

After decades of near neglect, the Air Force is embarking on a vast modernization of its portion of the nation's nuclear deterrence capabilities—but these modernization activities face a range of challenges. Nuclear-specific tasks related to testing and certification have not been performed at scale for many decades and will need to be relearned and revised for the current conditions. The sheer scale of the programs is daunting. And this ambitious set of programs will be fielded by Air Force Global Strike Command (AFGSC), a relatively young command with a relatively small staff that has limited experience in fielding new systems.

This report identifies and describes means to allay these challenges. The authors focus on the integrated planning and preparation for mission success across individual programs, with a special emphasis on the challenges of operational testing and nuclear certification.



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Managing Nuclear Modernization Challenges for the U.S. Air Force: A Mission-Centric Approach



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A Mission-Centric Approach

Don Snyder, Sherrill Lingel, George Nacouzi, Brian Dolan, Jake McKeon,
John Speed Meyers, Kurt Klein, Thomas Hamilton

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Preface

This report presents the results of research sponsored by the Director, Strategic Plans, Programs, and Requirements, Air Force Global Strike Command. The objective of the project was to identify and describe means to allay significant challenges to the fielding of new nuclear weapon systems. A particular focus was placed on the integrated planning and preparation for mission success across the programs, with a special emphasis on the challenges of operational testing and nuclear certification. The work was conducted in fiscal year 2018 under a project entitled “Air Force Nuclear Enterprise Modernization Sufficiency” within the Force Modernization and Employment Program of RAND Project AIR FORCE. It should be of interest to the nuclear community in the U.S. Air Force.

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Summary

After decades of near neglect, the Air Force is embarking on a vast modernization of its portion of the nation's nuclear deterrence capabilities. These modernization activities face a range of challenges that will need to be overcome. Nuclear-specific tasks, such as testing for survivability in environments with nuclear weapon effects and the design and operational nuclear certification of systems and units, have not been performed at scale for many decades and must be relearned and revised for the current conditions. The sheer scale of the programs, which touch on nearly every part of the weapons, delivery platforms, command and control, and weapon storage, is daunting. This ambitious set of programs will need to be fielded by Air Force Global Strike Command (AFGSC), a relatively young command with a relatively small staff that has limited experience in fielding new systems. All of this is happening in a tight fiscal period with some opposition to various nuclear systems in favor of other national priorities. In addition, as these programs unfold, they do so with the expiration of the New Strategic Arms Reduction Treaty (New START) in 2021 and emerging cyber threats, evolving situations that the Air Force will need to adapt to.

After reviewing policies and documentation for both new programmed systems and historical systems, and interviewing an extensive array of subject-matter experts in the Air Force and Navy, both active and retired, we find that the Air Force as a whole, and AFGSC in particular, could be much better postured to face these challenges in fielding the next generation of nuclear systems. To address these deficiencies, we offer several recommendations.

To better meet the challenges facing nuclear modernization in the Air Force, we recommend that the Air Force develop a master plan for each of the two nuclear roles that AFGSC supports: the land-based strategic deterrent and the strategic bomber deterrent. These master plans would adopt a strategies-to-tasks framework to show a detailed decomposition of the means by which each of these missions will be sustained over time and how these systems contribute to national-level objectives. These plans should each be a dynamic resource, not a static, periodically updated physical document. They should pay equal attention to the sustainment of legacy systems, fielding of new systems, and the transition from legacy to new.

The master plans would document the integrated activities necessary for all the systems and processes needed to perform the land-based and bomber missions. These dynamic plans would be designed to support decisions that

- assist in identifying resource deficiencies or problems with coordination
- assist in balancing resource allocations in the budget
- assist in addressing any queries regarding alternative force structures that might arise during deliberations for arms control agreements, the next Nuclear Posture Review, congressional actions, or other future deliberations that affect nuclear posture.

We also recommend that the Air Force use this strategies-to-tasks framework for its nuclear roles to strengthen the coordination of advocacy across the Air Force. Some organization in the Air Force should advocate for its nuclear roles in a similar manner that the Office of the Special Assistant for Intercontinental Ballistic Missile Modernization Matters did for the Peacekeeper in the 1980s. We recommend that it be

- a single, coordinated voice across the Air Force
- supported by strategies-to-tasks constructed master plans tied to national-level objectives;
- agile enough to respond to the pace of Washington, D.C.
- empowered to represent the Air Force to the Secretary of Defense, the White House, and Congress
- imbued with personnel with the expertise to make sound, convincing arguments.

We further propose that AFGSC consider establishing a formal, small presence in the national capital region. Such a presence would help AFGSC remain aware of and react to issues in the Pentagon in a timely fashion, and to proactively represent AFGSC's interests. This presence could take the form of a detachment, highly coordinated with the Deputy Chief of Staff for Strategic Deterrence and Nuclear Integration, and provide an office for the AFGSC commander to use during frequent visits to Washington, D.C., to add the weight of that office to unified Air Force positions on strategic nuclear matters.

Part of these plans for sustaining nuclear missions would be end-to-end, enterprise views of nuclear-specific processes. After examining electromagnetic pulse (EMP) testing and nuclear certification as case studies, we draw some general conclusions about enterprise process management and make some recommendations specific to these two processes.

For all processes that nuclear systems must pass, such as testing, nuclear certification, verification of the effectiveness of the nuclear systems, cybersecurity, and others, it is prudent to focus on early steps in processes to avoid injudicious choices that amplify in later stages. The earliest phases are when standards and criteria are written and the resultant system design is fixed. The more attention paid to these phases to get them as sound and integrated as possible, the more payoff for subsequent phases and lower costs over the life cycle of the weapon systems. The Air Force currently fails to do this well for EMP testing or nuclear certification.

The more these processes can be managed from end to end, the easier it will be to identify any issues early (e.g., resource shortfalls), identify ways to correct for them, and get them into the budget and defend the budget adequately. Managing from the process view also identifies gaps and resource constraints that might not be identified by individual programs, and helps avoid sequencing errors, such as writing standards after major design endeavors begin.

The more these processes can be managed in coordination with other related processes, the better suited the systems designs will be for the nuclear mission, and the more the Air Force can economize on resources for process verification (testing, certification).

For EMP testing, we recommend that a single manager in the Air Force do the following:

- Manage the EMP testing process.
- Levy requirements on systems for surviving nuclear weapon effects based on a mission perspective.
- Prioritize EMP and other testing of nuclear weapon effects for both legacy and new systems.
- Serve as a center of excellence for nuclear weapon effects in the Air Force and oversee the functional management of this workforce.
- Ensure that the end-to-end EMP (and other nuclear weapon effects) process is coordinated and that injudicious choices early in the process do not amplify as they cascade.
- Ensure that EMP testing data are collected and maintained and supply Air Force technical inputs into the writing of Defense Threat Reduction Agency standards.
- Ensure that EMP requirements and testing are holistic, integrating all forms of EMP with those of other electromagnetic environmental effects during systems engineering.

We recommend that the Air Force use the current needs to test legacy aircraft to justify hiring and developing an augmented EMP workforce today. Doing so would give this workforce valuable experience prior to the surge in need when the newer programs reach the testing stages.

For nuclear certification, we recommend that nuclear certification review be introduced into acquisition milestone decisions. That would focus program offices on the need to consider the implications, if any, for their systems. We further recommend better integration of the nuclear certification process, the process to ensure the effectiveness of the systems, and the cybersecurity process. Combining these will yield a better system design, avoid injudicious choices early in the processes, and better utilize scarce resources. We also advocate for an increased workforce, especially for reviewing and rewriting nuclear certification criteria.¹

To compensate for the inexperience of AFGSC and the Air Force as a whole in procuring and fielding new nuclear systems, we advocate that AFGSC find more opportunities to reach out to other major commands to learn from their experiences. Some nuclear issues are unique to AFGSC, but many other aspects of fielding systems have much in common.

We caution that, beyond the direct effects of resource constraints, management also needs to be alert to an insidious indirect effect. Organizations within a large bureaucracy with competition for limited resources have knowingly underestimated their expected workforce requirements because of a fear of “being laughed out of the room.” In our discussions throughout the Air Force nuclear enterprise, we heard some anecdotal evidence of this phenomenon. Leaders will need to be attuned to this possibility and actively seek to correct it. Inaccurate feedback regarding resourcing needs will further complicate the challenge of advocating for and securing proper resourcing.

¹ As we write this in September 2018, the Air Force is preparing a plan to address the nuclear certification issues identified in Peery and Simpson, 2017.

Maintaining institutional knowledge of nuclear system development and acquisition is challenging because of the long lifespans of the systems. Few personnel who were directly involved with the development, acquisition, or fielding of the previous generation of systems remain in the workforce, either in industry or government. Given the expected lifespan of the programmed new systems, the likelihood is high that when the next intercontinental ballistic cruise missile, nuclear cruise missile, or nuclear bomber is fielded, they, too, will exceed the careers of many current members of the nuclear enterprise. Because of this, actively recording the lessons learned during today's modernization programs could be very advantageous to the success of the future enterprise. We recommend that historians be involved in these activities, recording the struggles and successes and, as best they can, the causal links in order to invest in the future.

Specifically, we recommend that

- technical, programmatic, and fielding challenges be recorded, along with any corresponding remedies
- records be retained, even for special access programs
- oral interviews of key participants be conducted and archived.

With these efforts, the Air Force should be in an improved position to meet the many challenges in sustaining and modernizing its roles in the nation's nuclear missions.

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Steve Flanagan, Jim Powers, and Jim Thomson provided critical reviews of the report that strengthened it.

That we received help and insights from those acknowledged above should not be taken to imply that they concur with the views expressed in this report. We alone are responsible for the content, including any errors or oversights.

Abbreviations

ACAT I	Acquisition Category I
ACC	Air Combat Command
AF/A10	Deputy Chief of Staff for Strategic Deterrence and Nuclear Integration
AFGSC	Air Force Global Strike Command
AFNWC	Air Force Nuclear Weapons Center
AFSEC	Air Force Safety Center
CBRN	Chemical, Biological, Radiological, and Nuclear
CSOG–N	CBRN Survivability Oversight Group–Nuclear
DTRA	Defense Threat Reduction Agency
EMP	electromagnetic pulse
GBSD	Ground Based Strategic Deterrent
HEMP	high-altitude electromagnetic pulse
ICBM	intercontinental ballistic missile
ITW	integrated tactical warning
LRSO	Long Range Standoff [cruise missile]
NC3	nuclear command, control, and communications
NPR	Nuclear Posture Review
RD-M	Office of the Special Assistant for Intercontinental Ballistic Missile Modernization Matters

1. Managing the U.S. Air Force's Nuclear Mission for the Future

Challenges

The early 1990s saw the breakup of the Soviet Union, the demise of the Warsaw Pact, and the demonstration of conventional, precision-strike airpower in the First Gulf War. These watershed events prompted the Air Force to deprioritize the modernization of the nuclear forces for two decades in favor of investment in conventional forces and, after September 11, 2001, counterterrorism. After an unauthorized movement of nuclear weapons in 2007 and a mis-shipment of sensitive nuclear components in 2006 (which were only recovered in 2008), the Air Force embarked on a number of initiatives to reinvigorate the nuclear enterprise.

