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America Can Afford Survival

**A Capable U.S. Nuclear Security Enterprise is Critical Part of
Deterrence**

Nuclear Triad Industry Study

ES-6700

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Seminar 16

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**The Dwight D. Eisenhower School
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ABSTRACT

The United States is embarking on a much overdue, decades-long program to modernize the nuclear triad and the nuclear security enterprise (NSE). The U.S. nuclear triad consists of fielded weapons systems across three legs: land-based Intercontinental Ballistic Missiles (ICBM) make up the ground leg, submarine-launched ICBMs aboard nuclear-powered submarines make up the sea leg, and heavy bombers armed with bombs and cruise missiles make up the air leg. Distinct from the triad but still crucial, the NSE comprises the warhead design capability, weapons production, and the Defense Industrial Base (DIB) supporting these platforms. Both the triad and NSE are essential for deterrence but are currently outdated and in dire need of modernization. The modernization effort is simultaneous with the rise of a Great Power Competition (GPC), with China and Russia as nuclear peers. Global supply chain disruptions and a weakened U.S. industrial base have exposed vulnerabilities in the NSE.

Through multiple engagements with senior NSE leaders and analysts over nearly 20 weeks, the seminar identified three recurring themes: slow planning and procurement cycles, inadequate infrastructure, and inadequate leadership focus. The seminar conducted extensive research on the nuclear enterprise, participated in both in-person and virtual briefings with experts, traveled to laboratories, military bases, production, research, and development facilities across the U.S., and attended the Strategic Weapons of the 21st Century Symposium to thoroughly research this topic and make specific recommendations.

The seminar recognized that the challenges facing the NSE far exceed what can be captured holistically in a single paper. To develop actionable recommendations, the seminar framed its initial research using Strategic Posture Commission Report (SPCR) categories: Stakes, Threat, Strategy, Strategic Posture, Nuclear Security Enterprise, Non-Nuclear Capabilities, Allies and Partners, and Risk Reduction, and conducted a Porter's five forces industrial base analysis.

Following broad investigation, the seminar refined its focus to high-priority, near-term opportunities to make significant improvements. The goal of this paper is to provide recommendations that enable national policy, NSE, and industrial base leaders to create conditions that will build a credible and effective nuclear deterrent amidst evolving global threats and strategic competition.

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PREFACE

Nuclear Triad Industry Study Seminar Members (AY 23-24)		
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	Mr. Kenneth Lam	Department of State
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	Lieutenant Colonel William Root	U.S. Air Force
	Ms. Pamela Shepherd	Department of Defense
	Lieutenant Colonel John Tolin	U.S. Army
	Colonel Michelle Waguespack	U.S. Army
	Lieutenant Colonel Tobin Walker	U.S. Marine Corps
	Mr. Evan Ward	Department of the Air Force
	Mr. Kyle Wilhelm	Department of Energy

Table 1 – Nuclear Triad Industry Study Members

The Nuclear Triad Industry Study (IS) was expertly coached and mentored by IS Faculty lead Mr. Brad Clark and IS Faculty Deputy Mr. Robert Williams. The IS Student Lead was Colonel James Rodriguez, U.S. Air Force. The collective of seminar students (the “seminar”) was comprised of military O-5/O-6 and government civilian GS14-15 level representatives of the U.S. Army, U.S. Navy, U.S. Marine Corps, U.S. Air Force, and the Departments of Defense, State, and Energy, with diverse backgrounds, experience and expertise across acquisition, information operations, personnel management, diplomacy, policy, and tradecraft skillsets.

INDUSTRY STUDY OUTREACH AND FIELD STUDIES

The Seminar participated in numerous engagements with nuclear weapons policy leaders and subject matter experts across the Departments of Defense (DoD), Energy (DOE), and State (State), Congress, the military departments, national laboratories, think tanks and industry. The tables below synopsize key presentations, symposia and field studies.

Presentations	
PRESENTATIONS	Nuclear Strategy and Strategic Posture Commission Report. Robert Soofer, The Atlantic Council, and Matthew Costlow, the National Institute of Public Policy.
	2022 Nuclear Posture Review, Paul Amato, Director for Nuclear Deterrence Policy.
	OSD A&S/NCB/Nuke Matters. DoD nuclear weapons enterprise, interagency Nuclear Weapons Council, and DoD interface with DOE's National Nuclear Security Administration (NNSA).
	OSD A&S/A/Strategic, Space, and Intelligence Portfolio Management (SSIPM). Nuclear system acquisition programs.
	U.S. Air Force Strategic Deterrence and Nuclear Integration Office, HAF/A10. Air Force nuclear programs.
	U.S. Navy Strategic Systems Programs, Washington Navy Yard. Navy nuclear triad current platforms and modernization programs.
	China's strategic build-up and U.S. Strategy and Force Posture. Mr. Pat McKenna, Senior Deterrence Analyst, USSTRATCOM, Strategic Deterrence Directorate.
	National Geospatial-Intelligence Agency. Monitoring Russian nuclear weapons, DPRI Nuclear Pursuit, Counter-Proliferation/WMD, DOE/IN, Creating Common Assessments, Defense Counterproliferation (DCP3).
	Extended Deterrence and U.S. Nuclear Forces: how allies in the Pacific view U.S. nuclear-extended deterrence guarantees. Brad Glosseman, and Sugio Takahashi.
	Strategic Forces Subcommittee. Jonathan Epstein, Adam Truss, Peter Schirtzinger, Maria Vastola. Subcommittee Staffers' perspective on the nuclear triad modernization program and the industrial base.
	National Nuclear Security Administration (NNSA). NNSA Defense Programs perspective on weapons modernization programs, NNSA infrastructure modernization, interaction with the Department of Defense, and challenges facing the NNSA production complex.
	Department of State. DAS Robert Koepcke, Office of Korean and Mongolian Affairs: Peter Sloan, DPRK Unit Chief, Wade Boese, Director, Office of Strategic Stability and Deterrence Affairs, Anny Vu, Deputy Coordinator for Bilateral Affairs, Office of China Coordination. Policy briefs on the complexities of bilateral and multilateral relationships in the two-peer competitive environment.

Table 2 – Presentations

Industry Study Outreach and Field Studies	
SYMPOSIUM	 <p>18th Annual Symposium on Strategic Weapons in the 21st Century Symposium “Nuclear Deterrence in a Fundamentally Different Setting” Co-hosted by Los Alamos and Lawrence Livermore National Laboratories, this conference provides a forum for policymakers and experts to engage in substantive dialogue on the nature of strategic conflict and the intersections of technology, strategy, and policy.</p>
	 <p>Naval Submarine Base Kings Bay, Kings Bay, GA Provides support to the fleet, fighter and family by maintaining and operating the facilities of the Trident submarine force. The East Coast home of the Navy’s Ohio class submarine force.</p>
	 <p>NNSA Pantex Plant, Amarillo, TX Serves as the nation’s primary facility for the final assembly, dismantlement, and maintenance of nuclear weapons. One of six production plants in the NNSA enterprise.</p>
	 <p>BAE, Hill AFB, Salt Lake City, UT Provides sustainment of the Minuteman III and system transition to digital engineering environment to modernize ICBM management.</p>
FIELD STUDIES	 <p>Little Mountain Test Facility, Hill AFB, Ogden, UT Provides testing in support of nuclear hardness and survivability for Minuteman and priority DoD and DoE programs, military systems, and aerospace products.</p>
	 <p>Sentinel and Minuteman III System Program Offices, Hill AFB, Ogden, UT Encompasses the entire lifecycle management of the Air Force’s nuclear weapon systems – acquisition, sustainment, modernization, and ultimately, disposal and demilitarization.</p>
	 <p>Raytheon Technologies, Tucson, AZ Provides integrated mission solutions through Strategic Strike capable weapons through the Raytheon Missiles and Defense Business Segment.</p>
	 <p>Air Force Nuclear Weapons Center, Kirtland AFB, Albuquerque, NM Nuclear focused center within Air Force Materiel Command (AFMC). Synchronizes all aspects of nuclear materiel management on behalf of the AFMC commander in direct support of Air Force Global Strike Command.</p>
	 <p>NNSA Sandia National Laboratories, Albuquerque, NM A federally funded Research and Development Center (FFRDC); Sandia National Laboratories provides innovative science and engineering to anticipate and solve the most challenging national security problems; it is a design agency for Kansas City National Security Complex.</p>
	 <p>NNSA Y-12 National Security Complex, Oak Ridge, TN Y-12 maintains the U.S. nuclear stockpile/nuclear weapons program mission; one of six production plants in the NNSA enterprise; retrieves and stores nuclear materials and fuels the nation’s naval reactors components in support of the U.S. nuclear deterrence.</p>
	 <p>General Dynamics – Electric Boat Quonset Point RI, and Groton, CT Provides manufacturing, hull fabrication, steel processing, coatings, modular construction, and fleet support for the nation’s submarine fleet.</p>

Table 3 – Symposia and Field Studies

Acknowledgments

The presentations, symposium, and field studies were foundational to the seminar's understanding of U.S. nuclear weapons and infrastructure capabilities and capacity within the context of the current global security environment. Many thanks to Mr. Brad Clark and Mr. Bob Williams, who developed and executed a world-class course agenda and briefing schedule featuring leaders, experts, and organizations within the Nuclear Security Enterprise (NSE).

This paper is the result of an exemplary group effort with significant contributions from the entire seminar. Draft paper development, organization and integration was led by Mr. Evan Ward. Mr. Kyle Wilhelm and Colonel Rodriguez served as final editors. All members of the seminar contributed critical thought, subject matter expertise, and content to the paper. To the extent that it reads with one voice, credit goes to our advisors and editors.

EXECUTIVE SUMMARY

Great Power Competition (GPC) with two nuclear peers/near-peers is driving the United States to confront the realities of an aging nuclear weapons stockpile and production infrastructure, shrinking manufacturing base, and a nuclear enterprise strategy that has been focused for a generation on maintenance and caretaking rather than investment and recapitalization. China's rapid ascent to near-peer nuclear power status, Russia's nuclear saber-rattling in its war against Ukraine, and the emergence of North Korea as a nuclear threat in the Pacific that could conceivably strike the U.S. have all focused U.S. national security leaders across current and recent administrations on the critical importance of the U.S. Nuclear Security Enterprise (NSE). While focus and rhetoric are important, overcoming the significant challenges to reinvigorating the U.S. NSE will require fortitude, a whole of government approach, and enduring political will.

The United States has now begun a long overdue, decades-long program to modernize both the nuclear triad and the NSE. The U.S. nuclear triad consists of fielded weapons systems across three legs: Land-based Intercontinental Ballistic Missiles (ICBM) make up the ground leg, submarine-launched ICBMs aboard nuclear-powered submarines make up the sea leg, and heavy bombers armed with bombs and cruise missiles make up the air leg. Distinct from the triad but no less important, the NSE encompasses the warhead design capacity, weapons production, and the Defense Industrial Base (DIB) supporting these platforms. After decades of post-Cold War neglect, modernization of the triad and NSE are both vital to maintaining the long-term credibility of the U.S. nuclear deterrent. Deferred modernization has mortgaged margin and over-leveraged the flexibility of operational systems. Neglect, global supply chain disruptions, and a weakened U.S. industrial base have exposed vulnerabilities in the NSE.

