hexagons (it actually should be the greatest integer function applied to that number); however, Figure 3.6 depicts the general relationship between barrage area and number of warheads.

Figure 3.6
The Continuous Mobile Concept



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There are real land requirements and possible constraints involved with a mobile ICBM system. To put these in perspective for illustrative purposes, Figure 3.6 plots two relevant areas on the x-axis based on land availability in the Nevada desert, and Figure 3.7 shows these areas in even greater relief. To achieve survivability beyond the current silo-based force, Figure 3.6 shows that 10,000 km^2 seems to be the land area requirement starting point (which corresponds to just over the 900-RV requirement for a 2:1 attack on Minuteman silos). This is a large area, but, as shown below, the number alone does not communicate the other considerations and restrictions associated with mobile ICBM basing. To be cost-effective and to mitigate some of the operational risk, mobile systems have historically been analyzed over flat terrain and in locations with very little inclement weather. Snow, for example, could complicate the operation of mobile TELs. This probably restricts use to warm, flat areas of CONUS. To gain traction politically and publicly, ICBMs might have to be based away from populated areas to reduce the threat of potential fallout in case of a nuclear attack on those ICBMs or for other public interface and security concerns. Remaining area candidates may be an over-constrained set; we choose to overlay 10,000 km^2 around the Nevada Test Range because it may be one of the few areas that could support mobile operations given the potential constraints we outline. Lastly, mobile systems that depend on roads or rail lines visible via overhead imagery effectively shrink the target area and could significantly lower the number of missiles required to barrage mobile systems. Short of paving over a vast patch of southwest Nevada, this may force mobile systems to include off-road capability, a daunting requirement for a truck carrying at least a 35,000-lb. missile. At least, however, rough roads could be built more cheaply than hard-paved roads.

Historically, land limitations, mobile system hardness limits, and operational risks all tended to transform mobile system concepts into various sorts of deceptive MPS concepts. These deceptive schemes could be made much harder than an HML (e.g., 600–1000 PSI versus 15–30 PSI), thus reducing deployment area requirements. The current silo system with one missile in each silo is a "trivial" MPS system with

Figure 3.7
Nevada Test Range and Surrounding Areas

Land use:

- Wildlife Reserve
- Nellis Air Force Range
- NNSS
- Area 51

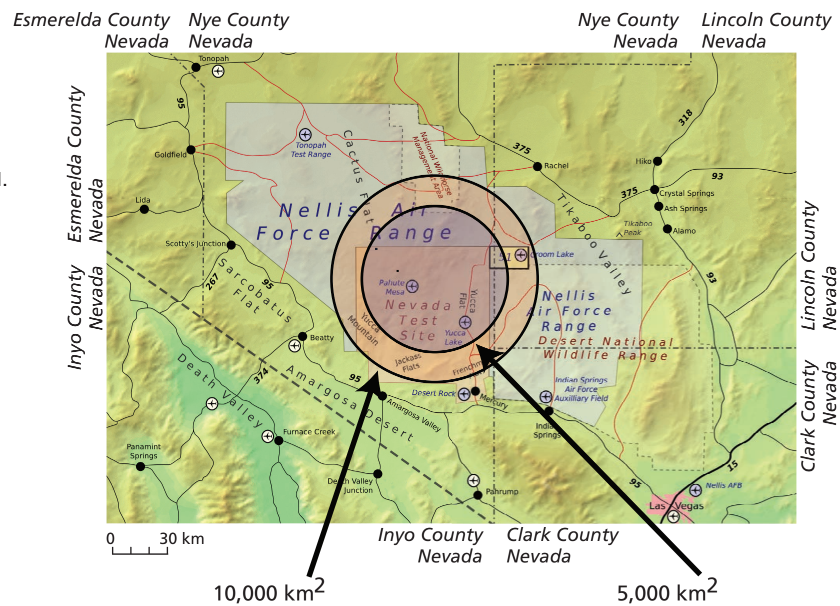
Sources differ as to whether the "Area 51" box is part of the Nevada National Security Site, or is under joint NNSS/Air Force control.

Legend:

- *Military airfield*
- Civilian airfield
- City
- Town or village
- Public road
- Private road
- State boundary
- County boundary

Location:

Location of main map



SOURCE: Finlay McWalter, "Federal Lands in Southern Nevada," Wikimedia Commons, last updated September 9, 2005. Used in accordance with Creative Commons licensing guidelines.

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one shelter per missile.[19] To keep the number of aim points that the attacker would have to destroy high enough that a desired survivability level could be achieved against the prescribed threat requires that several shelters be deployed for each ICBM; for example, the Peacekeeper MPS system typically calculated survivability with 10–20 shelters per missile. The MPS operation became a complex "shell game," in which missiles were moved between shelters.[20]

In general, deceptive schemes work by proliferating aim points for an attacker, thereby raising the cost to attack. Because additional aim points would have to convince an attacker that they are in fact "true" aim points, the added cost imposed depends on the number of "false" aim points and the quality of the deception. A deceptive concept is based on its underlying basing scheme. For fixed-silo basing, the deception would entail the proliferation of silos (or at least points that look like silos to a potential attacker); for mobile schemes, mobile TELs or HMLs would be proliferated. For this reason, we limit our discussion of basing alternatives to the fundamental underlying classes: fixed and mobile.

Conclusion

Today, only Russia is capable of attacking U.S. ICBMs. Even in that situation, however, an attack would require a substantial fraction of Russian RVs under the New START ceiling. Basing ICBMs in current silos is survivable against all other potential nuclear adversaries for the foreseeable future. In particular, China is now incapable of such an

[19] With the drawdown of Minuteman, the potential exists to keep the emptied silos in a "warm" or ready state, which would offer operational advantages in keeping alert rates high during maintenance activities, and might also turn the silos into a modest MPS system (more silos than missiles).

[20] This scheme presented arms control issues. Systems that depend on hiding missiles are at odds with the transparency needed for treaty verification. Various design schemes were proposed—for example, periodically opening "viewing ports" in the shelters to make the contents visible. However, verification issues were secondary to other concerns that we have outlined, most notably, public acceptance, cost, and operational risks.

attack. How the threat changes in the future in terms of either quality or quantity (quantity, of course, is relative to the total number of ICBM silos the United States fields) could change these conclusions.

Many alternative basing schemes have been proposed, analyzed, and even developed over the past four decades, but no scheme has replaced fixed silos because cost and land constraints have not eased and are likely to get even more rigid in the future. In particular, although land-mobile basing alternatives can theoretically achieve higher levels of survivability, they require significant capital investments and land areas with specific characteristics. Moreover, mobile schemes that are garrisoned day-to-day rely on strategic or at least tactical warning.

For the foreseeable future, cost and survivability assessments will likely limit basing options to existing missile silos and infrastructure. The bounds on costs that we detail in Chapter Five indicate that silo basing will likely continue to be cheaper than mobile options given the current baseline of survivability in terms of cost to an attacker. Options can and should explore the possibility of maintaining unoccupied silos in a "warm state"—that is, maintaining the silo and the associated LCC in a state of readiness without the missile—as the force is reduced or as missile size changes allow. While retaining unfilled silos will not offer any cost savings, they do offer a nondeployed "hedge" in the language of New START. Missile options should therefore be compatible with silo basing. We do note that smaller missiles offer potentially more future basing options than do larger missiles, as it is generally less costly to make a small missile mobile. We also note that, at least historically speaking, basing in existing silos, or modifying existing silos, is not a severe constraint: While it imposes no lower bound on missile size, even at the upper end, the 190,000-lb. Peacekeeper could be cold-launched from slightly modified Minuteman silos.

Although the calculus with respect to Russia drives our survivability and basing analysis, other actors and potential adversaries may influence what the United States thinks it wants out of its ICBMs. To that end, alternative basing modes could be extended to include launches from locations in CONUS that would minimize the risk of overflying Russia and China while distinguishing launches from sites historically associated with strategic deterrence. This could improve the perceived credibility among emerging nuclear states or nuclear-armed regional adversaries that U.S. ICBMs might play a role in certain situations.

In the next chapter, we examine options for adding capabilities to increase or change the set of targets that ICBMs hold at risk. Included in these analyses is an assessment of launches from extreme CONUS locations. We illustrate the potential of such launches to mitigate overflight risk by charting trajectories from Vandenberg and Cape Canaveral.[21]

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[21] Both Vandenberg and Cape Canaveral have been used for ICBM test launches. Minuteman III tests still take place from silos at Vandenberg. Silos at Cape Canaveral have been deactivated or buried; the last ICBM test there was the final Minuteman III research and development launch on December 14, 1970. See U.S. Air Force, History Milestones, 1970–1989, undated.

CHAPTER FOUR

Effectiveness and Lethality

To hold a target at risk, ICBMs must first be able to deliver a payload to that target, then produce the intended effects to destroy or sufficiently damage it. Ever since the original Minuteman was developed and fielded as a three-stage, solid rocket missile in the early 1960s, the first part of this sequence—range—has been determined largely by a range-payload equation given by the specific impulse of solid rocket fuels and the dry weight of the missile. A desired payload can be tracked through this equation to give range and missile size trade-offs. ICBM effects have always been nuclear, and, although the large effect areas can offset accuracy uncertainties, the United States has sought to improve the accuracy of its systems over the years.

In this chapter, we discuss the future of missile propulsion. We then examine boost, reentry, and payload alternatives according to the options framework we outlined in Chapter Two. In the first section, we reinforce the benefits of solid rocket propulsion for bounds on range and the ability to conduct plane changes or "fly south." In the section on MaRVs, we discuss the potential for current development programs to fundamentally change underlying reentry technologies and therefore the assumptions on ICBM range-payload trade-offs. We then examine a nonnuclear, or conventional, ICBM. Any of these capabilities comes with a price. For example, one relevant plane change that we discuss requires double the fuel mass, and hence double the missile size. A conventional ICBM could require significant research, development, test and evaluation (RDT&E) and procurement costs.

ICBM Propulsion

ICBM propulsion is an important consideration because the choice of propulsion not only determines the range and payload of a missile of a given size but can also shape the operational concept of the ICBM force. Starting with the development of Germany's V1 and V2 rockets, long-range rocket propulsion systems developed rapidly in the early decades of the Cold War from cryogenic liquid propellants to storable liquid propellants to solid rocket motors in the 1960s. In this section, we describe how advances in propulsion technology may offer future alternatives and options. We first review the basic propulsion requirements of ICBM systems and the related engineering trades, then detail the performance range of available propulsion system technologies and discuss the areas of current research in advancing propulsion technology. We find the that significant propulsion technology advances over current SRM systems are unlikely and that the well-understood reliability of today's SRMs likely make them the most cost-effective option for future ICBMs.

ICBMs must put payloads into ballistic trajectories to achieve ranges of 5,500 km or greater.[1] Minuteman III was designed to carry three nuclear warheads, and an Air Force LGM-30G Minuteman III Factsheet states that the system is almost 80,000 lb. at launch and has a range of over 6,000 mi. (9,600 km).[2] Although the relationship is by no means linear, one can trade a decrease in payload for an increase in range, or vice versa. Therefore, de-MIRVing the Minuteman III to a single warhead increases its range.

The key performance characteristics of ICBM propulsion, other than size, are specific impulse and dry mass. Specific impulse is the amount of rocket thrust per unit mass of fuel, analogous to the mileage delivered by a car per gallon of gas, and it largely reflects the selection of chemical propellants, fuel, and oxidizer. *Dry mass* refers to the weight of everything except the propellants. The primary components of dry mass are the tankage and engine mass for liquid rockets and casing

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1 All STARTs define ICBM range as 5,500 km.

2 See, for example, U.S. Air Force, "LGM-30G Minuteman III," Factsheet, July 26, 2010.

and nozzle mass for solid rockets. The higher the specific impulse and the lower the dry mass, the greater the payload or range of a missile of a given size.

The specific impulse of a propulsion system is primarily determined by the choice of propellants, a combination of a fuel, and an oxidizer. Accounting for the cancellation of units of thrust over mass, specific impulse is measured in seconds, the higher the better. Rocket propellants are broadly classified as liquid, solid, or hybrid, which is typically a solid fuel with a liquid oxidizer.

Table 4.1 shows that liquid propellants, especially cryogenics, are much more efficient per pound of propellant than solid propellants. Liquid rocket engines are also more controllable than SRMs. They can be throttled, shut off, and restarted. However, they are correspondingly

Table 4.1
Specific Impulse of Various Rocket Propellants

Propellant Class (Specific Type)	**Specific Impulse (seconds)**
Liquid, cryogenic	
Liquid hydrogen and oxygen (LH_2 and LOX)	350–450
Hydrocarbon fuel and liquid oxygen (RP-1 and LOX)	260–320
Liquid, storable	
Unsymmetrical di-methyl hydrazine and nitrogen tetroxide (UDMH and N_2O_4)	200–320
Hybrid	
Rubber and liquid oxygen (HTPB and LOX)	250–320
Solid	
Carboxyl-terminated polybutadiene (CTPB)	250–290
Hydroxy-terminated polybutadiene (HTPB)	250–290

NOTE: These specific impulse values are representative of those found in George P. Sutton, *Rocket Propulsion Elements: An Introduction to the Engineering of Rockets,* 6th ed., New York: John Wiley & Sons, 1992; and Wiley J. Larson and James R. Wertz, eds., *Space Mission Analysis and Design*, 2nd ed., Hawthorne, Calif.: Microcosm Inc., 1992, including sea level to vacuum numbers.

more complicated and more expensive and have greater dry mass than SRMs. Solid propellants may not be as efficient as liquids, but they have a number of advantages: greater total thrust for similarly sized systems, more storable for extended periods of time with much faster launch readiness times, and arguably greater reliability and safety under military operating conditions. Reliability and safety are highly dependent on the specific system design, regardless of whether the propellant is liquid or solid, as well as operational procedures. Hybrid rockets have a combination of liquid and solid propellant traits, and therefore share a mix of their characteristics. Because hybrid propellants typically use liquid oxygen, their storability and day-to-day readiness is limited.

Historically, the Titan II ICBM used storable liquid propellants in order to achieve greater performance for delivering nuclear weapons over great distances. As mentioned above, relying on liquid propellants came at a cost. The considerable difficulties and safety issues in handling liquids took time, equipment, and even lives.[3] With the development of smaller nuclear warheads and improved solid propellants, the storability and launch readiness advantages of SRMs have won out over liquid rockets. The last three ICBMs developed, Minuteman, Peacekeeper, and SICBM, have all been based on solid propellants for these reasons,[4] and we do not expect that this will change for future U.S. ICBMs since SRMs now have a long-established history of meeting ICBM performance requirements. Moreover, a change in operational concept would be required to consider the use of alternative fuels. In particular, time and manpower to fuel liquid systems would have to be reincorporated into ICBM launch procedures.

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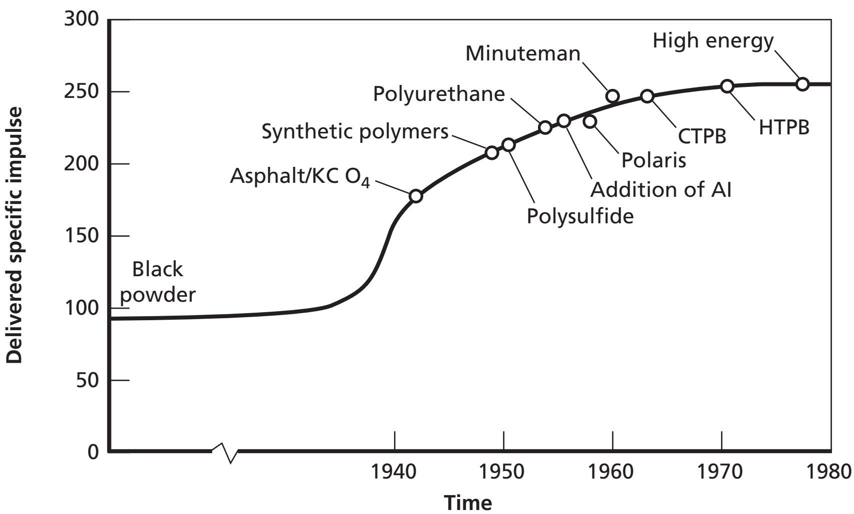
[3] In *The Secret of Apollo: Systems Management in American and European Space Programs* (Baltimore, Md.: Johns Hopkins University Press, 2002), Stephen B. Johnson describes "dangerous liquid-propellant loading operations that destroyed launch pads and killed workers." Jacob Neufield, in *Ballistic Missiles in the United States Air Force 1945–1960*, Washington, D.C.: Office of Air Force History, United States Air Force, 1989, details the dangers: Liquid propellant loading required "nearly surgical cleanliness to prevent contamination. Even a minute amount might cause an explosion."

[4] W. S. Kennedy, S. M. Kovacic, E. C. Rea, and T. C. Lin, "Solid Rocket Motor Development for Land-Based Intercontinental Ballistic Missiles," *Journal of Spacecraft and Rockets*, Vol. 36, No. 6, November–December 1999, pp. 890–901.

Solid rocket propellant technology is a relatively mature field. Figure 4.1 shows how specific impulse improvement has slowed since the early years of SRM development. Current goals for ongoing research in SRM propellant that meet other current design requirements, such as manufacturability and safety, are to exceed 260 seconds at sea level. Current solid rocket propellant research focuses primarily on improving other aspects of SRMs while maintaining current performance. These include manufacturing reliability and cost, the environmental impacts of SRM propellant manufacturing, exhaust products, decommissioning, and operational safety through reduction of the explosive hazard.[5]

Figure 4.1
Solid Rocket Propellants over Time



SOURCE: Philip D. Umholtz, "The History of Solid Rocket Propulsion at Aerojet," presented at the 35th American Institute of Aeronautics and Astronautics (AIAA)/American Society of Mechanical Engineers (ASME)/Society of Automotive Engineers (SAE)/American Society for Engineering Education (ASEE) Joint Propulsion Conference and Exhibit, AIAA-99-2729, June 24, 1999, p. 15.
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5 Alain Davenas, "Development of Modern Solid Propellants," *Journal of Propulsion and Power*, Vol. 19, No. 6, November–December 2003, pp. 1108–1128.

Other approaches to improving SRM performance focus on reducing the dry mass of the system. Improved SRM cases made of more-advanced composites allow for higher pressures, which can improve specific impulse, or reduced casing mass, which can be exchanged directly for payload increases. Similarly, exhaust throats and nozzles made of heavy metal components, which must survive the extremely hot and corrosive elements of SRM exhaust, can be replaced by advanced carbon-carbon composite throats and extendible nozzle exit cones, such as on the Peacekeeper and in continuing research.[6] However, a typical SRM is 95 percent propellant by mass. Even an impressive 20 percent reduction in dry mass, however, only translates to 1 percent of total system mass.

Lastly, significant investments have been made in monitoring the reliability and aging of current SRMs.[7] The primary method of assessing manufacturing reliability and aging surveillance is destructive testing, which is effective but expensive.[8] With established aging reliability databases, along with SRM environmental monitoring and modeling and simulation (M&S), we have confidence in the reliability of today's SRM-based ICBMs. Using newer, advanced solid propellant mixtures for ICBMs would require the reestablishment of such databases. Continuing M&S advances will likely reduce the number of required destructive tests necessary to achieve the same level of confidence. Nonetheless, the costs of achieving the level of confidence that

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6 Kennedy et al., 1999; Daniele Bianchi, Francesco Nasuti, and Marcello Onofri, "Thermochemical Erosion Analysis for Graphite/Carbon–Carbon Rocket Nozzles," *Journal of Propulsion and Power*, Vol. 27, No. 1, January–February 2011, pp. 197–205.

7 Eugene F. Lund, "Minuteman Long Range Service Life Analysis Overview," presentation at the AIAA/SAE 12th Propulsion Conference, Palo Alto, Calif., AIAA 76-716, July 26–29, 1976; R. Scott Hyde, "A Solid Rocket Motor Manufacturer's View of Sensors and Aging Surveillance," presentation at the 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Salt Lake City, Utah, AIAA 2001-3285, July 8–11, 2001.

8 There may be ways to supplement traditional engineering risk assessments with devices that can quickly obtain and relay information about whether a Minuteman III missile failed during boost (or additionally during the post-boost warhead deployment). Such a "report-back" monitoring system could alert operators that the launched missile is unlikely to reach its target—perhaps useful for BDA—but would not account for systemic issues or provide information on how to address failures.

has come from decades of testing and hundreds of Minuteman III SRMs would be significant.

Solid rocket motors are, and will very likely continue to be, the preferred propulsion system for ICBMs due to their ability to maintain a high state of launch readiness. Because solid rocket technology is a mature field, improvements in SRM performance are anticipated to be evolutionary rather than revolutionary over the coming decades. Limited specific impulse improvements due to advanced propellants are possible, but they come at the cost of reestablishing confidence in the aging properties of the new ICBM SRMs and their reliability. Structural improvements that reduce the dry mass of the SRM would likely come with less hidden cost but are limited by the law of diminishing returns given the small fraction of the dry mass on today's SRMs. An AoA should focus on using established SRM technology with an established knowledge base using a traditional size-range-payload trade-off to meet requirements. Any alternatives premised on improved propulsion technology must include the costs of replacing the established knowledge base in addition to RDT&E and production costs. If future ICBM requirements drive fundamental changes in payload delivery or ICBM operational and basing constructs discussed elsewhere in this report, then new ICBM system designs will depart from today's force and may affect the relative cost of introducing new propulsion technologies.

ICBM Boost Characteristics

We next examine range, flight paths that may trigger Russian or Chinese warning systems, and we look at alternative launch and reentry concepts. The point is to characterize current and potential future ICBM capabilities for boost and reentry while drawing bounds for feasibility and highlighting potential cost drivers or physical constraints. In our options framework, *standard boost* refers to ballistic shortest path great-circle trajectories. Anything other than this we call *non-standard*. For example, avoiding overflight of Russia and China in targeting particular countries from current silos would require a ballistic plane change or a southern launch.

Avoiding Overflight of Russia and China

Because the new security environment includes emerging nuclear states, holding targets within these states at risk while not triggering Russian or Chinese early warning or other launch detection systems is a concern. Triggering those countries' radars or early-warning systems may have little to do with actual overflight because these systems have footprints larger than their geographical space.[9] Nevertheless, we begin by examining overflight as a starting point.

One proposed solution for avoiding overflight is the ability to conduct midcourse plane changes. Another is referred to as a *southern launch*, which specifically refers to a launch that does not minimize geodesic distance and instead goes "the long way around." Since both the United States and most foreseeable targets are in the Northern Hemisphere, these launches actually constitute trajectories over the Southern Hemisphere. Southern launches significantly increase the change in velocity, or Δv, which is required because of the increased distance and which therefore increases missile size and cost. However, as we demonstrate, the relationship between Δv and distance is not linear.

Plane Changes

Although the ability to conduct plane changes might allow an ICBM to avoid some overflight issues, it raises others. To Russia or China, knowing that U.S. ICBMs could change flight paths midcourse would turn any launch into a risky launch. A plane-changing U.S. ICBM force could be destabilizing, since the Russians or Chinese might perceive any launch as unpredictable. The Soviet Fractional Bombardment

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9 David Hoffman ("Cold-War Doctrines Refuse to Die," *Washington Post*, March 15, 1998) chronicles the "Black Brant scare" of 1995 in which a research sounding rocket launched from Norway triggered Russian early-warning radars. Hoffman describes a tense situation that led to "a heightened level of alert throughout the Russian strategic forces . . . and marked the first time a Russian leader had to use his nuclear briefcase in a real alert."

System (FOBS)[10] provides a historical precedent to the types of issues that could arise. FOBS was, and continues to be widely regarded as, destabilizing.[11] In 1967, the Outer Space Treaty banned nuclear weapons in earth orbit,[12] but the Soviets continued to test FOBS without live warheads. Twelve years later, in 1979, Strategic Arms Limitation Talks (SALT) II again prohibited the fielding of systems capable of placing weapons of mass destruction (WMD) in partial earth orbit, and FOBS was gradually phased out. While we acknowledge that plane change would very likely raise similar issues and therefore impose political costs, in this section we focus on the engineering costs of conducting plane changes and demonstrate how even from the technological perspective, plane-change capabilities require enormous resources.

Technically, conducting any significant plane changes requires a large amount of additional thrust and therefore requires a larger missile. We looked at two possible plane-change options, both of which assume that the incoming and outgoing flight path angles are equal and that the height corresponds to a minimum energy launch. The two options correspond to a minimum angle plane change and a plane change at apogee. While the true optimization is unsolved here, numerically we examine plane changes both at apogee and at minimum angles.