A central part of those initiatives has been to modernize the nuclear forces. Given the long hiatus, the nuclear systems have aged considerably, and the strategic environment has evolved. Peer and near-peer states have been modernizing their nuclear forces during this period. Russia has been developing new systems, and China has been expanding its delivery modes for nuclear weapons.² North Korea has become a nuclear-capable state with the stated capability of attacking both its neighbors and the continental United States. With the U.S. withdrawal from the Joint Comprehensive Plan of Action, the United States might be confronted with a nuclear-capable Iran within the life cycle of new programmed weapon systems. And the threat environment has expanded to include significant concerns about cybersecurity.

Modernization plans for nuclear systems in the Air Force touch nearly every part of the nuclear enterprise. There are active programs at various stages for a new bomber for the strategic nuclear air mission, a new dual-capable aircraft for the nonstrategic nuclear air mission, a new nuclear cruise missile, a replacement for the entire intercontinental ballistic missile (ICBM) capability, helicopters for security of the missile sites, and major portions of the Air Force's considerable share of the national nuclear command and control systems, in conjunction with life-extension programs for most of the nuclear weapons and new weapon storage facilities.

Executing this massive modernization effort and successfully fielding these new systems poses numerous challenges.

Nuclear-Specific Tasks

Nuclear systems place distinctive tasks on the requirements, acquisition, and fielding processes, in addition to the usual tasks shared by nonnuclear systems. Two salient areas are nuclear certification and testing for survivability in environments with nuclear weapon effects.

² Coats, 2019; Defense Intelligence Agency, 2019.

The Air Force nuclear certification program ensures that all procedures, equipment, software, facilities, personnel, and organizations sufficiently perform nuclear weapon functions before conducting nuclear operations with weapons or weapon systems.³ Certification requires various organizations to establish evaluation criteria, design a certifiable system, create safe processes, train to a high standard, and undergo rigorous evaluations. Nuclear certification is composed of two components: a design certification of the systems and an operational certification of the operational units.

Nuclear systems need to operate in environments in which one or more nuclear weapons have detonated. Nuclear weapons produce prompt x-ray and gamma-ray radiation, fallout, blast, flash blindness, thermal radiation, radio blackouts, high-energy particles that can pump up the Van Allen belts, and electromagnetic pulse (EMP). These effects require special concepts of operations, system design considerations, and facilities and domain knowledge to test for survivability.

All of these are considerations for the acquisition and operation of nuclear systems that are not typically done for nonnuclear platforms.

Multiple, Large, Concurrent Programs

The number of nuclear programs planned or underway is clearly large. Compounding the challenge presented by the sheer number of programs is that several of these programs alone are quite ambitious endeavors. The Ground Based Strategic Deterrent (GBSD), which is a full replacement of the Minuteman III ICBM program, is an enormous undertaking. This program will design, test, and field a new missile and guidance system, new launch facilities, new launch command centers, new test and integration facilities, and a new weapon system command and control system. The infrastructure itself is vast: The number of deployed missiles is planned to be 400 at more than 450 sites spread over a considerable geographic area in the northern part of the western United States, all which must be accessible by truck and secured against the world's most challenging threats.

Not only are the number and size of the programs challenging, many of these initiatives are being done concurrently. Nearly all fall under the organize, train, and equip responsibilities of Air Force Global Strike Command (AFGSC). While individual program offices can focus on activities specific to their respective systems, AFGSC will need to manage the fielding of these systems simultaneously. Complicating this concurrency is the need to sustain legacy systems and orchestrate the intricate transition from legacy to new systems. This transition will be especially complicated for the transition from Minuteman III to GBSD. AFGSC will need to provide the enterprise oversight to ensure that the Air Force as a whole is able to handle this workload to meet the nation's nuclear deterrent objectives.

³ Air Force Instruction 63-125, 2017.

Experience

Given the hiatus that began in the 1990s, the last time the Air Force acquired and fielded a major nuclear weapon system was in the 1980s, when it procured the B-2 bomber and the Peacekeeper ICBM.⁴ In the 30-some years that have elapsed since then, much of this workforce, both in the government and in industry, is now long retired. Some of the art of engineering these systems—how to do nuclear certification, how to test for survivability for nuclear weapon effects, and the challenges of training the operators and fielding these systems—is lost. Whole institutions that once supported these activities were disbanded for cost savings in the 1990s. Gone in the Air Force are the Nuclear Criteria Group (oversight of nuclear-weapon-effect survivability), all high-altitude electromagnetic pulse (HEMP) threat-level test facilities, an organization dedicated to nuclear weapon effects (as the Air Force Special Weapons Center was), and many more.

Unfortunately, when these programs were last done, those involved left an incomplete written record of their experiences. Our surveys of the extant records from past major nuclear systems reveal a record that is spotty at assisting the current workforce. In some cases, the record is extensive but not compiled in a useful way. In others, sometimes because of classification, records were destroyed. There is little evidence that experience from these development programs has been explicitly incorporated into Air Force training. Words of wisdom set down for a future generation after a program was fielded are scarce.

One example is the last bomber program, the B-2. The commander of AFGSC recently asked the command historian to compile lessons learned from the B-2 program to assist the oversight of the B-21 program. The effort, dubbed “Project Raider,” was conducted by an Air Force historian with uncommon experience in documenting technical matters, particularly with strategic bombers. Despite this background, gathering disparate information and building a programmatic narrative and some lessons learned required half a year of concerted effort. Because of the lack of easily accessible information, historians who did not have such a suitable background would have struggled to complete this task.⁵ Even so, because there was so little surviving information on the B-2, the endeavor was largely refocused on the B-1.

On top of these challenges, AFGSC is a young command. AFGSC was created in the aftermath of the incidents in the 2006–2008 time frame, being activated on August 7, 2009, and reaching full operational capability on September 30, 2010. Given its youth, the command has not fielded a major weapon system. For its first experiences in fielding weapon systems (and weapon storage facilities), it will be grappling with multiple, large, simultaneous programs.

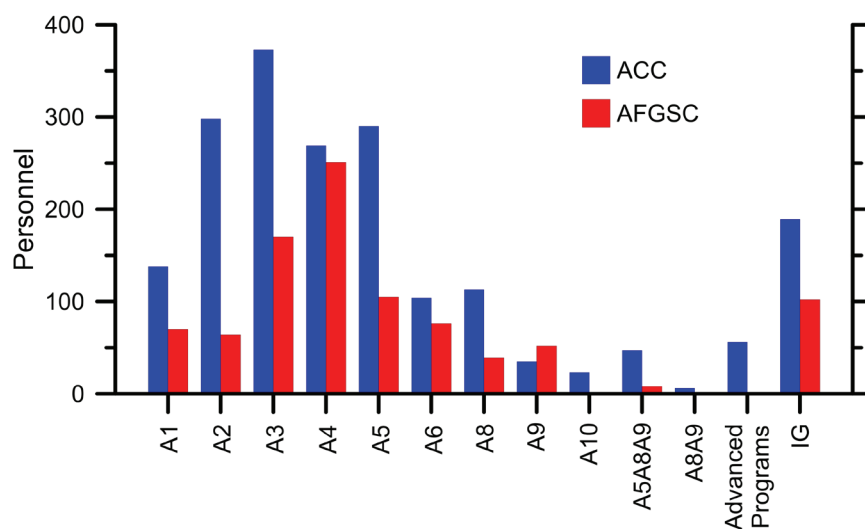
The scale of these acquisition programs is ambitious even for an experienced sponsoring major command. But to further complicate matters, AFGSC is not resourced at the level of more

⁴ The Peacekeeper was also known as the MX.

⁵ Interview with AFGSC History Office.

mature commands. Consider the staffing of Air Combat Command (ACC), a command well experienced in fielding weapon systems, and that of AFGSC. Figure 1.1 shows the relative staffing of these two commands for officer, enlisted, and civilian personnel. The staffs are organized slightly differently, with, for example, no A10 in AFGSC and a separate organizational unit for advanced programs at ACC. Differences in the missions of the commands also drive different needs, most markedly a need for a much larger A2 staff at ACC. But the data show significantly lower staffing at AFGSC than at ACC. Relevant to the fielding of new systems, the A3, A5, and A8 staffs are significantly smaller at AFGSC.

Figure 1.1. AFGSC and ACC Command Headquarters Staff Counts

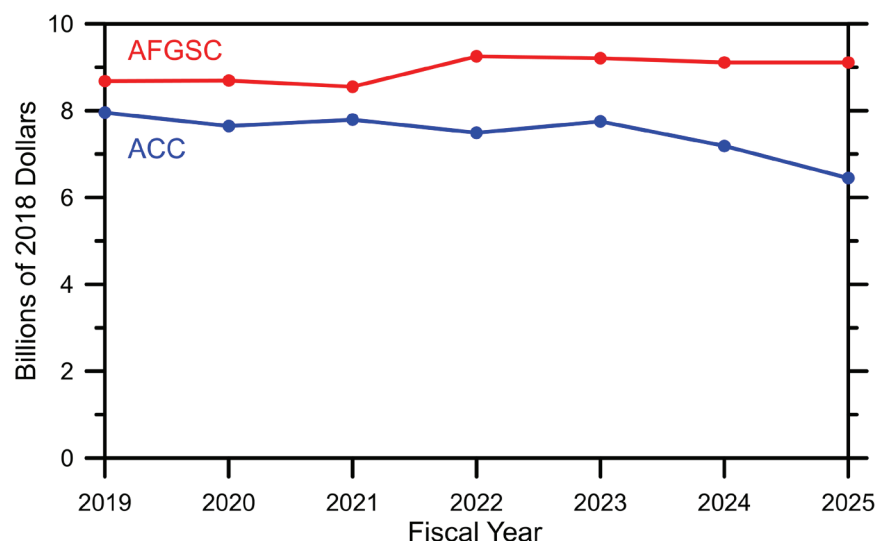


SOURCE: Unclassified Air Force Manpower Programming and Execution System (MPES) Database.

NOTE: IG = Inspector General.

Yet, the future demands for acquisition are comparable. Figure 1.2 shows the estimated summed costs in fiscal year 2018 dollars for the Acquisition Category I (ACAT I) programs that each command has planned through 2025. The data in Figure 1.2 are aggregated from system acquisition reports and publicly released estimates. Although a coarse estimate of the necessary future fielding activities, this figure gives a rough indication that the task that lies ahead for AFGSC is comparable to that handled by ACC, the largest and most experienced command at fielding weapon systems in the Air Force.