The initial plan for triad modernization, first embarked on late in the Obama administration, is now widely understood to be insufficient in the current global security environment. The NSE is struggling to support the new demands placed on it, and its infrastructure modernization plans are inadequate to support an uncertain future. Great Power Competition demands not only that the United States field weapons systems that address today's threats and ensure deterrence, but also that it invest in and sustain an enduringly robust NSE. Rather than simply manage a stockpile, this NSE must have the capability to produce all the nuclear material, designs, and critical components required to ensure that the U.S. nuclear deterrent can scale, evolve, and react to a dynamic and volatile world. The capability of the U.S. nuclear enterprise is itself a critical component of a credible deterrent, and should be prioritized as such. Being a nuclear superpower brings many responsibilities, and maintaining the NSE is one of them.

SUMMARY OF CHALLENGES

Slow Planning & Procurement Cycle – There is a significant disconnect between the speed at which the strategic environment is evolving and the speed at which U.S. nuclear posture and requirements change. This is concretely illustrated by the Strategic Posture Commission Report finding that the nuclear modernization POR is “necessary but not sufficient.”

Inadequate Infrastructure – The industrial base and production complex that make up the NSE is in dire need of complete overhaul and recapitalization; the authors believe the metaphor of the imminent threat caused by an arterial bleed accurately captures the urgency of the situation.

Inadequate Leadership Focus – There is a disconnect between the importance of the nuclear

deterrent to U.S. national security and the willingness of political leaders to expend political capital to ensure it remains safe, secure, and effective. The Biden Administration National Security Strategy is clear that deterrence remains “a top priority for the Nation and foundational to integrated deterrence,” but neither the executive nor legislative branches are allocating sufficient time, attention, funding, or unity of effort to reflect this priority.

SUMMARY OF RECOMMENDATIONS:

Whole of Government Recommendations

Apply Appropriate Perspective & Avoid Zero Sum Thinking – U.S. political and military leaders must constantly contextualize U.S. nuclear deterrence and advocate for all the resources required to keep that cornerstone of U.S. national security strategy on firm foundation.

Centralize Coordination and Accountability – The President should appoint an advisor at the Deputy National Security Advisor or Deputy Assistant to the President level on the National Security Council to coordinate and oversee a whole of government approach to the modernization of the triad and the NSE.

Streamline Acquisition of Strategic Systems – Congress and the executive branch should coordinate to develop and expand the use of unique acquisition authorities like the National Sea-based Deterrence Fund for strategic systems in order to promote flexibility and enhance industrial capacity and supply chain stability within the nuclear industrial base and the NSE.

Strengthen Supply Chains – The U.S. must deploy a whole of government approach to strengthen the reliability and resilience of the supply chains on which both the NSE and the nuclear triad rely.

Recommendations for Near Term Modifications to Nuclear Posture

Expand Recapitalization of B-52 – The U.S. should expand its recapitalization of B-52 delivery systems beyond the planned 46 bombers.

Plan to MIRV Minuteman III – The U.S. should develop plans to increase the number of warheads fielded on the current Minuteman force to hedge against Sentinel transition risk and the likely event that Russia abandons New START.

Deploy dual-capable aircraft and weapons to the Indo-Pacific – The U.S. should coordinate with partners and allies in the region to forward deploy dual-capable aircraft and associated nuclear weapons and bolster the credibility of extended deterrence with minimal additional stress to the NSE.

Recommendations for Investments Beyond the POR

Develop Capabilities to Address Hard and Deeply Buried Targets (HDBT) – The United States must develop the capability to hold at risk the command-and-control elements, weapons, and other adversary capabilities that are either deeply buried or oriented in ways that make reaching them difficult.

Invest in Defense and Survivability – Hardening critical nodes provides a hedge against the emerging threat posed to U.S. nuclear systems by hypersonic weapons and other emerging technologies. Additionally, investing in strategic defense in the late 2020’s and early 2030’s can provide flexibility to bridge deterrence gaps that may be created by triad modernization programmatic delays.

Acquire and Field Tomahawk Based SLCM-N – The U.S. must hedge against the survivability risks to the sea leg of the triad posed by quantum sensing. This can be accomplished by growing the number of nuclear-capable submarines, and the fastest way to accomplish this is to arm fast attack submarines (SSN) with nuclear-capable Sea-Launched Cruise Missiles (SLCM-N) based on the Tomahawk cruise missile.

Accelerate Conventional Hypersonic Strike Capability – The U.S. must quickly develop its hypersonic technology to hold adversary targets at risk as counter-missile technology progresses. The U.S. should continue to develop hypersonics as conventional weapons but should provision designs to enable rapid adaptation to employ nuclear weapons. Doing so would provide the U.S. with the ability to match adversary nuclearization of hypersonics and would provide a credible tradeoff for future arms negotiations.

Recommendations for Nuclear Security Enterprise Infrastructure

Build Capacity to Support a GPC Strategy – Develop an updated NSE infrastructure modernization plan scoped to support a GPC strategy. This plan must consider the robust

capability and capacity of the NSE itself as a key component of deterrence and as an independent requirement beyond any requirements derived from current posture needs.

Boost NSE Infrastructure Investment – The Executive Branch should advocate for and Congress should appropriate additional funding for NSE infrastructure investment, including, at a minimum, all funding required to cover overruns and schedule slips against the current modernization plan as well as funding to expand the NSE infrastructure modernization program to one appropriately scoped to support a GPC strategy.

Develop NSE Workforce – Options for flexible work arrangements and attractive incentives such as performance-based pay raises and employee assistance packages must be standardized recruitment and retention tools across the NSE.

Develop and Cultivate a Mission-Driven Culture – Highlighting the importance of the NSE mission and the critical role STEM work has in its success will inspire and engage future employees for generations.

Create Buy-In at All Levels –NNSA should begin implementing programs that create opportunities for buy-in at all levels for current and future NNSA mission planning.

Recommendations Beyond the U.S. Nuclear Enterprise

Exploit the Benefits of Digital Design – Digital design tools have changed what is possible when designing complex systems, and the DoD and NNSA should exploit digital design tools to the fullest extent possible.

Invest in Technology AND Capacity –The DoD and DOE/NNSA should invest directly in additional capacity for casting and forging and similar cross-cutting bottlenecks in parallel with coordinated investment into promising new technologies.

Protect Sensitive Technology Transfer – Nationally coordinated basic security clearances should be required for individuals conducting research identified as sensitive in order to mitigate the risk posed by potential insider threats and to signal the importance the federal government places on the work.

INTRODUCTION

Nuclear weapons are now a central focus of U.S. foreign policy for the first time in decades. Two subsequent presidential administrations have acknowledged the return of Great Power Competition (GPC). The U.S. will soon face two nuclear peer adversaries with ambitions to undermine the post-Cold War international order, by force if necessary. China is engaged in a “breathtaking” and “explosive” nuclear expansion.¹ Xi Jinping has ordered the People's Liberation Army (PLA) to be capable of invading Taiwan by 2027.² Russia is routinely brandishing its strategic arsenal as it invades and occupies Ukraine. North Korea now fields nuclear weapons and delivery systems capable of striking the U.S. homeland. Driven by the need to keep pace with these dramatic changes, the U.S. is at the beginning of what will be a decades-long nuclear modernization program. The U.S. nuclear triad consists of fielded weapons systems across three legs. Land-based Intercontinental Ballistic Missiles (ICBM) make up the ground leg, submarine-launched ICBMs aboard nuclear powered submarines make up the sea leg of, and heavy bombers armed with bombs and cruise missiles make up the air leg. The U.S. nuclear security enterprise (NSE) includes warhead design capability, weapons production complexes and associated engineering, and the portions of the Defense Industrial Base (DIB) that support the nuclear triad delivery platform modernization. The triad and NSE are distinct, but they are both in urgent need of modernization and both essential for U.S. deterrence. While this program to modernize everything all at once is essential, its outcome is by no means certain. It is replete with risk and presents a monumental challenge to an enterprise operating with uniformly old and often decrepit infrastructure. These risks cannot all be eliminated, but they can be mitigated. The purpose of this paper is to identify, analyze, and offer practical steps to eliminate, reduce, or manage risks facing both the triad and the NSE.

Compounded Problems

The re-setting of the strategic nuclear landscape coincides with another reckoning occurring across the U.S. and the developed world. The snarling of global supply chains during the COVID-19 pandemic threw into stark relief the geoeconomic entanglement that proliferated during America's 'unipolar moment'.³ Massive consolidation in the U.S. defense industry and general trends among U.S. companies toward financialization and away from capital-intensive manufacturing have caused grave concern about the capacity of the U.S. DIB.⁴ Recent shortages of everything from automobiles to baby formula prove that these are real-world problems, not just academic handwringing.⁵ While these macro-economic trends have caused deep and concerning wounds to the broader U.S. industrial base, in the NSE they combine with decades of neglect and inattention to produce the equivalent of an arterial bleed. Without urgent intervention, the long-term credibility of the U.S. nuclear deterrent is at extreme risk.

Deferred modernization in the triad has mortgaged margin and over-leveraged the flexibility of operational systems. All three legs of the triad currently rely on systems operating decades beyond their designed lifetimes. Major portions of the nuclear production complex still operate in facilities built in the 1940's for the Manhattan Project. Reliance on numerous single points of failure throughout the NSE would make any strategist or program manager sweat. The agency most responsible for the maintenance and modernization of this complex, the National Nuclear Security Administration (NNSA), is pervaded by a culture of compliance paralysis and risk aversion. The recent Congressionally authorized Strategic Posture Commission Report (SPCR) concluded that the infrastructure enabling the "development and fielding of strategic capabilities needs to be overhauled."⁶ While this is certainly true, the problem is both more acute

and more urgent. Combined, the state of the U.S. nuclear triad and NSE present a profound strategic risk.

Major Themes

The seminar identified the following three major themes that inform all sections of the paper and the recommendations:

- 1) **Slow Planning & Procurement Cycle** – There is a significant disconnect between the speed at which the strategic environment is evolving and the speed at which U.S. nuclear posture and requirements change. This is most concretely illustrated by the SPCR finding that the nuclear modernization program is “necessary but not sufficient”⁷
- 2) **Inadequate Infrastructure** – The industrial base and production complex that make up the NSE is in dire need of complete overhaul and recapitalization; the authors believe the metaphor of an arterial bleed accurately captures the urgency of the situation.
- 3) **Inadequate Leadership Focus** – There is a disconnect between the importance of the nuclear deterrent to U.S. national security and the willingness of political leaders to expend political capital to ensure it remains safe, secure, and effective. The Biden Administration National Security Strategy is clear that deterrence remains “a top priority for the Nation and foundational to integrated deterrence”, but neither the Executive nor Legislative branches are currently allocating sufficient time, attention, funding, or unity of effort to reflect this priority.⁸

THE TRIAD AND NUCLEAR POSTURE

America’s Aging Nuclear Triad – America has delayed the recapitalization of nuclear assets until the platform and weapon age across the nuclear enterprise has made further life extensions all but impossible. The strategic landscape of a decade ago made these delays seem tolerable, but

the return of GPC is throwing the cost into stark relief. The triad modernization Program of Record (POR) now requires the simultaneous replacement of the major systems at the core of all three legs of the triad, along with their command-and-control systems and warheads, and all just in time to replace systems reaching the bitter end of their already extended lives.⁹ This eleventh-hour, everything-all-at-once replacement will leave the U.S. increasingly vulnerable over the next two decades, with limited options to hedge against expanded and enhanced threats.