In the first of two relevant examples, we note that launches from Minot to some areas in the Middle East region would overfly Russia. Avoiding this overflight could require a plane change over the Black Sea of about 25 degrees or greater. This plane change is visualized in Figure 4.2.

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10 FOBS was a Soviet ICBM program from the 1960s that would launch warheads and their RVs into a low-earth orbit and then de-orbit them to attack. Because the system put the warheads into orbit, FOBS had no range limit and would not reveal the intended target. Putting the RV into orbit also allowed FOBS to avoid U.S. early-warning systems (until the United States later developed satellites to detect FOBS attacks).

11 See, for example, Barry M. Blechman, *Preventing Nuclear War*, Bloomington, Ind.: Indiana University Press, 1985.

12 See Article IV of the Outer Space Treaty (U.S. Department of State, *Treaty on Principles Governing the Activities of Statesin the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies*, 1967).

Figure 4.2
Illustrative Minimum Angle Plane Change to Avoid Overflight of Russia

RAND *MG1210-4.2*

Similarly, minimal great-circle routes from Minot to some Asian regions could intersect both China and Russia. Depending on the target, in order to avoid overflight of China, a plane change of at least 10–15 degrees over the Golden Horn Bay may be required, although this route would still overfly Russia. To substantially avoid overflight of Russia, an increased plane change of about 20–25 degrees over the southern tip of Kamchatka Krai may be required, again depending on the target. These two plane-change options are visualized in Figure 4.3. To completely avoid overflight of Russia would require an even greater degree of plane change.

To get an idea of the additional imposed costs of these plane changes, we explicitly calculate the additional rocket mass required to increase coverage of the Middle East region while using plane change to avoid overflight of Russia. Plane change at apogee to some targets could increase the total ground track by 500 nm or more in addition to requiring a plane-change angle of 35–40 degrees. The increase in distance translates to only a small increase in Δv requirement, 1.4 percent; however, the additional Δv required to perform the plane change corresponds to a Δv increase of 21–23 percent. In total, the ICBM would need to have a 22- to 24-percent increase in Δv capability.[13] Based on the standard rocket equation analysis[14] and assuming a specific impulse of 250 seconds, this Δv requirement leads to a need for a 100-percent increase in rocket mass, i.e. twice the size. This plane change and the resulting ground track are shown in Figure 4.4.

As a starting point, even minimal relevant plane changes or divert capabilities add significant costs. Moreover, such launches could, in effect, make any launch a risky one. Russia and China would need to be convinced that a launch trajectory poses no threat of diverting to sensitive targets on their own soil. Such a guarantee may be impossible given how much we know—or really how much we may not know—of their warning systems or their ability to withstand an attack. Uncertainty over how Russia or China might react to these launches adds to the risk.

Southern Launches

Another possible solution to avoid overflight is to fly "the long way around," also referred to as a *southern launch*. These launches require

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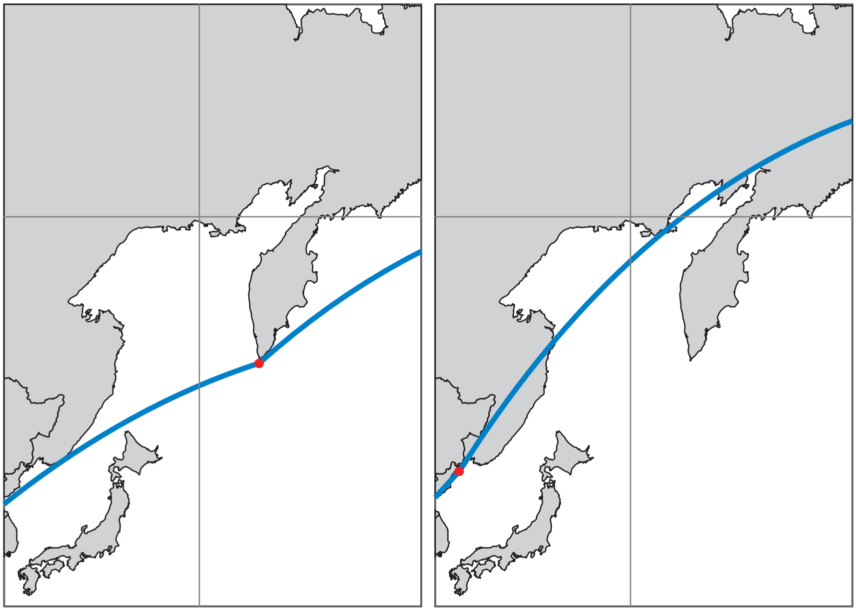
[13] Calculations were done assuming a nonrotating earth. This assumption leads to ground tracks that correspond to the great-circle route. In addition, no Δv advantage or disadvantage was given based on launch direction due to the earth's rotation.

[14] See, for example, Philip Hill and Carl Peterson, *Mechanics and Thermodynamics of Propulsion*, 2nd ed., Boston, Mass.: Addison-Wesley, 1992.

Figure 4.3
Illustrative Minimum Angle Plane Change to Minimize Overflight of Russia and China



RAND *MG1210-4.3*

additional Δv because of the increased ground distance; however, the relationship between ground track distance and Δv requirement is nonlinear. Based on Δv calculations for minimum energy launches, and assuming that all southern launches require a Δv sufficient to put the missile in a low-earth circular orbit, we can compare the difference between northern launches and southern launches. Figure 4.5 shows this comparison in terms of the launch velocity required to reach a target at various ranges for both northern launches and southern launches. The two launch velocities can be applied to the standard rocket equation, assuming a specific impulse of 250 seconds, to compute the mass ratio between a minimum-sized rocket for a northern launch compared to a rocket for a southern launch. For example, for a target 6,100 nm downrange, an increase in rocket mass of 23.5 percent is required to perform a southern launch.

Figure 4.4
Apogee Plane Change to Avoid Overflight of Russia

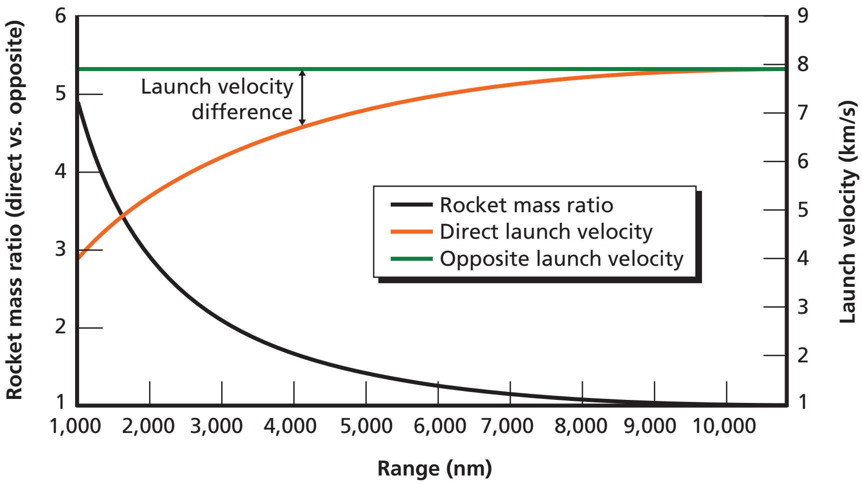
RAND *MG1210-4.4*

As in the case with plane changes, the southern launch replaces one type of risk with another as it seeks to mitigate overflight, but it may present early warning and detection challenges to Russia or China. While the southern launch may again bring to the fore some of the issues raised by FOBS, no warheads would be maintained in orbit, unlike with FOBS.

Alternative Launch Locations

Overflight issues so far have been discussed in the context of launches from existing Minuteman III wings (specifically, calculations use Minot as the starting point), with a proposed solution for avoiding overflight by either a plane change or a southern launch. Another possible solution is to consider alternative basing locations. This is almost an aside to the discussion of basing alternatives in Chapter Two; however, the

Figure 4.5
Launch Velocity Difference Between Northern and Southern Launches and Corresponding Rocket Mass Ratio



RAND *MG1210-4.5*

United States does maintain silos at two "extreme" CONUS locations, Vandenberg and Cape Canaveral, which could be used in situations where overflight is sought to be minimized or avoided. While Minot, Malmstrom, and Warren all provide similar great-circle trajectories—meaning that no one base provides significantly different or improved trajectories than another—if ICBMs could be launched from substantially different locations, such as Vandenberg or Cape Canaveral, different trajectories, both northern and southern, are possible.

If we include Vandenberg and Cape Canaveral as possible launch points in addition to the three current wing locations, we find that only Cape Canaveral offers a northern launch option that can broaden ICBM reach into Middle Eastern regions while avoiding overflight of Russia; southern launches from all launch locations, however, can avoid overflight of Russia while broadening reach. We additionally find that a southern launch from Cape Canaveral avoids overflight of all countries except some in Central America. Southern launches from the other four basing locations avoid overflight of all countries except the Arabian Peninsula and, in some cases, Mexico.

For regions that border China to the east, most all northern launches will overfly some sensitive areas. There are some northern launches from Vandenberg that could avoid overflight of Russia and China completely, depending on the target.

The risks of triggering early-warning alert systems and the concerns about southern launches that we have outlined above remain issues for flying out of any CONUS location, including Vandenberg and Cape Canaveral. If Russian or Chinese radars could distinguish between launches from current wings and more extreme CONUS basing, perhaps these risks could be somewhat mitigated. Systems other than ICBMs may be better suited for circumstances when overflight or risk of triggering warning systems is of significant concern and outweighs the benefit of the ICBM's readiness and 30-minute flight time.

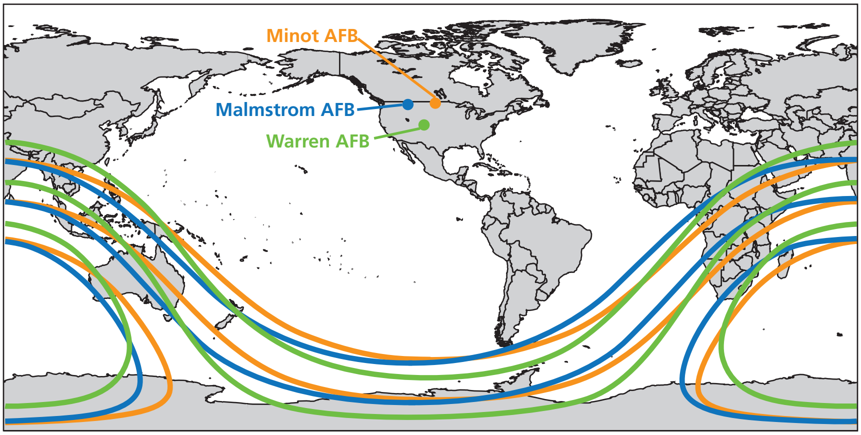
Geographical Coverage of the Current Minuteman III ICBM Force

The total world coverage of an ICBM force is the union of the areas within range of each basing location. Current basing at Minot, Malmstrom, and Warren provide very similar coverage area due to their relatively close proximity. By de-MIRVing Minuteman III, current ICBM ranges are likely to be sufficient for worldwide reach from any of the current three wings. Assuming a range of 6,500 nm, the current ICBM basing can target almost any place in the world, except Southeast Asia, Oceania, Southern Africa, India, and the Arabian Peninsula. However, at a range of 7,500 nm, the area not within range of current ICBM bases is drastically reduced to only parts of Southeast Asia and Oceania, as well as Southern Africa. At 8,500 nm, the entire world is within range of current ICBM basing except for a portion of Madagascar. These ranges are shown graphically for 6,500 nm, 7,500 nm, and 8,500 nm in Figure 4.6.

Geographical Coverage with Expanded Basing

Expanding basing to southern launch locations such as Vandenberg and Cape Canaveral does not provide any increased coverage of Northern Hemisphere targets. In fact, these additional basing locations only provide additional coverage of Africa, Southeast Asia, and Oceania. Because of this, adding basing locations on the southern coasts of the

Figure 4.6
Range of an ICBM from Current Missile Bases



RAND *MG1210-4.6*

United States does not increase the coverage in a meaningful way. The additional coverage from both Vandenberg and Cape Canaveral is shown in Figure 4.7.

The driving reason to consider Vandenberg or Cape Canaveral is therefore to reduce, though not necessarily eliminate, the risk of overflying Russia or China. This may be a capability decisionmakers find attractive, especially in the context of extended deterrence or in dealing with certain emerging nuclear states or regional nuclear adversaries. However, the option to launch nuclear weapons from either location comes with some cost. Ensuring the proper handling of nuclear weapons, to include a storage facility at each site, is a nontrivial consideration.

Improving Missile Accuracy

Early ICBMs and SLBMs were relatively inaccurate by modern standards. Through the 1950s and into the early 1960s, U.S. and Soviet ICBMs and SLBMs were capable of achieving CEPs only on the order of 1–2 nm.[15] That level of accuracy is more than adequate to destroy a

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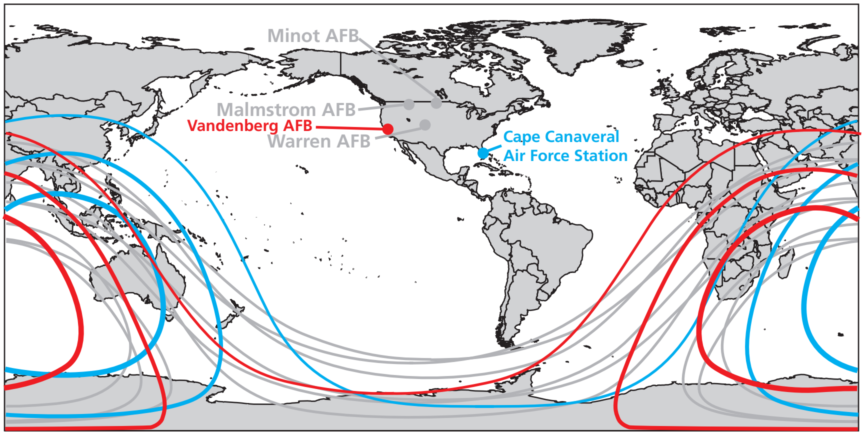
[15] Donald A. Mackenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance*, Cambridge, Mass.: MIT Press, 1990, pp. 428–429.

Figure 4.7
Range of an ICBM from Expanded Basing Locations



RAND *MG1210-4.7*

city or some other large, unhardened target (e.g., perhaps unprotected aircraft and other "soft" targets on a military airfield) but not nearly good enough to destroy hardened military targets, such as the ICBM silos that came along later. As a result, such weapons would have been sufficiently effective to destroy cities and much of an enemy's civilian society ("assured destruction," in the vernacular of the times) plus soft military targets. However, they would have been relatively ineffective in disarming "counterforce" attacks against an enemy's ICBM forces once those missiles were placed in hardened silos. For some strategists, that was a good thing. For others, it was not.

Very early in its ICBM and SLBM programs, the United States began a comprehensive and aggressive program to improve the accuracy of its strategic ballistic missiles because accuracy was the critical variable in determining the effectiveness of nuclear-armed missiles against hardened targets. The task was quite formidable because the error budget of an ICBM or SLBM is very complex, involving a large number of individual and largely independent error sources. Some of the major error components included accelerometer scale factor, gyro drift rates, gravity and geodesy models of both the launch area and the target area, winds and atmospheric conditions in both the launch and target areas, and the exact location of both the missile launcher and its target.[16] Driving one down, while helpful, merely turned the spotlight on another. Deputy Director of Defense Research and Engineering John Walsh described the situation very candidly in 1976:[17]

> In 1971 the gravity and geodesy term decreased significantly. . . . At the same time . . . we had a greater guidance and control error. . . . [I]n 1970 we were just wrong.
>
> [A]s these other large error terms go down, we began to wonder how to account for the errors we were observing [and] concluded that the reentry dispersion was probably greater than we thought.
>
> . . . It is not clear that we can make it go away.

Most of the errors that have been identified are random, which means that the individual error terms can be "root-sum-squared (RSS)" to calculate an expected value of the overall error. However, from the very beginning, there has been speculation that there are bias errors as well. Biases are important because they are additive to the expected value derived from the RSS of the random terms in the error budget. Thus, they can have a disproportionate effect on the overall expected accuracy of the missile. Also, they can be very hard to measure or even identify. The argument over bias errors has sometimes achieved almost cult-like status within the guidance community.

Throughout most of the history of ICBMs and SLBMs, the major emphasis within the guidance community has been on improving the quality of inertial instruments (i.e., gyros and accelerometers) because it was those terms that dominated the error budgets over much of that period. In addition to the formidable technical issues involved, institutional biases and clout, budgets, operational needs (and dogma), and personalities became important factors as well in determining the best

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16 Kenneth R. Britting, *Inertial Navigation Systems Analysis*, New York: Wiley-Interscience, 1971, esp. pp. 114–152; Averil B. Chatfield, *Fundamentals of High Accuracy Inertial Navigation*, Reston, Va.: AIAA, 1997, esp. pp. 253–312.

17 Mackenzie, 1990, pp. 368–369.

path to take. Still, by the standards of these things, accuracy improvement programs for U.S. ballistic RVs have been very successful. With the use of improved inertial instruments and some other less dramatic refinements, unclassified estimates for the late 1980s–early 1990s generation of deployed or planned U.S. ICBMs and SLBMs state that CEPs improved by a factor of about 30 over the first-generation systems that were fielded some 30 years ago.[18]

Maneuvering Flight and Reentry Vehicles

While improving missile accuracy through improved inertial instruments and other areas of exploration (e.g., the use of midcourse guidance updates, such as star trackers) was moving along, other missile "front-end" areas were not being neglected. Beginning very early in the period of ICBM and SLBM guidance evolution, the United States conducted a very aggressive research and development (R&D) program on MaRVs.[19] MaRVs could offer a range of potential operational advantages, depending on their particular design characteristics. Possibilities include the following:

- improved accuracy
  - "inertial" MaRVs, which include an inertial guidance package, which allows the reentry vehicle to sense and compensate for reentry errors caused by winds or other atmospheric anomalies. This is the simplest and cheapest type of MaRV to implement and may provide adequate accuracy for some applications.
  - terminally guided MaRVs that contain a sensor of some sort either to guide a MaRV to a particular set of geographic coordinates on the ground or to detect and home on some specific

[18] Mackenzie, 1990, pp. 428–429.

[19] Thomas B. Cochran, William M. Arkin, and Milton M. Hoenig, *Nuclear Weapons Databook*, Vol. I: *U.S. Nuclear Forces and Capabilities*, Cambridge, Mass.: Ballinger Publishing Company, 1984, pp. 108–110.

target signature. All manner of sensing possibilities have been considered over the years.

- enhanced survivability: One of the first and most enduring missions envisioned for MaRVs was evading BMDs. A maneuvering target considerably complicates the already very difficult task that a BMD system has.[20] Of course, MaRVs can also be designed to both evade defenses and provide greater accuracy. Naturally, design trades are required to accommodate the two missions simultaneously. Conversely, emphasizing one may come at the expense of the other, which obviously complicates the MaRV design process.
- expanded "footprints": Another possibility is using the MaRV's maneuver capability to expand the size of the area that the one missile's warheads could cover. That became a potential issue for the Trident D-5 missile in the early 1980s when developing the capability to fight a protracted nuclear war was in vogue. The issue was that the SSBN (the Navy's hull classification for nuclear-powered submarines carrying ballistic missiles) force was correctly viewed as being the most survivable leg of the U.S. strategic "triad" and the one most likely to be able to contribute large numbers of nuclear warheads late in a protracted nuclear war. The problem was that, in the late stages of a protracted nuclear war, there might not be that many targets left, and those that remained intact might be widely dispersed. Using the very valuable highly MIRVed ballistic SLBMs to attack such sparse, widely spaced targets could prove to be unacceptably inefficient. Using MaRVs with very large footprints might have been a potential solution to that problem. In fact, the idea was proposed but was eventually rejected.
- attacking mobile targets: Another potential for MaRVs is attacking mobile targets. This application would stress the vehicle

[20] For detailed discussions on evaluating MaRV engagements with defenses, see Paul Zarchan, *Tactical and Strategic Missile Guidance*, 6th ed., Reston, Va.: AIAA, 2012, esp. Chapters 20, 25, and 27; and Frank J. Regan and Satya M. Anandakrishnan, *Dynamics of Atmospheric Re-Entry*, Reston, Va.: AIAA, 1993, esp. Chapter 9.

> dynamics and either the onboard sensors or the communication links or both, depending on whether the vehicle had to acquire and track targets itself or was relying on information from off-board sensors. This is probably the most demanding MaRV application and the one that has been investigated the least.

The first MaRV test flight was conducted in August 1966. The test vehicle was known as the MBRV-1.[21] It basically demonstrated the feasibility of large MaRVs. That was the first in a series of extensive MaRV flight testing of progressively more-advanced vehicles for increasingly demanding missions.

The first MaRV to be subjected to a full-blown developmental flight test program was the Mk500 Evader. As the name suggests, the Mk500 was designed exclusively to evade ABM defenses.[22] The Navy conducted five flight tests of the Mk500 in the mid-1970s. Because the vehicle lacked a terminal or onboard inertial guidance system, it sacrificed some accuracy to achieve its maneuver capability. Specifically, the Mk500 was intended as a hedge against the Soviet Union's "breaking out" of the ABM Treaty[23] and rapidly deploying a nationwide ABM system. The Mk500 was designed to be deployed on the Navy's Trident I SLBM should the need arise. To make that option more feasible, the Navy instituted the Readiness Maintenance Program to minimize the time and risk involved in actually deploying the Mk500 at some point. Essentially, that involved, among other things, keeping a "hot" production line open in order to move out quickly if the decision were ever made to deploy the Mk500. However, the threat never materialized, so the Navy canceled the program when the cost of keeping the production line open exceeded the cost of having simply deployed the system in the first place. Nevertheless, the Mk500 program was an important step in the evolution of MaRV development in the United

21 Cochran, Arkin, and Hoenig, 1984, p. 108.

22 Cochran, Arkin, and Hoenig, 1984, p. 110.

23 United States and Union of Soviet Socialist Republics, *Treaty Between the United States and the Union of Soviet Socialist Republics on the Limitation of Anti–Ballistic Missile Systems*, October 3, 1972.

States. It laid the groundwork for more-advanced MaRV systems. It was also the closest the United States ever came to actually deploying a MaRV on a strategic missile. (The U.S. Army did briefly deploy a terminally guided "accuracy" MaRV on the intermediate-range ballistic missile, Pershing II, before that whole class of weapons was banned by the INF Treaty.)

The successor to the Mk500 Evader MaRV was the Advanced Maneuverable Reentry Vehicle (AMaRV). AMaRV was also an evader MaRV. However, it also contained an inertial guidance system to allow the vehicle to maintain or even improve its accuracy compared with that of a standard ballistic RV. It explored other advanced technology options as well. AMaRV was flight tested three times but never deployed operationally.[24]

AMaRV was succeeded by the Precision-Guided Reentry Vehicle (PGRV). PGRV added a terminal guidance sensor to the MaRV, thereby significantly increasing its accuracy and potentially expanding the variety of target types that it could attack effectively.[25] Like its predecessors, PGRV was never deployed operationally. There were other advanced reentry vehicle programs as well—e.g., the Boost Glide Reentry Vehicle (BGRV), Advanced Control Experiment (ACE), and Sandia Winged Energetic Reentry Vehicle Experiment (SWERVE). Extensive documentation exists for these programs.[26] That none of these programs led to actual operational systems is less important than the fact that they provided a comprehensive, massive body of knowledge that could be applied to the development of operational maneuvering reentry systems in the future. Accordingly, they provide a solid technical foundation for exploring advanced systems of the sort we have been considering in this analysis.

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[24] Cochran, Arkin, and Hoenig, 1984, pp. 109–110.

[25] Cochran, Arkin, and Hoenig, 1984, p. 110.

[26] For an extensive list of documents generated by various advanced reentry programs, see, for example, A. Martellucci, S. Weinberg, and A. Page, *Maneuvering Aerothermal Technology (MAT) Data Bibliography (Task 2)*, Wayne, Pa.: Science Applications, Inc., BMO-TR-82-15, March 24, 1981.

The current force of deployed intercontinental strategic systems is built around ballistic missiles and ballistic reentry vehicles with nuclear weapons. Maneuvering reentry vehicles as discussed above have been developed and tested and are understood if not deployed. There are yet additional approaches to systems of strategic range that are quite different in character from ballistic missiles but that are at much earlier stages of development than deployed systems. These new approaches are intended to be conventionally armed, and, given their current state of development, these are unlikely candidates to replace the existing force of ICBMs. Nevertheless, their technologies could be used in future nuclear-armed systems, so they are discussed here.