Figure 1.2. AFGSC Versus ACC ACAT I Program Total Projected Costs



Institutional Frictions

Institutional frictions exacerbate the environment within which AFGSC must modernize its nuclear enterprise. None of these are new, but they will pose yet more difficulties for AFGSC to resolve. Scarce resources across government and an increasing federal debt place these nuclear programs in a highly competitive budgetary environment.⁶ The Congressional Budget Office estimates that the nuclear modernization in the government will cost \$1.2 trillion in 2017 dollars over the 2017–2046 period.⁷ Exacerbating this challenge is the fact that political opposition persists for many of these initiatives. In particular, former high-ranking officials and politicians have recently challenged the wisdom of ICBMs, nuclear cruise missiles, and some nuclear weapons.⁸ Because the nuclear weapons are owned by the Department of Energy and are highly integrated with the delivery platforms, many of the programs face interagency coordination challenges. Coordination across agency boundaries is exacerbated by separate budgets, different acquisition processes and milestones, and contrasting cultures. Technical difficulties and cost overruns in one agency can imperil an associated program in another. In addition, the Air Force has operated with a fairly constant budget over the past decade, forcing tough decisions on priorities and threatening sustainment of adequate funding levels.

⁶ See, for example, Bertuca, 2018.

⁷ Congressional Budget Office, 2017. See also Congressional Budget Office, 2019.

⁸ For a sampling, see Lewis, 2012; Perry and Weber, 2015; Perry, 2016; Feinstein and Tauscher, 2016; Tirpak, 2018; ExchangeMonitor, 2018; and Doubleday, 2018. For counter views, see Evans and Schwalbe, 2017; and Gunzinger, Rehberg, and Evans, 2018.

Evolving Geopolitical Environment

Behind all of these challenges lies an evolving geopolitical environment. Many of these weapon systems are expected to be in the inventory for many decades. The strategic landscape that these new weapon systems must address for the nation is likely to evolve during their long life cycles. New nuclear powers are possible. The New Strategic Arms Reduction Treaty (New START), which sets arms control limits between Russia and the United States, is set to expire in February 2021. These factors require a certain flexibility in the overall force structure. AFGSC will need to be able to assess and communicate the range of the possible and what resources would be needed to achieve different postures.

Emergent Threats

When strategic nuclear systems were last developed, their computer and communication systems were isolated from other systems simply by the limits of the then-current technology. That is not the case today. The growing threats through cyberspace mean that new systems must meet a new and particularly difficult environment.⁹ Given the awesome destructive power of nuclear weapons, they must have the highest level of defenses and robustness to all levels of cyber operations. Providing such assurances has proven a vexing problem for much less sensitive systems. It is not adequate just to be secure; for deterrence, all adversaries and allies under extended deterrence must be convinced they are secure. The Air Force will need to specify sound cybersecurity requirements, place them on contract, test them continuously, and integrate them into the nuclear certification criteria. All this is new since the 1990s.

What Needs to Be Done

AFGSC is in a unique position, as both the sponsoring major command for most of these systems and the lead major command for the strategic nuclear mission, to ensure that the Air Force's role in the strategic nuclear mission is provided continuously into the future. This will require sustaining legacy systems, fielding new systems, and managing the sometimes complicated transition between them.

Like any weapon system, these systems need to be able to perform their missions when called upon. But more so than other weapon systems, nuclear systems are meant to deter. Two key attributes of deterrence of importance to this argument are that weapon systems need to work reliably and effectively when called upon to do so, and all adversaries must be convinced of this ability. That means that even if the system works and is properly secure, if an adversary has convinced themselves that they hold the weapon system at risk, deterrence fails.

It is critically important that certain criteria be met continuously over time. Strategic nuclear force structure is largely constrained at the national level by treaty. It is vital not only that

⁹ Unal and Lewis, 2018.

strategic nuclear systems not only operate, but that the exact specified number be available or on alert at all times. Failure to meet prescribed levels could result in failure of deterrence.

The purpose of this report is to provide a framework and recommendations for how AFGSC can better support the nation's nuclear deterrence needs given the formidable challenges. There are no simple fixes to these challenges. By examining some specific cases, we propose a number of actions that should help the Air Force navigate better through these challenges. We argue throughout this report that maintaining a mission-oriented view is central to these actions.

Research Approach

The full scope of all the activities for all the planned nuclear programs and initiatives is too great to treat in any detail in this report. We discuss an enterprise view and management from a mission perspective, in contrast to managing an aggregate of individual programs. We focus on two of the nuclear-specific challenges: nuclear certification and testing for survivability against one nuclear weapon effect, HEMP.

We concentrated our research on three programs—GBSD, B-21, and the Long-Range Standoff (LRSO) cruise missile—and the weapon storage facilities (which are not managed by the acquisition process under program structures, but as military construction).

We conducted numerous interviews with subject-matter experts at all levels in the nuclear enterprise, both within the program offices and with other key stakeholders in the Air Force.¹⁰ We also interviewed a number of senior leaders in the nuclear enterprise in the Air Force and the Navy Strategic Systems Program, both on active duty and retired, and at the Defense Threat Reduction Agency (DTRA).

We examined relevant policies and reviewed program plans, schedules, and related documentation for these three programs when available. We also reviewed historical documents, with a concentration on those from the B-2, Peacekeeper, and Minuteman III programs.

In Chapter Two, we dissect the processes for HEMP testing and nuclear certification to uncover a common structure for these processes. We use this common structure to argue where key problematic issues lie, where effort is best focused, and how these issues can be managed across systems. In Chapter Three, we then expand this argument beyond specific processes to missions, and in Chapter Four we close with specific findings and recommendations.

¹⁰ Meetings in the Air Force included discussions with various leaders within AFGSC, the Office of the Deputy Chief of Staff for Strategic Deterrence and Nuclear Integration (AF/A10), Air Force Nuclear Weapons Center (AFNWC), Air Force Safety Center (AFSEC), Air Force Historical Research Agency, Air Force Research Laboratory, Air Force Operational Test and Evaluation Center, ACC, the program offices for GBSD, B-21, and LRSO, and a number of retired Air Force senior leaders.

2. Process-Level Management

As the lead major command, AFGSC has the organize, train, and equip responsibilities for the nuclear systems under its purview for the nation's nuclear deterrence needs. Yet for these programs to be successfully fielded, many other Air Force organizations, separate and independent of AFGSC, play crucial roles in a number of processes. In this chapter, we focus on the nuclear-specific challenges for fielding the new programmed weapon systems. (In Chapter Three, we will take up the remaining challenges.) We discuss the nuclear-specific challenges by examining two prototypical processes for nuclear systems: testing for survivability in an EMP environment and nuclear certification. EMP testing is a good example of the challenges posed to the test community: It is nuclear-specific, uses infrastructure that takes years to build, and has atrophied in the Air Force. EMP testing is just one area of survivability in environments with nuclear weapon effects and is illustrative of how other survivability areas can also be managed. Nuclear certification is a good example of a process that has not been done on a full system for decades and faces new challenges with the changing threat environment, specifically new threats through cyberspace.

We examine these processes from a whole-of-Air-Force perspective. Although each has domain-specific attributes, we argue that they share similar structures. This enterprise view of the process structure suggests areas for better management of the processes. These insights, then, can be extended more generally to other processes.

EMP Management

Nuclear bursts generate EMP by a number of mechanisms. If deterrence systems are not sufficiently robust against EMP, and known not to be so, deterrence could fail, because an attacker would be tempted to initiate high-altitude EMP blasts to pave the way for a disarming first strike. The details of EMP generation, its effects on systems, and how to design and test to survive in EMP environments are highly technical. For the purposes of this report, most of these details are not necessary to understand. However, some background is needed to follow the process of managing EMP.

The EMP of concern for most circumstances comes from nuclear bursts 30 kilometers above the earth and higher collectively called HEMP. HEMP is often described in three phases called E1, E2, and E3. E1 is a very short, high-electric-field-strength pulse. It lasts for about a millionth of a second, can reach electric-field strengths of tens of thousands of volts per meter, and can have frequency content up to about 1 gigahertz. All electronics over a region of thousands of square kilometers can be exposed to E1 HEMP. Depending on the design of a U.S. system, its orientation relative to the earth's magnetic field at the time of a nuclear burst, and whether it is

powered on or off, its electronics can have a wide variety of responses. They can experience anything from no effect at all from E1, to being permanently damaged. Only empirical testing can inform how equipment might respond.

E2 HEMP arises from the same underlying phenomenology, but lasts about a second and reaches electric field strengths about one hundred times less than that of E1. It is lower in frequency than E1.¹¹ E2 is often considered a less-included case of E1, unless the E2 frequencies couple with an electromagnetic collector, such as an antenna.

E3 HEMP arises from two separate phenomena. Both distort the earth's magnetic field on a global scale. This variation in the geomagnetic field induces an electric field in the earth. The wavelength is so large that the field is approximately a direct current gradient over continental scales. Systems grounded over long distances, such as power grids and telephone lines, can experience voltage and current asymmetries. These asymmetries can lead to transformer saturation and damage, and introduce higher-order harmonics in power sources. Small systems are not directly affected by E3 and cannot practically be shielded to it. If they are connected to a long collector, such as a power grid, the mitigation must be on the side of the power grid—for example, the configuration of the grounding architecture of the grid.

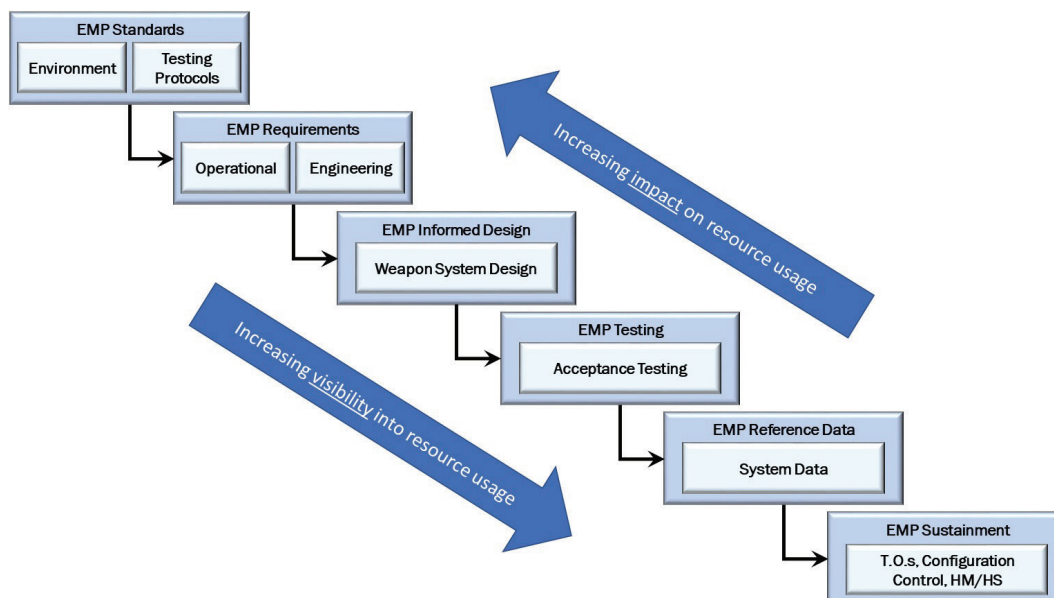
From an infrastructure point of view, E3 HEMP (and the analogous effect from extreme space weather) is of high concern. From the point of view of individual systems, E1 HEMP is of highest concern. The remaining focus in this chapter is on E1 to illustrate process management. E3 should have a parallel treatment.