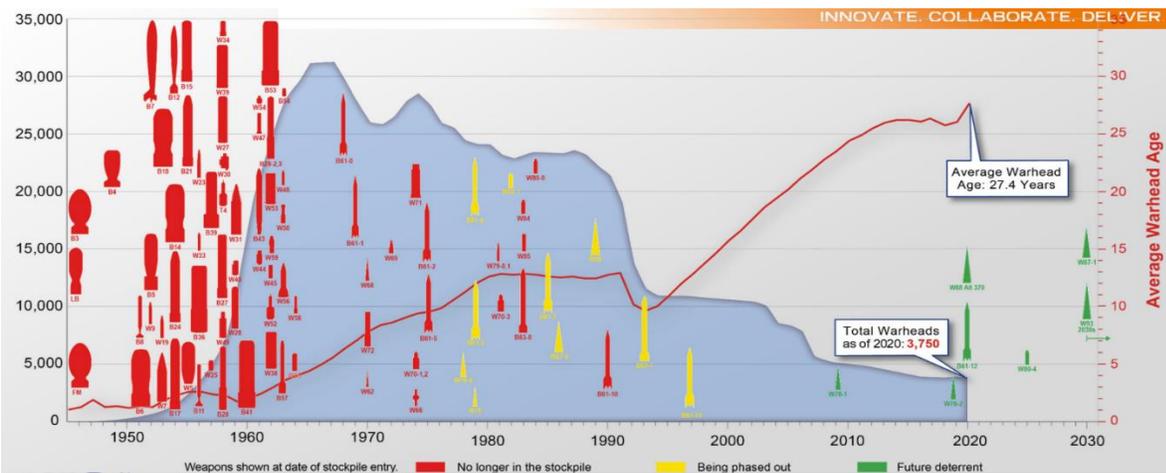


Figure 1 - Average Age of U.S. Warheads

Current Program of Record – Under the POR, multiple complex and enormously expensive systems are being replaced simultaneously, including all of America’s Intercontinental Ballistic Missiles (ICBM) and their supporting infrastructure, the Air-Launched Cruise Missile (ALCM), the strategic bomber fleet, and the ballistic missile submarine (SSBN) fleet. Each leg of the triad provides unique capability – ICBMs are most responsive, the air leg provides visibility and flexibility, and SSBNs guarantee survivability – no single leg can fully compensate for the degradation of others.¹⁰ Taken individually, the scale, complexity, expense, and novelty of these efforts make them highly prone to cost overruns, schedule delays, and technical setbacks. Taken together, the cumulative risk is larger than the sum of its parts, as the age and health of all legs of

the triad diminish their utility as a reliable hedge while other portions of the enterprise undergo transition.

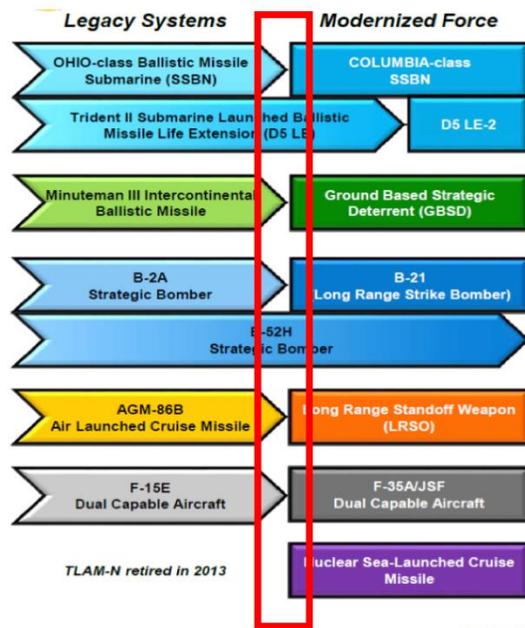


Figure 2 - Triad Modernization

The responsiveness of ICBMs, combined with the targeting challenge their numbers create for an adversary, make them irreplaceable for America's deterrence posture. Unfortunately, ICBMs also carry the most risk in the U.S. triad due to the age of the Minuteman III missiles, cost overruns on the Sentinel replacement program, and uncertainty in support infrastructure.

The air leg of the U.S. triad carries less risk than the ICBMs due to the success of the B-21

Bomber and Long-Range Stand-Off (LRSO) cruise missile programs. The B-21 bomber has completed its first flights and is on track to be operational by the late 2020's, with a total planned buy of 100 bombers.¹¹ The B-21 has relied on multiple key factors to keep the program on track: requirements, design and funding stability, and special status as a program under the Air Force Rapid Capabilities Office, giving it rapid access to senior decision-makers and streamlined oversight.¹² The B-52 is undergoing modernization upgrades and will provide 46 bombers capable of employing the LRSO cruise missile in significant numbers. However, the ALCM currently used by the air leg is over thirty years past its original end of service, increasing reliability risk until its replacement can be fielded.¹³ The program slated to replace the ALCM, LRSO, is on track to meet its Initial Operating Capability (IOC) by 2029.¹⁴

The sea leg of the U.S. nuclear triad is crucial to maintaining assured second-strike capability, and it faces the least amount of risk among the modernization programs. While the Columbia program is facing delays, the continued viability of the Trident submarine-launched ballistic missile (SLBM) and the ability to further extend the lifetimes of some of the Ohio-class submarines that carry them mitigate the impacts of those delays on deterrence posture.¹⁵ The Navy is purchasing fewer of the new SSBN class but says reduced maintenance demands will allow for a similar patrol schedule.¹⁶

Risks Beyond the POR – While the simultaneous recapitalization of all three legs of the U.S. nuclear triad would create a hazard to U.S. deterrence posture in the most benign of environments, this risk is compounded by circumstances not accounted for by the POR. The emergence of two adversarial nuclear peers and at least one hostile lesser nuclear power changes U.S. deterrence requirements dramatically compared to when the POR was originally developed during the late Obama Administration, and emerging technologies threaten to further undermine the strategic posture the POR was crafted to support.

Two Peers Plus – Unlike when the POR was originally developed during the first years of the Obama Administration, Russia is directly threatening NATO, China is dramatically increasing its nuclear arsenal, and North Korea is capable of ranging the Continental U.S. with nuclear weapons. America can no longer focus solely on deterring Russia while ignoring North Korea and treating China as a “lesser included case”.

Russia still poses the most significant nuclear threat to the United States. Russia continued to modernize its nuclear arsenal after the Cold War, allowing it to maintain a healthier

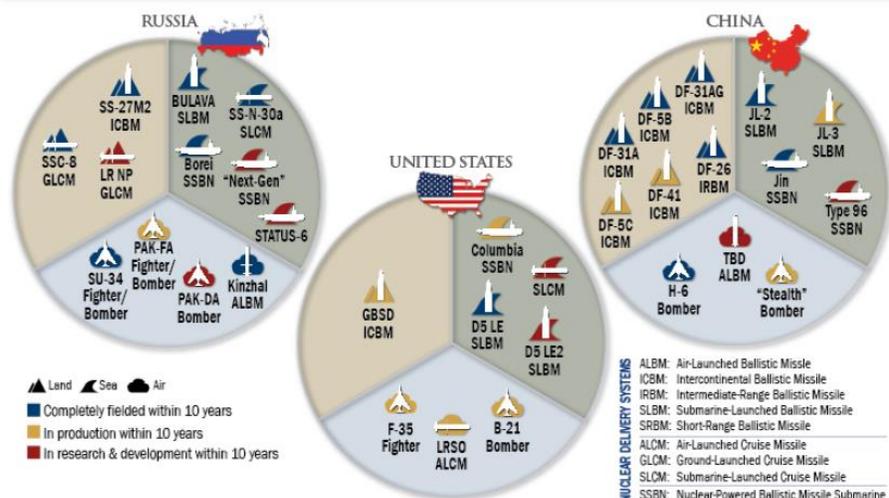


Figure 3 - Fielded and Planned Nuclear Forces

nuclear industrial base than the U.S. The New START Treaty has thus far limited Russia's strategic nuclear arsenal; however, the current conflict in Ukraine and strained relations with the U.S. make a follow-on treaty unlikely. Russia also possesses at least 2,000 non-strategic or theater nuclear weapons exempt from New START limitations.¹⁷

Where the People's Republic of China (PRC) once had limited nuclear capacity, it has begun rapidly growing its nuclear forces along with its broader military capability and sphere of influence. It is replacing older nuclear warheads with increased numbers of more capable systems that could total over 1,000 warheads by 2030.¹⁸ The PRC also now possesses a true nuclear triad, and its capabilities range from regional to intercontinental systems. While its arsenal is much smaller, North Korea's newly acquired capability to target the continental United States adds yet one more threat vector to be considered in designing and equipping the U.S. triad to deter aggression.¹⁹

Emerging Technologies Threaten Deterrence Posture – Over the next two decades, emerging technologies are poised to complicate America's strategic deterrence challenge further.

Hypersonic weapons and quantum sensing - particularly when combined with artificial intelligence, big data analytics, and autonomous systems - have the potential to undermine portions of the U.S. nuclear triad and deterrence posture by reducing reaction time and threatening the U.S. capability of assured second-strike (additional technical details included in Appendix C). The speed and maneuverability of hypersonic weapons being developed and fielded by U.S. adversaries already render current U.S. missile defenses inadequate and mean the President would have significantly less time to respond than if the nation were under a ballistic missile attack. At the same time, extremely sensitive quantum magnetometers, gravimeters, and acoustic sensors, along with anti-neutrino detectors capable of observing nuclear reactor emissions from the other side of the Earth, might make it impossible for America's current and upcoming generation of submarines to hide.²⁰ This would undermine the security of America's most survivable triad leg, just as hypersonics make a surprise first-strike against the U.S. more feasible. U.S. research and development into both emerging technologies could help America leverage the deterrence effect of its own hypersonic programs, but industrial base constraints may hinder any such efforts.

STATE OF THE NUCLEAR INDUSTRIAL BASE

Porters Five Forces – Analysis of the industrial base supporting the nuclear triad and the NSE reveals incredibly diverse and unique conditions. The following analysis uses Porter's Five Forces model to focus on the nuclear-unique market. The nuclear-unique market consists of technologies, components, and services that only have utility within nuclear weapons and/or delivery platforms and primarily comprises bilateral monopolies. DOE national laboratories and production sites are government-owned and contractor-operated. The market also includes highly

specialized firms that produce defense-only products, such as nuclear-powered submarines and cruise missiles.

Rivalry among Competitors: Competition within the nuclear-unique market can be categorized in two ways. In the first category, there is no conceivable competition because barriers to entry are insurmountable for private industry alone. For example, for nuclear-powered submarines, Electric Boat, with support from the U.S. government, has made unparalleled capital investments in infrastructure, tooling, and fixtures. In the second category, competition is conceivable, however, many factors contribute to dissuade rivalry. For example, the majority of DOE laboratories and production sites are managed by Limited Liability Companies (LLC), such as Consolidated Nuclear Security (CNS). These contracts tend to be long-term and include services that range from basic facilities management and administration to highly specialized security and advanced engineering support that require a skilled workforce with unique, specialized knowledge and security clearances. In many cases, the prime contractor subcontracts with multiple other firms, creating complex networks of interdependence and reduced competition. Therefore, overall competition between firms is low, with firms choosing to share the market rather than compete in it.²¹

Power of Suppliers: Supplier power is strong, as the firms in the nuclear-unique market provide specialized services that no other firms can reasonably provide without substantial investment. For example, BWX Technologies possesses a complete monopoly on the supply of naval nuclear reactors. Similarly, for the DOE laboratories, each site's management firm has decades of experience navigating bureaucratic oversight and highly regulated processes to manage one-of-a-kind laboratories and production sites. Supplier power is high because contracts

tend to be worth several billions of dollars over long durations. Furthermore, supplier power is bolstered by the U.S. prioritization of nuclear deterrence.