Over the past several years, the United States has been developing and flight-testing concepts for so-called long-range, boost- or hypersonic-glide systems. Such a system would use a booster to launch a hypersonic glider and payload delivery vehicle capable of delivering a conventional warhead with the speed and reach of current nuclear-armed ICBMs but with the increased accuracy required to make a conventional warhead effective. Such systems are being explored as a means to provide the capability to mount strikes with conventional warheads against high-value targets at great distances from U.S. soil.[27]

Technologically, these systems require long-duration hypersonic flight, which has been one of the greatest unanswered challenges in aeronautical science. The extreme speed creates significant heating and ablation of the aircraft, and aerodynamic surfaces are subjected to extreme and often unstable forces. Many of the technologies required to make sustained hypersonic flight successful are still being studied

[27] Because such systems would not follow a ballistic trajectory over a majority of their flight path, the United States has argued that boost-hypersonic glide systems do not meet the definitions of *ICBM* or *SLBM* that are established in the U.S.-Russian START and New START Treaties. Moreover, because these conventionally armed, boost-hypersonic glide systems fly significantly different flight profiles from those of nuclear-armed ICBMs or SLBMs, the possibility that a country would mistake a strike carried out by a conventionally armed hypersonic glide vehicle with an attack by a nuclear-armed ICBM or SLBM would likely be diminished. This is in contrast to the U.S. position on conventionally armed ICBMs built on current boosters, which would include them as strategic delivery vehicles. Critics counter that such a system might be used in ways that destabilize existing silo-based systems or nuclear command and control systems.

at a fundamental level, meaning that deploying a hypersonic vehicle would require major RDT&E investments and acceptance of significant technological risk and would require significant lead times.

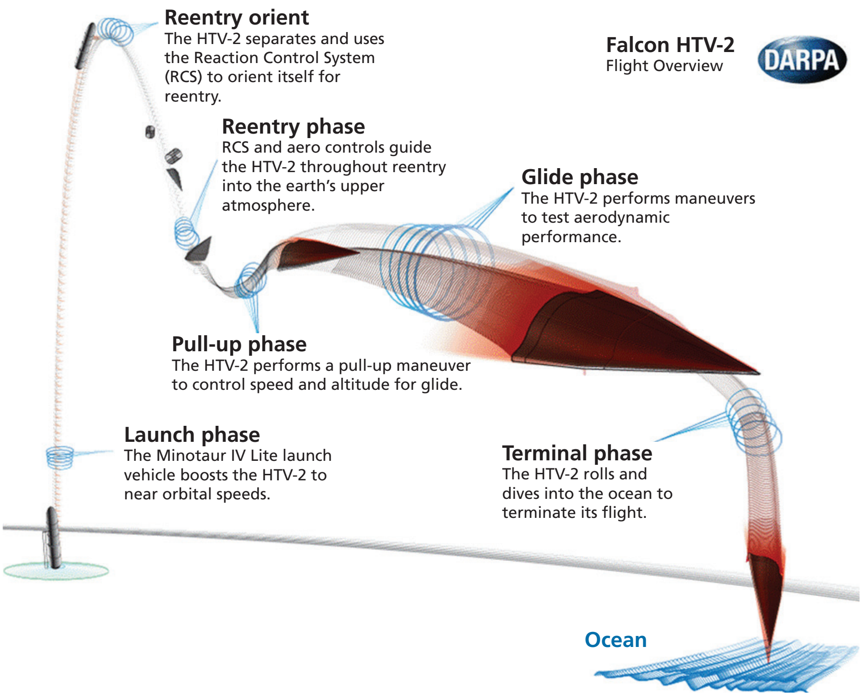
To take a specific example, DARPA's Falcon (Force Application and Launch from CONUS) program is a two-part program to develop a hypersonic vehicle and a launch platform. As a technology demonstration, DARPA built and flew an HGV, denoted HTV-2. Demonstration tests called for the glide vehicle to be launched on an Orbital Sciences' Minotaur IV Lite rocket and then released for the reentry phase, during which potential energy would be exchanged for kinetic energy. Once the vehicle attained sufficient speed in the atmosphere, it would perform a pull-up maneuver to enter the glide flight segment. At the end of the glide segment, the glide vehicle would perform a series of maneuvers to enter the terminal phase. This flight profile sequence is illustrated in Figure 4.8.

A test in April 2010 was only partially successful because communication with the vehicle was lost shortly after it separated from the Minotaur IV Lite rocket on which it was launched.[28] A follow-on powered test vehicle, the HTV-3X, was canceled before its first flight.

MaRVs provide many of the terminal benefits of a hypersonic vehicle but could be carried on current nuclear missile systems. By using current technology and only upgrading the RV, the required RDT&E to develop a MaRV is significantly less than to develop an HGV such as DARPA's Falcon program. These MaRVs have the potential to improve the range, accuracy, and defense penetration abilities of ICBMs. Significant research has been conducted and is still ongoing. In particular, the Navy has pursued the Conventional Trident Missile (CTM) program, which mates a new MaRV with an existing Trident missile. The ability to maneuver could increase the accuracy sufficiently to allow for attacking targets with conventional munitions. This redesigned RV has a flight envelope similar to the current nuclear-armed Mk4 but includes a new inertial measurement unit (IMU), GPS receiver, along

[28] An August 2011 test of the HTV-2 also experienced a midflight failure during the aerodynamic segment of flight, most likely due to loss of control. An August 2012 test of Boeing's Hypersonic X-51A WaveRider also failed reportedly due to a problem with a control fin.

Figure 4.8
DARPA HTV-2 Flight Profile



SOURCE: DARPA, "Tactical Technology Office, Falcon HTV-2," website, undated.
RAND *MG1210-4.8*

with a control system and trailing edge flaps. These additional systems allow for terminal guidance with the objective of hitting within 10 m of the target. Currently, the RV contains no explosives and relies on kinetic energy for effect. Its overall effectiveness can be increased by dispersing large quantities of tungsten rods before impact.

ICBM Payload

Conventional prompt global strike (CPGS) is the military capability to hold any location on the globe at risk in a relatively short time, loosely defined as minutes or hours rather than days. CPGS has a history that reaches at least as far back as the idea of space-based weapons itself.[29] Adapting nuclear-armed ICBM systems to a conventional mission is an often-proposed approach to developing CPGS. This section explores the potential of adapting ICBM systems for CPGS. However, we do not consider numerous other approaches to achieving CPGS capabilities nor do we compare those alternatives.

We study the potential effects of a conventional warhead delivered by an ICBM by first understanding the accuracy requirements. Today's nuclear warheads with closed guidance systems (i.e., those that depend only on inertial navigation) and without maneuverable reentry have accuracies that are potentially significantly affected by atmospheric effects and weather, even with offboard, midcourse positioning updates. For ICBMs, it has historically been the case that accuracy uncertainties have been more than offset by the large blasts and effects range of nuclear weapons. This is not necessarily true of a conventionally armed ICBM.

To illustrate, we examine the effects of a unitary 2,500-lb. conventional warhead, which is a decent proxy for some ICBM payload sizes. If we assume that 50 percent of the warhead weight accounts for high explosive and that the warhead impacts at approximately 1,000 m per second (m/s)[30] so that, if it survives impact, it would have an effects

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[29] See, for example, the history and discussion given in Robert Preston, Dana J. Johnson, Sean J. A. Edwards, Michael D. Miller, and Calvin Shipbaugh, *Space Weapons, Earth Wars*, Santa Monica, Calif.: RAND Corporation, MR-1209-AF, 2002. Conventional fractional orbital bombardment is one of the many systems described and evaluated therein.

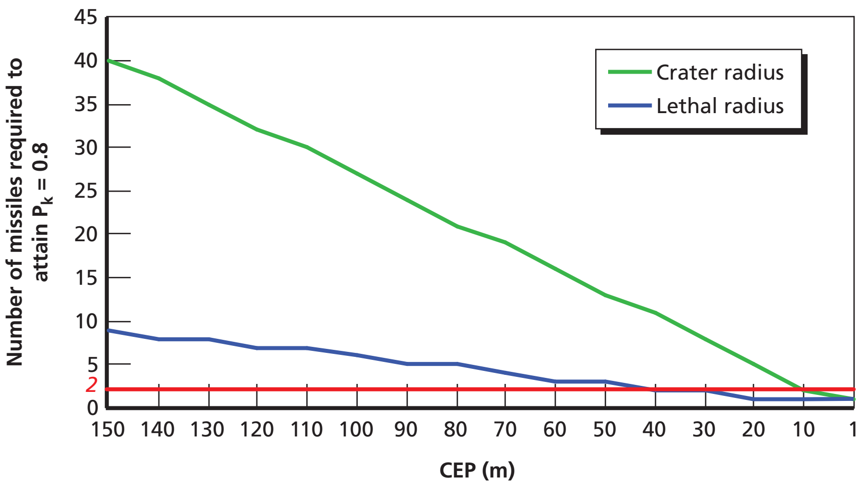
[30] Impact velocities for reentry vehicles can vary considerably depending on the characteristics of the reentry vehicle and atmospheric conditions. In fact, reentry errors are inherently very difficult to predict accurately because of the fundamental uncertainties in major variables (Mackenzie, 1990, p. 369). For a ballistic (i.e., nonlifting) reentry vehicle, the key design parameter is the *ballistic coefficient* (β), which is defined as the vehicle's weight-to-drag ratio (John Joseph Martin, *Atmospheric Reentry: An Introduction to Its Science and Engineering*, Englewood Cliffs, N.J.: Prentice-Hall, 1966, p. 24). In general, the higher the vehicle's ballistic coefficient, the more quickly it passes through the atmosphere, and the lower its reentry errors.

radius of no greater than 50 m, depending on target hardness.[31] Assuming a desired P_k of 80 percent, Figure 4.9 shows the number of missiles required given a range of accuracies.

If we assume that two is a likely threshold of the number of strategic systems the United States would be willing to expend on a single target in order to have 80 percent confidence, the CEP must be 20 m or less for soft targets and lower than 10 m for more-hardened targets. ICBM systems with accuracies much beyond 20 m CEP may therefore not be suited to handle this notional unitary payload.

To make a conventional ICBM viable against any target therefore likely means either increasing the lethal or effects radius of the conventional payload or improving system accuracy. Figure 4.10 demonstrates how warhead footprint and system accuracy may be traded. Assuming accuracies in the 100- to 300-m CEP range, to achieve an SSPk

Figure 4.9
Warhead Requirements as a Function of Accuracy



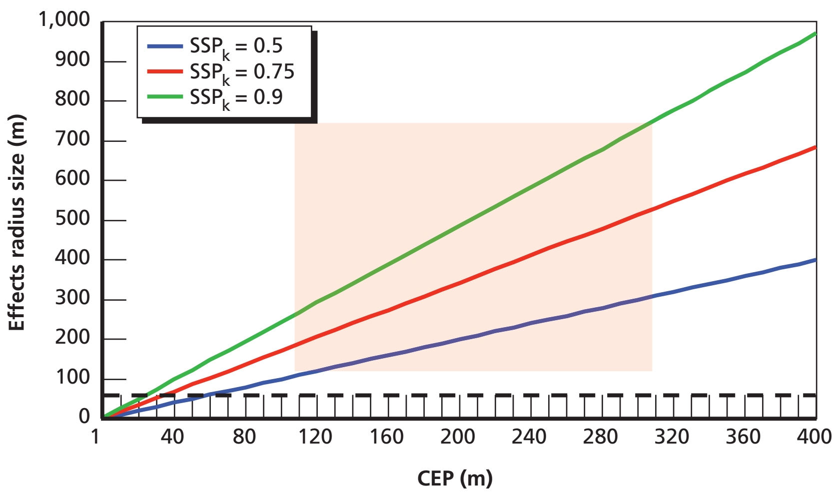
RAND *MG1210-4.9*

31 The calculation extrapolates known LRs from 1,000- and 2,000-lb. Joint Direct Attack Munitions (JDAMs) to account for potentially higher energies at impact due to greater velocities. The expected crater radius is approximately 10 m; the LR to a human is less than 50 m.

of between 0.50 and –0.90, the effects radius of the warhead would have to be in the 100- to 750-m range, as indicated by the red box in the middle of Figure 4.10. This is already significantly larger than the 50-m radius we derive for a 2,500-lb. conventional unitary weapon, as indicated by the black dotted line. To achieve the SSPk likely to be required of a strategic system, 0.75 or above, we see that, without accuracy improvements, the effects radius should be on the order of 200 m or larger.

Probably the only way to achieve a larger lethal footprint using conventional HE is to space and spread the delivery of the HE over a larger area. This has been historically done via submunitions; effects radii of hundreds of meters are possible with small, fragmentary submunitions. If we again assume that 50 percent of the warhead weight of a 2,500-lb. ICBM-class payload warhead could be devoted to 1-lb. submunitions and that the submunitions were optimally spaced to ensure multiple hits against large aircraft in the open, a quick calculation shows that a radius of approximately 400 m is attainable. However, small 1-lb. submunitions are only effective against soft targets,

Figure 4.10
Effects Area and Accuracy Trade-Off



RAND *MG1210-4.10*

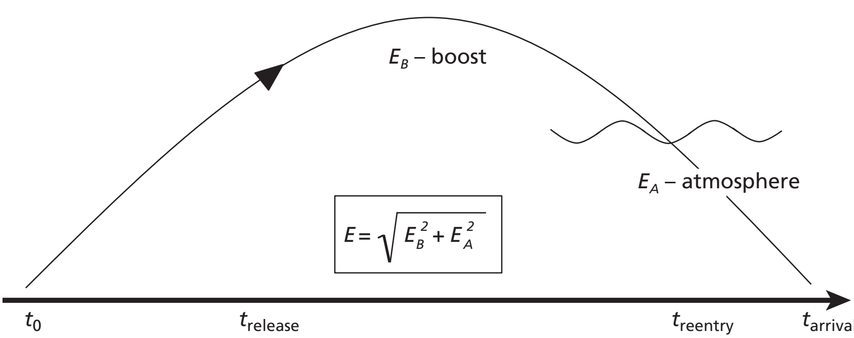
such as light infantry or aircraft parked in the open, and are easily defeated by even a low level of hardening. The military use is limited by this constraint.

A viable unitary conventional weapon delivered by an ICBM is therefore a problem of accuracy constraints. ICBM systems accumulate error throughout weapon delivery; Figure 4.11 shows a much-simplified depiction of how this happens. While there are numerous sources of induced flight trajectory error, they can be broadly classed into boost error, *EB*, and atmospheric reentry error, *EA*. If boost error can be determined during the exoatmospheric coast phase of the trajectory (by a midcourse stellar update or with GPS), then a maneuvering thrust control system can make adjustments before reentry. However, atmospheric and weather reentry error alone can introduce significant errors on even high-β RVs. Even eliminating all other error and retaining just reentry error may still not be good enough.

Reducing or minimizing reentry error requires an RV with a control system, something the current Minuteman III missile does not have. The new RV would need to be maneuverable and may require midcourse updates and post–boost phase course correction.

Even with a perfectly accurate conventional unitary ICBM, the class of targets held at risk is narrow due to the small amount of HE. For example, here we evaluate possible effectiveness against hardened

Figure 4.11
Error Accumulation in Ballistic Trajectories



RAND *MG1210-4.11*

and deeply buried targets (HDBTs). Penetrating hardened targets is primarily a function of warhead mass and velocity. Given the extreme velocities of reentry, an ICBM would seem to be ideally suited in this regard. However, ballistic reentry velocities are so great that munitions will not survive impact. Any HDBT-penetrating warhead would need to decelerate to a maximum survivable impact speed of around 1,000 m/s, and at this speed, the warhead would need to be 95 percent structure and only 5 percent HE. Even a 4,000-lb. penetrating warhead would deliver only 200 lb. of high explosive.

Successful penetration attacks are extremely dependent on angle of impact and typically require an angle of impact greater than 60 degrees, with a 90-degree perpendicular impact being ideal. If the impact angle is less than 60 degrees, the warhead is likely to broach, ricochet (see Figure 4.12), or structurally fail. ICBM ballistic trajectories, however, typically have terminal angles of less than 60 degrees. Moreover, a totally ballistic ICBM would have to loft its launch trajectory to achieve such extreme angles, which would significantly deteriorate range. This is therefore another case that would likely need a MaRV.

Assuming perfect accuracy and a proper impact angle, a 4,000-lb. penetrator with 5 percent HE that can survive 800 m/s impacts could penetrate up to 65 feet of high-strength (5,000 PSI) concrete or the equivalent amount of earth or rock. Figure 4.13 describes concrete penetration estimates for various weapons. For comparison, a 4,000-lb. penetrator dropped from high altitude could penetrate half that depth, or 35 ft. While this is a nontrivial level of hardness, truly valuable targets, such as nuclear storage facilities or nuclear fuel fabrication sites, are likely to be buried significantly deeper than 65 ft.[32]

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[32] See, for example, U.S. Secretary of Defense, in conjunction with the Secretary of Energy, *Report to Congress on the Defeat of Hard and Deeply Buried Targets in Response to Section 1044 of the Floyd D. Spence National Defense Authorization Act for Fiscal Year 2001, PL106-398*, July 2001, p. 9:

> Hundreds of much harder facilities (having concrete overburden equivalent of 70 to 300 feet) protect strategic functions (e.g., leadership, command and control, WMD) and were built using either conventional drill-and-blast tunneling techniques or more modern mining equipment.

Figure 4.12
Penetration Angles

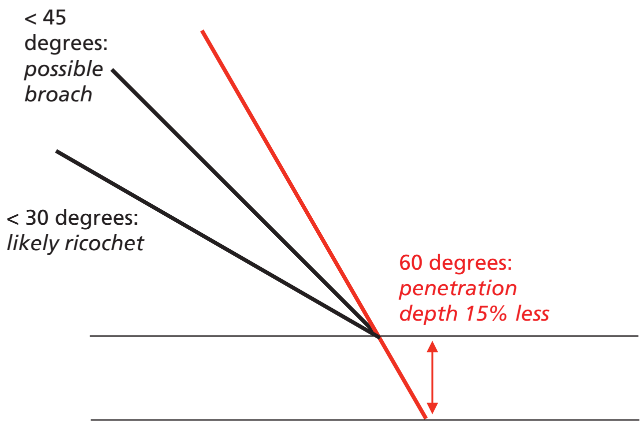

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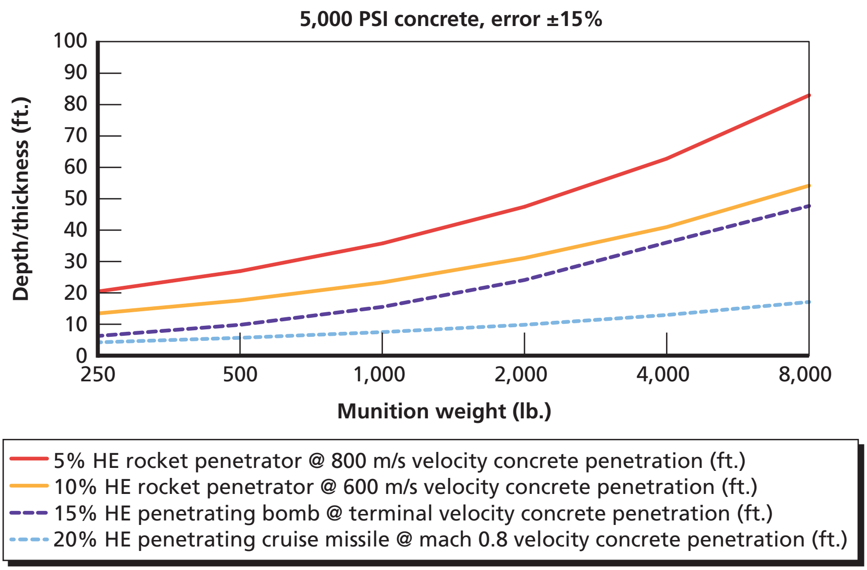
Figure 4.13
Concrete Penetration of Various Munitions



RAND *MG1210-4.13*

Adapting an ICBM system for CPGS requires, at a minimum, improvements in accuracy likely only achievable with a MaRV. Any additional requirements to hold broader classes of targets at risk, such as mobile targets and HDBTs, require even more. To hold mobile targets at risk, ISR assets outside of CONUS would be required to provide additional targeting information during flight, and the ICBM guidance system would have to be datalinked to these ISR assets, something not currently done. Even with such improvements, this capability could only be as effective as about half the throw weight in HE, and much less for penetrating warheads.[33]

Conclusion

The next ICBM AoA should consider propulsion, boost, reentry, and payload issues as it defines and evaluates the various alternatives. In this chapter, we have outlined and listed ICBM options that could deliver more capability than the current Minuteman III offers. Specifically, these options may allow ICBMs to hold a larger class of targets at risk while mitigating overflight concerns. A strategic nuclear ICBM, however, is a different system from a conventional ICBM. While avoiding the collateral damage concerns that a nuclear weapon poses, a conventional ICBM can only hold a narrowly defined set of targets at risk because of the relatively small amount of available payload. For any follow-on ICBM system to remain a true strategic deterrent, its focus should be nuclear. Conventional payloads could, however, be considered as a swap-out option for ICBM designs. Technically, making conventional payloads viable—in particular, conventional payloads that can penetrate hardened targets—requires drastic accuracy improvements achievable only by adding a control system to the reentry vehi-

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33 Preston et al. (2002) come to a similar conclusion over the niche uses of this class of weapons. They write,

> Space-based weapons may have a few unique and some useful niches in terrestrial conflict. They might compete well with some terrestrial basing alternatives for some tasks. . . . Useful niches might include prompt, long-range force projection; strikes on highly defended surface targets; and strikes on large surface vessels. (p. 106).

cle. The United States has experience developing and testing MaRVs and a consistent record of continually improving the performance of IMUs that would have to be integrated and tested.

Propulsion will likely continue to be based on solid fuels. They are well understood, relatively safe, and reliable, and they enable the United States to keep ICBMs on day-to-day alert. If overflight of Russia and China remains a dominant concern for the ICBM, the most cost-effective mitigation may be to add launch options to Vandenberg and Cape Canaveral. Although overflight from current wing locations could be addressed by launching south or by changing planes, both options add significantly to missile size requirements and present destabilization dangers. Technologies and platforms that could change the nature of intercontinental-range delivery, such as the HGV concept, are also currently in early stages of testing and development. These have the potential to change the relationships between range, payload, reentry, and propulsion that have long been established for SRM ICBMs. These programs are still in their early development stages and may therefore accrue substantial RDT&E costs before demonstrating technical readiness.

It is ultimately the job of the upcoming AoA to examine how these options meet future requirements. Although we cannot determine the specific alternatives until the AoA requirements are defined, we can introduce several concepts built from these options and make rough estimates of their cost ranges. The next chapter does this by comparing possible concepts that differ from Minuteman III in varying degrees.

CHAPTER FIVE

The Cost of ICBM Alternatives

Previous chapters have discussed a broad range of possible design and employment considerations for future ICBM capability. The requirements specified in the future AoA will determine the specific choices to be evaluated. In this chapter, we explore the costs associated with a range of possible options that fall into six broad categories. Our analysis draws from many prior studies and official documents. The intent is to include minimal original cost estimation, thereby minimizing the time needed to complete the work. An additional benefit is increased acceptance of the findings by all the relevant stakeholders because the cost estimates herein were fully vetted with the ICBM stakeholder community prior to the publication of this report.

Our review of the 2006 AoA on land-based strategic deterrent (LBSD)[1] was an essential early step in understanding prior analyses addressing the question of the future of the ICBM force. The baseline case in that AoA is a complete new build of the existing ICBM force, along with a comprehensive rebuilding of the existing silos. While this approach is certainly possible, it did not strike RAND as the natural baseline for the capability of the existing ICBM force. Instead, we chose the existing Minuteman III system, with the benefit of many sustainability and modernization upgrades, as our baseline. We assume that basic sustainment of Minuteman is possible for as long as it is cost-effective. We refer to this as indefinite incremental moderniza-

1 Trevor Flint (Major, U.S. Air Force), *Land-Based Strategic Deterrent (LBSD) Analysis of Alternatives (AoA): Final Report*, Peterson AFB, Colo.: Air Force Space Command, April 28, 2006. Not available to the general public.

tion (IIM). Determination of cost-effectiveness is the ratio of estimated costs of sustaining Minuteman over the long term and estimated costs of acquiring its replacement and sustaining that replacement over the same period.