The Process

The overall process for EMP management is shown schematically in Figure 2.1. Setting standards for EMP is the first step of this process. Standards are of two types: an environmental standard and standards for testing protocols. The environmental standard specifies the EMP fields that systems could be exposed to and in which they are expected to function. But here is where EMP design gets a little complicated. For E1 HEMP, shielding, filtering, and grounding techniques are used to protect sensitive electronics from the pulse. But how effective these are depends on the details of the actual article. For example, two airplanes, or circuit boards, off the same production line can vary considerably in how they respond to the insult of a pulse. Test equipment to assess a system's response are highly specialized, and most are unique to EMP testing. In addition, test equipment vary in the degree to which they can produce the desired waveform. These and other variables demand disciplined test protocols to ensure that the response of the system to the threat field is well understood. The writing of the environmental standard and the standards for testing protocols are the responsibility of the DTRA.

¹¹ Although electric-field strengths of E2 and natural lightning are similar, these phenomena are sufficiently different that design strategies to mitigate one will not necessarily mitigate the other.

Figure 2.1. Key EMP Management Activities



NOTES: HM/HS = hardness maintenance/hardness surveillance; T.O. = technical order.

These standards guide the requirements levied on systems. The using command, through the Joint Capabilities Integration and Development System process, writes the operational requirements, and, using these, the responsible program office writes engineering (design) requirements that can be put on contract. The contractors then design a system to be survivable in the prescribed EMP environment with a design informed by the environmental standard and knowledge of how the system will be tested. This design is reviewed and approved by the program office. There are two families of EMP tests, and the first comes at the stage of accepting the system for operations. This test, called the system verification test, applies a simulated threat-level E1 HEMP pulse to the system following testing protocols in the standards.

Beyond supporting the operational testing of the system, the data collected on these tests have two important functions. The first is that they form an important baseline for future EMP tests of the system during sustainment. The second is that they provide the underlying data about testing variability that are used to write the testing standards. The more that data are collected by these tests on test articles, the greater the knowledge of the variance of the articles. If enough data accrue to demonstrate a smaller variance than expected by the testing protocols, those protocols can be relaxed.

It cannot be overemphasized that the way a system responds to EMP depends on the details of the real article. How well a seal is installed, whether parts have migrated over time, whether surfaces have corroded, and many other factors can fundamentally alter the performance of EMP mitigation measures. Sustaining a system to continuously meet EMP standards requires that the system configuration be controlled, that technical orders specify procedures for ensuring that EMP design elements are maintained, and that the effectiveness of all sustainment efforts be

verified by additional testing. This second family of tests, called hardness maintenance/hardness surveillance, applies a low-level electromagnetic field swept through frequencies to verify EMP hardness and identify any areas for redress. The baseline data from the system verification tests helps the interpretation of these data.

Insights for Enterprise Management

This process reveals some key enterprise-wide insights into managing this critical activity for sustaining legacy systems and fielding new ones. All the steps in this process must be accomplished for a system or that system is at risk of not surviving an EMP environment. Further, for deterrence, it is not enough that the systems be able to survive; all adversaries and allies that rely on the United States for extended deterrence need to be convinced that U.S. systems can survive any plausible adversary attack. This process needs to be well executed for all relevant systems, and the fact that it is being done should be known. It is also important that this process be perceived within government to work well. Given the political skepticism surrounding some of the future Air Force nuclear programs, and the close attention paid to EMP by many,¹² perceived sloppiness on EMP requirements and testing would give further ammunition to those who would rather see resources spent elsewhere.

Another important observation is that inaccuracies in the early parts of this process (those in the upper left of Figure 2.1) get amplified in later parts of the process. Suppose that the testing standards, for example, are written more conservatively than they need to be. This could happen as a result of a dearth of testing data, and therefore higher uncertainties that are compensated for by more stringent testing. Those standards lead to more-conservative designs, which likely result in more-expensive procurement costs. Overly conservative standards also lead to increased recurring costs for sustainment, as a system is maintained for years to meet protocols that are unnecessarily strict. Getting the activities as precise as possible early in the process is important to save money and manpower in the later steps, especially for the recurring ones in sustainment.

A specific example is the testing protocols for missiles. As of 2018, no standard exists for testing protocols for missiles; the writing of this standard is in its early stages. Design for the new ICBM is, however, simultaneously underway. Writing the standard during the design of the GBSD is not an ideal sequence. If the testing protocols were already established, design engineers could consider these needs as part of systems engineering trade-offs. Testing protocols not known during design might give rise to more-costly changes to design later in the program, or more costly testing to accommodate a design not created with these considerations in mind.

No overarching oversight assigns requirements based on *mission* needs. Requirements for EMP hardness are managed in the Air Force system by system. There are two manifestations of the way that EMP is currently managed. First, for a given concept of operations, multiple

¹² The congressionally created Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack makes EMP a high-visibility area. See Public Law 114-92, 2015, Section 1089.

systems might be required, such as bombers and aerial refueling aircraft. Also, some systems might be needed for some concepts of operations that are not generally considered nuclear systems (e.g., suppression of enemy air defenses or battle management). By not levying requirements based on these mission concepts of operations, the requirements on individual systems might be inconsistent and ill-suited for all missions they might be called upon to support. Second, the current focus is on levying requirements only on platforms rather than weapon systems, so that critical support equipment might have different requirements than the systems they support (e.g., support equipment that enable an aircraft to generate a sortie). In the end, for most programs, there is no mandate for EMP, and the engineering (design) requirement devolves to the program office and becomes part of the cost-performance-schedule trade space rather than a mission-driven requirement.

Acceptance testing for EMP (system verification test) is another critical area, especially for ICBMs. ICBMs pose several challenges for EMP acceptance testing. The missile itself is large and requires a facility able to handle a test article of that size and weight. The facilities that were used to test the Minuteman II and III, the Peacekeeper, and the Navy's Trident II (D5) were Air Force facilities at Kirtland Air Force Base.¹³ These were all decommissioned in the early 1990s as part of the national reprioritization away from nuclear forces. Fortunately, a major range and test facility base at Naval Air Station Patuxent River appears capable of handling tests on the GBSD missile.¹⁴ One difference between testing a missile in flight and an aircraft is the missile has a long exhaust plume that is electrically conductive and the missile sees multiple, different configurations after staging. These factors affect the testing of the article and will be specified in the testing protocols, once written.

Another facet of verification tests for the GBSD will be the necessary testing of the nonmissile components of the weapon system, of which the main components are the launch control centers, the launch facilities, and the weapon system command and control systems. For acceptance testing of the smaller components (on the order of a few meters), there are several facilities in the U.S. government that can perform these tests, including one in the Air Force at the Little Mountain Test Facility near Ogden, Utah. The testing of large, underground facilities such as the launch control centers and launch facilities requires specialized, mobile test equipment, for both acceptance and sustainment testing.

EMP testing for cruise missiles, including the LRSO, can be done at either of at least two facilities: those at Naval Air Station Patuxent River and the Army's test facilities at White Sands. Acceptance testing for aircraft can only be done at Naval Air Station Patuxent River.

¹³ Most of the tests were performed in the Advanced Research Electromagnetic Pulse Simulator (ARES) facility. See Braddock, Dunn, and McDonald, Inc., 1972.

¹⁴ Based on interviews with personnel at Naval Air Station Patuxent River on July 3, 2018, and a review of technical documentation.

The next step in the EMP management process is the collection and archiving of test data. These data, as mentioned above, are useful for two purposes. One is to inform a baseline for a given weapon system to use during sustainment testing. These data are also useful at the individual “tail number” level to give insight into the peculiarities of each platform. But these data are also quite helpful for informing the writing of testing protocols. The infrequency of doing EMP testing in the Air Force has led to a paucity of such data, and therefore, a paucity of influence on the specifics of testing protocols.¹⁵

The last step is sustainment. Because EMP hardness is so sensitive to details, sustainment of EMP hardness is a critical activity. A wonderfully designed system that passes acceptance testing can fail to survive as desired in an EMP environment if not properly maintained and tested. Doing so requires well-written technical orders and periodic hardness maintenance/hardness surveillance testing. There is only one independent facility in the Air Force that can do such testing on aircraft.¹⁶

Overall, the gutting of research on nuclear weapon effects in the Air Force and the decommissioning of most of the EMP test facilities have left the service with very few personnel familiar with EMP. An extremely low number have deep technical expertise on the design of testing equipment and protocols. Although the Air Force had some expertise in this area to influence the writing of the standard for aircraft testing protocols, because of its aging workforce, the Air Force is unlikely to be able to influence the next version of that standard or to participate at the technical level on the writing of the missile standard.

One area of omission in the process outlined in Figure 2.1 is E3 HEMP. Requirements for E3 survivability, and its closely related cousin, ground-induced currents from extreme space weather,¹⁷ are not levied on programs. Responsibility for E3 mitigations are levied on the installations, and therefore largely in the civil engineering functional area. No centralized oversight exists for E3 management and no center of excellence exists to assist local entities to grapple with this threat.

Conclusions Regarding EMP Management

The most important theme that runs through most of these issues is that no organization has overall responsibility in the Air Force for managing the EMP testing process. This lack of oversight has either led to or exacerbated many of the issues.

A single manager could

- better set EMP requirements to reflect mission needs (versus system needs)
- better enforce those requirements on programs so they are nonnegotiable

¹⁵ Most system verification EMP test data on aircraft come from testing of the Navy’s E-6B.

¹⁶ There are two facilities, one at Tinker Air Force Base (Oklahoma City Air Logistics Complex) and one at Palmdale, but these two facilities share equipment that must be shipped between these sites.

¹⁷ See, for example, Rivera et al., 2016.

- better prioritize testing and ensure adequate testing capacity
- better manage the EMP workforce to ensure that the requisite knowledge is maintained in the Air Force
- better incorporate E3 mitigations
- better foresee the sequencing of activities such as writing of the testing protocol standard for missiles in time for GBSD and LRSO programs' Milestone A decisions.

We, therefore, recommend a single manager in the Air Force for EMP. This manager would have the following responsibilities for EMP and other nuclear-weapon-effect requirements and testing.