Power of Buyers: Buyer power is strong, as the U.S. Government is the sole buyer of nuclear-unique products. As a monopsony, the U.S. government sets the demand and controls the profit structure. Additionally, the U.S. government maintains the authority to terminate contracts for convenience at any time. Although the implications of termination are substantial, there is precedent for management contracts being re-competed by DOE, as is currently happening with CNS's management of Pantex and Y-12.²²

Threat of Substitution: There are no direct substitutes for many of the technologies and components of these critical defense systems. For example, although many foreign navies operate diesel-electric and fuel-cell-powered submarines, the U.S. Navy's requirement is for submarines to operate submerged for long periods of time and over vast distances silently, meaning there is no viable alternative to nuclear power. Additionally, security requirements and restrictions prohibit foreign suppliers from competing for submarine construction. Furthermore, there is no substitute for the nuclear explosive package of a nuclear warhead, and the Comprehensive Nuclear-Test-Ban Treaty inhibits further development of potential substitutes.

Threat of New Entrants: There is minimal threat of new entrants. Participation requires enormous capital investment, a highly skilled workforce with requisite security clearances, meeting onerous regulations and safety standards, and achieving high-end/high-quality production. Additionally, many of the contracts are joint ventures in which one company's reputation is tied to another's performance. Thus, a lack of reputation within the industry hinders new entrants who might seek to participate in a joint venture contract.

Gap Identification – Analysis of this unique market unveils the following gaps which will be further detailed in subsequent sections:

1. After decades of neglect, there are fewer suppliers, insufficient production lines, and a lack of skilled workers to support what the DoD requires of the industrial base. These years of underinvestment have led to cold production lines.²³
2. DOE/NNSA failing infrastructure and inconsistent funding. The nuclear-unique market faces skilled labor shortages.
3. Nuclear regulations and restrictions inhibit competition, adoption of new technologies, and new entrants in the market.
4. Vulnerabilities presented by numerous single points of failure research and production facilities and supply chain nodes.

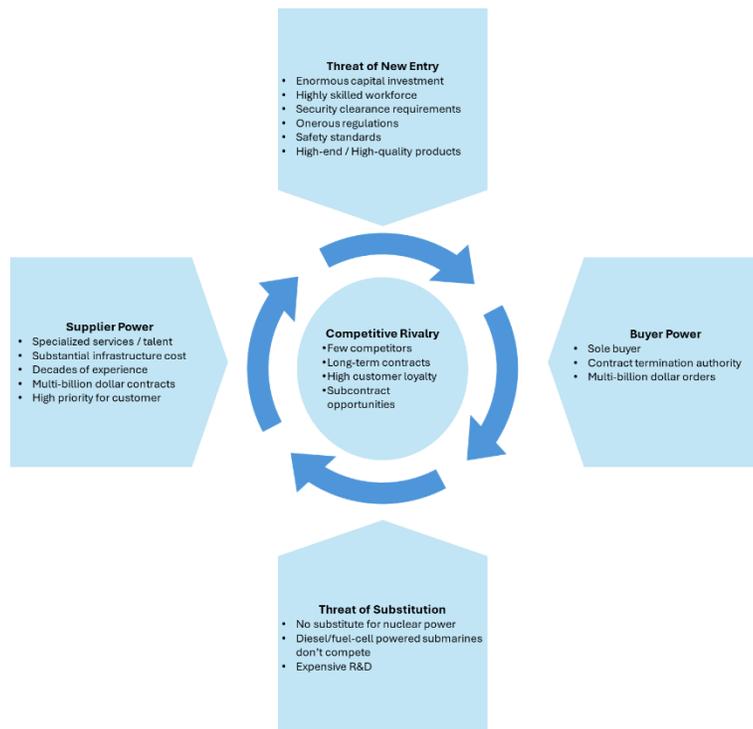


Figure 4 - Five Forces Analysis

INFRASTRUCTURE OF THE NUCLEAR SECURITY ENTERPRISE

National Nuclear Security Administration Facilities and Equipment – The U.S. NSE still primarily operates out of infrastructure dating back to the Manhattan Project. Despite reductions following the end of the Cold War, the DOE’s National Nuclear Security Administration (NNSA) still operates over 5,500 facilities.²⁴ Of those facilities, 41% are older than 61 years, 16% are 41-60 years, and 43% are 40 years or younger.²⁵ The condition of this infrastructure directly reflects its age. NNSA assesses 57% of its facilities are in poor to very poor condition, 24% are in fair condition, and only 18% are in good condition.²⁶

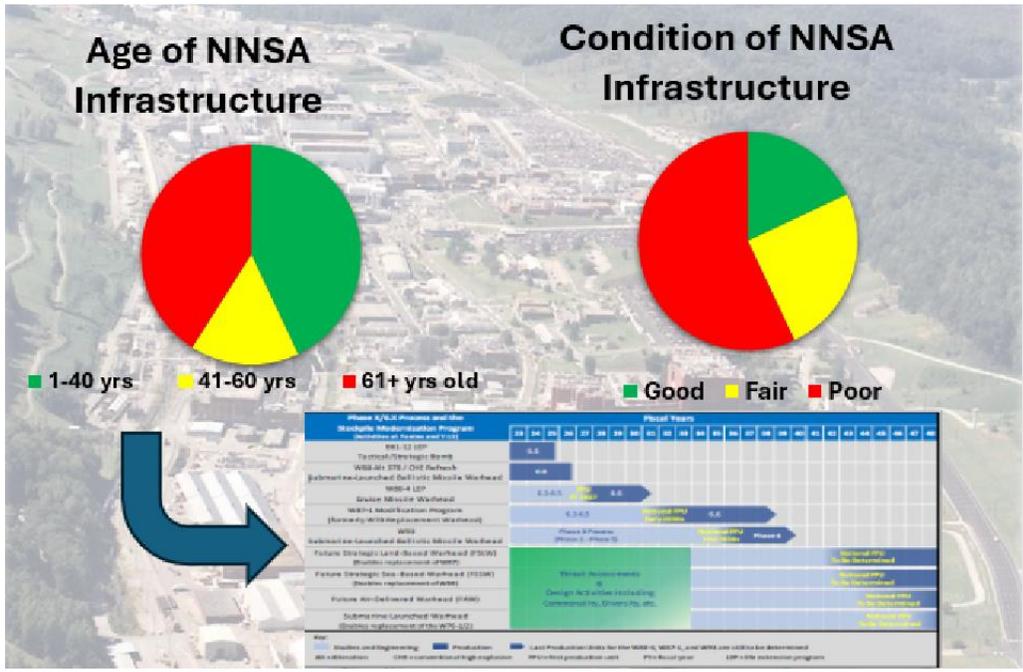


Figure 5 - NNSA Infrastructure Age & Condition

A nuclear superpower that extends its deterrence guarantee to allies across two oceans should not have allowed its weapons infrastructure to decay to this point, but a benign strategic environment and optimism about the apparent decreasing salience of nuclear weapons combined to lead well-intentioned national policymakers to place the nuclear weapon complex into sustainment mode in the early 1990s. This trend continued until late in the Obama

Administration, and while it has now begun to respond to the dramatically more threatening strategic environment, decades of neglect cannot be erased quickly.²⁷

The current nuclear weapons infrastructure modernization program was initially scoped to support the demands of the 2010 Nuclear Posture Review.²⁸ The program developed NSE infrastructure modernization requirements predicated on a streamlining strategy that reduced weapon variety to three ballistic warheads, one cruise missile warhead, and one bomb, and did not include the capacity to execute any new development, modification, alteration, or Life Extension Programs (LEP). This strategy has not survived contact with the contemporary security environment, and while the plans for warhead and delivery platform production have moved beyond those originally conceived a decade ago, it is not clear that plans for NNSA's infrastructure modernization and capacity expansion have kept pace. The complex is struggling to deliver on the current modernization plan, which has an estimated cost of \$34 billion.²⁹ Today's DoD delivery platform modernization plans result in a more aggressive delivery schedule than was accounted for in 2013 and are largely driven by evolving strategic threats. Figure 6 outlines the current and concurrent weapon activities of the NNSA.³⁰

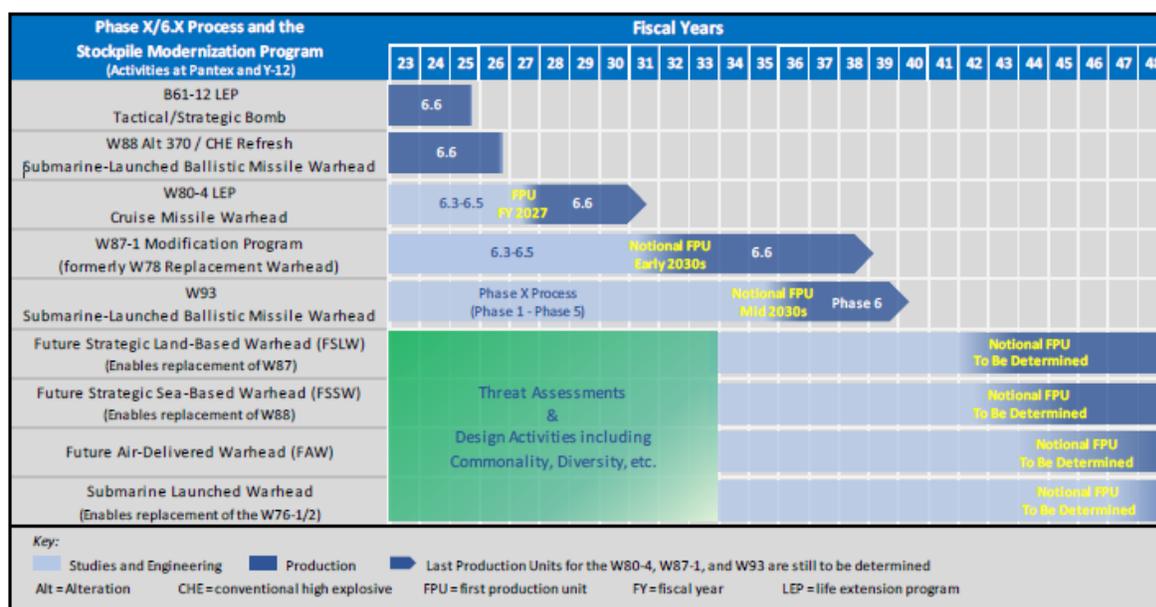


Figure 6 - NNSA Weapons Activities

Exacerbating the challenges to the already overburdened NSE, as of FY20 the average age of a nuclear explosive package of a warhead or bomb was 28 years (see Figure 1).³¹ Additionally, certain critical components of each warhead (e.g., plutonium pits) have not been replaced or refurbished since their original production date and aging of these components is increasingly becoming a concern with the potential to impact weapon surety and performance characteristics. In a 2020 response to Congress regarding a 2019 report by the JASON advisory group, NNSA stated that it "... [R]ecognizes that there is continued uncertainty in assessing the performance of older pits due to radioactive decay of the plutonium."³² NNSA does not currently have the capability to produce new pits, and while it is actively pursuing a plan to restart that capability, it has yet to produce even one "War Reserve Ready" pit and expects the first production unit certification in 2024.³³ NNSA now acknowledges that it will not meet the Congressional requirement for pit production of 80 pits per year by 2030, and currently plans to reach a rate of 50 per year at Savannah River and 30 per year at Los Alamos "...as close as possible..." to 2030.³⁴ Both Congress and the Government Accountability Office (GAO) have

questioned the practicality of NNSA's pit production plan based on the lack of existing capabilities and current progress.³⁵

Pit production is the best-known example of delays and cost overruns; problems endemic across the NNSA production base. The GAO estimates that the current 18 major infrastructure projects collectively face a 16% (\$2.1 billion) cost increase and a six-and-a-half-year schedule increase for completion.³⁶ NNSA Administrator Hruby noted at the 2023 Nuclear Deterrence Summit, "an acute shortage of specialized craft and trade workers who are certified to work on our critical nuclear projects."³⁷ Additionally, new infrastructure projects require conformance to modern safety requirements, raising technical and regulatory requirements above those that existed when most of the nuclear weapon complex was constructed shortly after the Second World War. The infrastructure crisis the NNSA now faces is largely the result of the simultaneous realization of two risks: the decay or obsolescence brought by age and the rigid inability of existing production capacity to flex to meet growing threats. Today, the NSE cannot enrich defense-purposed uranium, produce war reserve plutonium pits, or consistently produce meaningful quantities of high-grade explosives. History will repeat on other capabilities and lead to a series of continual crises unless the lessons of today are learned. Long-term risk in Tritium production is an illustrative example. Although successfully meeting today's demands, NNSA relies on third-party reactors encumbered by numerous constraints to do so. Like so much else in the NSE production complex, the future of U.S. tritium production is at the mercy of numerous and disparate outside forces rather than firmly in the control of a robust and well-resourced NSE.