To determine the feasibility of long-term basic sustainment, we questioned multiple independent and authoritative offices and individuals during our interviews of the greater ICBM acquisition and sustainment community. Beyond finding no evidence that would necessarily preclude the possibility of long-term sustainment, we found many who believed the default approach for the future is incremental modernization, that is, updating the sustainability and capability of Minuteman III system as needed and in perpetuity.

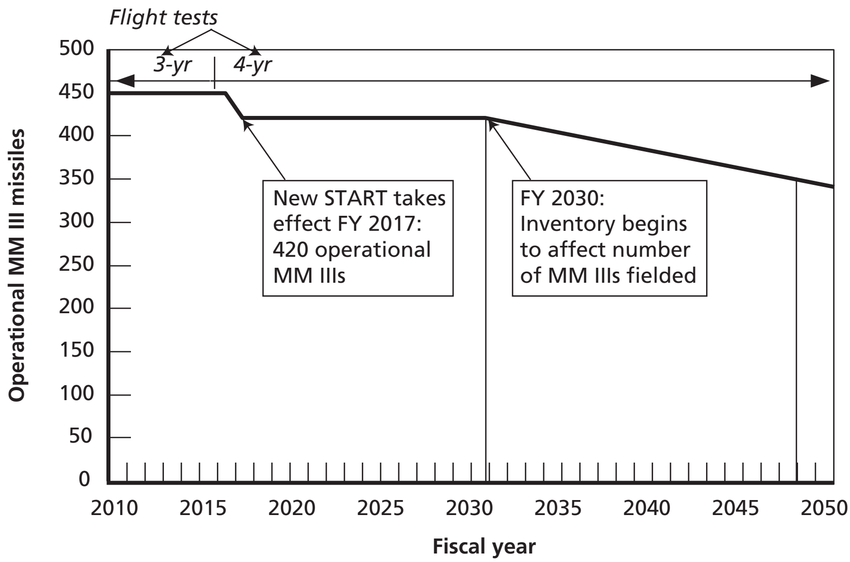
However, there is at least one potential constraint on the lifespan of the current system: the decline in missile body quantity over time as a result of required annual test firing. Minuteman III test firing has occurred at a rate of three missiles per year for decades. An increase to four per year—recommended by the ICBM system program office (SPO)—was not funded in the FY 2012 Future Years Defense Program (FYDP). This increase was stated as needed to attain all the data needed to ensure the efficacy of the system as it continues to age, so in our assessment, we assume that beginning in 2017, four test fires per year will be the norm.

Figure 5.1 provides a better understanding of the implications of the declining inventory of missile bodies over time. The decline in missiles shown assumes

- a total Minuteman III missile inventory of 500 in FY 2010
- an operational inventory of 450 missiles until the implementation of New START in 2017
- three test firings per year through FY 2016
- an operational inventory of 420 missiles (or fewer as inventory allows) from 2017 forward
- four test firings per year from FY 2017 forward.

If test firing is increased to four per year in 2017, a force of 420 operational Minuteman missiles is not sustainable beyond 2030

Figure 5.1
Operational Minuteman III Missiles over Time



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without the manufacture of all-new units. Force size diminishes from 2030 forward through total asset depletion in 2135. Prior to New START this might have posed a problem, but recent and potential future reductions will essentially extend the ability for IIM. Given this, the decline of missile quantities below 420 beginning in about 2030 may somewhat delay the test-firing problem.

Tests are critical to ensure effectiveness of the Minuteman III system. While reducing the number of tests could limit engineering-level assessments of the effects of aging and the effects of combining new and existing parts in any SLEP, there may be some ways to conduct component-wise tests that could reduce the number of full flight tests. However, we did not examine the possibility of modifying (lowering) the test rate, and we base our assessment only on SPO recommendations.

Current Plans for ICBM Modernization

The most recent Air Force plans for modernizing the ICBM force are embodied in the October 2010 "ICBM Master Plan."[2] Cornerstones of that plan are

- Minuteman III is sustained through 2030
- a follow-on system is assumed
- an ICBM follow-on is not a program of record
- no initial operating capability (IOC) date for the follow-on system is specified.

The plan states that "beginning in 2020, large-scale investment will be required to sustain MM III through 2030. These modernization efforts must support both sustainment through 2030 and recapitalization for a Minuteman Follow-on after 2030."[3] Also stated is "MM III sustainment funding must continue until Initial Operational Capability of a new or replacement weapon system. . . . "[4] The FY 2012 FYDP with budget plans through FY 2016 has no funding for a follow-on program, and no official budget estimates exist for a follow-on system.

ICBM Future Force Options

Most options for a future ICBM force fall into one of the six categories described below.[5] From the top category to the bottom, system characteristics go from rather well defined and narrowly scoped to much broader and ambiguous. In general, the life-cycle costs of the categories go from least expensive to most expensive.

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2 Jeffry F. Smith (Brig Gen, U.S. Air Force), *ICBM Master Plan*, Barksdale AFB, La.: Headquarters (HQ) Air Force Global Strike Command (AFGSC), October 2010.

3 Smith, 2010, p. 25.

4 Smith, 2010, p. 26.

5 A few concepts, such as the launching an ICBM from an airborne platform, are not included in the above categories.

1. Continue basic sustainment until the system is ineffective or unsustainable.
2. Continue IIM until the system is ineffective or unsustainable.
3. Acquire "Minuteman IV" (MM IV) (which we define to be "Minuteman III–like"). Replace the current system with one of similar capability and with a virtually identical employment concept.
4. Acquire an all-new-design ICBM to be based in existing Minuteman silos with a similar employment concept.
5. Acquire an all-new-design ICBM with an alternative basing scheme but using existing U.S. Air Force military base infrastructure and footprint.
6. Acquire an all-new-design ICBM with an alternative basing scheme requiring use of public lands or enhanced U.S. Air Force military base infrastructure and footprint.

No Replacement System Categories

Basic Sustainment

Basic sustainment serves as our baseline and serves as a reference point for cost and capability to which other options are compared. It suggests that the current system be sustained indefinitely without incremental modernization or supportability upgrades. This is most likely an unrealistic option; replacement of failed items with exact replicas is not possible in some instances because the necessary manufacturing methods or materials are no longer viable or available. In addition, in some cases the replacement of unsupportable system components brings the opportunity for upgrades at a cost that can sometimes be less than that of attempting to replicate the existing design. Finally, updating technology at the time of replacement in many cases provides enhanced supportability characteristics, thus reducing overall system O&S costs. For all these reasons, this option is not a realistic way forward, but it does serve as a point of comparison for other options.

Indefinite Incremental Modernization

Incremental modernization suggests that the existing system can be incrementally modernized with the aim of indefinite sustainability. This approach is only viable so long as the system remains effective from a capability perspective, and is cost-effectively sustainable. It could be achieved with incremental modernization efforts through a series of projects and programs of all sizes that keep the current system from becoming unsupportable or ineffective. It assumes incremental improvements in both capability and supportability as more modern technology replaces the existing Minuteman III subsystem technologies. This approach is viable from a capability standpoint as long as the capability required from the Air Force's ICBM system is not substantially changed. Substantial additional capability is unlikely to be introduced under the now standard "form-fit-function" modernization programs that require the system to remain operational at all times. This option represents the approach taken to perpetuating Minuteman III since the end of the Cold War and is official Air Force policy through 2030. Over time, incremental modernization could resemble a "replace in place" strategy that piece-by-piece turns a Minuteman III missile into a Minuteman IV–like system.

Replacement System Categories

New-Build Modernized Minuteman

The third category calls for newly built Minuteman IV missiles that are essentially the same size, capability, and employment concept as Minuteman III. This approach must be adopted if an essentially identical capability is desired and the current system can no longer be sustained. As discussed later in this chapter, this is the least expensive of the options to replace the existing Minuteman system. The design of the Minuteman IV would be based on Minuteman III and should be considered the next generation of the same. Minuteman IV would use the same, albeit extensively refurbished, silos as the current system. This category represents the approach assumed in the 2006 ICBM AoA.

All-New Silo-Based Missile

The fourth category replaces Minuteman III with an all-new ICBM that is substantially different. This ICBM might be bigger or smaller than Minuteman III, depending on requirements. The constraint is that it would fit in the existing silos; thus, its minimum size would be about that of the Midgetman or SICBM and its maximum size would be about that of the Peacekeeper. The employment concept would be similar to that of the current Minuteman. An ICBM alternative in this category would presumably be chosen if a substantially different capability than that of the current system were needed, but one that still requires silo basing. Because this is an all-new ICBM design, its cost would be higher than options that fall into category 3.

All-New Mobile-Based Missile on Existing Federal Lands

The fifth category replaces Minuteman III with an all-new-design ICBM that is not silo launched. The point of such a system is the potential for enhanced survivability via mobility. The two most commonly cited modes of mobility for a missile large enough to have intercontinental range are road mobile and rail mobile. As discussed in Chapter Three, there are many possible basing and dispersion constructs for each mode. The only constraint we put on this category is that the mobile ICBM system utilize existing U.S. military base and land footprints, meaning that no non-U.S. military lands are to be acquired or utilized in the day-to-day operations and training for the system. Because this is an all-new-design ICBM that must remain reliable under the rigors of periodic movement and because a mode of survivable mobility must be acquired, options in this category would be more costly than those that fall into category 4.

All-New Mobile-Based Missile on New Lands

The sixth category is similar to the fifth in that it replaces Minuteman III with an all-new-design ICBM that employs a mobile concept of operations. The primary difference here is that system options in category 6 would require the use of additional lands beyond the existing U.S. military base footprint. This might involve the use of U.S.-owned federal public lands, privately owned lands, or publicly and privately owned lands and infrastructure, such as public roads and privately owned railroad tracks and rights-of-way. Because this would probably require access to and development of additional lands for its employment, its cost would be higher than options that fall in category 5.

Initial Cost Ranges

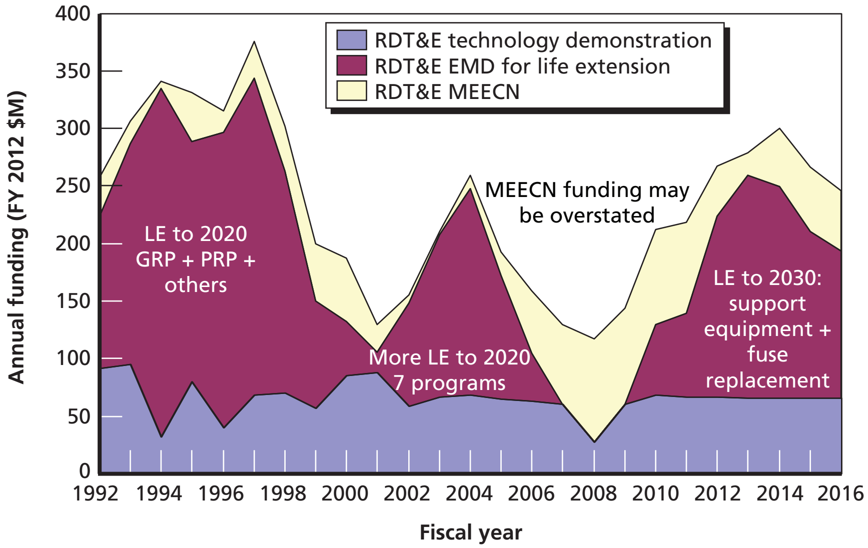
To gain a better understanding of future costs for a follow-on ICBM, we next explore historical costs for the current system. Specifically, we examine actual costs and cost estimates for other historical ICBM weapon systems and applicable cost estimates from the 2006 LBSD AoA.

Minuteman III became operational in 1970, more than 40 years ago. Many upgrades and improvements have been required over its operational life. The costs to keep the system viable over the last two decades provide a reference for expected future costs to keep the system viable, though we acknowledge the fact that recent SLEPs have not considered to a detailed extent the risks and future costs of maintaining and modernizing many other components. This includes nonmissile aspects like silo refurbishment and NC3 infrastructure.

The sustainment approach over the past 20 years is most like our IIM option for the future and forms a reference for that option. The dozens of programs funded with modification budgets over 20 years have improved Minuteman's capability mostly at the margin and have enhanced its supportability (or at least to keep its supportability from degradation). With this in mind, we piece together the life-cycle costs for development, procurement, and O&S for Minuteman III over that period to provide context for expected future life-cycle costs under basic sustainment or an incremental modernization approach. We also examine Minuteman III investment levels in the FY 2012–2016 FYDP. All costs shown are in constant year 2012 dollars, thus removing the effects of inflation over time.

Figure 5.2 shows development investments for Minuteman III, 1992 through 2011, plus those planned in the FY 2012–2016 FYDP. These costs fall into three general categories: technology demonstra-

Figure 5.2
Minuteman III RDT&E Investment, 1992–2001 and FY 2012–2016 FYDP



NOTE: MEECN = Minimum Essential Emergency Communications Network. LE = life extension. GRP = Guidance Replacement Program. PRP = Propulsion Replacement Program.
RAND *MG1210-5.2*

tion, engineering and manufacturing development (EMD) for life extension programs, and RDT&E for MEECN.[6]

Technology development includes all non–program-specific efforts targeted at ICBMs. It continues at a relatively stable rate with or without a replacement ICBM system. Life extension program (LEP) development investments come in waves. The first two are to extend the Minuteman III system to 2020, and the third is intended to extend the system to 2030. The absence of this type of funding in FY 2007–2009 occurred because, during the planning period for those years, it was expected that a replacement for Minuteman III would be acquired.

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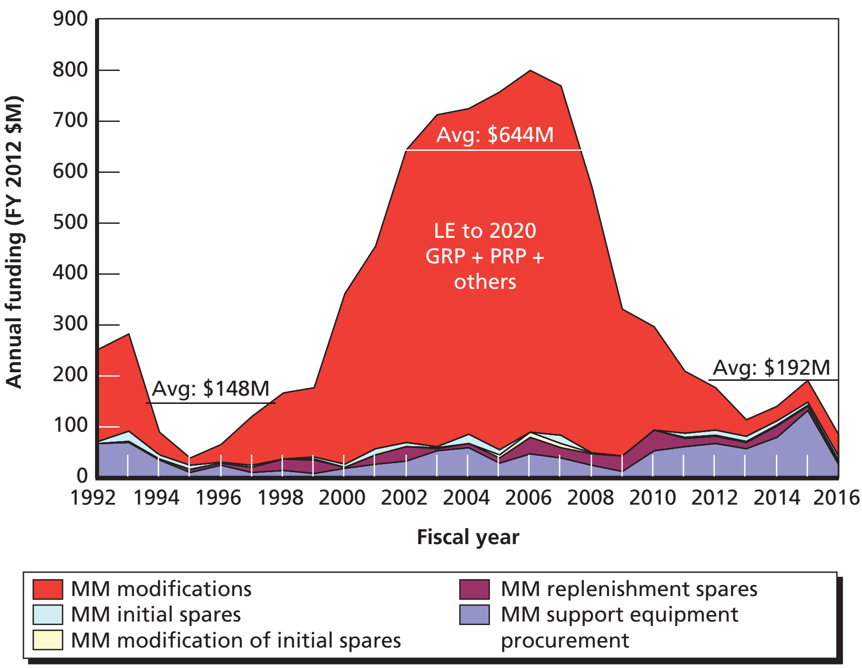
[6] MEECN is a network of systems that extend to all aspects of U.S. nuclear forces. Currently, the U.S. Air Force investment in MEECN is focused on the Minuteman MEECN Replacement Program, though MEECN does encompass systems on nuclear-capable bombers.

Once that plan was scuttled, the next set of Minuteman-related SLEPs was implemented. Funding for the aging communications network MEECN appears in every year, but varies considerably from year to year.

Over the 20-year historical period, annual development budgets of the three categories in aggregate have varied between $117 million and $376 million (FY 2012 dollars), with an average of $227 million per year. Planned FYDP funding for FY 2012–2016 was above that level in every year. This level of funding is envisioned to extend the life of the current Minuteman system to 2030 through the replacement of support equipment and design of a new fuse.

Figure 5.3 is a snapshot of 20 years of procurement investments in Minuteman plus procurement expected in the FY 2012–2016 FYDP.

Figure 5.3
Minuteman III Procurement Investment, 1992–2001 and FY 2012–2016 FYDP



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Procurement investments fall into five general categories: replacement of support equipment, replenishment of spares, modification of initial spares, new initial spares, and weapon system modification. Expenditures are dominated by weapon system modification. Within that category, the PRP and GRP make up a large share of all expenditures. These programs rebuilt or replaced two of the most critical Minuteman missile subsystems and represent 60 percent of total procurement expenditures for Minuteman III over the 20-year historical period. They were the major portion of a set of programs designed to extend the life of Minuteman to 2020.

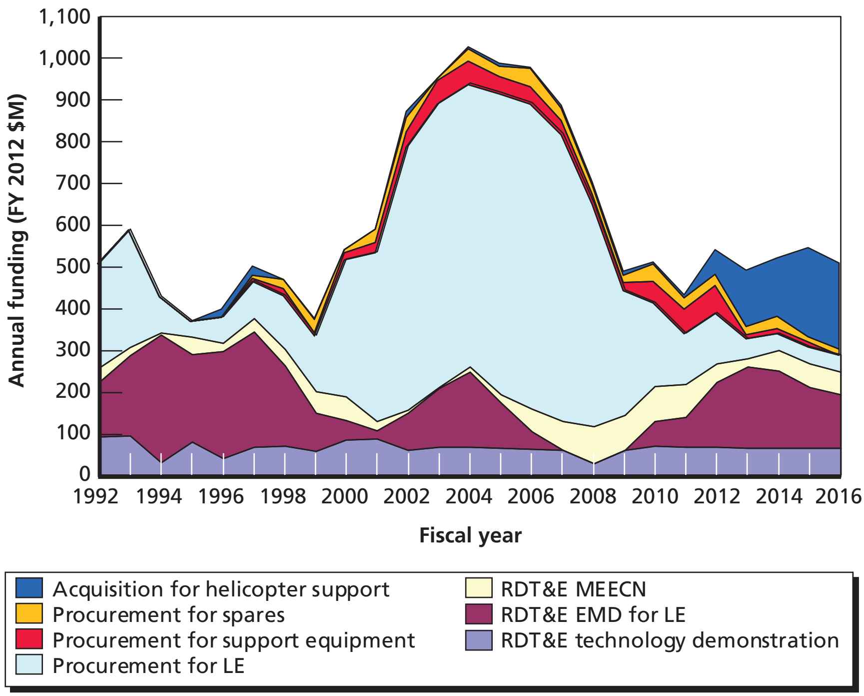
Over the 20-year historical period, annual procurement budgets of the five categories in aggregate vary widely between $37 million and $800 million (FY 2012 dollars) and averaged $390 million per year. The historical long-run annual average procurement is about $156 million if the GRP and PRP programs are excluded. Prior to the substantial investments in LEPs to 2020, annual procurement expenditures averaged $148 million per year. During the period including the GRP and PRP programs, the annual average increased to $644 million. In the period thereafter and extending into the FY 2012–2016 FYDP, the annual average is about $192 million. A large part of the planned procurement in the FY 2012–2016 FYDP was procurement of replacement support equipment needed to extend the life of the weapon system. Note that the FYDP does not extend far enough into the future to begin to show the costs of the procurement programs (in development during the FYDP) that extend the weapon system to 2030.

Figure 5.4 shows total historical acquisition investments for Minuteman III over the same 20-year period plus the FY 2012–2016 FYDP. This includes the development and procurement shown in prior figures plus the cost of the Common Vertical Lift Support Platform (CVLSP). The CVLSP program is intended to replace the UH-1N for missile field security.[7]

In the figure, we see minimum annual acquisition funding of just under $400 million (FY 2012 dollars) in FY 1995, and maximum just over $1 billion (FY 2012 dollars) in FY 2004. The planned acquisition

[7] Since the FY 2012–2016 FYDP, the CVLSP program has been deferred.

Figure 5.4
Minuteman III Acquisition Investment, 1992–2001 and FY 2012–2016 FYDP



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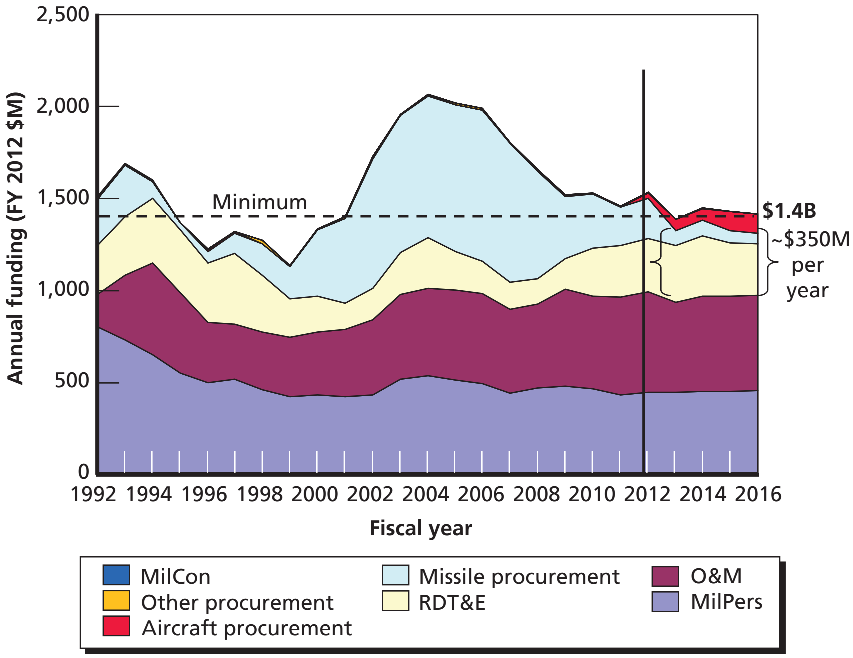
funding, including the CVLSP units for Minuteman missile silo fields, is about $500 million (FY 2012 dollars). These values provide good reference points for the level of annual acquisition investment that might be needed in future years if the incremental modernization option were followed.

Minuteman III Total Annual Costs

Given sufficient system capability, the annual cost to maintain that capability is arguably the most important concern. In Figure 5.5, we accumulate all costs associated with Minuteman III by adding together the previously discussed acquisition costs and those for O&S. O&S costs include system-related operations and maintenance (O&M) and military personnel (MilPers) expenditures.

Figure 5.5
Minuteman III Historical Total Annual Cost, 1992–2001 and FY 2012–2016 FYDP



NOTE: MilCon = military construction.
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Historical budget justification documents and FYDP data over 20 years show that annual O&M plus MilPers expenditures average about $1 billion. Over that period, the number of deployed Minuteman missiles has been relatively stable, decreasing from 500 to 450. The trend over the period shows a slight reduction in personnel costs as efficiencies were introduced and the number of missiles declined, along with a slight increase in O&M costs as the system aged. These two trends have mostly offset each other over time.

The long-run total annual cost, or TAC, to retain Minuteman III is between $1.4 billion and $2.0 billion. Figure 5.5 shows the TAC over 20 years plus projected TAC over the FYDP. Using this history to project into the future, the minimum estimate of $1.4 billion is relevant if an acquisition program for a replacement ICBM system were in development and therefore only minimal incremental modernization were needed to keep Minuteman viable through the full operational capability (FOC) date of the replacement system. The $1.4 billion is the sum of $500 million MilPers, $500 million O&M, and $400 million acquisition. The maximum of this range, just over $2.0 billion, represents the high end of what might be expected if an IIM approach were adopted based on historical SLEPs. This estimate includes $1.0 billion for acquisition plus the same $500 million for MilPers and $500 million for O&M as in the minimum estimate. The TAC range of $1.4 billion to $2.0 billion applies to a current-size ICBM force. The planned reduction from 450 to 420 missiles should slightly reduce costs, but the effects of continued aging may offset this saving.

Because most of the weapon system's costs are essentially fixed at each base, substantial force-size reductions, including closure of at least one of the two ICBM-only bases, would be required to substantially reduce current ICBM costs. A reduction in missile quantity at any base without base closure would bring only modest savings. Total annual O&S costs for the Minuteman III fleet plus the fixed costs of the two ICBM-only bases sums to less than $1.4 billion. If one of the two ICBM-only bases were closed, then the costs of its missile wing plus the fixed costs of the base could be saved, amounting to approximately one-third of the total annual O&S costs at a theoretical top end. In practice, however, Base Realignment and Closure savings tend to take a while to realize. Moreover, most nuclear specialty career field authorizations are outside of the wings. Together, this means that realistically, the potential for near-term savings by removing a wing are likely to be some fraction of the possible $400 million to $500 million.