This managing organization would be empowered to levy requirements on systems for surviving nuclear weapon effects. It would have this authority for all systems, not just ones with a specific nuclear role. The organization would be able to levy requirements on the acquisition process that cannot be traded with other requirements, and it would do so from a mission perspective. This would augment the efforts of the Chemical, Biological, Radiological, and Nuclear (CBRN) Survivability Oversight Group—Nuclear (CSOG-N).¹⁸ Because mission-level requirements involve details of systems and concepts of operations that reside at the service level, we recommend that these requirements be levied by the Air Force with the consultation of the CSOG-N and U.S. Strategic Command. Such an organization once existed: the Air Force Nuclear Criteria Group, which was disestablished in the early 1990s.¹⁹

The organization would also prioritize EMP and other nuclear-weapon-effect testing for both legacy and new systems. It would examine and ensure that adequate testing capabilities and capacities are available to meet Air Force needs.

The organization would serve as a center of excellence for nuclear weapon effects in the Air Force and oversee the functional management of this workforce.

The organization would ensure that the end-to-end EMP (and other nuclear weapon effects) process is coordinated and that injudicious choices early in the process do not amplify as they cascade (from upper left to lower right in Figure 2.1). It would ensure that EMP testing data are collected and maintained and supply Air Force technical inputs into the writing of DTRA standards.

The organization would ensure that EMP requirements and testing are holistic, not only integrating E1, E2, and E3 HEMP, but other forms of EMP, and that these be integrated with other electromagnetic environmental effects during systems engineering.²⁰

A second recommendation would be to augment the EMP savvy workforce. Managing all of the modernization programs on the horizon, including testing, will place heavier demands on the workforce for EMP expertise. To meet these future needs, the force should grow both in numbers

¹⁸ Department of Defense Instruction 3150.09, 2015.

¹⁹ Air Force Regulation 80-38, 1989 (rescinded).

²⁰ Department of Defense Instruction 3222.03, 2014; Prather and Rooney, 2016.

and technical expertise. The growth in workforce would help Air Force to better inform standards, engineering requirements, and design reviews and to better prepare the Air Force for future testing (procurement of new test facilities, sensor placement on systems, and data interpretation).

The justification for this growth in work force need not be tied solely to future programs. The need for additional testing of legacy aircraft, both acceptance and sustainment testing, can be used to justify hiring and developing this workforce today. Doing so would give this workforce valuable experience prior to the surge in need when the newer programs reach the testing stages.

Although many organizations outside of AFGSC play key roles in ensuring EMP survivability, it is AFGSC that has the ultimate responsibility to organize, train, and equip survivable systems to perform nuclear missions. To help guide AFGSC in this area, we have listed some key questions in Table 2.1 regarding the management and oversight of EMP in the Air Force. These questions are not exhaustive, but are shaped to drive discussion within the command in a way that enlightens ways to improve enterprise management. The questions are meant to be for the reflection of senior leaders and not to drive additional reporting tasks for staff.

Table 2.1. Key Considerations for AFGSC for Managing EMP

Process Step	AFGSC Considerations
EMP Standards	• How can the Air Force better engage with DTRA for standards development? • What steps is the Air Force taking to ensure growth in technical expertise in EMP testing standards?
EMP Requirements	• Who is the EMP manager for the Air Force? • Are the EMP requirements appropriate given current concepts of operations? • Where is the center of excellence for E3 EMP? • Should concepts of operations be reconsidered given EMP survivability? • How are requirements written to ensure that EMP requirements are integrated with other electromagnetic environmental effects during systems engineering?
EMP Informed Design	• How have the vendors designed the B-21, LRSO, and GBSD for EMP survivability?
EMP Testing	• What is the Air Force plan for EMP testing of the GBSD infrastructure? • Where will the acceptance tests of all the new systems be performed, and when? Have the schedules been deconflicted with non–Air Force tests at these sites? • What is the EMP testing plan for legacy systems?
EMP Reference Data	• What EMP testing reference data exist within the Air Force to inform future testing protocols? Are these data adequate? How might they best be improved?
EMP Sustainment	• Are the maintenance technical orders for all systems adequate to sustain EMP hardness? • What is the sustainment plan for EMP for all Air Force systems? Missions?

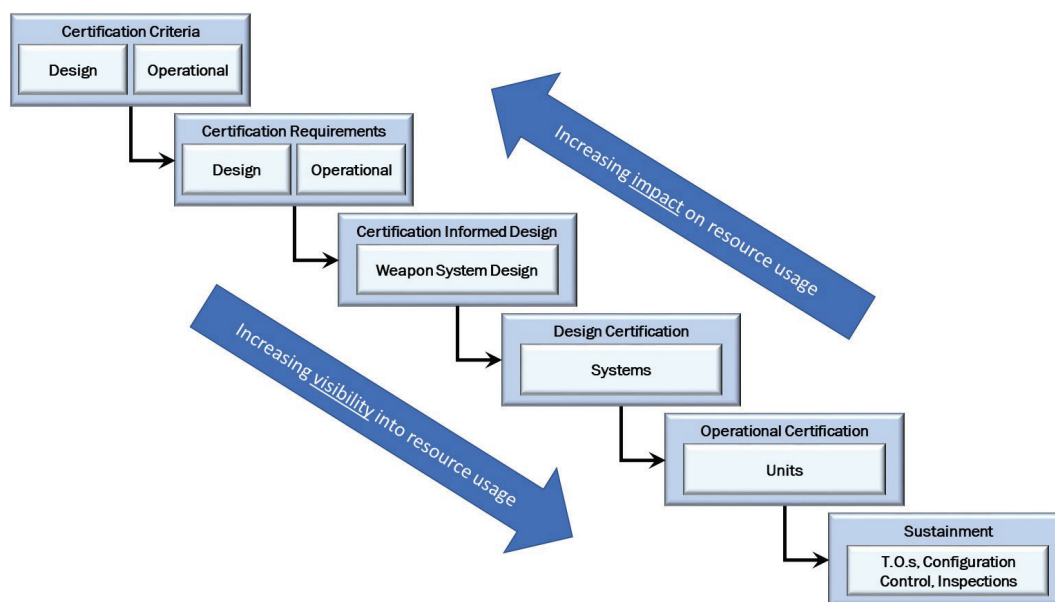
Nuclear Certification

Nuclear certification displays parallel structures with EMP management, yielding some similar as well as some different management issues. As part of operational safety, suitability, and effectiveness,²¹ all “procedures, personnel, equipment, software, facilities, and organizations that handle, maintain, or operate nuclear weapons or nuclear weapon systems” must be nuclear certified.²² Nuclear certification comes in two components: design certification and operational certification. Nuclear design certification focuses on the design, rules, and technical orders for the systems. Nuclear operational certification focuses on operational units’ training, personnel reliability program, and initial nuclear surety inspections. Both design and operational certification must be satisfied before a system is nuclear certified. Both nuclear certification components focus on safety, which means they are meant to ensure that accidents be prevented. Neither examines the system or operations in order to ensure mission effectiveness.

The Process and Insights for Enterprise Management

Like EMP management, the process for nuclear certification covers the entire life cycle of a weapon system. The basic structure of the nuclear certification process is similar to EMP management and is depicted schematically in Figure 2.2.

Figure 2.2. Key Nuclear Certification Activities



NOTE: T.O. = technical order.

²¹ Air Force Materiel Command Instruction 63-1201, 2017.

²² Air Force Instruction 63-125, 2017.

The process begins in the upper left of Figure 2.2 with the writing of certification criteria. These are written by the Air Force Safety Center (AFSEC) and establish the standards by which systems and units will be evaluated. Like the EMP process, all the steps must occur in the order given. Any injudicious choices in early stages of the process get amplified later; unnecessarily conservative criteria can cost money in design and procurement, and then recur during sustainment.

Some choices that come early in the design of a system can have profound effects on nuclear certification. The system architecture is one of the best examples. Any time a nuclear-critical portion of a system is altered during a weapon system's life cycle, it must go through the nuclear certification design review. If the architecture of the system partitions these critical portions such that they are sufficiently separated from the rest of the system, the design certification is simplified and can be accomplished with more confidence and lower manpower. If not, potentially the entire system might be subject to nuclear certification, making the task onerous and more complicated (and therefore less certain).

Should poor choices be made in design that are too costly to change, such as poor architectural design, a waiver can be sought. However, that waiver might bring operational restrictions to the system. Not only does that restrict the operator and the Air Force's ability to serve the nation's deterrence needs, it also reduces the value to the nation of the investment in the system. With the political opposition that some of these systems face, the consequences could be loss of critical support of the systems and possibly even program termination.

Some legacy criteria are vestigial from a time when criteria were written in a prescriptive fashion rather than an outcome-based fashion. A prescriptive criterion might read that a system not fail in some fashion for all currents on a circuit up to a specific threshold. An outcome-based criterion might read that the failure not happen given certain environments and leave the design of how to do that to the engineers. An older, prescriptive criterion might have specified that a system be safe with a given current because a relay operated at that level. Modern circuits might operate at fractions of that threshold and not need to withstand such pulses. This change from specifying design details to engineering outcomes was made for military standards in the 1990s for efficiency and effectiveness reasons. Nuclear certification design criteria could benefit from a thorough review from this perspective.

Another change that affects nuclear certification is the new domain of cyber. Threats through cyberspace pose a new risk to safety of nuclear systems that were not of the same concern decades ago, when the last large nuclear systems were designed and fielded. Writing these requirements well entails a combined understanding of nuclear systems, operations, and the technical aspects of cybersecurity. Techniques for making this manageable will be needed, because many systems now use tens of millions of lines of code of staggering complexity. It is therefore important to update certification criteria.²³

²³ Peery and Simpson, 2017.

Unfortunately, like EMP management, the rewriting of nuclear certification criteria is coming late relative to the design of significant, large programs. This could lead to injudicious choices that get amplified later in these programs. No formal mechanisms exist to ensure that project, initiatives, and programs get informed of nuclear certification needs early. Our interviews with key stakeholders indicate that some programs have been engaged with the process very early and have integrated nuclear certification considerations into early design phases. The B-21 program is said to be an exemplar. Others realize late the need to consider nuclear certification. The weapon storage facilities initiative is said to be an example of the latter.

Just as the EMP management process overlaps with other electromagnetic environmental effects management and should be handled together in systems engineering, nuclear certification also overlaps with other processes. Nuclear certification is meant to ensure that systems and operators are acceptably safe with respect to nuclear functions. Nuclear systems and operators also must be able to perform their functions when authorized, often in very trying circumstances (e.g., trans- and post-nuclear attack environments). (This is sometimes called nuclear surety, although the term *surety* does not have consistent usage in the nuclear community, so we generally avoid the term in this report.) Ensuring that a system is “fail safe” is sometimes at tension with ensuring that it works when needed. Sound systems engineering considers these needs together during design. Systems (and operators) also must be able to perform adequately in the face of a cyber attack and guard information from cyber exfiltration. This cybersecurity assurance is managed through the risk management framework process.²⁴

These three processes overlap in two important ways. The first is during design, when sound systems engineering considers these needs simultaneously and balances any trade-offs. The second is that the artifacts needed to do certification, ensure effectiveness, and assess cybersecurity are similar. Coordination could reduce the burdens of each of these processes and use scarce manpower more effectively.