Department of Defense Facilities and Equipment – The DoD's infrastructure issues for the modernization of the nuclear triad revolve around the sheer size and scale of the undertakings and the fact that similar infrastructure has not been built since the early 1970s. Senior Air Force

leaders have characterized the infrastructure required for the Sentinel program as one of our generation's most significant public works projects, equating its scale to that of the interstate highway system. Likewise, the size and scope of the new class of SSBN stresses a limited shipyard production capacity, requiring an enormous investment just to produce the first hull.

Sentinel ICBM cost increases and programmatic delays were attributed by the Service Acquisition Executive to service design changes mainly focused on support infrastructure costs. The scope is staggering, with 450 launch facilities spread across five of the largest states in the lower 48. The existing silos and launch facilities designed for the Minuteman III require substantial modifications to accommodate the Sentinel missiles. Ensuring these silos meet safety, security, and operational requirements is complex and costly, and any unforeseen change in one silo is likely to drive significant costs as the impact ripples across all 450 facilities.³⁸ Another scale problem for the Sentinel program involves below-ground communications infrastructure. The Air Force determined an entirely new communication network using fiber-optic cable was necessary, requiring the replacement of 7,500 miles of copper cable connecting 450 silos to launch control centers and other vital facilities. This is enough cable to run from the East Coast to the West Coast and back again with about a thousand miles of cable to spare. Designing, installing, and testing this network poses significant technical and logistical challenges.³⁹

The Columbia program, which is modernizing the sea-based leg of the nuclear triad, is experiencing challenges very similar to the Sentinel program. There are currently only two firms capable of producing submarines, General Dynamics Electric Boat and Huntington Ingalls Industries (HII) Inc.⁴⁰ Despite the two firms within the industry, Electric Boat has been the sole prime contractor building nuclear submarines for the U.S. Navy since the 1970s.⁴¹ Electric Boat and the Navy invested significant capital in building new facilities at Groton and Quonset Point

to facilitate the size and scope of the Columbia-class ballistic missile submarine. Electric Boat has further reduced the rivalry with HII by forging a sub-contractor arrangement with their Newport News shipyard to produce sections of the Virginia fast-attack and Columbia ballistic missile-class submarines, fostering collaboration, not competition, amongst the firms.⁴² These issues are further exacerbated by the Navy's programs to procure conventional armed assets such as the newest class of nuclear-powered attack Virginia-class submarines or surface ship production from HII, leading to competition on the limited naval production infrastructure and workforce.⁴³

Nuclear Enterprise Workforce – The workforce challenges facing the NSE have contributed to a significant lapse in development and management activities within the associated industries and have created knowledge reconstitution and preservation issues. This is especially crucial in the context of attracting, developing, and retaining talent in the NSE. The unique cohort of individuals that shepherded the nuclear stockpile through the end of the Cold War possess unique skills and experience, and they are aging out of the workforce. The Fiscal Year 2024 Stockpile Stewardship and Management Plan indicated NNSA's retirement eligibility is 21.6%, showing it will lose a major portion of its most experienced talent. Compounding the problem of knowledge retention, up to 70% of essential personnel across DoD and NNSA-owned or leased sites have five or fewer years of

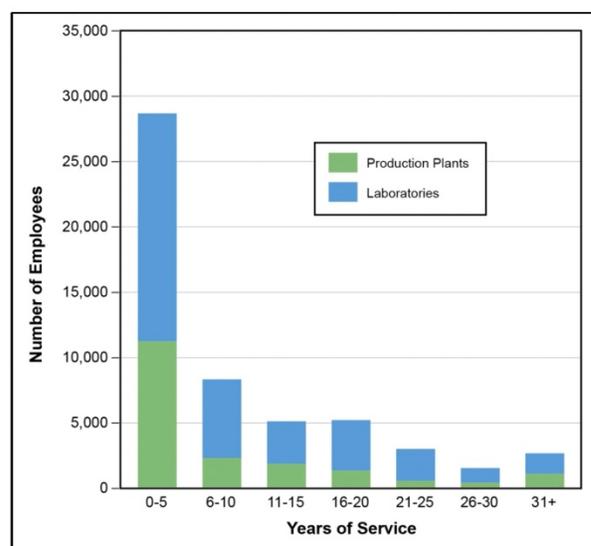


Figure 7 - Workforce Breakdown (of national security laboratories, the Nevada National Security Site, and weapons production facilities by years of service)

experience. This demographic ‘bathtub curve’ highlights the urgent need to capture and transfer critical knowledge from the aging generation to the developing workforce.⁴⁴

A significant issue for successfully modernizing and growing the NSE workforce is finding enough of the right people. Individuals must (1) meet stringent security clearance requirements, (2) possess the educational or experience requirements in STEM, skilled-trades, and other technical fields, and (3) have a desire to work within this highly specialized field, sometimes at an opportunity cost when compared to private sector benefits. The security clearance processing backlog is a critical impediment to recruitment in the technical sector for civilian and military personnel. For example, the Air Force is currently facing a clearance backlog of up to two years for missile crew members and maintenance personnel.⁴⁵ This necessitates a need to examine current adjudicative processes to identify choke points and opportunities to expeditiously vet security clearances.

The U.S. economy has slowly transitioned to a digital and service-based economy, causing a significant decline in the manufacturing workforce. In 2021, the manufacturing sector in the U.S. had 1.1 million workers, down from three million in 1985.⁴⁶ Last fall, DoD estimated that the U.S. industrial base would require more than four million jobs to sustain throughput over the next decade, and a \$1 trillion impact to GDP if the skilled trades gap is not addressed by 2030.⁴⁷ The mass exodus of manufacturing overseas in the late 20th century saw companies profiting from lower labor costs, less stringent regulations, and access to emerging markets. Despite renewed efforts to re-shore this capacity, workforce availability continues to be impacted.⁴⁸

Education statistics for U.S. institutions also indicate that the U.S. faces significant challenges in science and engineering (S&E) fields without intervention to increase student

enrollment. A 2012 report from the National Science Foundation (NSF) found that enrollment in S&E-related undergraduate programs remained consistent at 15-17% over 15 years while demand for workers in those fields was increasing significantly.⁴⁹ The NSF also revealed S&E-eligible workers electing to use their degree within the U.S. Government decreased from 6.4% in 1993 to 4.5% in 2010.⁵⁰ An economy with a low unemployment rate of just 3.8 percent and a high demand for those educated or experienced in a STEM or skilled-trades field means that those looking for a job in the U.S. do not stay in the market for very long.⁵¹ This problem will become increasingly worse in coming decades as competition for these workers increases.

Despite myriad nuclear modernization efforts, the nuclear industry faces a constrained talent pool largely due to widespread lack of awareness among potential recruits about career opportunities in the field.⁵² Further exacerbating this issue, workforce planning initiatives to assess and understand current and future manning shortfalls and critical skill gaps are limited across the nuclear security enterprise. Forecasting workforce needs is crucial to ensure the right talent is in place to support enterprise objectives and address challenges posed by demographic shifts.

Adding to the workforce challenge are the conditions enabling retention. Quality of life concerns include geographic locations, resources and opportunities for family members, and outdated work facilities.⁵³ A June 2022 RAND report describes employee dissatisfaction with facilities and technology infrastructure as a recurring theme in surveys.⁵⁴ Continued investment in modernizing critical infrastructure and technology systems to improve working conditions contributes to employee retention. Moreover, the demanding nature of nuclear security work leads to burnout and negative work-life balance.

Nuclear Enterprise Supply Chain – Risks to the NSE supply chain continue to impact both the modernization and production of end-item military capabilities. Globalization of supply chains supporting the nuclear stockpile has compounded these risks. While there are supply chain risks associated with every step of production for the items produced by the NSE, the most notable risks are related to foreign influences, regulation, and availability/obsolescence considerations.

Within the NSE, availability and obsolescence risks typically arise from the government's need to purchase small batches of highly specialized products in small quantities separated by long intervals. Many businesses choose to divest the capabilities required to produce unique items because the costs involved to make them do not justify retaining the capabilities. The government can mitigate these types of supply chain risks by guaranteeing agreeable purchase quantities to keep the supply chain active. There are, however, availability and obsolescence risks that are unpredictable and that can threaten the entire supply or even the existence of a material vital to the NSE. 3M's recent decision to cease the manufacture of polyfluoroalkyl substances (PFAS), also known as "forever chemicals" is an illustrative example of these unpredictable risks.⁵⁵

3M, one of the leading suppliers of PFAS to the NSE, faced thousands of lawsuits seeking damages associated with widespread PFAS contamination of land and municipal drinking water supplies. In June 2023 3M elected to settle these claims for \$10.3 billion rather than continue to litigate and has announced that it will cease manufacturing PFAS altogether by 2025.⁵⁶ The NSE relies on PFAS to manufacture conventional high-explosive components of nuclear weapons.⁵⁷ While suitable alternatives to these chemicals might be found for other DoD applications, substitution within nuclear weapon systems is much more difficult given that the U.S. does not conduct nuclear tests. Identifying and validating a PFAS replacement without the

benefit of test data would pose significant risks and is likely not feasible. Pentagon officials have told Congress that the loss of PFAS materials “would undermine military readiness.”⁵⁸ The government must work within the NSE supply chain and the interagency to identify vulnerable supply lines and materials that could be impacted by these or similar financial risks as the complex expands to meet production and modernization goals.

Another supply chain risk particularly relevant to the NSE is the globalization of supply chains and the decline of key U.S. manufacturing capabilities. The U.S. has increasingly turned to foreign supply chains to meet needs once fulfilled by U.S. manufactures, introducing a host of challenges to include product quality, integrity, and availability. Globalization increases supply chain exposure to disruptions caused by natural and man-made disasters (e.g., pandemic, war, floods, tsunamis, etc.). Globalization also creates dependency on foreign regulatory schemes and foreign political considerations. An allied nation choosing not to supply items intended to support the NSE because they believe that to be in conflict with their obligations under the Nuclear Non-Proliferation Treaty is an example of this type of dependency.⁵⁹ The U.S. must make clear the importance of maintaining U.S. nuclear assurances to allies and partners to ensure their continued support to vital supply chains of the NSE, and to identify and develop redundant suppliers for critical materials, components, and equipment.