If the Air Force decides to incrementally modernize Minuteman for the foreseeable future, the expected TAC should fall between $1.5 billion and $2.0 billion in constant FY 2012 dollars. The lower end of that range represents the investment level if there is no need for large modernization programs such as the PRP and GRP; the upper end of that range represents investment levels of funding assuming that these modernization programs at their highest funding years (FY 2003–2006) are needed in every future year.

Out-Year Minuteman III Modernization Programs Are Underfunded or Unfunded

The current Minuteman system requires both supportability and modernization funding to remain mission-capable. The ICBM program office submitted its non-O&S funding requirements for the weapon system to the 2012 AFGSC Program Objective Memorandum (POM). Excluding the helicopters, which are not managed by AFGSC, some 19 new Minuteman programs that support Minuteman III were specified. These programs included support equipment; MilCon efforts; and replacement or modification of various portions of the missile, its infrastructure, and systemwide command and control functionality. Total requested funding for these efforts over the FY 2012–2016 FYDP is shown in Figure 5.6. Requested funding grows to over $1 billion annually in FYs 2015 and 2016.

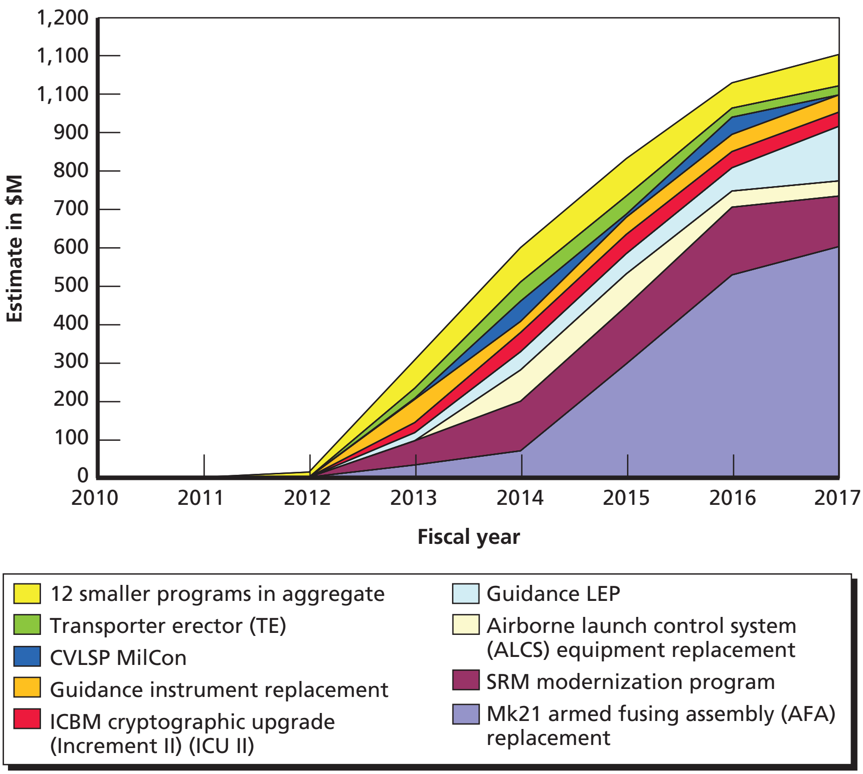
As indicated by the brackets at the center-right in Figure 5.5, actual funding in the FY 2012–2016 FYDP, excluding the program for security helicopters, is about $350 million per year. This funds current ongoing supportability and modernization programs plus any new programs added during the FYDP period. Comparison of the POM submission and the level of funding in the FYDP clearly show that only a fraction of the AFGSC request was funded. Right now, it is unclear how these underfunded and unfunded programs may affect Minuteman modernization.

Cost Considerations When a Follow-On System Is Anticipated

If Minuteman is replaced with a follow-on all-new ICBM, estimating future costs must include both those of the follow-on weapon system and those of continuing to operate Minuteman III for the years prior to and during the acquisition of the follow-on system. The following list shows Minuteman III costs that must be included in any calculation of TACs for the ICBM capability over the coming decades:

- continuing RDT&E for Minuteman III at least through IOC of the replacement system

Figure 5.6
AFGSC FY 2012–2016 POM Submission



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- continuing procurement (primarily modifications and spares) for Minuteman III through FOC of the replacement system
- continued MilCon for Minuteman III through demilitarization and disposal
- continuing MilPers for Minuteman III at least through the date of retirement of final Minuteman III assets
- continuing O&M for Minuteman III through its demilitarization and disposal.

Likewise, follow-on system costs that must be included in any calculation of TACs for the ICBM capability over the coming decades include

- RDT&E costs from Milestone A through the life cycle of the new weapon system—development, procurement, and operating and support
- procurement costs from their initiation prior to Milestone C through the remaining phases of the new weapon system's life cycle—procurement and operating and support
- MilCon through the life cycle of the new weapon system
- MilPers from prior to IOC through the remaining phases of the new weapon system's life cycle
- O&M from prior to IOC through the remaining phases of the new weapon system's life cycle.

Estimates of costs in each of these ten categories (five for Minuteman III and five for the follow-on system) are affected by plans, assumptions, and other factors that are both within and outside the control of the Air Force.

Minuteman costs in the near term are well understood. The TAC required to sustain Minuteman while a follow-on ICBM is procured will slowly decrease beginning when the formal acquisition program for the replacement system begins. Minuteman costs will continue until a few years after it is completely replaced, which will be presumably a few years after FOC of the follow-on system. Follow-on system costs will officially begin with the system's Milestone A. In each year during the acquisition of the follow-on system, Minuteman sustainment costs will slowly decline as first acquisition costs, and then sustainment costs, are incurred for the follow-on system.

The primary factors driving Minuteman III costs through its demilitarization and disposal are the acquisition start date for the replacement system and the final retirement-of-asset date. As of this writing, there is no planned date to begin acquisition of a follow-on system. Because that system's characteristics are unknown, there is no acquisition plan and therefore no planned FOC date. We do know that formal acquisition of the follow-on system is not within the FY 2012–2016 FYDP, and according to the 2010 ICBM Master Plan, it will not occur until at least 2020. That system's FOC date is unknown and will remain so until a few years prior to its occurrence.

The plan to soon begin the ICBM AoA suggests that if a replacement system is called for, it will achieve its Milestone B in the early 2020s. This means that Minuteman III must continue with all expenditures required for IIM of the system for the next ten years. Once the follow-on system's formal acquisition program is begun, the scope of acquisition investments required for the continuation of Minuteman operations will decline with each passing year as certain investments that would be required under an incremental modernization and sustainment strategy are no longer needed due to the system's eventual retirement.

Costs of the follow-on system are dependent on both the schedule for its acquisition and deployment and the system's characteristics. Uncertainties associated with the former are small compared with those of the latter. Many factors will affect the cost of the follow-on system. In general, the more differences between the follow-on system and the current system, the greater the technical, schedule, and cost risks inherent in its acquisition will be. Technical and schedule problems ultimately manifest themselves not only in difficulty meeting requirements and deadlines but in increased costs. Changes between Minuteman and its possible follow-on that add uncertainty to the acquisition of follow-on program include, but are not limited to,

- ICBM size
- basing concept other than housing in the existing Minuteman III silos
- launch constructs, e.g., mobile modes
- trajectory, e.g., other than ballistic, nonmaneuvering RVs
- payload, e.g., nuclear versus conventional.

ICBM Cost Estimates Relevant to Potential Follow-On Systems

The most relevant cost data for estimating a follow-on ICBM system are historical cost estimates for actual ICBM systems and estimates from the 2006 LBSD AoA. Table 5.1 shows actual costs from four historical ICBM programs.

The four ICBM weapon systems are listed in the leftmost column of Table 5.1. In the top title row are the three substantial components of any acquisition program—development, procurement, and MilCon. Also in that row is Average Procurement Unit Cost (APUC), which is the procurement estimate divided by the number of procurement units in the program. The second title row indicates the type of inflation index used to convert each program's costs to FY 2012 dollars. Two indexes were used: Air Force, which is specific to funding type (aircraft and missile system development or procurement; MilCon) and Producer Price Index (PPI), which is specific to the aerospace industry. While neither index is completely accurate for this application, in the cost analysis community, it is widely believed that the PPI provides a more accurate adjustment for the effects of inflation. The third title row indicates the type of dollars below; either then-year dollars (TY$ or budget) or base-year 2012 dollars (BY12$ or FY 2012). The figures relevant to this analysis are those in the bold print that are in BY12$.

The proper interpretation of the figures in Table 5.1 requires a thorough understanding of the context of each of the numbers. Nuclear warhead costs are excluded from the program costs shown. Costs for Minuteman include newly built missiles from a design that modified and improved upon the previous Minuteman II (MM II).

Table 5.1
Historical ICBM Program Cost Estimates, in Millions of Dollars

	Development			Procurement				APUC	MilCon		
		USAF	PPI		USAF	PPI		PPI		USAF	PPI
	TY$	BY12$	BY12$	TY$	BY12$	BY12$	Qty.	BY12$	TY$	BY12$	BY12$
MM III	2,408	10,048	**14,900**	5,251	19,578	**26,400**	794	**33**	20	80	**100**
Peacekeeper	11,001	21,126	**26,800**	9,279	14,963	**17,500**	102	**172**	313	554	**700**
Peacekeeper Rail[a]	2,472	3,675	**4,700**	4,017	5,200	**6,100**	50	**22**	639	875	**1,100**
SICBM[a]	11,650	18,127	**21,400**	30,678	41,172	**48,700**	623	**78**	2,401	3,202	**3,800**

[a]These programs were never deployed.

Because existing silos were retained and used for the then follow-on Minuteman III system, no new basing or substantial base infrastructure was required. The Minuteman III program created an upgraded missile within existing infrastructure. A development cost estimate of $14.9 billion and APUC of $33 million are therefore reasonable for a Minuteman IV missile development and APUC. The MilCon bill for Minuteman III was minimal given similarities to the Minuteman II system it replaced and, more importantly, the fact that the silos were only about ten years old at the time this modernization took place in the early 1970s.

The Peacekeeper program is the only all-new ICBM program completed in the past 30 years. This makes its acquisition cost arguably the most relevant to estimating any ICBM weapon system centered around an all-new missile. The $26.8 billion development cost of the Peacekeeper is at the high end of what one might expect to replace the current missile since Peacekeeper was much larger than Minuteman and was cold-launched from Minuteman silos. Total Peacekeeper procurement was $17.5 billion, but this bought just 102 missiles. Barring a substantial force structure reduction, a hypothetical Minuteman III follow-on may need a purchase in the realm of 500 missiles to field a force size consistent with current deployment.[8] The $172 million APUC cost of the Peacekeeper is a more relevant number, but it is almost certainly high due to the missile's relatively large size and the relatively small number of Peacekeepers purchased. The Peacekeeper program's $700 million MilCon cost is somewhat relevant as new facilities were required for its support. However, this cost is certainly low compared to that for a Minuteman III because only 50 Minuteman silos were ultimately refurbished to accommodate this much larger, cold-launched missile. Purchase of an all-new missile may require refurbishment of as many as 450 silos.

Although Peacekeeper was an all-new missile, that program did not have costs associated with alternative basing modes. The Peacekeeper Rail Garrison program proposed to disperse and deploy Peace-

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[8] The additional units beyond the 420 operational are for annual test firings over the life of the system.

keeper missiles via trains utilizing the U.S. commercial rail infrastructure. This program was canceled four years after its Milestone B, with production canceled 27 months past that milestone. No procurement money was expended. As a result, the costs shown in Table 5.1 are estimates from about midway through the system's major development. Cost estimates from the program are for the employment mode and do not include the cost of the 50 Peacekeeper missiles (and their initial spares) that were to ride the rails. Most of the funding in the program was to acquire 25 trains, each of which was to carry two Peacekeeper missiles plus multiple support rail cars. The remaining program funding was to acquire seven garrisons, each of which would house four missile trains when not deployed. Each garrison complex was to include all the support functions needed for the personnel to operate and maintain the trains. The program's development and procurement estimates represent those for the 25 missile trains and seven garrisons. The MilCon estimate represents housing and other base infrastructure costs to support the envisioned garrison complexes. We draw on these cost estimates to make estimates for mobile ICBM options that fall into categories 5 and 6. The SICBM program proposed to build an all-new smaller ICBM initially deployed at Minuteman ICBM launch facilities, with the future option of southwestern U.S. basing using a random movement mode to enhance survivability. The SICBM was to be mounted on HMLs. The program was first canceled early in development, just after its initial System Design Review (SDR).[9] Some of the latest estimates for the HML employment concept are those reported just before that cancellation—from the June 1987 SDR in the June 1987 Selected Acquisition Report. The $21.4 billion development estimate was to design the missile, the HML, all command and control functionality, and the entire support infrastructure. The $48.7 billion procurement estimate was for the 623 missiles needed to field 500 operational units, plus at least 500 HMLs to carry the operational missiles. The missiles were estimated at $19.8 billion; the HMLs and command and control hardware were estimated at $28.9 billion. The

[9] A production program with Minuteman silo basing only (no HML) was briefly reinstated in March 1991, but the entire program was permanently canceled shortly thereafter.

procurement estimate per missile was $32 million, that per HML was about $55 million, and that per deployed missile (500) and its HML was $97 million. The figure in Table 5.1 of $78 million is per acquired missile (623). The $3.8 billion MilCon estimate covered the envisioned road infrastructure and other necessary facilities at two Minuteman III bases, without the random movement mode. Southwestern basing was not included in these estimates. Because the force size of 500 operational missiles with 623 procured is close to the number expected for a Minuteman III follow-on system, the SICBM program estimates make good references for any option that envisions a road-mobile, smaller ICBM.

The 2006 LBSD AoA developed detailed cost estimates for replacing Minuteman III with an essentially identical system, and for four follow-on weapon system options. We used an identical replacement cost estimate as a baseline reference for the follow-on options. All options assumed 500 deployed missiles and fell into our third "Minuteman IV" category. The LBSD AoA also provided rough estimates for the additional cost to acquire mobile ICBM options—a rail-garrison or road-mobile system. Table 5.2 shows the data from the LBSD AoA, with estimates inflated from the FY 2004 dollars shown in that report to FY 2012 dollars using official Air Force inflation indexes.

The development estimates from the LBSD AoA are similar to the historical cost of designing Minuteman III from the Minuteman II design. This appears reasonable given that each missile alternative

Table 5.2
2006 LBSD AoA Cost Estimates (FY 2012 $B)

Acquisition Cost Category	Low Estimate of Four LBSD Options	High Estimate of the Four LBSD Options
Missile RDT&E	13.8	16.1
Missile procurement	17.6	19.8
MilCon (silo refurbishment)	5.9	5.9
Total acquisition	37.3	41.8
	Additional Costs for Alternative Basing Modes	
Rail garrison	29.4	
Road mobile	41.2	

analyzed could be described as a "Minuteman IV." The range of estimates for procurement, when divided by 623 missiles (presumably the number required for purchase to field 500 operational missiles over several decades) is between $28.3 million and $31.8 million per missile. This estimate range is lower than the historical cost of $33 million APUC to procure 794 Minuteman III missiles. The estimate seems even lower when compared to the estimated $32 million missile unit cost for much smaller missiles in the SICBM program. The analytical source for the MilCon estimate was the 2005 LBSD Basing Study. The estimate is more than $100 million per operational silo, which is much higher than in any of the historical programs. The 2005 LBSD Basing Study[10] outlines a comprehensive refurbishment of silos bordering on complete reconstruction.

Estimates for the alternative basing modes are considerable. The nearly $30 billion for the rail-garrison concept assumed 100 trains, five missile cars per train; one launch car per train; three security cars per train; three living cars per train; and one maintenance car per train. The garrison structure assumes 25 garrisons with four trains per garrison and a maximum of two garrisons per base. This means that the system would be spread out over 13 different bases, each of which would require a 140-acre housing complex in support of each garrison. The estimate included construction of 1,000 miles of additional track (40 miles per garrison) and the purchase of additional land for adequate dispersal of garrisons. The employment concept assumes that the trains would remain in garrison unless dispersed by executive order. In accordance with the treaties of the time, little to no random movement would occur. There would be no fixed sites for dispersal because locations would be specified via GPS coordinates. Depot-level maintenance would occur at a single base, with base-level maintenance infrastructure scaled to the number of trains at each garrison.

The more than $41 billion estimate for the road-mobile concept assumes 500 tractors, 500 launch vehicles, 15 ground-mobile LCCs, three fixed LCCs, and 20 launch control relays. The garrison structure, employment concept, and support concepts are similar to those

[10] Flint, 2006.

of the rail mode. The system assumes 25 garrisons with 20 systems per garrison, 13 base housing garrisons, 140 acres per garrison, and 4,000 miles of additional road (160 per garrison) and the purchase of additional land for adequate dispersal of garrisons. The employment concept assumes that the mobile launchers would remain in garrisons unless dispersed by executive order. As in the rail-garrison case, little to no random movement would occur, and there would be no fixed sites for dispersal, as locations would be specified via GPS coordinates. Again, depot-level maintenance would occur at a single base, with base-level maintenance infrastructure scaled to the number of trains at each garrison.

Cost Estimates for Selected Possible Future Force Options

Figure 5.7 depicts our estimates for four future ICBM options derived from cost estimates in the 2006 LBSD and from current and historical ICBM systems. Each pair of bars shows approximate minimum and maximum estimates for each of the options. Totals are for the period 2012 through 2050, inclusive, or 39 years.[11] This period was chosen because it encompasses the entire acquisition of any replacement system and the early part of that system's operational life. It does not go so far into the future as to require LE efforts to that replacement system. This is based on the assumption that the acquisition of a replacement would begin around 2020 and would be completed by 2040.

In each case, life-cycle costs are shown as a stacked bar of the four primary cost categories: RDT&E, procurement, MilCon, and O&S.[12] In the last three categories, costs include both those for continuing the current Minuteman system and those for its replacement. In the rail-garrison and road-mobile options, the missile, Minuteman V, is different than the Minuteman IV in the second category, which accounts for necessary modifications to make the missile robust while mobile. The

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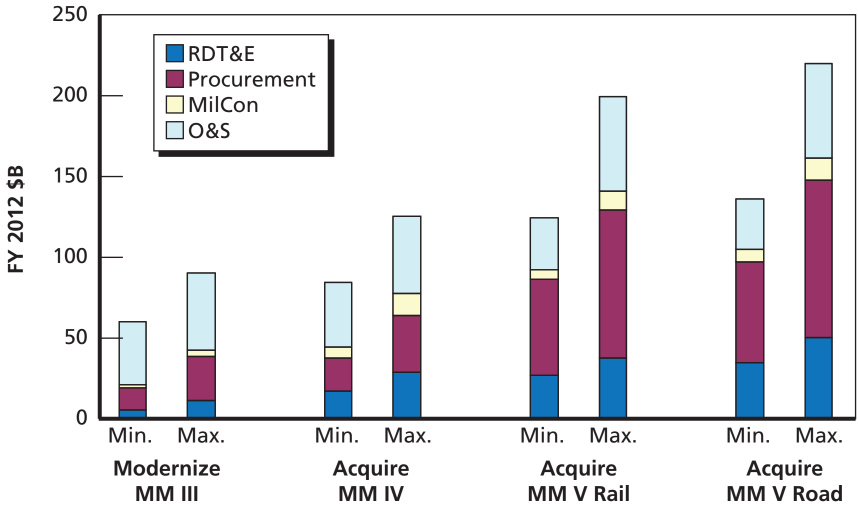
11 This research was conducted in FY 2011.

12 Demilitarization and disposal costs are typically small in the context of overall life-cycle costs and are therefore omitted from the totals.

Figure 5.7
Life-Cycle Cost Estimate Minimums and Maximums for Four Potential ICBM Future Force Options, FY 2012–2050



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mobile missile must be designed and built to more-demanding specifications then a silo-based ICBM.

The bars on the far left of Figure 5.7 show the cost estimate range for incremental modernization and sustainment of Minuteman III. From the categories earlier defined, this is the option in category 2. Estimated costs for basic sustainment would be similar. The second pair of bars from the left represent the cost range for acquiring a follow-on "Minuteman IV." The minimum is the lowest plausible cost for a system built around a new missile that is smaller than the current system with a virtually identical employment concept. The maximum is the highest plausible cost for a system built around a new missile that is larger than Minuteman III with a similar employment concept. This range covers the options that fall into categories 3 and 4. The two pairs of bars on the right of the figure represent the ranges for acquiring a "Minuteman V" missile in two different mobility schemes. The minimums are the lowest plausible cost for a system built around a new, smaller mobile missile with an employment concept requiring lands within the existing Air Force military base scheme. The maximums are the highest plausible cost for a system built around a new, larger mobile missile with an employment concept requiring lands acquired beyond those of the existing Air Force military base scheme. This range from the minimum to the maximum of the four stacked bars covers the options that fall into categories 5 and 6. Table 5.3 shows the totals for each of the stacked bars in Figure 5.7 and the annual averages, given the 39-year time span.

Rough Cost Estimates by Category

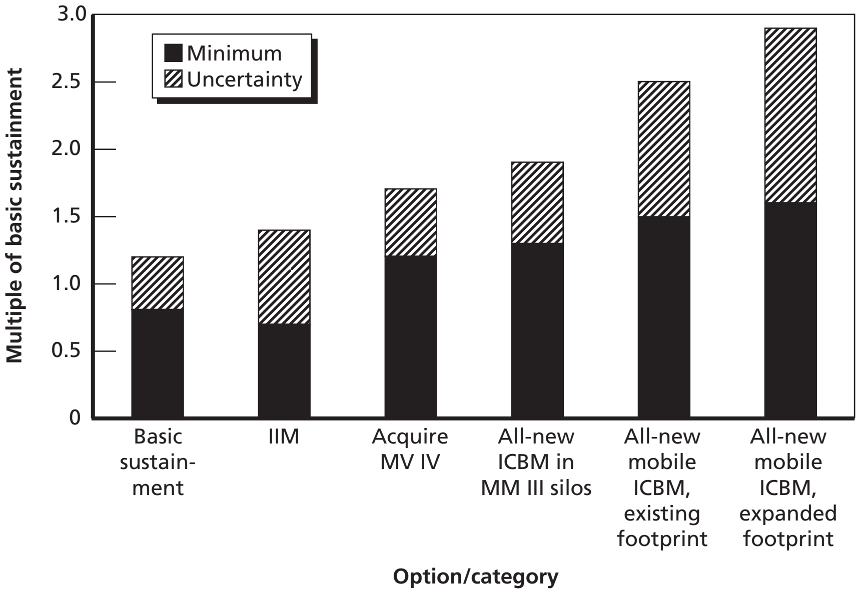
Estimating costs of future ICBM weapon system concepts is highly subjective without specifically defined weapon system concepts. As noted earlier, the unknowns in each of the six successive categories increase. It follows that the cost uncertainty in each successive category grows as well.

Even with this uncertainty, we can still compare relative costs of system concepts in the six categories. Figure 5.8 provides these relative costs, whose ranges should be considered notional. Much more detailed analysis would be required to reduce the uncertainties within each category, and significant uncertainty will remain even after an ICBM AoA. The relative figures represent total life-cycle costs over a 50-year period, FY 2013 through 2062. Total life-cycle costs over the specified 50-year period include all development, procurement (including modifications), MilCon, and O&S costs for the next-generation

Table 5.3
Total 39-Year Life-Cycle Costs and Average Total Annual Costs of Four Plausible Future ICBM Options (Billions of 2012 $)

	39-Year Life-Cycle Cost		Average Total Annual Cost	
Option	**Minimum**	**Maximum**	**Minimum**	**Maximum**
IIM of MM III	$60	$90	$1.6	$2.3
MM III to MM IV	$84	$125	$2.2	$3.2
MM III to MM V rail garrison	$124	$199	$3.2	$5.1
MM III to MM V road mobile	$135	$219	$3.5	$5.6

Figure 5.8
Notional Relative 50-Year Life-Cycle Costs by Category



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ICBM. Note that O&S costs include all those for O&M and MilPers. The 50-year period was chosen because this typically covers the entire life cycle of a modern weapon system.