Conclusions Regarding Nuclear Certification Management

Unlike EMP, nuclear certification does have a single manager, the Air Force Nuclear Weapons Center (AFNWC). This centralized management makes coordinating and improving the process easier and avoids the ambiguities of roles and responsibilities that affects some aspects of EMP testing. Despite the central management, the AFNWC is not in a position to be aware early on of all of the programs or other initiatives that might need nuclear certification. It is only well positioned to see programs under the program executive officer for strategic systems. To help future programs see any nuclear certification needs early enough to reduce injudicious design choices, we recommend that nuclear certification review be introduced into

²⁴ National Institute of Standards and Technology, February 2010; Department of Defense Instruction 8510.01, March 12, 2014, Incorporating Change 2, July 28, 2017; Air Force Instruction 17-101, 2017.

acquisition milestone decisions. That would focus program offices on the need to consider the implications, if any, for their systems.

We further recommend better integration of three related processes: the nuclear certification process, the process to ensure the effectiveness of the systems (sometimes called nuclear surety), and the cybersecurity process. Writing common requirements to participate together in systems engineering trades and sharing common assessment artifacts would better utilize scarce resources.²⁵

The manpower needed to do nuclear certification is estimated to increase substantially in the future to meet the needs of new programs, especially for the GBSD program.²⁶ However, the estimates of the amount of manpower needed are subject to several uncertainties. At the time of this writing in 2018, certification design criteria were still undergoing revision. This leads to uncertainties in the certification workload. And, as argued above, the manpower needed to do nuclear certification depends on how well certification criteria are considered in system design. GBSD is still in early design. The management of this process needs to prepare for the possibility that the needed resources for certification could be larger than the best estimates currently possible.

Getting the estimated needed resources is, nevertheless, still challenging. AFSEC has not been able to augment its workforce to the estimated needed levels.²⁷ AFSEC faces a bureaucratic challenge with which AFGSC can help. When submitting its budget requests for the Air Force program objective memorandum, it has the advocacy of a two-star general. Most other submissions, including that of AFGSC, have the advocacy of a four-star general. Because the nuclear certification is critical to the success of AFGSC missions, AFGSC could assist in the advocacy for these resources. By taking a mission view, as discussed in the next chapter, AFGSC could identify key limiting resources for mission success and use its position as the nuclear organize, train, and equip major command to advocate for the limiting resources, regardless of where they appear in the budget.²⁸ We recommend that AFGSC play such a role, and we develop this point further in Chapter Three.

In the same spirit as we did in Table 2.1 for EMP, Table 2.2 lists a number of questions regarding the management and oversight of nuclear certification in the Air Force. Again, these questions are not exhaustive, but are shaped to drive discussion within the command in a way that enlightens ways to improve enterprise management. The questions are meant to be for the reflection of senior leaders and not to drive additional reporting tasks for staff.

²⁵ The GBSD program office has begun such an integration.

²⁶ Peery and Simpson, 2017.

²⁷ As this report was being written in September 2018, the Air Force was in the process of preparing a plan to address the nuclear certification issues identified in Peery and Simpson, 2017.

²⁸ That was the intent of the core function leads, before they were disestablished in favor of the Air Force Warfighting Integration Capability.

Table 2.2. Key Considerations for AFGSC for Managing Nuclear Certification

Process Step	AFGSC Considerations
Certification Criteria	• How is AFGSC supporting AFSEC's development of certification criteria? • What steps is AFGSC taking to ensure the necessary growth in nuclear certification expertise (e.g., helping AFSEC defend its budget requests for resourcing)? • How is AFGSC keeping AFNWC and AFSEC apprised of any future programs or initiatives that might require nuclear certification?
Certification Requirements	• Are certification requirements appropriate given current concepts of operations? • How are requirements written for systems to ensure that nuclear certification, nuclear surety, and cyber security are integrated in design?
Certification Informed Design	• What is the risk that waivers will be requested for any of the designs for the B-21, LRSO, and GBSD for nuclear certification?
Design Certification	• How should cybersecurity concerns be addressed in nuclear certification? • What should AFGSC do to ensure that the AFNWC is appropriately resourced for design certification?
Operational Certification	• Is there a master plan and schedule for operational certification across all systems?
Certification Sustainment	• What is the appropriate resourcing level for the inspector general and other staff to ensure certification over time?

General Conclusions at the Process Level

For all processes that nuclear systems must pass, such as testing, nuclear certification, verification of the effectiveness of the nuclear systems, cybersecurity, and others, it is prudent to focus on early steps in processes to avoid injudicious choices that amplify in later stages. The earliest phases are standards and criteria writing and the resultant system design. The more attention paid to these phases to get them as sound and integrated as possible, the more payoff for subsequent phases and lower costs over the life cycle of the weapon systems. To engage these processes early in programs will necessitate attention that the right personnel get access to special access programs during the early stages.

The more these processes can be managed from end to end, the easier it is to identify any issues early (e.g., resource shortfalls), identify ways to correct for them, and get them into the budget and defend the budget adequately. Managing from the process view also identifies gaps and resource constraints that might not be identified by individual programs.

The more these processes can be managed in coordination with other processes, the better suited the systems designs will be for the nuclear mission, the better the events can be sequenced (such as writing standards and criteria before major design activities), and the more the Air Force can economize on resources for process verification (testing, certification).

Even when resource deficiencies are identified and future budget is allocated to address those deficiencies, the problem might not yet be solved. The nuclear skills needed in the workforce for specialized tasks such as EMP testing and nuclear certification are in short supply. As these

modernization programs grow, competition will grow for hiring this specialized workforce. Even if the Air Force can attract the applicants, there might not be enough skilled workers to fill the demand. The Air Force could help with this problem by finding ways to begin to hire and train the appropriate workforce now to be prepared for the future. Shortfalls in current activities, such as EMP testing of legacy systems or the need to revise nuclear certification criteria, are solid justifications for hiring and training now.

These two representative processes show the importance of managing from a holistic perspective. But these are only two of many processes, each of which need to be managed in an integrated fashion. We argue in the next chapter for the benefits of a more mission-centered view of managing the nuclear missions.

3. Mission-Level Management

In the previous chapter, we argued that improved end-to-end oversight of critical nuclear-specific processes could enhance the Air Force's ability to overcome some of the challenges listed in Chapter One. By taking such a view, issues can be identified and addressed earlier. Particular attention to activities early in the processes, such as setting sound standards and criteria that drive good design, can reduce manpower needed over time, thereby using scarce resources more efficiently and achieving better outcomes.

In this chapter, we discuss how an integrated view of the nuclear mission beyond individual processes can further help meet the challenges listed in Chapter One. The Air Force's role in the nation's nuclear mission is expressed in the most recent Nuclear Posture Review (NPR)²⁹ and other high-level policy documents, all subject to potential changes from future legislation or arms control agreements. The direction from the NPR and arms control agreements places close constraints and some rigid demands on the Air Force nuclear force structure.

The Air Force supports three nuclear roles for the nation: a land-based strategic deterrent provided by ICBMs, a strategic bomber deterrent provided by bombers equipped to carry cruise missiles and gravity bombs, and a nonstrategic mission to support the North Atlantic Treaty Alliance. We focus in this report on the first two missions, whose organize, train, and equip responsibility rests with AFGSC.

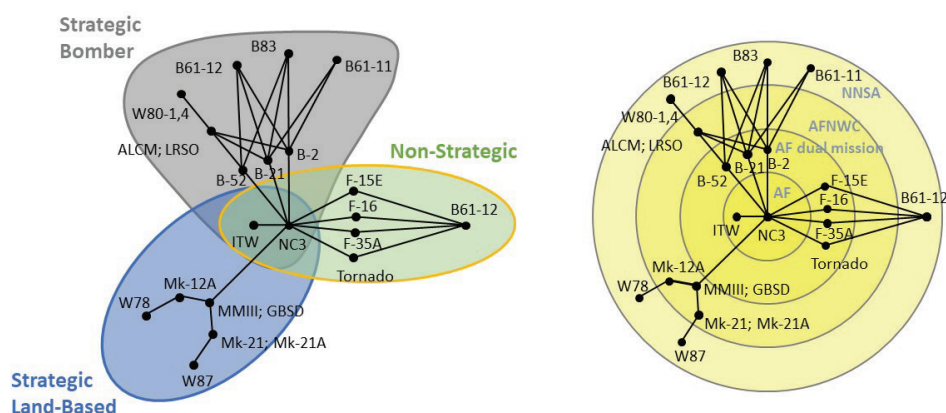
A challenge to overcome is that management structures run orthogonal to these nuclear roles. This dichotomy complicates integrated sustainment of each nuclear role and is illustrated in Figure 3.1. The figure shows two simplified diagrams depicting nuclear systems and their interrelations. Both diagrams share a common network of black-colored dots that represent systems and black-colored links that represent first-order interrelationships. The systems in the core are the supporting systems of integrated tactical warning (ITW) and nuclear command, control, and communications (NC3). The nuclear weapons lie at the outer edge, and the delivery platforms lie between the core and the edge.

Superimposed over this network are two groupings, one shown in each of the two diagrams. The diagram on the left groups the three Air Force nuclear roles, which run radially outward, overlapping at the core. The diagram on the right groups the management structures. At the core, ITW and NC3 are managed across the Air Force (Air Force Space Command, AFNWC, AFGSC). The next ring outward contains platforms managed by the Air Force Life Cycle Management Center, Rapid Capabilities Office, and a Joint Program Office (F-35A). The next ring outward contains those managed by the AFNWC, and the outer ring includes systems managed by the National Nuclear Security Administration. The management structures run

²⁹ Office of the Secretary of Defense, 2018.

concentrically and orthogonal to the nuclear roles illustrating how the roles and management are aligned differently.

Figure 3.1. Nuclear Systems in a Mission Perspective



SOURCE: Adapted from Snyder et al., 2013, Figure 1.2.

NOTES: MMIII = Minuteman III; NNSA = National Nuclear Security Administration. AF = Air Force. ALCM = air-launched cruise missile.

Some misalignments in organizations are inevitable. All management structures facilitate certain activities and present seams for others. Even if it were desirable to realign the roles depicted in Figure 3.1, it is not feasible. The Air Force must grapple with how to manage these nuclear roles given the existing structures to continuously support the nation's nuclear deterrence needs, and if called upon, employ nuclear weapons.