Like many large-scale defense programs, the Sentinel and Columbia-class programs face supply chain disruptions. This was exacerbated during the COVID-19 pandemic; however, a June 2023 GAO report indicated that the Sentinel program continues to experience supply chain disruptions and indicates Northrop Grumman is “working on multiple supply chain mitigations to address the issue.”⁶⁰ A review of Northrop Grumman’s 2023 10-K report cites that their ability to produce and deliver products will continue to be significantly hampered by supply chain

disruptions as some of their systems components have only one supplier or one domestic supplier, and that being subject to increased regulatory requirements on a global scale may render them unable to find suitable alternatives to meet obligations.⁶¹ This phenomenon is not limited to Northrup Grumman but is pervasive throughout the NSE. Supply chain issues with highly specialized components indicate the importance of an early procurement strategy for long-lead items and argues for creating redundancy to mitigate against these forms of supply chain risks.

LOOKING BEYOND THE U.S. NUCLEAR ENTERPRISE

Relative Strengths of the PRC and Russian Nuclear Enterprises – This section aims to open the aperture and examine Russia and the PRC to determine if their approaches hold lessons for how the U.S. might approach its modernization program. The following graphic identifies attributes benefiting adversary nuclear programs, two of which are highlighted further below (additional information on all factors can be found in the comparison table in Appendix A).

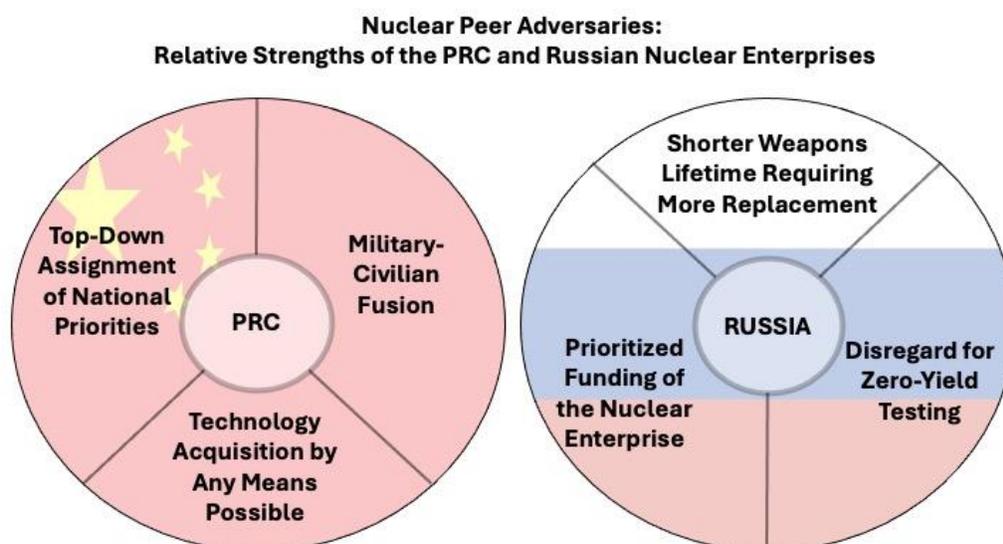


Figure 8 - Relative Strengths of PRC and Russia

Russia - Shorter Weapon Lifecycles & Stable Demand – Russia’s management of its nuclear stockpile relies on frequent maintenance and the rebuilding of its nuclear warheads because their systems have a design life of only 10 to 15 years.⁶² Stockpile maintenance also relies on regular pit replacement to ensure weapons surety, unlike the sophisticated modeling and surveillance programs that the U.S. uses to establish confidence in aging weapons.⁶³ While Russia requires more intensive stockpile management and is more inefficient from a resource perspective, it keeps the nuclear enterprise active and preserves industrial expertise among the workforce. Conversely, U.S. life extension programs have advanced surveillance capabilities and nuclear physics knowledge but neglected weapons design and pit production. The U.S. stopped regularly producing pits in 1989, thus few current national lab personnel have any experience hand-producing plutonium pits, which were previously made by the hundreds per year.⁶⁴

PRC – Technology Acquisition by Any Means Possible – The PRC aggressively pursues sensitive defense-related technology through illicit (cyber theft) and licit (acquisition of dual-use technology) activities. There is limited public information on how it has specifically aided its nuclear weapons buildout; however, it is known that the PRC leverages initiatives such as the Thousand Talents Program to lure Western-educated researchers to run PRC laboratories that fulfill specific defense needs. The number of Los Alamos National Laboratory-related researchers at PRC institutions was so large that the group was informally dubbed the “Los Alamos club”.⁶⁵ An investigative report noted that 162 researchers were recruited to work in the PRC, of which 15 were permanent staff with at least one holding a DOE Top Secret “Q” clearance.⁶⁶ Similarly, the U.S. has famously benefitted from absorbing foreign talent to develop its nuclear program. The religious persecution and deteriorating political environments before

World War II motivated about 100 physicists to emigrate to the U.S. from Europe, of which seven received Nobel prizes including Albert Einstein, Niels Bohr, and Enrico Fermi.

Nevertheless, the main difference between the two trends was that the U.S. represented a humanitarian refuge while the PRC has been unscrupulously targeting foreign-trained researchers to harness their expertise to bolster the PRC's nuclear capability.

RECOMMENDATIONS

Near-term modifications to nuclear force posture can provide flexibility and reduce the risk of deterrence gaps as the U.S. makes the required investments in triad modernization and in recapitalizing the NSE for the era of GPC.⁶⁷ As the SPCR concluded, the POR originally conceived during the first term of the Obama Administration is not sufficient to face the current or future strategic environment. The U.S. must take action to fill near-term deterrence gaps not covered by the POR. Not only must the United States field weapons systems that ensure deterrence by addressing today's threats, but it must also invest in and sustain a robust and enduring NSE. Rather than simply manage a stockpile, this NSE must have the capability to produce all the nuclear material, designs, and critical components required to ensure that the U.S. nuclear deterrent can scale, evolve, and react in the future to a dynamic and volatile world.

Whole of Government Recommendations

Apply Appropriate Perspective & Avoid Zero Sum Thinking – U.S. political and military leaders must contextualize and candidly advocate for the resources required to sustain U.S. nuclear deterrence. Can the U.S. afford to simultaneously modernize the triad and the NSE? The

scope of individual programs like Sentinel or Columbia that cost hundreds of billions of dollars can be mind-boggling, but context is both clarifying and essential. In 2018 The DoD estimated that its triad re-capitalization will cost 6.4% of the DoD budget in its peak year.⁶⁸ The entirety of NNSA’s currently planned recapitalization effort is estimated to cost \$32 billion, or less than 0.6% of the U.S. annual federal spending.⁶⁹ Given the existential importance of the U.S. nuclear deterrent, this context is critical. U.S. political and military leaders must constantly contextualize U.S. nuclear deterrence and advocate for all the resources required to keep that cornerstone of U.S. national security strategy on firm foundation.

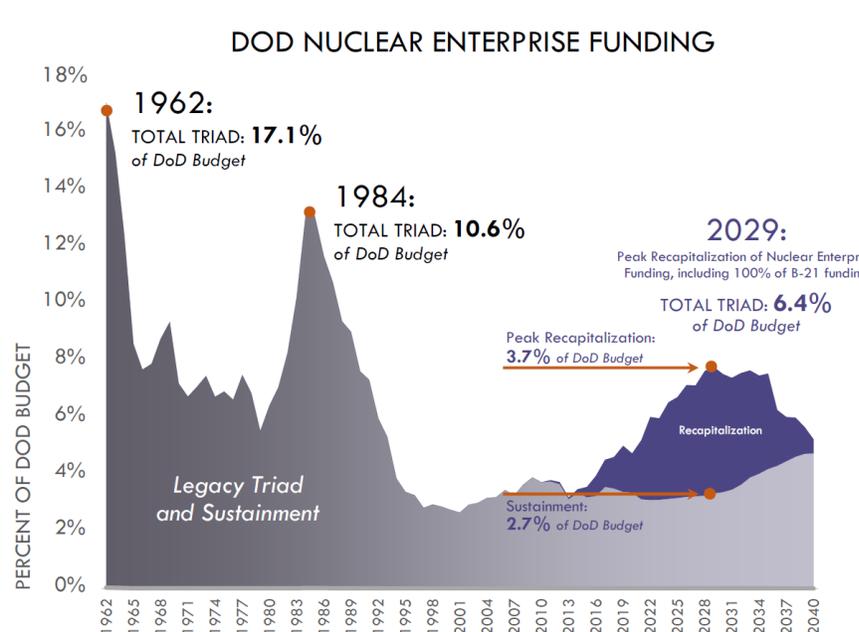


Figure 9 – DoD Nuclear Funding in Context

Centralize Coordination and Accountability – The President should appoint an advisor to coordinate and oversee a whole of government approach to the modernization of the triad and the NSE. This critical effort is too urgent to be managed by committee. Unity of effort to ensure accountability, allocate resources, and drive urgency is required. The National Security Council is the appropriate venue in which to accomplish this given its inter-agency convening authority.

The President should appoint an advisor to serve on the NSC who would coordinate a whole of government approach to nuclear policy including all associated investments and modernization efforts. This position should be at the Deputy National Security Advisor or Deputy Assistant to the President level to appropriately reflect presidential prioritization. The Biden Administration's appointment of a Deputy Assistant to the President & Coordinator for Indo-Pacific Affairs demonstrated the administration's prioritization of Asia-Pacific strategy and is a good model.

Streamline Acquisition of Strategic Systems – Congress and the executive branch should coordinate to develop and expand the use of unique acquisition authorities for strategic systems in order to promote flexibility and enhance industrial capacity and supply chain stability within the nuclear industrial base and the NSE. The National Sea-based Deterrence Fund is an example of the type of funding authorities that could be expanded. DoD and DOE leadership should ensure acquisition programs are protected from excessive bureaucracy by streamlining acquisition chains of command and limiting program reviews. The B-21 program structure provides rapid access to decision-makers and requirements and funding stability that other programs should replicate.

Strengthen Supply Chains – The U.S. must deploy a whole of government approach to strengthen the reliability and resilience of the supply chains on which both the NSE and the triad rely. This effort must include both mitigation of supply-side vulnerabilities and cultivation of flexibility toward demand-side fluctuations. An empowered Deputy Assistant to the President for Nuclear Modernization should coordinate with the interagency to ensure all appropriate tools are brought to bear. The DoD and NNSA should guarantee purchase agreements to suppliers of

highly specialized components in exchange for retaining capacity, the Departments of State and Commerce should coordinate with allies and partners who benefit from extended deterrence to ally-shore key links in the supply chain, the Department of Justice and the Environmental Protection Agency should work to mitigate litigation and regulatory risks to the NSE, and the DoD's Office of Industrial Base Policy should work to expand U.S. capacity in key bottlenecks like casting and forging that impact the broad DIB as well as the NSE and the triad.

Recommendations for Near-Term Modifications to Nuclear Posture

Expand Recapitalization of B-52 – The U.S. should expand its recapitalization of B-52 delivery systems beyond the planned 46 bombers. This would provide a hedge against B-21 programmatic risk as well as the option to maximize capacity in the air leg of the triad in the likely event that Russia continues its current course and chooses not pursue renewal or renegotiation of New START or should Sentinel or Columbia modernization be further delayed.

Plan to MIRV Minuteman III – Under New START, the U.S. has limited itself to single-warhead armament of ground-based ICBM. The currently fielded Minuteman III can carry up to three nuclear warheads in Multiple Independent Reentry Vehicles (MIRV). The U.S. should develop plans to increase the number of warheads fielded on the current Minuteman force. In the likely event that Russia abandons New START, the U.S. should implement this increase, providing significant additional flexibility during the transition from Minuteman to Sentinel.