Relative costs are normalized to the basic sustainment of the current system without its upgrade or modernization. Even this option has substantial uncertainty in its future costs over the next 50 years. The modal or most likely cost estimate for basic sustainment assumes that no all-new system is acquired in the coming 50 years. The cost of basic sustainment of Minuteman III is nominally set as 1.00, with an uncertainty range of plus or minus 20 percent. Therefore, the figure shows a minimum of 0.80 and a maximum of 1.20 for basic sustainment.

The modal cost estimate for incremental modernization of the existing system is also 1.00, but with a larger uncertainty range of plus or minus 30 percent. The modal cost estimate of this approach also assumes that no all-new system is acquired in the coming 50 years. The reason for the same most likely cost as the basic sustainment option is that incremental moderization provides the opportunity to trade off modernization investments in the most problematic areas of the weapon system against the potential payoff of lower O&S costs resulting from those upgrades. In the basic sustainment option, investments in the most problematic areas would also be made over time, but modern materials and designs would not be leveraged to improve inherent supportability. Incremental modernization of Minuteman III has most of the underlying cost uncertainty causes as basic sustainment does, plus the added uncertainty of incremental modernization. Therefore, the cost estimate uncertainty for this option is larger. Modernization and sustainment over the long run could cost less—or more—than the basic sustainment approach to keeping Minuteman III viable. While modernization carries more cost uncertainty than category 1, it has less mission-capability risk. Basic sustainment, by definition, includes no capability enhancements or supportability improvements. These restrictions do not apply to modernization, hence the reduced mission capability risk.

Category 3 is the least costly and has the lowest cost uncertainty of those categories that involve a replacement system for the current Minuteman system. This category, acquiring a Minuteman IV, has a modal cost estimate of 1.30, or 30 percent higher than that for basic sustainment or IIM. The uncertainty range for this category is 1.20 to 1.70, meaning that the plausible range for its cost is between 0.10 less and 0.40 more than the modal estimate. Prior acquisitions research shows that the probability of a weapon system coming in below its original cost estimate is small.[13] When this does occur, actual costs are less than the estimate by only a small margin. This explains why the minimum of this range is just 0.10 below the modal estimate. The same research also shows that when costs come in over the original estimates, they do so over a larger range. In the context of major defense acquisition programs, the acquisition of a "Minuteman IV" is a relatively low-risk effort, hence the relatively low worst-case estimate of

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[13] See Mark V. Arena, Robert S. Leonard, Sheila E. Murray, and Obaid Younossi, *Historical Cost Growth of Completed Weapon System Programs*, Santa Monica, Calif.: RAND Corporation, TR-343-AF, 2006, p. xii.

1.70. The reason for the higher cost of the system concepts that make up this category (i.e., infinite permutations of the exact capability and content of a "Minuteman IV" system) in comparison to basic sustainment and incremental modernization is the acquisition of the new system. The operating and support costs for "Minuteman IV" should be similar to those of the current system.

Category 4 is more costly than category 3 because the new ICBM to be acquired is of an all-new design and different size than Minuteman III. These differences mean a larger development bill for the new ICBM and a larger refurbishment cost for the existing silos in which the all-new ICBMs are to be based. O&S will also be higher during the transition period since the two categories have little system support in common. This category, the acquiring of an all-new, differently sized ICBM, has a modal cost estimate of 1.45, or 45 percent higher than the costs for categories 1 and 2. The uncertainty range for this category is 1.30 to 1.90, meaning the plausible range for its cost is between 0.15 less and 0.45 more than the modal estimate. This range is larger than that of category 3 because of the added cost risk of an all-new ICBM design, the uncertainty of the size of the all-new ICBM, and the added uncertainty associated with low commonality in system support between the outgoing Minuteman III and the incoming, all-new-design ICBM.

Category 5 involves the acquisition of an all-new-design ICBM but utilizes a strikingly different concept of operation because of the ICBM's mobility. The portion of this all-new system design that provides mobility adds substantially to the costs and cost uncertainty of options in this category compared with options that fall into categories 3 or 4. The costs of the mobility vehicle (rail cars, on-road, or off-road vehicles) and associated infrastructure (rail infrastructure, roads, bridges, etc.) add to all the other costs of the options in categories 3 and 4. The one exception is silo refurbishment, which is part of categories 3 and 4 but clearly not needed for options that fall into category 5. Past mobility schemes suggest that the cost of acquiring a mobility vehicle far exceeds that of refurbishing existing silos. In addition, the all-new-design ICBM must operate reliably under the added rigors imposed by its movement. Silo-based ICBMs reside in a benign environment compared to that experienced by a mobile ICBM launched from an above-ground vehicle. This category has a modal cost estimate of 1.70, or 70 percent higher than that for the basic sustainment or modernization options. The uncertainty range for this category is 1.50 to 2.50, meaning the plausible range for its cost is between 0.20 less and 0.80 more than the modal estimate. The huge increase in uncertainty results from a lack of success by the United States in fielding a mobile ICBM in the past. Both weapon system programs from the Cold War era that proposed such a system—the original road-mobile construct for the SICBM and the rail-mobile Peacekeeper program—were canceled prior to their becoming operational.

Category 6 is more costly than category 5 because the all-new-design mobile ICBM is to operate on an expanded footprint, adding the costs of accessing the additional land area and the cost of a larger infrastructure on which the system can deploy. In all other aspects, the options that fall into category 6 are similar to those that fall into category 5. Options that fall into category 6 have a modal cost estimate of 1.80, or 80 percent higher than that for the basic sustainment or IIM options. The uncertainty range for this category is 1.60 to 2.80, meaning that the plausible range for its cost is between 0.20 less and 1.00 more than the modal estimate. All of the uncertainty from category 5 applies to category 6, plus additional issues associated with the expanded footprint—including potential legal challenges, potential public interface issues and the associated politics, and expanded security concerns.

Cost Conclusions

We make the following insights on costs of future ICBM alternatives:

- Incremental modernization of Minuteman III is less costly than any option in categories 3 through 6.
- The silo-based "Minuteman IV"-type system concepts in categories 3 and 4 are less costly than mobile options in categories 5 and 6.

- Any mobile option is likely to cost about twice as much as continued and incremental modernization of the current Minuteman system.
- Uncertainty in the cost of any future ICBM force grows as the system design and employment concept diverge from the current missile and its silo basing.

In particular, what jumps out most prominently from Figure 5.7 above is that acquisition costs alone for any mobile system are at least as much as all current expenditures for Minuteman III (the top of the yellow part of the bar for the minimum mobile concept is about even with the top of the total bar for the maximum Minuteman III baseline). Further, none of the alternatives considered presents a net present value savings since costs are relatively equally distributed in the options over time. Therefore, any system that incorporates mobile aspects will cost more than the continuing incremental modernization and sustainment of Minuteman III, even if one could save 100 percent of O&S costs. In particular, the reality of a garrison-mobile system that colocates missiles on a day-to-day basis means that any O&S savings would be offset by the capital investment needed in mobile TELs and a new missile that is designed to handle the shocks and movement of a mobile carrier.

While we draw these insights from our synthesis of existing cost analysis and program data, we cannot make true cost-benefit comparisons until requirements are properly defined. The purpose of these estimates is to explore the range of options and potential costs that may be considered in the AoA. Although we can project costs to incrementally modernize and sustain Minuteman III with some confidence based on recent SLEP efforts and other carefully documented program dollars, investments for potential follow-on systems are more uncertain. This is one of the reasons why we rely somewhat more on relative costs for classes of follow-on alternatives.

CHAPTER SIX

Conclusions

U.S. strategic nuclear forces may be called on to play a role in a widening set of security situations. ICBMs in particular may find some new relevance in extending deterrence and assuring allies because they present a serious threat to newly emerged nuclear states that choose to base nuclear weapons and their means of delivery in the open or on alert. If these challenges demand more from the U.S. ICBM force than Minuteman III can deliver in a cost-effective way, a number of different alternatives are worth consideration. The upcoming ICBM AoA will have to assess these alternatives across a broad set of potential characteristics and situations weighed against the costs of the alternatives. We classify ICBM variants according to five basic categories: basing, propulsion, boost, reentry, and payload. We use this categorization to assess the survivability of basing alternatives and the effectiveness of possible alternatives to hold certain targets at risk. The following observations and findings are based on these assessments and on cost estimates for various classes of ICBM alternatives.

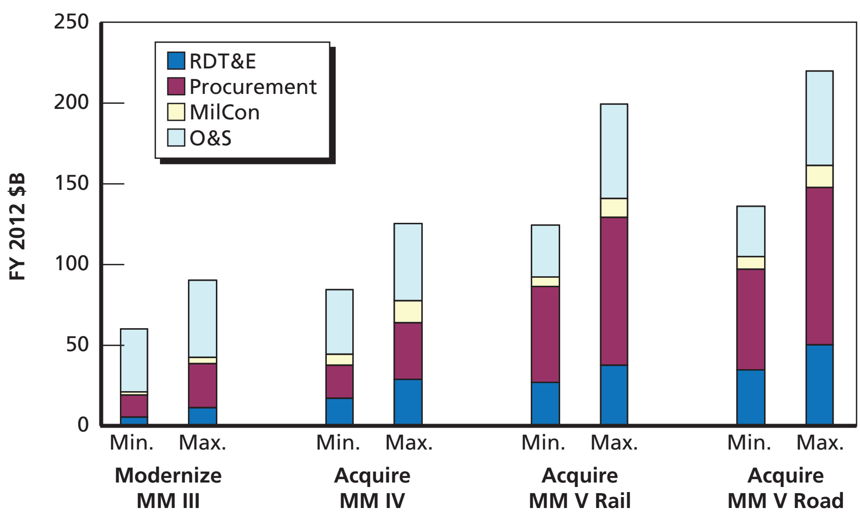
ICBM Cost Implications for the Upcoming Analysis of Alternatives

Our initial survey of options suggests that incremental modernization and sustainment of the current Minuteman III force is a cost-effective alternative that should be considered within the AoA. Detailed costs and risks involved in pursuing incremental modernization beyond 2030 have not yet been fully established, however. The modernization option of the AoA should include all key aspects of the ICBM system: silos, NC3, and other support equipment.

The biggest hurdle currently foreseen in sustaining Minuteman III up to and beyond 2030 with continued SLEPs is the declining number of missile bodies available to support an operational test program of three to four Minuteman III launches per year. If 420 Minuteman III missiles are retained for operations, the test inventory will be depleted by 2030. Maintaining a smaller force of 400 missiles would delay this milestone several years to 2035 by making more bodies available for tests; fielding even fewer missiles would proportionately extend the depletion date.

According to the estimates we derived in Chapter Five, any new ICBM alternative is likely to cost more than the incremental modernization of Minuteman III, as summarized in Figure 6.1. Any new ICBM alternative will very likely cost almost two times—and perhaps even three times—more than incremental modernization of the current Minuteman III system. The only viable argument for developing

Figure 6.1
Life-Cycle Cost Estimate Minimums and Maximums for Four Potential ICBM Future Force Options, Revisited, FY 2012–2050



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and fielding an alternative would therefore have to be requirements-driven. Options would be relevant only insofar as warfighting and deterrence demands push ICBM requirements beyond what an incrementally modernized Minuteman III can offer.

Options for Survivable Basing

Currently, only Russia is capable of attacking U.S. ICBMs effectively. Even in this situation, an attack would require a substantial fraction of Russian RVs under the New START ceiling. Thus, the long-standing vulnerability of U.S. ICBMs to a Russian (formerly Soviet) attack may no longer be the problem that it once was. It could take 60 percent of Russia's post–New START warheads to attack Minuteman silos. Depending on how much of its force Russia allocates to its ICBMs, this may be more than the total number of Russian ICBM RVs. Two matters could change this imposed cost: (1) a dramatic improvement in the quality of Russian systems, and (2) a change in the relative balance of forces with respect to the number of U.S. silos, which could occur either by Russian breakout or U.S. unilateral reductions. Mobile basing modes could improve survivability of U.S. ICBMs in either of these cases. However, the undesirable costs and features of mobile basing that precluded mobile basing decisions during the Cold War are only more restrictive now.

Cost and survivability assessments will likely limit basing options to existing missile silos and infrastructure for the foreseeable future. Any follow-on system should be compatible with existing Minuteman silos. Hedging options within the existing architecture could explore maintaining unoccupied silos in a "warm state" as the force is reduced or as missile force size changes. To ensure that basing in current silos remains a viable option into the future, Air Force Materiel Command (AFMC), the Air Force Nuclear Weapons Center (AFNWC) SPO, and AFGSC should expand SLEP activities to include nonflight-system elements, in particular silo infrastructure, in order to better understand the costs and mitigate the risks of sustaining the current force beyond 2030 to 2035, 2040, and 2050. A reduction of the ICBM force that may correspond to New START could be an opportune time to examine parts of the ICBM system more broadly. Recently emptied silos would be a good place to start an engineering forensics effort to identify possible areas of concerns.

Propulsion, Boost, Reentry, and Payload Options for ICBM Effectiveness

While ICBM propulsion will likely continue to be based on solid fuels, boost, reentry, and payload options can improve current capabilities and introduce entirely new capabilities to hold a potentially larger class of targets at risk while mitigating overflight concerns. If overflight of Russia and China remains a concern for the ICBM, one of the most effective ways to mitigate that concern may be to add launch options to Vandenberg and Cape Canaveral. Overflight from current wing locations can be addressed by launching south or changing planes; however, both options add significantly to missile size requirements and raise destabilization dangers that in the past have led to careful negotiations, treaties, and bans. For payload options, a strategic nuclear ICBM is both a quantitatively and qualitatively different system than a conventional ICBM. A conventional ICBM can hold only a narrowly defined set of targets at risk because of the relatively small amount of available payload and the potentially limited ability to strike mobile objects. The upcoming AoA should therefore focus on the nuclear capabilities necessary to deter attacks from established nuclear powers and to provide an effective counterforce capability against hostile emerging nuclear states in dangerous situations. An AoA could, however, consider conventional payloads as an option for some ICBM designs should the need arise. As we describe in Chapter Four, to make a conventional payload on an ICBM technically viable requires significant accuracy improvements. This translates into adding a control system to the reentry vehicle since atmospheric and weather effects alone can introduce significant errors. The United States has considerable experience developing and testing MaRVs and a consistent record of continually improving the performance of IMUs that would have to be integrated and tested.

Technologies and platforms that could change the nature of intercontinental-range delivery, such as the HGV concept, are also currently in early stages of testing and development. These have the potential to change the relationships among range, payload, reentry, and propulsion that have long been established for SRM ICBMs. Although these programs still seem to be in early stages and may therefore accrue substantial RDT&E costs before demonstrating technical readiness, the ICBM AoA should examine how these options could affect the calculus of adding capabilities.

ICBM Force-Size Reduction Implications

Congressional direction to cut substantial amounts from the DoD budget, as well as the NPR's stated goal of decreasing U.S. reliance on nuclear weapons, could drive force size lower than New START would otherwise prescribe. Only complete closure of an ICBM-only base, however, would bring about substantial annual O&S cost savings. Because total annual O&S costs are less than $1.5 billion, even in this case, the savings are likely to be relatively small and realized over a long time period.

Of interest to Air Force personnel and career field managers, we detail in the appendix the effects of further force reductions on ICBM manpower. We find that officers and enlisted personnel with key nuclear expertise will continue to be available even if the ICBM force size were reduced to 150 missiles. However, if the Air Force continues its current personnel policies, as the number of ICBMs decreases, supply and demand mismatches—specifically within the 13S nuclear specialty career field—will be exaggerated, and mismatches in the 2M0 career field may arise. Air Force manpower policies will need to adapt in the case of a decreasing force; personnel experts will require appropriate tools and techniques to manage these career fields. Nevertheless, when we examined decreasing the force to 150 ICBMs, we did not find a force size "redline" below which these and other career fields are completely unmanageable or that would require an entirely new ICBM operating concept.

While budgetary pressures may make it difficult to significantly upgrade or replace the current silo-based Minuteman, new challenges may call for capabilities beyond what Minuteman currently delivers. The upcoming AoA will have to weigh any potential gains against the likely costs. In this report, we have helped to set some terms of reference for the AoA and to narrow the focus of possible alternatives.

APPENDIX

Manpower Thresholds

Periodically, the United States has made adjustments to its ICBM missile force. Having evaluated its then current and projected security environment, the United States reduced its ICBM force from 1,000 launchers in 1990 to 550 by 1997. The numbers of missile wings and squadrons was cut in half, from six to three and from 20 to 11, respectively. In 2005, the number of ICBMs was further reduced to 500 with the deactivation of the 400th Missile Squadron and its 50 Peacekeeper missiles. In 2008, as a result of the 2006 Quadrennial Defense Review, the 564th Missile Squadron, with its 50 Minuteman III missiles, was deactivated. All of these ICBM reductions were accompanied by corresponding cuts in people and manpower funding.

At present, the U.S. ICBM force consists of 450 Minuteman IIIs, each deployed with between one and three warheads. These missiles are located at three Air Force bases, each with 150 missiles: F. E. Warren in Wyoming, Malmstrom in Montana, and Minot in North Dakota. The Minuteman III missiles are being downloaded to single RV designs and are undergoing a series of improvement programs to maintain combat effectiveness, as described in Chapter Five. With the removal of the Peacekeeper missile in 2005, the Minuteman III is the only U.S. land-based operational ICBM.

The Obama administration and Congress are again evaluating the current and projected security environment with implications for the ICBM force. In particular, the administration is considering plans that would reduce the number of Minuteman III missiles below current numbers, to 420 or perhaps lower. The administration indicated in the 2010 *Nuclear Posture Review Report* that, under New START, all the Minuteman III missiles will carry only one warhead. Still, some analysts have questioned why the United States must maintain such a large force of nuclear weapons.[1]

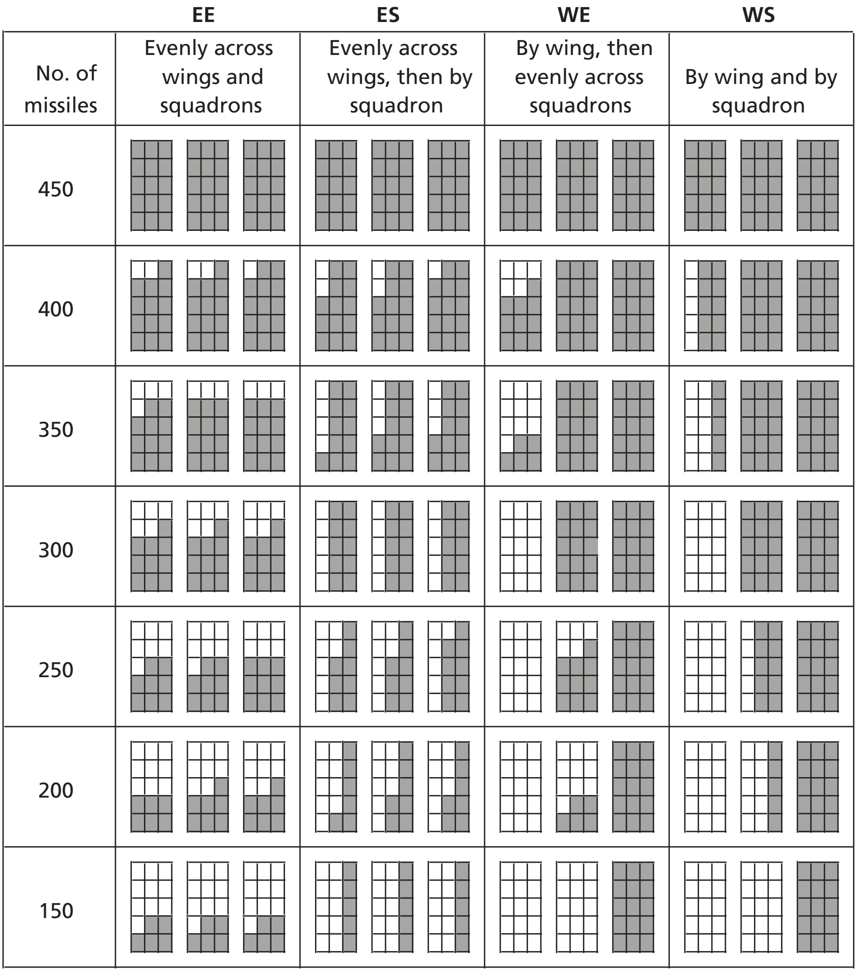
The number of personnel associated with the strategic offensive nuclear force has been moving downward since 1990. As the United States reviews and possibly changes its nuclear forces, Air Force force structure and manpower planners must assess the potential effects reductions may have on the Air Force's ability to retain sufficient human capital and infrastructure to maintain the safety, security, and reliability of the ICBM force. In particular, it must address whether "minimum thresholds" exist below which alternative organizational or career paths might become more appropriate. This appendix provides an initial assessment and offers a framework for continued evaluation as additional information becomes available.

Framework and Methodology

We begin with the organization and distribution of manpower authorizations across the three missile wings as of the end of FY 2010 and estimate how they would change if the ICBM force structure were reduced in various ways. Figure A.1 depicts the reduction scenarios that we considered, reflecting incremental cuts of 50 missiles at a time, starting with today's 450 Minuteman IIIs and cutting down to 150. Each missile wing has three squadrons, each with five LCCs controlling ten Minuteman IIIs apiece. We expect that cuts would come one LCC (ten missiles) at a time and that cuts of five LCCs (50 missiles) could be taken in the four ways illustrated. The larger the cut, the more of the figure's cells, each representing one LCC, go unshaded. For example, if 50 missiles (five LCCs) were eliminated, the four options for taking the cuts would

[1] See, for example, Sidney D. Drell and James E. Goodby, *What Are Nuclear Weapons For? Recommendations for Restructuring U.S. Strategic Nuclear Forces*, Washington, D.C.: Arms Control Association, 2005, updated October 2007.

Figure A.1
Reducing the ICBM Force in Different Manners and Amounts



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- EE: Distribute the cuts as evenly as possible across the wings and their squadrons, eliminating two LCCs from two wings and one from the third. Each wing that lost two LCCs would lose one LCC each from two of its three squadrons, while in the third wing only one squadron would lose an LCC.

- ES: Distribute the cuts as evenly as possible across the three wings but concentrate them in as few squadrons as possible, cutting two LCCs from one squadron in each of two wings and one LCC from one squadron in the third wing.
- WE: Concentrate the cuts in one wing and distribute them as evenly as possible across its squadrons, taking two LCCs from two of the affected wing's squadrons and one from its third squadron.
- WS: Concentrate the cuts in one wing and squadron, eliminating the squadron.

Excluding its top row, which reflects the baseline 450 missiles (45 LCCs) as the starting point for each column, Figure A.1 depicts 24 reduction scenarios.

We consider nine specialties that the cuts seemed more likely to affect significantly:

- Two officer specialties: space and missile operations (13S) and munitions and missile maintenance (21M)
- Seven enlisted specialties: command post (1C3), space and missile systems electronic maintenance (2M0x1), space and missile systems maintenance (2M0x2), missile and space facilities (2M0x3), missile and space systems superintendent (2M0x0), nuclear weapons (2W2), and security forces (3P0). At senior master sergeant (E-8) level, the three "feeder" specialties 2M0x1, 2M0x2, and 2M0x3 merge into one "capper" specialty, 2M0x0.

For each specialty and grade, Figure A.1 shows the total manpower authorized at the three ICBM wings and forcewide at the end of FY 2010, our before-reduction baseline. The numbers include authorizations in a few leadership positions at the ICBM wings—e.g., wing commander (91W), operations group commander (10C), logistics commander (20C), inspector general (87E), executive officer (97E), and group superintendent (9G1)—that people from these specialties nominally would hold. Although part of our analysis includes the positions authorized for civilians in the duty Air Force Specialty (AFS) Codes (AFSCs) listed in Table A.1, we do not report on them here

Table A.1
Authorizations at ICBM Wings and Forcewide for Nine Specialties (end of FY 2010)

Officer			Enlisted							
Grade	**13S**	**21M**	**Grade**	**1C3**	**2M0x1**	**2M0x2**	**2M0x3**	**2M0x0**	**2W2**	**3P0**
At three ICBM wings										
O-1/2	462	8	E-1/3	4	125	140	83		49	1,249
O-3	239	24	E-4	6	120	81	76		72	742
O-4	25	12	E-5	11	109	96	72		48	820
O-5	33	14	E-6	5	51	43	26		32	191
O-6	12	3	E-7	4	40	39	21		16	112
			E-8	1				16	5	22
			E-9					12	4	12
Total	771	61		31	445	399	278	28	226	3,148
Forcewide										
O-1/2	657	36	E-1/3	184	248	140	84		168	10,872
O-3	1,090	153	E-4	326	280	123	88		217	8,014
O-4	847	109	E-5	563	253	135	96		202	7,535
O-5	530	90	E-6	448	157	81	55		138	2,883
O-6	93	16	E-7	324	139	91	49		86	1,666
			E-8	76				69	23	348
			E-9	22				22	12	170
Total	3,217	404		1,943	1,077	570	372	91	846	31,488

because they are relatively few, their pay grades are not explicitly authorized, and we are looking primarily for obstacles that may confront entire officer or enlisted specialties or career fields as a result of ICBM reductions.