For managing the Air Force nuclear mission, what this means is that, at any given time, the Air Force must be able to (1) maintain an exact specified number of ICBMs on alert and bombers available (plus all supporting systems) and (2) be able to express whether different postures could be supported and what time and resources would be required to transition from the status quo to any new posture. The latter ability is necessary to inform arms control negotiations and future drafts of the NPR and to address concerns raised in Congress and elsewhere regarding the Air Force's nuclear roles.

Ensuring that the force structure meets national requirements at all times and being able to address paths to possible alternative postures involves all the challenges listed in Chapter One. The sheer number of programs and their complexity magnifies these tasks. It is not just coordinating and ensuring that all the major fielding activities will be done on time; the transition from legacy to new platforms is in itself a large problem. In particular, the transition from Minuteman III to GBSD presents considerable logistical complications. The legacy systems need to be sustained until the day they are decommissioned, and the new systems need to be ready the day they are needed. And this transition is not limited to the missiles and warheads, but also

encompasses an extensive infrastructure of launch control centers, launch facilities, and weapon system command and control.

AFGSC, as the lead major command, will need to confront these matters with a relatively small, inexperienced staff. AFGSC staff will need to navigate an environment that is likely to be resource constrained, and they will need to have the perspicacity to deal with an evolving geopolitical environment and emerging threats. To meet these needs, they will need management mechanisms to make the best use of constrained resources.

Mechanisms Used in the Past

None of the challenges the Air Force now faces are new. But it now faces these challenges with a smaller, less experienced nuclear workforce.

Strategies-to-Tasks

From the present day, it can seem that now successful programs were obviously sound choices and were well supported when being procured and fielded. That has often not been the case. One instructive example occurred around 1970, when the Air Force was attempting to buy the E-3 Sentry, developing what would become the F-15, and proposing a block buy of the new C-5A. There was opposition to these programs in Congress, and, in a single day, all three were stripped from the draft authorization bill. As part of this battle within the Senate, Senator Barry Goldwater requested that the Air Force provide justification for these programs so that he could fend off arguments to cancel them. The Air Force tasked the response to the action-officer level and returned a document that took a parochial, Air Force view, focused on technical details and programmatic milestones. It did not explain why these weapon systems were critical to national needs. That response was not received well in Congress, even by Air Force supporters.

In a second effort, a top-down framework was developed by Glenn Kent, the strategies-to-tasks framework, that justified the weapon systems based on their roles in national-level mission objectives. That approach placed the programs in a setting where they were described as playing critical roles to missions of high national importance. They were not described as individual programs of merit on their own right, or as intrinsic Air Force “missions.” The programs were restored to the authorization.³⁰

The strategies-to-tasks framework links national objectives to force structure in an end-to-end edifice.³¹ It decomposes objectives to strategies, strategies to campaign objectives, campaign objectives to operational objectives, operational objectives to operational tasks, and operational tasks to systems. These linkages in a hierarchical decomposition form an audit trail. One audit trail moves upward, showing how each system and activity contributes to higher-level efforts,

³⁰ Kent et al., 2008, pp. 115–121.

³¹ Kent, 1983; Kent, 1989; Thaler, 1993; Kent et al., 2008, pp. 115–121.

and eventually national objectives. It shows the consequences of failure to execute a step in a process or acquisition activity to *national objectives*. Another audit trail moves downward, demonstrating how national objectives are planned to be met by a plethora of orchestrated activities. Although developed to rationalize force structure investments, it has proven to be a powerful framework for planning.

Dedicated Advocacy

An example of a nuclear program that faced opposition was the Peacekeeper ICBM. Peacekeeper was a particularly complex case. The program evolved over many proposed configurations and basing modes from its initial definition in 1972 to its deployment in 1986. The strategic environment changed over this period, and the program faced numerous technical challenges. Nevertheless, the program, despite its many dramatic changes over time, successfully concluded with a deployed system. The ability of the Air Force to keep the program alive and moving forward in a difficult environment contributed to the overall success of U.S. foreign policy, especially arms control in the 1980s.

The Peacekeeper program was originally conceived in an atmosphere of intense superpower rivalry with the Soviet Union. It was designed to increase U.S. striking power compared with the Minuteman III by employing more accurate and more numerous reentry vehicles. In the 1970s and 1980s, there was widespread concern that the employment of more than one warhead on a single missile created a dangerous instability in the nuclear balance with the Soviet Union. Many in Congress and elsewhere wished that any new missile have a survivable basing mode, one that would require more than one or two Soviet warheads to destroy a missile with any confidence. This desire led to a lengthy and complex series of basing proposals and associated congressional votes on delaying, canceling, or restarting the program.³²

A remarkable aspect of this process is that, despite this turbulent environment, the development of the missile itself, independent of basing options, proceeded reasonably smoothly.³³ The Carter administration made a supplemental budget request to proceed with full scale development in December 1978,³⁴ and the first missiles reached initial operating capability in December 1986.³⁵ Although the Air Force would have ongoing reliability problems with the missile's complex inertial guidance system, the missile that was ultimately fielded had changed relatively little from the system the Air Force had advocated in 1976.³⁶

³² Spires, 2012; Boese, 2005.

³³ Stockman and Fornell, undated.

³⁴ Edwards, 1982, p. 169.

³⁵ Anonymous, 1986.

³⁶ Edwards, 1982, p. 131

Arguably, a key element of that success was the program leadership's attention to the political environment, especially in Congress. Central to that advocacy was the Office of the Special Assistant for Intercontinental Ballistic Missile Modernization Matters, designated RD-M.³⁷ RD-M was a small office with a staff of roughly a dozen highly qualified personnel chosen to cover the most critical aspects of ICBM modernization.³⁸ RD-M was headed by a one-star general, and the staff were chosen to have ICBM expertise in the range of issues that were in dispute, including personnel from civil engineering (for basing issues), intelligence (given the rapidly changing strategic environment), and public affairs; a lawyer; and others. The key attributes that RD-M had were expertise, the agility to respond to questions and criticisms in hours or days, and the ability to speak on behalf of the Air Force to the Secretary of Defense, the White House, the Central Intelligence Agency, and Congress. At one juncture, the leader of RD-M was briefing the Secretary of Defense on a weekly basis. The RD-M staff were intimately aware of any concerns about the ICBM programs, were responsive on the necessary timescales, and had the expertise to have good outcomes.

Recommendations

To better meet the challenges facing nuclear modernization in the Air Force, we recommend that the Air Force develop a master plan for each of the two nuclear roles that AFGSC supports: the land-based strategic deterrent and the strategic bomber deterrent. These master plans would adopt a strategies-to-tasks framework to show a detailed decomposition of the means by which each of these missions will be sustained over time. These plans should exist in a digital environment and be a dynamic resource, not a static, intermittently updated physical document. They should pay equal attention to the sustainment of legacy systems, fielding of new systems, and the transition from legacy to new.³⁹

Figure 3.2 shows a simplified depiction of what a strategies-to-tasks framework might look like for Air Force nuclear missions. The top of the figure shows a box for national-level objectives. This represents a set of specific statements in Presidential Policy Directives (and the equivalent), Executive Orders, the NPR and its Implementation Plan, the Guidance for the Employment of the Force/Contingency Planning Guidance, the Joint Strategic Capabilities Plan, and other guidance at this level, including arms control agreements and relevant law. All Air Force nuclear roles exist to fulfill these national-level objectives. The lower portions of the strategies-to-tasks framework show how every system and process combine to support major systems, which in turn combine to satisfy assigned Air Force roles, which in turn furnish

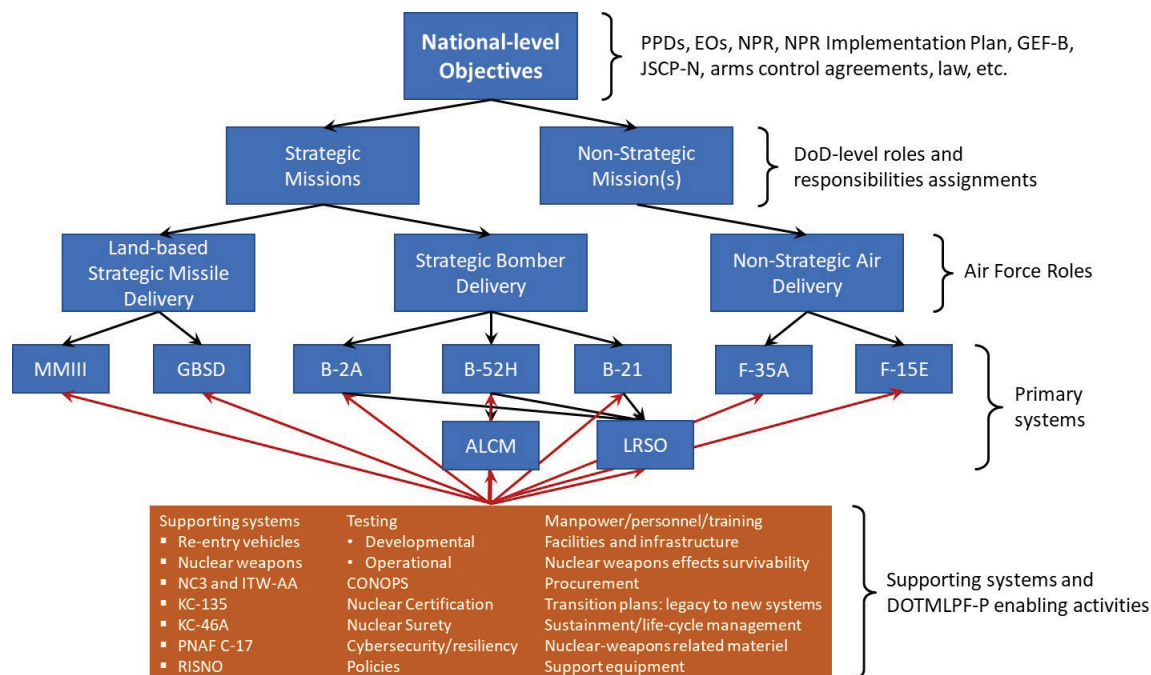
³⁷ Our discussion of the RD-M office is based on an interview with Lieutenant General (retired) Gordon Fornell (conducted by Dick Anderegg on June 13, 2018), who headed RD-M from 1982 to 1985, and an interview with General (retired) Bob Kehler (conducted by Don Snyder on February 1, 2018), who was on the RD-M staff.

³⁸ The Small ICBM program was also active at this time.

³⁹ See Snyder et al., 2013.

missions for combatant commanders, which ultimately fulfill national-level objectives, all in the form of a clear audit trail.

Figure 3.2. A Strategies-to-Tasks Framework for Air Force Nuclear Deterrence



NOTES: ALCM = Air-Launched Cruise Missile; CONOPS = concepts of operations; DoD = U.S. Department of Defense; DOTMLPF-P = doctrine, organization, training, materiel, leadership and education, personnel, facilities, [together with] policy; EO = executive order; GEF-B = Guidance for the Employment of the Force Annex B; ITW-AA = Integrated Tactical Warning and Attack Assessment; JSCP-N = Joint Strategic Capabilities Plan Nuclear Annex; MMIII = Minuteman III; NPR = Nuclear Posture Review; PNAF = Prime Nuclear Airlift Force; PPD = Presidential Policy Directive; and RISNO = Reconnaissance in Support of Nuclear Operations.