Deploy dual-capable aircraft and weapons to the Indo-Pacific – The U.S. should coordinate with partners and allies in the region to forward deploy dual-capable aircraft and associated nuclear weapons. This would significantly bolster the credibility of extended deterrence with minimal additional stress to the NSE.⁷⁰

Recommendations for Investments Beyond the POR

Develop Capabilities to Address Hard and Deeply Buried Targets (HDBT) –The retirement of the B83 gravity bomb and the trend of adversaries moving key infrastructure deeper underground demands the development of a new capability to hold essential targets at risk.⁷¹ The United States must develop the capability to hold at risk the command-and-control elements, weapons, and other adversary capabilities that are either deeply buried or oriented in ways that make reaching them difficult.

Invest in Defense and Survivability – Passive defense measures should be reinvigorated across the DoD. Facilities that house critical nodes, capability, and command and control are vulnerable to conventional attack. Hardening these critical nodes provides a hedge against the emerging threat posed to U.S. nuclear systems by hypersonic weapons and other emerging technologies. Additionally, investing in strategic defense in the late 2020's and early 2030's can provide flexibility to bridge deterrence gaps that may be created by triad modernization programmatic delays. The Ground-Based Midcourse Defense system is fielded but needs significant improvement. Advancements in missile defense technology are required in all three of its elements: sensors, interceptors or effectors, and command and control networks. Space-based

fire control quality sensors to direct interceptors, hypersonic defense systems, submarine tracking capabilities, and upgraded USNORTHCOM and NORAD air defense sensors are just some of the necessary active measures to implement.

Acquire and Field Tomahawk-Based SLCM-N – The U.S. must hedge against the survivability risks to the sea leg of the triad posed by quantum sensing. Early quantum sensors are likely to be fielded within the next decade, so the U.S. must create a difficult problem for adversaries attempting to locate its nuclear-capable submarines. The U.S. can accomplish this by growing the number of nuclear-capable submarines, but increasing the number of SSBNs on a short timeline is unrealistic. Instead, the U.S. should arm its fast attack submarines (SSN) with nuclear-capable Sea-Launched Cruise Missiles (SLCM-N) based on the Tomahawk cruise missile. The re-acquisition of this capability would not violate any international treaties and would mirror a capability that Russia currently possesses, making it a non-escalatory, non-provocative expansion of the U.S. arsenal.⁷² Fielding the SLCM-N would have the added benefits of providing a regionally-based, tailored, non-ballistic response option to the president, almost certainly reassuring allies who rely on U.S. extended deterrence.

For rapidity of fielding, SLCM-N should be based on the Tomahawk cruise missile, allowing it to be outfitted with existing warheads, greatly reducing the complexity of acquisition, and lowering strain on the NNSA.⁷³ Virginia-class submarines outfitted with the Virginia Payload Module (VPM) could carry up to 40 of these missiles.⁷⁴ Because it can leverage existing and previous systems, the Congressional Budget Office estimates that fielding SLCM-N could cost as little as \$9 billion in 2019 dollars, excluding training and vessel integration costs.⁷⁵ This is equal to the projected cost of each additional Columbia-class SSBN, but rather than adding

one vessel to an adversary's dilemma, fielding the SLCM-N would add the entire fleet of over 60 SSNs. The additional burden on the SSN fleet would be significantly mitigated by the fact that not all SSNs would have to be nuclear-armed. Just the threat that any SSN could be armed with up to 40 SLCM-Ns would mean that an adversary planning a first-strike would have to be able to track and target all of America's SSNs, in addition to all of its SSBNs, to be confident of achieving a first-strike without retaliation.

Accelerate Conventional Hypersonic Strike Capability – The U.S. must quickly develop its hypersonic technology in order to hold adversary targets at risk as counter-missile technology progresses. The U.S. should continue to develop hypersonics as conventional weapons, but should provision designs to enable rapid adaptation to employ nuclear weapons. Doing so would provide the U.S. with the ability to match adversary nuclearization of hypersonics and would provide a credible tradeoff for future arms negotiations. If the U.S. does not develop hypersonics with dual capability in mind, it will be trading a capability for no concessions from its adversaries.

Recommendations for Nuclear Security Enterprise Infrastructure

Build Capacity to Support a GPC Strategy – The current NSE infrastructure modernization program was scoped to support a nuclear posture developed more than a decade ago. This modernization program is still urgently needed, but it is insufficient to meet the production demands imposed by the new reality of GPC. The Secretary of Energy should direct the development of an updated NSE infrastructure modernization plan scoped to support a GPC

strategy. This plan must consider the robust capability and capacity of the NSE itself as a key component of deterrence and as an independent requirement beyond any requirements derived from current posture needs. The plan must include the capability to produce all the nuclear material, designs, and critical components required to ensure that the U.S. nuclear deterrent can scale, evolve, and react in the future to a dynamic and volatile world.

Boost NSE Infrastructure Investment – The executive branch should advocate for and Congress should appropriate additional funding for NSE infrastructure investment. This additional investment should include, at a minimum, all funding required to cover overruns and schedule slips against the current modernization plan as well as funding to expand the NSE infrastructure modernization program to one appropriately scoped to support a GPC strategy.

Develop NSE Workforce – Many proven solutions are available to mitigate the workforce challenges facing the NSE. Although these solutions have successfully increased the number of STEM workers in many other industries, their application must be tailored and combined to meet the unique requirements of the NSE. A practical overall approach to addressing future STEM workforce shortages involves a three-part solution: attracting STEM-educated professionals through mission-driven operations, providing those individuals with sufficient STEM training and education, and fostering a culture that promotes job satisfaction and encourages long-term careers within the NSE. Options for flexible work arrangements and attractive incentives such as performance-based pay raises, and employee assistance packages must be standardized recruitment and retention tools across the NSE.

Develop and Cultivate a Mission-Driven Culture – The NSE is an industry unlike any other in the United States. Much like active-duty soldiers, sailors, airmen, marines, and guardians share a bond by taking an oath to defend the Constitution, employees of the NSE share a sense of duty, obligation, and patriotism regarding their role in defending the nation. As such, the NNSA should invest heavily in an advertising campaign to highlight the importance of the strategic mission. Highlighting the importance of the NSE mission and the critical role STEM work has in its success will inspire and engage future employees for generations.

Create Buy-In at All Levels – To retain the talent and knowledge base that currently resides within the organization, NNSA should begin implementing programs that create opportunities for buy-in at all levels for current and future NNSA mission planning. Programs dedicated to facilitating these interactions provide returns in two ways. First, it forces current leadership to deliberately establish their mission guidance and articulate their intent to all organizational levels. These interactions allow lower-level leaders to discuss key tasks with higher-level leaders, exercise their own leadership by deriving implied tasks, and lead their own respective organizations toward achieving the overall NNSA mission intent. This model builds trust and confidence within an organization and would significantly improve retention within the NNSA. Second, the NNSA should implement required geographic rotations between sites within the administration for eligibility to advance to higher NNSA positions. Establishing a rotational component to the career progression of career NNSA professionals between headquarters, field offices, and federal and non-federal positions would flatten communications and increase job satisfaction within the organization. Another by-product of required rotations within the NNSA would be a leadership and responsibility-focused approach to risk management. Many

complaints from current STEM workers within the NNSA are the compliance-based approach to risk management at the expense of mission accomplishment. Properly training NNSA professionals and entrusting them to perform the duties they are charged to do is a guaranteed method to improve retention numbers for the STEM workforce across the NSE.

Recommendations Beyond the U.S. Nuclear Enterprise

Exploit the Benefits of Digital Design – Digital design tools have changed what is possible when designing complex systems, and the DoD and NNSA should exploit this to the fullest extent possible. While private industry is independently pursuing digital transformation to varying degrees, DoD and NNSA should take an active approach and guide these transformations to ensure that the government reaps the available benefits. Will Roper, former Air Force Service Acquisition Executive wrote frequently regarding the benefits of digital design, including providing the government the ability to efficiently oversee contractor progress, grow capacity and competition by providing access to non-traditional suppliers, reducing the hurdle cost for small or first-time vendors, and perhaps most importantly, increasing the speed at which new technologies can be fielded.⁷⁶ The DoD and NNSA should require the use of and leverage the benefits of digital design with their contractors wherever practical.

Invest in Technology AND Capacity – Casting and forging are bottlenecks not only in carrying out the U.S. nuclear modernization program but in numerous conventional acquisition and modernization programs as well. DoD has identified castings and forgings numerous times as “...critical to...all major defense systems...”⁷⁷ To date, most U.S. government efforts to address

this bottleneck have placed much hope in new technology like 3-D printing and are exemplary of a typical technology-focused approach. 3-D printing has the potential for dramatic benefits, but it is not mature enough to address the urgent capacity needs of U.S. nuclear modernization.⁷⁸ The DoD and DoE/NNSA should invest directly in additional capacity for casting and forging and similar cross-cutting bottlenecks in parallel with coordinated investment into promising new technologies.

Protect Sensitive Technology Transfer – Systematically implement a national-level effort to protect sensitive technology transfers to Russia or the PRC that could aid their strategic nuclear programs. Greater cyber security monitoring and coordination amongst key research programs should be undertaken at the national level to mitigate any systemic weakness at risk of exploitation. Nationally coordinated basic security clearances should be required for individuals conducting research identified as sensitive in order to mitigate the risk posed by potential insider threats and to signal the importance the federal government places on the work.

Conclusion

The scale of the challenges facing the nuclear enterprise is difficult to capture on paper, as is the scale of the effort and cost that will be required to address them. But this daunting scale must not cause the U.S. to shrink from or ignore the challenge. America's nuclear deterrent has prevented great power war since the 1940's and remains foundational to the safe and secure future of the U.S. and the world. America built that deterrent, and built the infrastructure that supports it, and it can certainly do it again.

The problems facing the nuclear enterprise are daunting, but they are not new. The U.S. has a long

“America can afford survival.”

Secretary of Defense James Mattis to the Senate Appropriations Defense Subcommittee on 22 Mar 2017 when asked if the U.S. could afford nuclear modernization.

history of successfully mobilizing to meet new threats. Less than 20 years passed between the first use of nuclear weapons and having nuclear-armed bombers on continuous alert. There is nothing new about the challenges of building or rebuilding infrastructure. Bureaucratic hurdles, fractious congressional committees, budgetary pressures, and regulatory challenges all existed when we built the highway system, landed on the moon, and built the deterrent we have relied on for 80 years. There is nothing new about the perennial need of democracies to focus the will of political leadership on urgent priorities. The recent and overwhelmingly bi-partisan passage of the 2024 national security supplemental appropriation shows the enduring willingness of leaders across the congressional and legislative branches to prioritize America’s national security when the chips are down, even amid a bitterly divided political environment. Some of America’s proudest achievements have been moonshots, and the very fact that we still use that phrase proves that with leadership and resolve, America can rise to seemingly impossible challenges.