We identify the manpower authorizations for each organizational element (office symbol) within each squadron, group, or wing, estimate how each LCC cut would affect its authorizations,[2] and sum the estimates in the appropriate combination for each reduction scenario. Figure A.2 depicts results for the 13S and 2M0x1 AFSCs. The reductions are nearly linear with the missile reductions. Concentrating the cuts in fewer wings and squadrons would save somewhat more manpower. Next, we calculate how those changes would affect each specialty's total authorizations, summed across the force. Figure A.3 shows the numbers for 13S and 2Mx1, paralleling Figure A.2. The changes look more dramatic for the ICBM wings than across the force because each specialty has many positions elsewhere (to aid planning, policy, acquisition, logistics, and personnel issues at higher headquarters and support organizations, for example).

Reduction scenarios lead to diverse sets of questions. Are the prospective changes large enough to cause problems for the selected specialties? Would members have enough growth and leadership opportunities to expect continued career development? Would the Air Force need to alter its accession, cross-training, or retention programs in order to shape and sustain personnel inventories consistent with the altered authorizations? Would many members need to work in jobs above or below their grades or skill levels? Should any specialties be merged or subdivided to better fit the authorizations? How many cuts would it take before such problems emerged? One way to address these questions is to compare the anticipated authorizations with personnel inventories of the same sizes whose mixes of experience and grades would be consistent with past retention, cross-flow, and advancement and promotion patterns. We do this even with some uncertainty over whether future authorizations are compatible with behavioral patterns

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2 For most units, our estimates assume that officer and enlisted leadership would be retained until the unit is eliminated and that subordinate manpower would shrink in proportion to the relevant LCC cuts. Especially at Minot AFB, home to the 91st Missile Wing, some units would shrink by less because they also support the base's 5th Bomb Wing. We also need to be specific about which wings and squadrons would shrink first and which would shrink last when a reduction scenario offers options. Somewhat arbitrarily, we assume that Malmstrom and lower-numbered squadrons would shrink first and that F. E. Warren and higher-numbered squadrons would shrink last.

Figure A.2
Estimated Reduced Authorizations for Two Specialties at Missile Wings

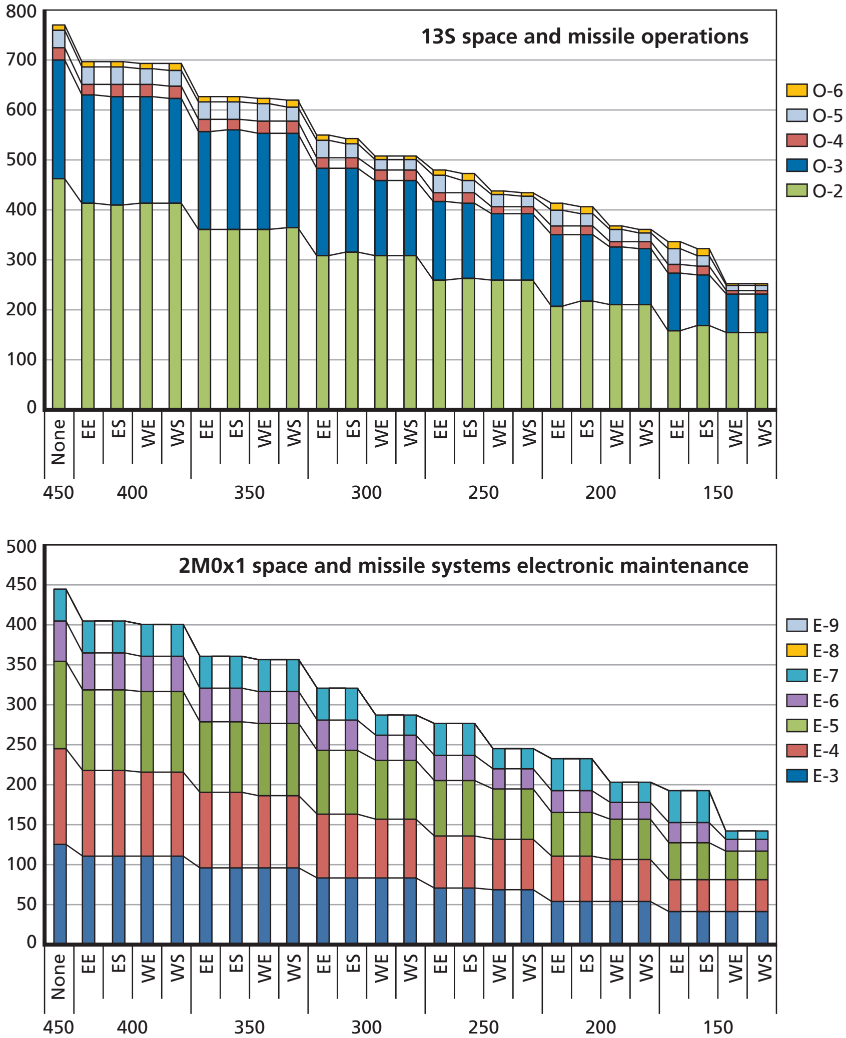

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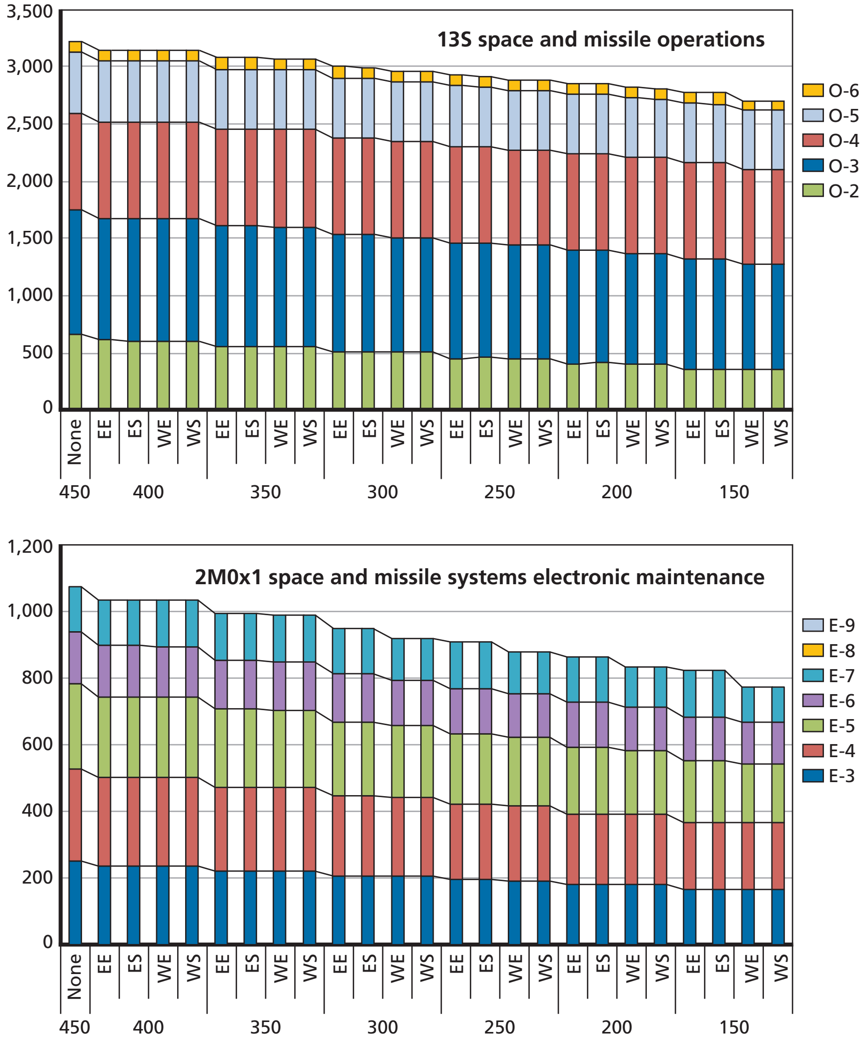
Figure A.3
Estimated Reduced Authorizations for Two Specialties Across the Force



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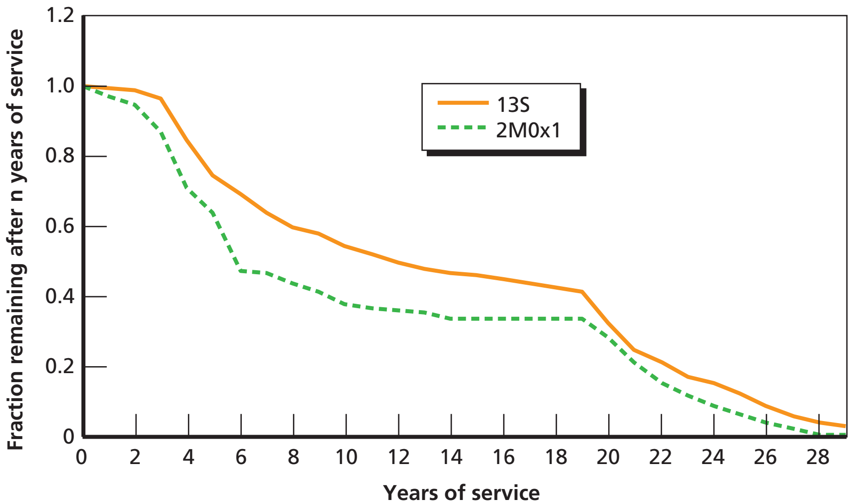
already known to be achievable and whether those patterns will or should persist.

We use standard Air Force cumulative continuation rates (CCRs)[3] to establish anticipated authorizations and personnel inventories. Figure A.4 shows CCR-based experience profiles (also known as "sustainment profiles") for the 13S and 2M0x1 specialties. Both profiles show considerable attrition during the earlier YOSs, less attrition during about years 10–19, and then more again at 20 years and later once military members become eligible for retirement benefits. The

Figure A.4
CCR-Based Sustainment Profiles for Two Specialties



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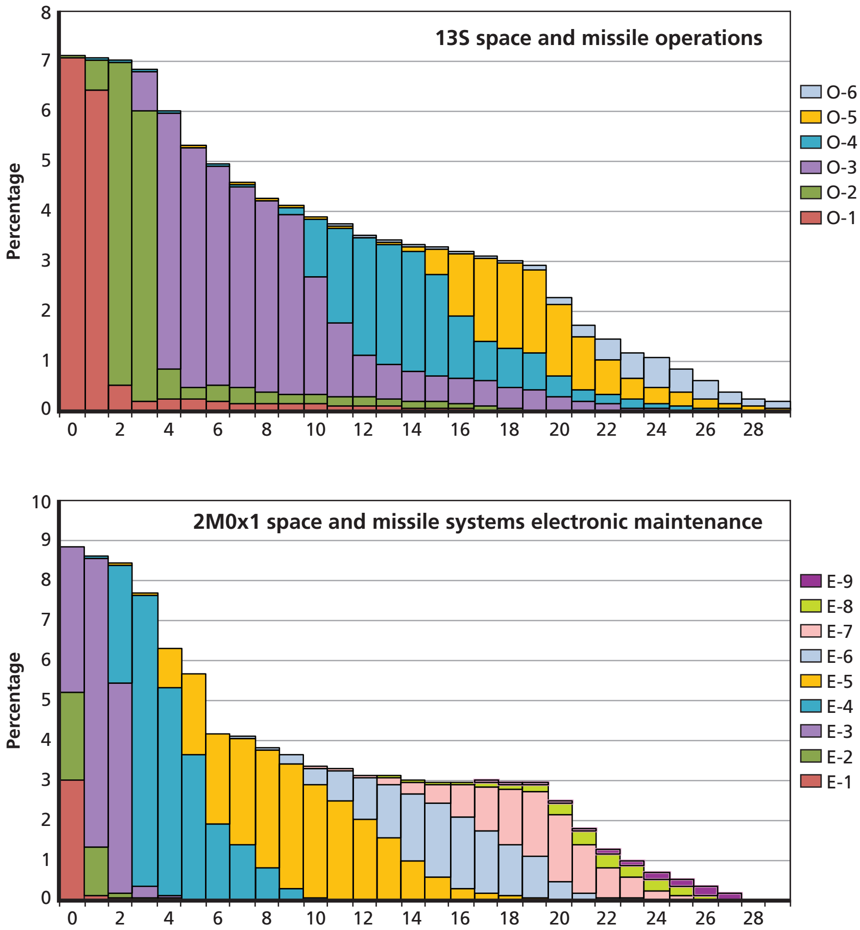
3 CCRs reflect several years' retention and cross-flow experience and estimate how many of a specialty's members, in the Air Force after X years of service (YOSs) or commissioned service, will still be in the Air Force after Y YOSs or commissioned service. For example, about 64 percent of 13S officers with four years of commissioned service will be expected to still be in the Air Force and in the 13S career field after ten years of commissioned service. Calculations for our nine career fields use CCRs obtained from Force Management Division, Directorate of Force Management Policy (AF/A1PF), in August 2011, based on experience during 1998–2010 (omitting 2006–2008 when "force-shaping" programs were actively shrinking the force and consequently lowering retention rates below their normal levels).

comparison between the 13S profile and the 2M0x1 profile is fairly typical: More enlisted members tend to leave in the early years and almost all of those who stay through about 15 years continue until 20.

It is further helpful to translate experience profiles into grade mixes to compare directly with any grade mixes estimated for future authorizations. Figure A.5 illustrates the application of historical dis-

Figure A.5
Sustainment Experience and Grade Mixes for Two Specialties



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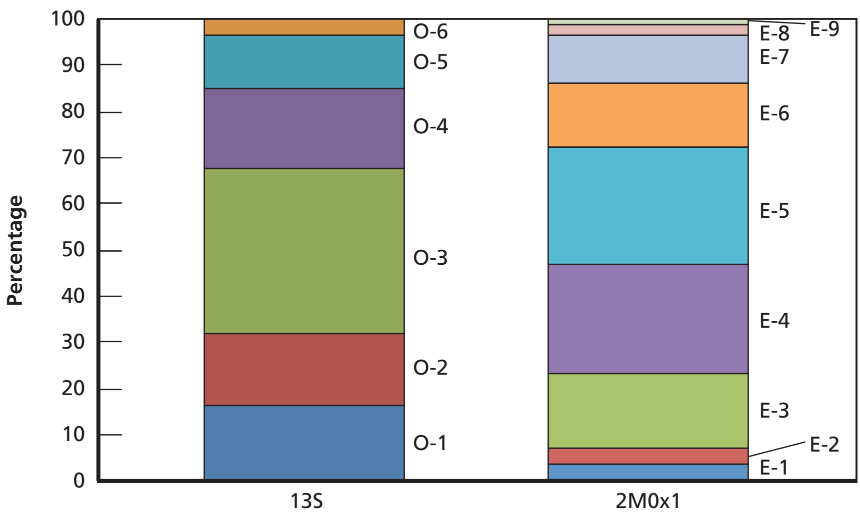
tributions of grades per YOS (commissioned service for officers) to the sustainment profiles in Figure A.4.[4] Summing over the YOS axes in graphs like that of Figure A.5 (the x-axes) yields sustainable grade mixes like those shown in Figure A.6 for the same two specialties.

We can compare estimated future authorized grade mixes like those in Figure A.3 with scaled versions of sustainable grade mixes like those in Figure A.6 to assess the degree of match or mismatch, helping to quantify how difficult it may be to fulfill future authorizations and how necessary it may be to restructure or reorganize somehow in order to bring future demand and supply into closer alignment.[5] For a hypothetical enlisted specialty, Figure A.7 illustrates the calculation of indi-

Figure A.6
Sustainment Grade Mixes for Two Specialties



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[4] We drew grade mixes by years of service (YOS) or cumulative years of service (CYOS) from the Air Force Personnel Center's Interactive Demographic Analysis System (IDEAS) data system, website, last reviewed August 1, 2011.

[5] Our subsequent assessments use sustainable grade mixes obtained from AF/A1PF, the office that calculates, maintains, and applies those mixes to help the various functional communities analyze and plan for their specialties' management and development.

Figure A.7
Evaluating the Match or Mismatch Between Authorizations and Personnel Inventory for a Hypothetical Enlisted Specialty

Grade	Sustainment grade mix	Right-sized personnel inventory	E-3	E-4	E-5	E-6	E-7	E-8	E-9	Total
			Authorization							
			475	490	485	290	280	70	25	2,115
			Best match between authorizations and inventory							
E-1	3%	73	73							73
E-2	3%	74	74							74
E-3	16%	343	329	15						343
E-4	23%	492		475	17					492
E-5	26%	558			468	90				558
E-6	14%	297				200	96			297
E-7	10%	216					184	33		216
E-8	2%	44						37	7	44
E-9	1%	18							18	18
Total	100%	2,115	475	490	485	290	280	70	25	2,115

Jobs (authorizations) filled . . .

	E-3	E-4	E-5	E-6	E-7	E-8	E-9	Total
Two grades low								
One grade low		15	17	90	96	33	7	258
At grade	475	475	468	200	184	37	18	1,857
One grade high								

	E-3	E-4	E-5	E-6	E-7	E-8	E-9	Total
% two grades low								
% one grade low		3%	3%	31%	34%	47%	28%	12%
% at grade	100%	97%	97%	69%	66%	53%	72%	88%
% one grade high								

	E-3	E-4	E-5	E-6	E-7	E-8	E-9	Total
One skill level low		15		90		33		137
At skill level	475	475	485	200	280	37	25	1,978
One skill level high								

	E-3	E-4	E-5	E-6	E-7	E-8	E-9	Total
% 1 skill level low		3%		31%		47%		6%
% at skill level	100%	97%	100%	69%	100%	53%	100%	94%
% 1 skill level high								

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cators of match or mismatch between an illustrative set of forcewide authorizations and a sustainable personnel inventory of the same size. Authorizations and inventory can be matched using the 27 cells that lie between the heavy boundaries. Cells shaded light blue (those on the diagonal) represent authorizations and inventory whose grades match;

they sum to 1,857, or 88 percent of the total in this illustration.[6] Cells shaded darker blue (below the diagonal) show where inventory is one grade higher than the authorizations; those cells are empty in this illustration because such mismatches are unnecessary. Cells shaded yellow (just above the diagonal) show where inventory is one grade lower than the authorizations; they sum to 258, or 12 percent, of the total in this illustration. Cells shaded red (just beneath the upper heavy boundaries) show where inventory is two grades lower than the authorizations; those cells, too, are empty in this illustration because such mismatches are unnecessary.

The mismatches calculated here differ from those seen frequently in Air Force personnel assignments, where jobs are often filled by people from adjacent grades (one grade higher or lower). Many such grade mismatches are temporary because the assigned officer or enlisted member is soon promoted to the position's grade. Some are deliberate because the individual assigned to the position is the person best qualified in the unit or needs the experience for developmental reasons. Others are necessary because people cannot be moved quickly enough to avoid them or because the specialty's actual grade mix is different from the authorized grade mix. Our calculations reflect only the latter: the match or mismatch between the specialty's inherently sustainable grade mix (based on historical retention and promotion rates) and any current or estimated future authorizations. For the enlisted specialties, we can also calculate skill-level mismatches, assuming that grades below E-4 represent skill-level 3 (apprentice), grades E-4 and E-5 represent skill-level 5 (journeyman), grades E-6 and E-7 represent skill-level 7 (craftsman), and grades E-8 and E-9 represent skill-level 9 (superintendent). Figure A.7 is illustrative and shows that only about half (137) of the 258 grade mismatches cross the skill-level boundaries, reflecting a skill-level mismatch of about 6 percent. As we consider the nine selected specialties in the remainder of this appendix, we will use 20 percent as a threshold for highlighting grade mismatches and,

[6] Authorizations at E-3 match inventory at grades E-1, E-2, and E-3 because enlisted authorizations label all positions below E-4 as E-3. Similarly, officer authorizations label all positions below O-3 as O-2.

for the enlisted specialties, 10 percent as a threshold for highlighting skill-level mismatches. Nothing egregious necessarily happens at those levels, but they help differentiate the degrees of match or mismatch among the specialties and how the imbalances vary as the potential ICBM reductions grow larger and are taken by either spreading or concentrating the cuts.

Relationships between grade and length of service can also be used to trace out the experience profiles that would be necessary to achieve any targeted grade mix. The remaining sections of this appendix demonstrate and interpret the results of such calculations and comparisons with the estimates of forcewide authorizations under the ICBM reduction scenarios.

Officer Specialties

This section summarizes findings from our initial sustainability analyses for two critical officer specialties common to Minuteman III wings. These analyses address overall numerical sustainability. More specifically, given the retention and promotion patterns associated with these specialties, we compare the expected relationship between human capital supply (inventory) and demand (manpower requirements) given various reduction scenarios. Although worthy of additional research, this section does not examine potential competency gaps that could surface when comparing competencies acquired from personnel assignment patterns with competencies needed for specific nuclear jobs.

Space and Missile Operations (AFS 13S)

Space and missile operations officers with the C-shred perform missile combat-crew operations. They maintain readiness to launch ICBMs applying current directives for targeting, execution, and positive control of ICBMs. It is critical that this specialty maintain a sufficient pool of officers with broad experience in ICBM-related assignments to serve in key missile leadership positions, including squadron, group, and wing commands. Other shreds in the 13S specialty include satellite command and control (A), spacelift (B), space surveillance (D), and space warning (E). The C shred comprises about 74 percent of 13S authorizations for lieutenants, about 29 percent for captains, and less than 15 percent at higher grades. Most 13S officers start out in 13SxC jobs and migrate into space-oriented work after their initial four years with ICBMs. Relatively few, about 45–60 per year, are selected to maintain their concentration in ICBMs and to develop toward the specialty's relatively few jobs at higher grades that demand ICBM expertise.

Figure A.8 compares the sustainable inventory (blue) with current forcewide requirements. The Minuteman III nuclear requirements are lieutenant-intensive, and the space requirements are greater at higher grades. The comparison indicates that, as a combined specialty, the principal sustainment problem relates to the majors' (O-4) requirements. In practice, captains must be assigned to substantial numbers of majors' billets, primarily space billets.