The mission perspective is paramount. It is the job of operational wings and program offices to track and report readiness at the system level. It is the job of higher-level headquarters to track and report current and projected future readiness at the mission level, expressed in terms of the ability to carry out national-level nuclear objectives.

Reading down from the top of Figure 3.2, national-level objectives drive two broad mission areas: strategic and nonstrategic mission(s). These drive, one more level down in indenture, three roles assigned to the Air Force for carrying out these missions: land-based strategic missile delivery, strategic bomber delivery, and nonstrategic air delivery. The next level down describes the primary systems that provide these roles—now and into the planned future. For these primary systems to successfully provide for the national objectives, they need many subsystems and processes; the principal ones are shown in the red box at the lowest-level indenture at the bottom of Figure 3.2.

The defining attribute of strategies-to-tasks is the linkage of all the elements of an enterprise, including all the systems and processes, to national-level objectives through this hierarchy. Every

role, system, or process at any level is justified by its contribution to the national-level objectives. Therefore, the framework explicitly shows, *for every system and process, a clear audit trail connecting it to the relevant statements in the documents for national-level objectives*. We recommend that such a framework be developed, in digital form, for Air Force nuclear roles.

As an illustration, consider first a system such as a specific communications terminal for NC3. How should the funding of this system be prioritized within the Air Force, and what is the appropriate narrative to justify its budget request for audiences outside the Air Force? Placing the system in a strategies-to-tasks framework shows all the higher-level systems that the NC3 system enables, how it relates to other systems, and, through the audit trail upward through the architecture, how the NC3 system contributes to specific national-level objectives. Its interrelationship with other systems and processes assists in prioritization within the Air Force. The audit trail to national objectives provides a compelling narrative for justifying the NC3 system's budget request for external audiences.

Now consider an activity such as nuclear design certification. What is its role in the nuclear mission, and what narrative should be developed to justify its funding levels? Like the example of the NC3 system, nuclear design certification supports a number of systems. It has an additional complexity, however, in supporting those systems to varying degrees over time. At one time, design certification might be a major task for one set of systems. At a later time, it might be a different set. And, as argued in Chapter Two, there might be critical times when a review and rewrite of nuclear certification criteria might be indicated. This additional temporal dimension for many processes, including the transitioning from legacy to new weapon systems, requires the strategies-to-tasks framework to include a time dimension in the digital database, which operates more horizontally in Figure 3.2 and therefore gives the vertical audit trails a temporal dependence.

The digital master plans that we advocate would provide that time-dependent audit trail. The plans would document the integrated activities necessary for all the systems and processes needed to perform the land-based and bomber missions shown in Figures 3.1 and 3.2. These dynamic plans would be designed to support decisions that

- assist in identifying resource deficiencies or problems with coordination
- assist in balancing resource allocations in the budget
- assist in addressing any queries regarding alternative force structures that might arise during deliberations for arms control agreements, the next NPR, or other future deliberations that affect nuclear posture.

We also recommend that the Air Force use this strategies-to-tasks framework for its nuclear roles to strengthen the coordination of advocacy across the three largest organizations in the Air Force for managing the nuclear mission: AFGSC, the AFNWC, and the Deputy Chief of Staff for Strategic Deterrence and Nuclear Integration (AF/A10). We cannot know how much of the ultimate success of the Peacekeeper program was due to the RD-M organization. It is clear, however, that it faced political opposition and that other interest groups in the Air Force were

vying for the funds. Having an organization that was nimble, skilled, and could work at the pace of Washington, D.C., was a strong asset to Peacekeeper.

The sense of urgency and of the importance of ICBMs to the nation's security are not as acute as they were in the 1980s; some former senior defense officials and political leaders even question the need to retain the ICBM force at all, advocating a move to a dyad.⁴⁰ Also, the budgetary environment today is more competitive than it was in the 1980s during the Reagan administration's military buildup. We recommend that a function similar to what RD-M performed be reinvigorated today. Whether it be placed in AFGSC or A10 is less important than that it be

- a single, coordinated voice across AFGSC, AFNWC, and AF/A10
- supported by strategies-to-tasks constructed master plans tied to national-level objectives
- agile enough to respond to the pace of Washington, D.C.
- empowered to represent the Air Force to the Secretary of Defense, the White House, and Congress
- imbued with personnel with the expertise to make sound, convincing arguments.

To assist in the coordination between AFGSC and AF/A10 and to improve AFGSC's reaction time to the pace of Washington, D.C., we propose that AFGSC consider establishing a formal, small presence in the national capital region. Such a presence would help AFGSC remain aware of and react to issues in the Pentagon in a timely fashion, and to proactively represent AFGSC's interests. This presence could take the form of a detachment, highly coordinated with AF/A10, and provide an office for the AFGSC commander to use during frequent visits to Washington, D.C., to add the weight of that office to unified Air Force positions.

In the same spirit as we did at the process level for EMP testing and nuclear certification, Table 3.1 lists a number of questions regarding the management and oversight of the Air Force's nuclear roles from a mission perspective. As before, these questions are not exhaustive, but are shaped to drive discussion within the command in a way that enlightens ways to improve enterprise management. The questions are meant to be for the reflection of senior leaders and not to drive additional reporting tasks for staff.

⁴⁰ Paltrow, 2017.

Table 3.1. Key Considerations for AFGSC for Managing from a Mission Perspective

Timeline	AFGSC Considerations
Today	• What is the strategies-to-tasks narrative for the AFGSC roles in national nuclear deterrence, for the land-based strategic deterrent and for the strategic bomber deterrent? • Does each have consistent nuclear survivability requirements for all concepts of operations? • What is the Air Force doing in Washington, D.C., to proactively advocate for its strategies-to-tasks narrative? • How can AFGSC better advocate for balanced budget positions for its nuclear roles, regardless of where those appear in the Air Force budget? • What can AFGSC do to improve coordination and transparency across AFGSC, AF/A10, and AFNWC? • What is AFGSC doing to learn from the experiences of more mature lead major commands in fielding weapon systems?
Future	• How will AFGSC support any future deliberations on nuclear force structure, such as arms control negotiations and the next draft of the NPR? • What is the Air Force doing to record lessons learned today to assist the next generation?

4. Discussion, Conclusions, and Recommendations

Political opposition and resource constraints, including both budget caps and limits on the Air Force end strength, are likely to continue to challenge the Air Force in its nuclear modernization efforts. In the past decade, the active duty end strength in the Air Force has declined by 2.5 percent.⁴¹ During that same period, the enacted Air Force base blue total obligation authority has remained nearly the same in constant dollars.⁴² During this decade, Air Force roles have expanded, particularly in cybersecurity, but the Air Force has not given up any other major roles or missions. Most of the resources to pay for this new mission have come out of a contraction of the total aircraft inventory by about 11 percent, and other efficiencies. As of early 2019, future year spending limits that could trigger sequestration have not been lifted, even as spending on nuclear modernization is planned to take an increasing share of the defense budget. Prospects for unrestrained resourcing appear to be dim. If that is the case, the Air Force will need to meet these challenges through accurate and timely anticipation of the needs for future resources, effective advocacy for those resources, and effective resource utilization.

Summary of Recommendations

Mission-Level Management

Above all, we recommend that the Air Force create and maintain dynamic master plans for the sustainment of its nuclear *missions*. These master plans would adopt a strategies-to-tasks perspective and be balanced across sustaining legacy systems, fielding new systems, and transitioning from legacy to new. They would be tied to national-level objectives and provide the information to help identify resource deficiencies or problems with coordination in time for action, help in preparing and advocating for balanced resource allocations in the budget, and help with assessing alternative future force structures.

Process-Level Management

One part of these plans would be an enterprise view of key nuclear processes. Managing these processes from a holistic view could assist in using scarce resources most effectively. The most benefit should come from focusing on getting the higher-level, early activities as precise as

⁴¹ The active duty end strength in 2007 was 333,495, and in 2018 it was 325,100. “2018 USAF Almanac,” 2018, p. 39.

⁴² In fiscal year 2007, the enacted Air Force base blue total obligation authority was \$122.6 billion in fiscal year 2017 dollars (\$104.5 billion in fiscal year 2007 dollars) (Faykes, 2007). In fiscal year 2017, the enacted Air Force base blue total obligation authority was \$123.9 billion in fiscal year 2017 dollars (Martin, 2017).

possible in these processes, because they drive later resource demands, with harmful consequences if injudicious choices are made.

Organizational Issues

We recommend that the Air Force use the master plans to support a single organization to advocate for Air Force nuclear initiatives. This organization will need to be able to respond at the pace of activities in Washington, D.C., and have the expertise to perform sound, convincing advocacy. AFGSC might consider a presence in the national capital region to help it stay within the fast decision cycles of the Pentagon.

To compensate for the inexperience of AFGSC and the Air Force as a whole in procuring and fielding new nuclear systems, we advocate that AFGSC find more opportunities to reach out to other major commands to learn from their experiences. Some nuclear issues are unique to AFGSC, but many other aspects of fielding systems have much in common.

We caution that, beyond the direct effects of resource constraints, management also needs to be alert to an insidious indirect effect. Organizations within a large bureaucracy with competition for limited resources have knowingly underestimated their expected workforce requirements due to a fear of “being laughed out of the room.” In our discussions throughout the Air Force nuclear enterprise, we heard some anecdotal evidence of this phenomenon. Leaders will need to be attuned to this possibility and actively seek to correct it. Inaccurate feedback regarding resourcing needs will further complicate the challenge of advocating for and securing proper resourcing.

Institutional Knowledge Capture

Maintaining institutional knowledge of nuclear system development and acquisition is challenging because of the long lifespans of the systems. Few personnel who were directly involved with the development, acquisition, or fielding of the previous generation of systems remain in the workforce, either in industry or government. Given the expected lifespan of the programmed new systems, the likelihood is high that when the next ICBM, nuclear cruise missile, or nuclear bomber is fielded, they, too, will exceed the careers of many current members of the nuclear enterprise. Because of this, actively recording the lessons learned during today’s modernizations programs could be very advantageous to the success of the future enterprise. We recommend that the historians be involved in these activities, recording the struggles and successes and, as best they can, the causal links in order to invest in the future.

Specifically, we recommend that

- technical, programmatic, and fielding challenges be recorded along with any corresponding remedies
- records be retained, even for special access programs
- oral interviews of key participants be conducted and archived.

With these efforts, the Air Force should be in an improved position to meet the many challenges in sustaining and modernizing its roles in the nation's nuclear missions.

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