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APPENDIX A – COMPARATIVE ASSESSMENT OF PRC AND RUSSIA

PRC	Russia
<p><i>Top-Down Assignment of National Priorities:</i> The PRC is an autocracy with unquestioned decision-making authority residing with the Chinese Communist Party and ultimately Chairman Xi. When there is senior-level interest in a priority project, bureaucracy can be bypassed, and ample resources mobilized which has proven successful in the past for the PRC. For example, the PRC constructed at least 300 new ICBM silos that were first noticed by civilian imagery analysis in the summer of 2021, but were then assessed to be completed as early as 2022.</p> <p>In contrast, the U.S. decision-making process invites debate to inform policymaking which can be inefficient with different parts of the government signaling different guidance.</p>	<p><i>Shorter Weapons Lifetime Requiring More Replacement:</i> The Russian model for maintaining its nuclear stockpile is based on relatively frequent maintenance and rebuilding of nuclear warheads which requires Russia to maintain a sizeable enterprise to ensure its nuclear capability requirements are met. While the Russian model requires more intensive stockpile management and is more inefficient from a resource perspective, it keeps the nuclear enterprise active and preserves industrial expertise among the workforce.</p> <p>The U.S. strategy of prolonging nuclear weapons through life extension programs has advanced surveillance capabilities and nuclear physics knowledge but has atrophied other areas such as weapons design and pit production.</p>
<p><i>Military-Civilian Fusion:</i> The PRC has accelerated its Military-Civilian Fusion policy which forces the integration of civilian academic and commercial sectors with the defense industry to spur technological advantages for its military. If the PRC were to build 1,000 warheads in the near term, it would have a shortfall of fissile material. The PRC however is constructing two fast-breeder reactors for purported civilian use but that can also produce weapons-grade plutonium for about 50 warheads a year when they come online.</p> <p>Almost in direct opposition to the PRC’s MCF model, the U.S. has kept civilian and defense-related nuclear activities separate as is enshrined in the Atomic Energy Act of 1954.</p>	<p><i>Prioritization of Funding for the Nuclear Enterprise:</i> The reliance on nuclear deterrence to offset a perceived Western conventional weapons superiority is core to how Russia values its nuclear weapons capability. There is no political opposition to spending significantly on their nuclear enterprise as there is broad consensus within the Duma on the importance of nuclear weapons. Based on ICAN estimates, Russia spent 11%, or \$9.6 billion, of its 2022 military spending on nuclear weapons expenditures.</p> <p>The U.S. in comparison allocated approximately 5% of its 2022 defense budget to its nuclear weapons program.</p>
<p><i>Technology Acquisition by Any Means Possible:</i> The PRC’s tactics range from illicit (cyber theft) to licit (acquisition of dual-use technology). National initiatives such as the Thousand Talents Program have lured Western-educated researchers to China to run laboratories that fulfill specific PRC defense needs. The number of Los Alamos National Laboratory-related researchers working for PRC institutions was reported to be so large that the group was informally dubbed the “Los Alamos</p>	<p><i>Disregard for Zero-Yield Testing:</i> There has been significant speculation regarding Russian nuclear testing that does not meet the explicit zero-yield standard that the U.S. abides by. As former DIA Director LTG Ashely noted “...Russia is probably not adhering to the nuclear testing moratorium in a manner consistent with the zero-yield standard....Russia’s testing activities would help it improve its nuclear weapon capability. If Russia is conducting low-yield tests, it would allow validation of new weapons designs and assist with</p>

<p>club”.¹ A separate investigative report highlighted that no less than 162 researchers were recruited to work in China, of which 15 were permanent staff with at least one holding a Department of Energy Top Secret “Q” clearance.</p> <p>The U.S. benefits from academic migration by attracting scientific talent with its open academic environment and in some cases as a humanitarian refuge.</p>	<p>certifying its stockpile without having to rely on high-end computer modeling as the U.S. does.</p> <p>Advancements in computer power and understanding of nuclear science have allowed the US to certify its stockpile with confidence. Nevertheless, US hyper-focus on surety and the “always [work] / never [accidentally detonate] rule” discourages innovation in favor of maintenance of the current stockpile.</p>
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Appendix B – Glossary of Acronyms

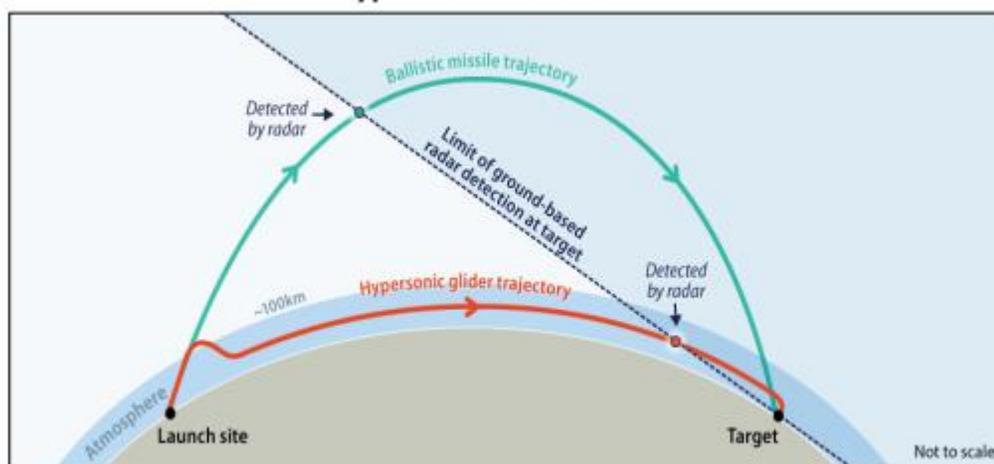
ALCM - Air-Launched Cruise Missile
CNS - Consolidated Nuclear Security
DIB - Defense Industrial Base
DoD - Department of Defense
DOE - Department of Energy
GAO - Government Accountability Office
HDBT - Hard and Deeply Buried Targets
HII - Huntington Ingalls Industries
ICBM - Intercontinental Ballistic Missiles
IOC - Initial Operating Capability
LEP - Life Extension Programs
LLC - Limited Liability Companies
LRSO - Long Range Stand-Off
MIRV - Multiple Independent Reentry Vehicles
NATO - North Atlantic Treaty Organization
NNSA - National Nuclear Security Administration
NORAD - North American Aerospace Defense Command
NPT – Nuclear Nonproliferation Treaty
NSE - Nuclear Security Enterprise
NSF - National Science Foundation
NSS - National Security Strategy
PFAS - polyfluoroalkyl substances
PLA - People's Liberation Army
POR - Program of Record
POTUS - President of the United States
PRC – People’s Republic of China
R&D - Research and Development
RAND – The Research and Development Corporation
S&E - Science and Engineering
SLBM - Submarine-Launched Ballistic Missile
SLCM-N - Sea-Launched Cruise Missiles
SPCR - Strategic Posture Commission Report
SSBN - Ballistic Missile Submarine
SSN - Fast Attack Submarine
START - Strategic Arms Reduction Treaty
STEM - Science, Technology, Engineering, and Mathematics
U.K. - United Kingdom
U.S. – United States
VPM – Virginia Payload Module

Appendix C – Additional Technical Details on Emerging Technology

Hypersonic Weapons

Hypersonic weapons are missiles or glide vehicles travelling at speeds exceeding five times the speed of sound (Mach 5). Unlike traditional ballistic missiles, which follow predictable trajectories, hypersonic weapons can maneuver unpredictably, making them challenging to intercept.⁷⁹ There are two main types of hypersonic weapons in development today, Hypersonic Cruise Missiles (HCMs) and Hypersonic Glide Vehicles (HGVs).⁸⁰ HCMs can fly within the Earth's atmosphere, using scramjet engines to maintain hypersonic speeds while evading enemy defenses and striking targets with precision. HGVs are launched atop ballistic missiles and then glide through the upper atmosphere, combining the speed of a ballistic missile with the maneuverability of an aircraft.

Figure 1. Terrestrial-Based Detection of Ballistic Missiles vs. Hypersonic Glide Vehicles



Source: CRS image based on an image in "Gliding Missiles That Fly Faster Than Mach 5 Are Coming," *The Economist*, April 6, 2019, <https://www.economist.com/science-and-technology/2019/04/06/gliding-missiles-that-fly-faster-than-mach-5-are-coming>.

Russia is likely the closest country to having a true operationally capable hypersonic weapon, even claiming to have employed one in Ukraine.⁸¹ However, China is pouring military funding into increasing research, development, and production of a hypersonic arsenal.⁸² The U.S. believes the

Chinese conducted hundreds of hypersonic missile tests from 2016 to 2019, compared to the U.S.'s nine tests during the same period.⁸³ In a celebration in 2019, the PRC paraded their new hypersonic missile known as the Dong Feng 17.⁸⁴ This weapon's specific objective is to attack U.S. aircraft carrier fleets. There are also other weapons in development to strike submarines and ground targets.⁸⁵ The Russians and the Chinese are not limiting their hypersonic efforts to conventional weapons. There is much speculation and rhetoric from both nations about developing the capability to field nuclear warheads on hypersonic delivery systems.⁸⁶ Because America's nuclear deterrence posture relies heavily on a small fleet of SSBNs, even a marginal increase in an adversary's ability to detect those submarines could have dramatic negative effects on deterrence.

Whether conventional or nuclear-armed, hypersonic weapons pose a significant threat to nuclear command and control and will complicate deterrence. The purpose of a hypersonic weapon is to penetrate enemy airspace quickly and precisely to destroy very specific targets both above and below ground level.⁸⁷ Their speed and maneuverability allow them to strike targets from unexpected angles, with a significant reduction in adversary reaction time.

Quantum Sensing

Where hypersonics will threaten command and control and reduce reaction time, quantum sensing threatens to undermine survivability by enhancing detection capabilities. It could take decades before that point is reached, but on a much shorter time horizon, targeted use of quantum sensing could augment other sensors and increase an adversary's ability to detect the previously undetectable SSBNs. This is particularly true if magnetic and gravitational anomaly detectors become small enough to be placed on unmanned aerial vehicles or satellites used to monitor America's two SSBN bases and the operational boxes dictated by SLBM flight limitations.⁸⁸

⁷⁹ Kelley M Saylor, "Hypersonic Weapons: Background and Issues for Congress," n.d.

⁸⁰ "The US Navy's Advanced Zumwalt-Class Ships Will Be the First Equipped With Hypersonic Missiles," April 23, 2024, <https://www.msn.com/en-us/news/us/the-us-navy-s-advanced-zumwalt-class-ships-will-be-the-first-equipped-with-hypersonic-missiles/ar-AA1nnPOq>.

⁸¹ Alex Hollings, "Here Are The Hypersonic Weapons Russia And China Have in Service," Text, The National Interest (The Center for the National Interest, December 19, 2021), <https://nationalinterest.org/blog/reboot/here-are-hypersonic-weapons-russia-and-china-have-service-198135>.

⁸² Hollings.

⁸³ Jeff Seldin, "What Are Hypersonic Weapons and Who Has Them?," Voice of America, March 19, 2022, <https://www.voanews.com/a/what-are-hypersonic-weapons-and-who-has-them-/6492459.html>.

⁸⁴ Larry Wortzel, "Hypersonic Weapons Development in China, Russia and the United States: Implications for American Security Policy," AUSA, March 23, 2022, <https://www.ausa.org/publications/hypersonic-weapons-development-china-russia-and-united-states-implications-american>.

⁸⁵ Wortzel.

⁸⁶ "U.S. Hypersonic Weapons and Alternatives | Congressional Budget Office," January 31, 2023, <https://www.cbo.gov/publication/58924>.

⁸⁷ Amy F. Woolf, "Strategic Nuclear Forces: Background, Developments, and Issues" (Washington, D.C.: Congressional Research Service, December 2021).

⁸⁸ D.F. Reding and J. Eaton, *Science & Technology Trends 2020-2040: Exploring the S&T Edge* (NATO Science & Technology Organization, 2020).