Figure A.9 compares the sustainable inventory with requirements given under the most severe reduction scenario. It shows that in this

Figure A.8
Current AFS 13S Sustainment Profile Versus Manpower Authorizations (Pop. 3,199)

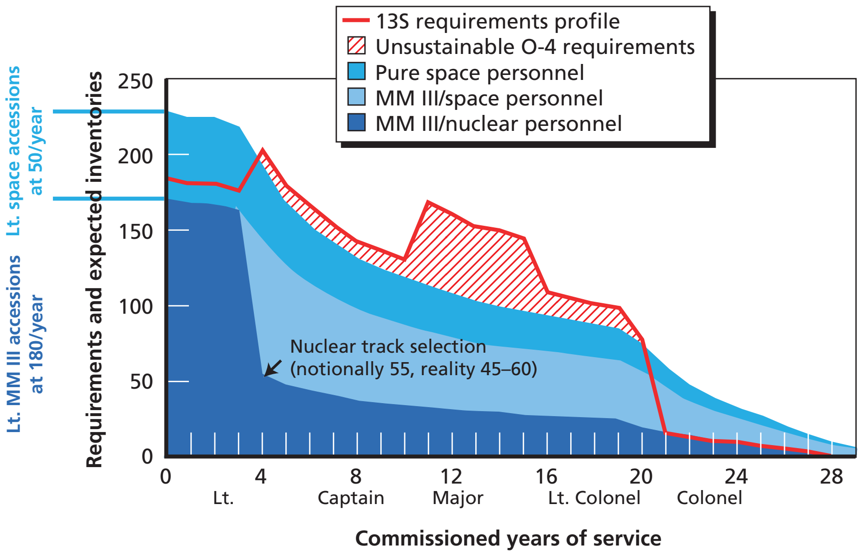

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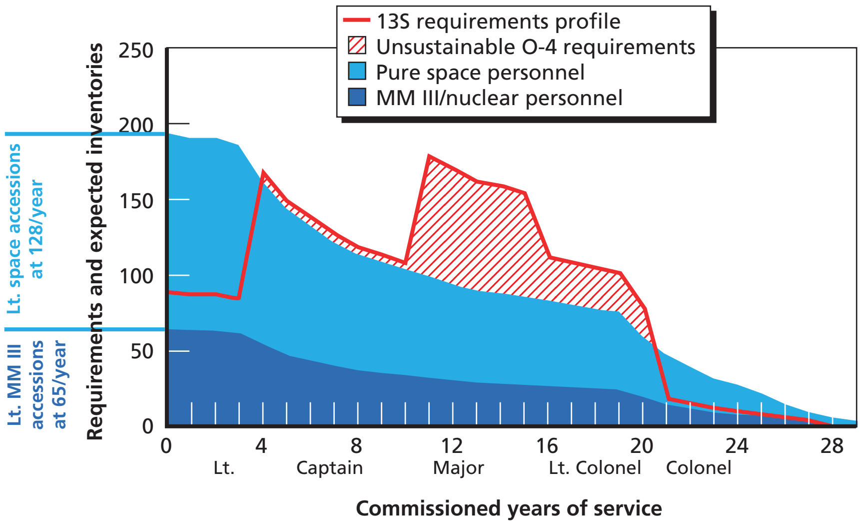
Figure A.9
Worst-Case AFS 13S Sustainment Profile Versus Manpower Authorizations (Pop. 2,691)



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case, the O-4 sustainment problem would be aggravated, and additional problems would arise. First, the space portion of the specialty would have to become self-sustaining. This suggests reassessing the grade requirements and redistributing them in a manner that produces more lieutenant entry-level space jobs. Although this may be feasible numerically, it may be impractical because of the limited number of space "cockpits" available in operational units. Second, the Minuteman III and nuclear accession requirements would be driven by the requirements for nuclear personnel at wing level and above instead of by lieutenant jobs in operational missile wings. The problem probably would result in organizational and career-path changes. Third, a comparison of Figures A.8 and A.9 shows that the cross-flow from Minuteman III to space would be eliminated.

Force structure and manpower planners would need to watch for thresholds that would trigger organizational or career-path changes. Our comparison of sustainable grade mix and the anticipated forcewide 13S authorizations indicates a starting mismatch of roughly

14 percent, i.e., about 4–5 percent of 13S officers in an inventory with the specialty's sustainable grade mix would need to fill jobs at a lower grade and 9–10 percent at a higher grade. The mismatch would grow with larger ICBM reductions, reaching 20 percent if the number of ICBMs were cut to 200, regardless of whether the cuts were spread as evenly as possible or concentrated as much as possible. It would peak at nearly 28 percent at 150 ICBMs if the cuts were spread as evenly as possible.[7]

The reduction scenarios that eliminate wings or squadrons would cut the numbers of leadership jobs that are critical for missileers' development and career progression (squadron commanders and operations officers, group commanders, and wing commanders). Even so, most of the envisioned cuts would reduce the number of subordinate 13S positions by even more, in relative terms, so still fewer missileers would compete for the reduced leadership opportunities.

Munitions and Missile Maintenance (AFS 21M)

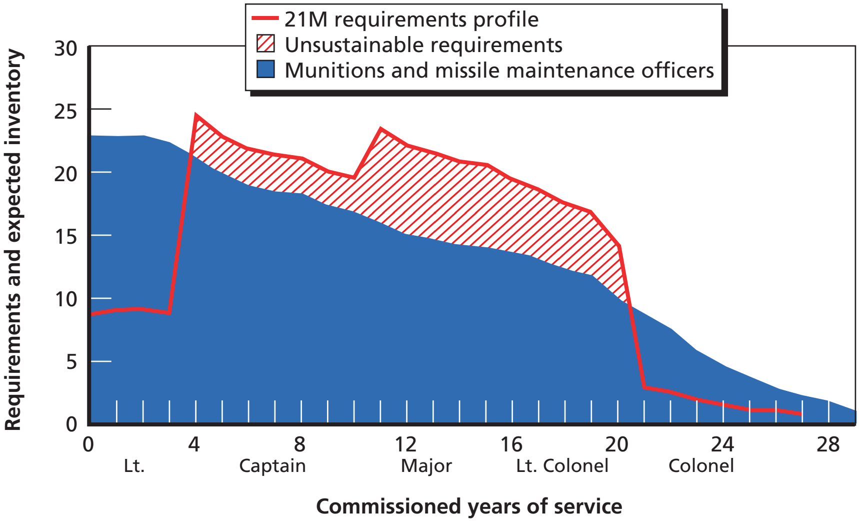
Munitions and missile maintenance officers manage the maintenance and modification of conventional munitions, nuclear weapons, ICBMs, and associated equipment. They formulate and implement maintenance procedures that help ensure that missiles and munitions are stocked, functional, and ready to be deployed. Duty assignments for these officers are not limited to Minuteman III operations; they are needed worldwide.

Figure A.10 compares the sustainable inventory with current requirements for AFS 21M, a relatively small specialty with about 400 billets. The comparison indicates that lieutenants are probably serving in captains' jobs and captains are serving in majors' jobs. This specialty is unable to fill its majors' (O-4) jobs with majors who started as lieutenants in the specialty.

Figure A.11 compares the sustainable inventory with requirements under the worst-case scenario that would make the largest reduction.

7 Recall that this option leaves more of the higher-grade leadership positions in the ICBM wings and cuts the most-junior positions relatively more, even though concentrating the cuts as much as possible cuts more manpower in total.

Figure A.10
Current AFS 21M Sustainment Profile Versus Manpower Authorizations (Pop. 397)



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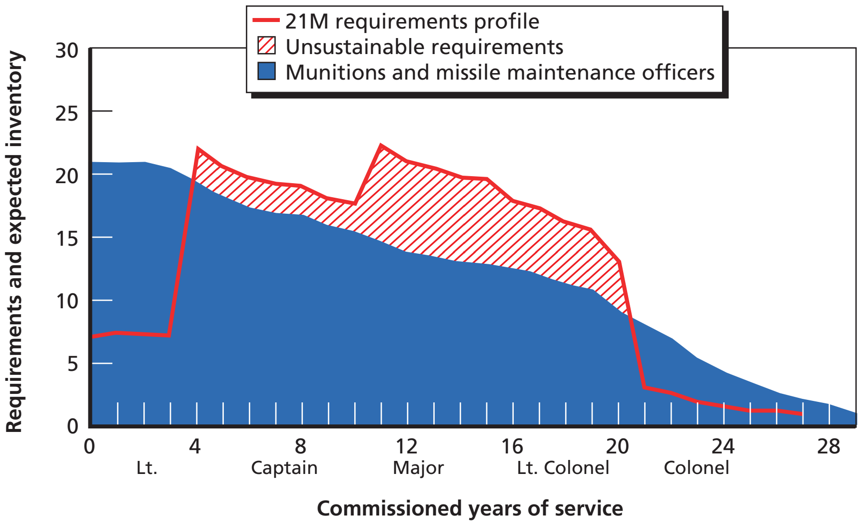
It would cut 21M's forcewide authorizations roughly 10 percent. Our comparison of supply and demand finds that the current problems would be slightly aggravated under this scenario. With no cuts, about 21 percent of the jobs would need to be filled by officers from adjacent grades. The percentage would rise to about 23 percent under the worst-case scenario.

Comparing the current and worst-case sustainment profiles reveals no additional thresholds that would trigger new needs for organizational or career-path changes for this specialty; however, there would be a mild worsening of problems already faced. As with the 13S specialty, eliminating missile wings and squadrons would cut 21M's growth and developmental opportunities in the field grades, but not as much as it would cut positions at lower grades, so the developmental situation would not necessarily grow worse for 21M officers. Fewer of them would still compete for limited opportunities, but the numbers of competitors would shrink faster than the numbers of developmental opportunities.

Figure A.11
Worst-Case AFS 21M Sustainment Profile Versus Manpower Authorizations (Pop. 361)



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Enlisted Specialties

This section summarizes findings from our initial sustainability analyses for critical enlisted specialties common to Minuteman III wings. As with the officer analyses, these analyses address overall numerical sustainability. Assuming that the retention and promotion patterns associated with these specialties continue, we compare the expected relationship between human capital supply (inventory) and demand (manpower requirements), given various reduction scenarios. Again, although potential competency gaps are worthy of research, this section does not examine those that could surface when comparing competencies acquired from actual personnel assignment patterns with competencies needed for specific nuclear jobs.

Command Post (AFS 1C3)

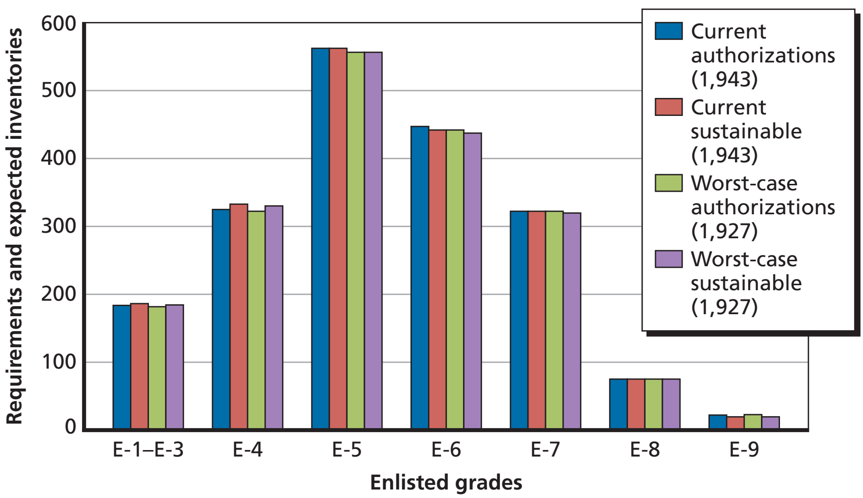
Enlisted personnel in this specialty perform activities within command posts, operations centers, rescue coordination centers, and command centers. They receive, process, and disseminate emergency action messages via voice and record copy systems. This includes encoding, decoding, transmitting, and relaying presidential decisions to execute and terminate nuclear and conventional force operations.

Figure A.12 compares 1C3's forcewide authorizations with sustainable inventories for today's 450 ICBMs and as estimated if two ICBM wings were eliminated. The ICBM reductions scarcely have an effect, and the authorizations are very well matched with the sustainable grade mix. With sustainable grade mixes, more than 99 percent of 1C3 authorizations would match with inventory at the same grade under all of the reduction scenarios.

Missile and Space Systems Maintenance (AFS 2M0)

This career field encompasses the skills, functions, and techniques used to acquire, activate, assemble, transport, install, and maintain missiles

Figure A.12
Command Post (1C3) Sustainment Versus Manpower Authorizations, Current Versus Worst-Case Reduction



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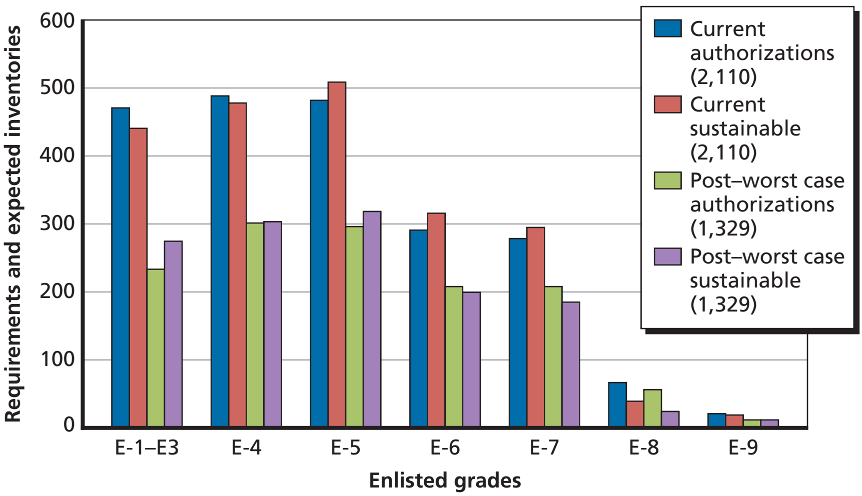
and subsystems. Accordingly, it comprises four specialties. Systems electronic maintenance specialists (AFSC 2M0x1) operate, calibrate, inspect, maintain, or oversee these actions on missiles, missile and aircraft integration systems, aerospace vehicle equipment, operational ground equipment, automated and manual test equipment, spacelift boosters, and payloads. Missile and space systems maintainers (AFSC 2M0x2) perform missile maintenance actions at flightline; railhead; support base; and launch, launch control, and storage facilities and ensure compliance with international treaties. Missile and space facilities specialists (AFSC 2M0x3) maintain, operate, service, and repair power generation and distribution systems and environmental control and associated support systems and equipment for missile, spacelift, and R&D facilities.

These three feeder specialties merge at E-8 into missile and space systems maintenance, AFSC 2M0x0, whose members manage maintenance, processing, acquisition, and operation of ground- and air-launched missiles, aircraft missile rotary launchers and pylons, spacelift boosters, payloads, related subsystems, test, calibration, support and handling equipment, and facilities. They also manage activities associated with R&D. For brevity, we aggregate these four AFSCs in Figure A.13 at the AFS level, 2M0.

Figure A.13 shows nearly a 40 percent reduction in space and missile manpower authorizations if the greatest-cut scenario should occur. Airmen in this specialty would still have job opportunities in the remaining Minuteman III force, bomber force, and various above-the-wing assignments (e.g., major command headquarters and DoD agencies). Nonetheless, reducing the number of Minuteman III bases should cause reconsideration of career patterns. It turns out that merging the 2M0 specialties in Figure A.13 masks some important differences. Our more detailed analysis prorates 2M0x0's authorizations at E-8 and E-9 to the feeder specialties and examines their current and future estimated authorizations with sustainable inventories of the same sizes. The 2M0x1 subspecialty exhibits the least mismatch, starting with a grade mismatch of about 3 percent and a skill-level mismatch of about 2 percent that grows with increasing ICBM cuts. The skill-level mismatch would reach 10 percent at 200 ICBMs under the

Figure A.13
Space and Missile Maintenance, AFS 2M0 Sustainment Versus Manpower Authorizations, Current Versus Worst-Case Reduction



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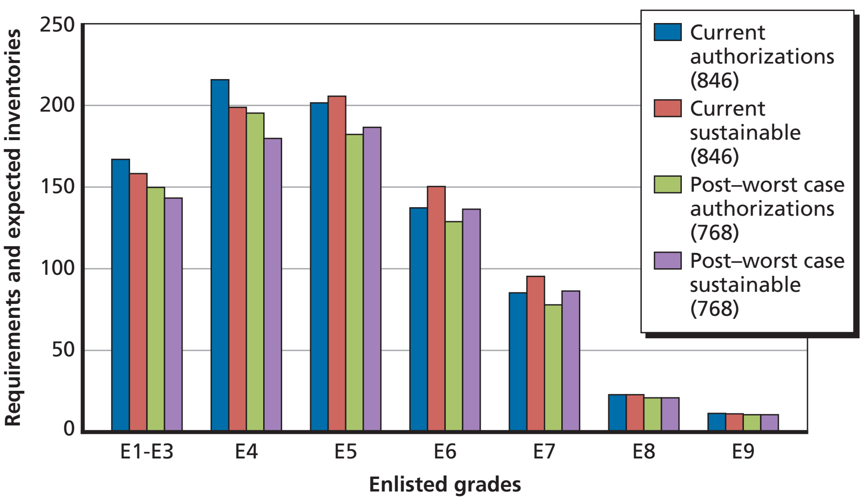
scenarios that would spread the cuts evenly among the missile wings and would rise to nearly 13 percent at 150 ICBMs. The grade mismatch would breach the 20 percent threshold only at 150 ICBMs under the same spread-the-pain reduction policy. 2M0x2 starts with grade and skill mismatches of about 6 percent and 2 percent, respectively, which also would grow with increasing cuts and breach our 20 percent and 10 percent thresholds at 300 ICBMs if the cuts were distributed across wings, though not if an entire wing were cut. Its mismatch would continue growing with larger cuts, reaching roughly 40–50 percent grade mismatches and 20–25 percent skill-level mismatches with cuts to 150 ICBMs. The 2M0x3 subfield's projections look much like those for 2M0x2, although the AFSC is notably smaller. Cutting to 150 ICBMs would roughly halve the authorizations for both 2M0x2 and 2M0x3, probably leaving 2M0x3 small enough to consider merging it with another AFSC, perhaps within the enlisted civil engineering (3E) career field.

Nuclear Weapons Maintenance (AFS 2W2)

These specialists perform maintenance, inspection, storage, handling, modification, accountability, and repair for nuclear weapons, weapon components, associated equipment, and general or specialized test and handling equipment. They inspect, assemble, disassemble, maintain, and modify nuclear weapons, bombs, missiles, reentry vehicles and systems, launchers, pylons, penaids, and associated test and handling equipment. They also maintain and operate associated permissive action link equipment.

Figure A.14 shows a potential 9 percent reduction in nuclear weapon maintenance manpower authorizations if the worst-case scenario should occur. Similar to the space and missile maintenance career field, people in this specialty would still have job opportunities within the remaining Minuteman III force, bomber force, and various above-the-wing assignments. However, the magnitude of the personnel reduction is not large enough to warrant reconsideration of career patterns. The disparity by grade appears normal and would resolve during the actual assignment process. Neither 2W2's grade nor its skill-level

Figure A.14
Nuclear Weapons Maintenance, AFS 2W2 Sustainment Versus Manpower Authorizations, Current Versus Worst-Case Reduction



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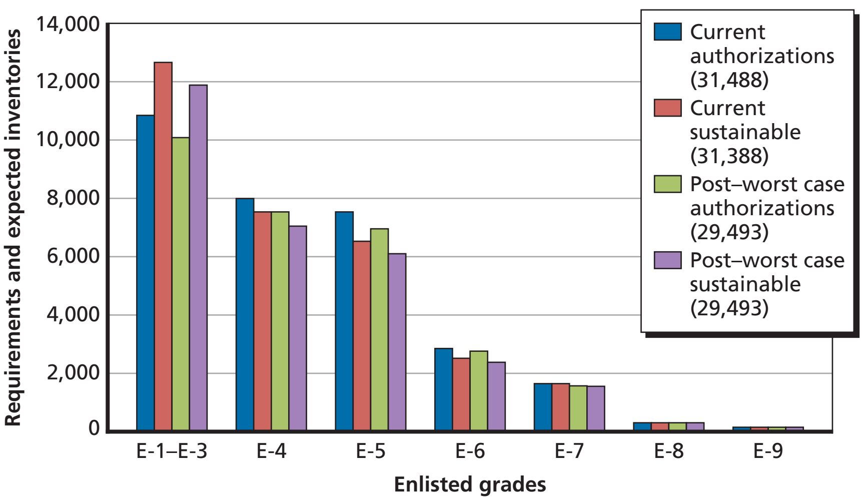
mismatch would exceed even 3 percent under any of the reduction scenarios.

Security Forces (AFS 3P0)

Security forces personnel perform force protection activities, including installation, weapon system, and resource security; antiterrorism; law enforcement and investigations; military working-dog function; air base defense; armament and equipment; training; pass and registration; information security; and combat arms. They are deployed and employed worldwide, including in sensitive or hostile environments created by terrorism, sabotage, and nuclear, chemical, biological, or conventional warfare.

Figure A.15 shows slightly more than a 6 percent reduction in security forces manpower authorizations if the worst-case scenario should occur. Security forces personnel are assigned to bases worldwide with about 10 percent of enlisted personnel assigned to Minuteman III locations. Typically, a security forces specialist would not have more than one assignment at a Minuteman III location. Accordingly,

Figure A.15
Security Forces, AFS 3P0 Sustainment Versus Manpower Authorizations, Current Versus Worst-Case Reduction



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even the worst-case Minuteman III scenario would have only marginal effects on career patterns for this specialty. Our calculated grade and skill-level mismatches for 3P0 begin at about 11 percent and 7 percent, respectively, and never rise to even 13 percent or 8 percent, respectively, under any of the reduction scenarios.

Summary

Table A.2 summarizes our initial assessment of specialty sustainment implications under the ICBM reduction scenarios. At today's 450 ICBMs, the 13S officer specialty's forcewide authorizations appear to already be somewhat out of step with its sustainable grade mix. That mismatch could double with large cuts in the ICBM force. The 21M officer specialty appears to be currently even further out of step with its sustainable grade mix, but its mismatch would worsen little under the postulated reductions. The Air Force would need to consider alternative approaches to organizing and managing both officer AFSCs. The space and missile community has relied for many years on a substantial foundation of company-grade positions in the ICBM wings to absorb new 13S officers and provide a ready source of flows into higher-graded jobs in activities that concentrate on space missions. That flexibility would shrink under major ICBM cuts, and larger shares of the fewer officers who started in missile operations would need to continue their emphasis on ICBMs in order to grow the future leaders in that realm. Perhaps the initial tours in missile operations could be shortened somewhat to continue channeling enough incoming officers through initial ICBM operational experiences. Alternatively, the space-oriented elements of the specialty would either need to become more self-sustaining, for example, through redesign of jobs and training programs to let more officers begin their careers in space operations, or find other sources of officers who could migrate into space operations. Other options could be to look for ways to substitute civilian, enlisted, or contractor personnel for officers at levels that are particularly hard to fill with suitably experienced and qualified 13S officers. Even without drawdowns, the 21M community should consider revising its authorizations to be more

Table A.2
Summary of Compatibility Between Sustainable Grade Mixes and Forcewide Authorizations Estimated Under ICBM Reduction Scenarios

	Authorizations		Baseline Mismatches		Largest Mismatches		Where Is Mismatch Threshold Crossed?		
Specialty	Baseline	Largest reduction	Grade	Skill level	Grade	Skill level	Grade	Skill level	New sustainment issues?
Officer									
Space and missile operations (13S)	3,217	14%	14%		28%	—	250	—	Yes
Munitions and missile maintenance (21M)	404	10%	21%		23%	—	450	—	No
Enlisted									
Command post (1C3)	1,943	1%	2%	1%	2%	1%	—	—	No
Space and missile systems electronic maintenance (2M0x1)	1,077	23%	3%	2%	24%	13%	150	200	Yes
Space and missile systems maintenance (2M0x2)	570	39%	6%	2%	53%	22%	300	300	Yes
Missile and space facilities (2M0x3)	372	43%	6%	3%	50%	25%	250	250	Yes
Missile and space systems superintendent (2M0x0)	91	19%	← Prorated 2M0x0’s E-8 and E-9 authorizations to feeder specialties →						Yes
Nuclear weapons (2W2)	846	8%	3%	1%	3%	2%	—	—	No
Security forces (3P0)	31,488	5%	11%	7%	12%	8%	—	—	No

consistent with achievable personnel inventories in cases where more officers may be needed in total because too few are available at some key grades.

On the enlisted side, even the largest ICBM drawdowns are unlikely to introduce major new difficulties for the 1C3, 2W2, and 3P0 specialties, compared with potentially significant issues associated with the 2M0 career field. Even though the 2M0 specialty conforms to authorizations with today's 450 ICBMs, dropping to 300 or fewer ICBMs would take those specialties' forcewide authorizations out of sync with established behavioral patterns, shrinking the authorizations at lower grades substantially more than at higher grades. Career-field managers would need to consider cross-flowing more airmen into these specialties. Strategies could include creating or enhancing incentives for members to stay in the Air Force and in these specialties who might otherwise leave, or cycling young airmen through more categories of each specialty's work more quickly in order to meet the needs at higher grades for more knowledge and breadth of experience. Consideration also could be given to reorganizing or restructuring the remaining jobs to accommodate more junior members, also cutting back the numbers of jobs requiring more senior enlisted personnel.

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The U.S. Air Force will soon begin a formal Analysis of Alternatives for the next-generation intercontinental ballistic missile (ICBM). RAND was asked to examine and assess possible ICBM alternatives against the current Minuteman III system and to provide insights into the potential impact of further force reductions. The researchers developed a framework consisting of five categories—basing, propulsion, boost, reentry, and payload—to characterize alternative classes of ICBM and to assess the survivability and effectiveness of possible alternatives. Using existing cost analyses and cost data from historical ICBM programs, they derived likely cost bounds on alternative classes of ICBM systems. Finally, they developed force reduction scenarios, examined their impacts on several key nuclear specialty career fields to understand the implications of reductions on the current organizational structure, and compared sustainment and requirement profiles within the various reduction scenarios.

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