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Nuclear Triad Industry Study

Final Report

Assuring the Nation's Strategic Deterrent: Nuclear Enterprise Modernization Challenges and Opportunities

The views expressed in this article are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

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TABLE OF CONTENTS

NUCLEAR TRIAD INDUSTRY STUDY 2021

ABSTRACT

As Russia completes its nuclear modernization and China expands its nuclear force, the United States faces two nuclear-capable, strategic peer competitors for the first time. Unlike Russia and China, most systems in the U.S. nuclear enterprise have served far beyond their initial design life. The decades-long hiatus between legacy and recapitalization programs created a "modernization gap" that now presents numerous challenges for both the U.S. government and industry as the nation attempts to sustain and modernize the nuclear enterprise simultaneously. This report identifies several critical contextual factors and cross-cutting challenges affecting U.S. nuclear enterprise recapitalization efforts. It assesses the Department of Defense (DoD) and industry's ability to execute simultaneous modernization efforts for all three legs of the triad and associated nuclear command, control, and communication (NC3) architecture. Optimizing this effort requires DoD to communicate a consistent strategic narrative, develop comprehensive strategies, transfer best practices across the enterprise, and increase the use of incentives to drive innovation within industry.

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Virtual Presentations:

Central Intelligence Agency
Congressional Research Service
Department of Energy National Nuclear Security Administration
Defense Intelligence Agency
Defense Threat Reduction Agency
General Dynamics Mission Systems
Institute for National Strategic Studies, National Defense University
L3 Harris
Lawrence Livermore National Laboratory
MIT Lincoln Lab
NC3 Program Executive Office
Office of the Deputy Under Secretary of Defense for Industrial Policy
U.S. Air Force Global Strike Command
U.S. Navy Columbia-class Submarine Program Office (PMS-397), Office of the Assistant Secretary of the Navy for Research, Development, and Acquisition
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On-Campus Presentation:

National Security Agency

Field Studies:

BAE Systems, Ogden, UT
Boeing, U.S. Air Force Little Mountain Test Facility, Ogden, UT
General Dynamics-Electric Boat, Virginia Advanced Shipbuilding and Carrier Integration Center (VASCIC), Newport News, VA
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U.S. Air Force, Strategic Deterrence and Nuclear Integration Directorate, Pentagon
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EXECUTIVE SUMMARY

Nuclear deterrence is the foundation of U.S. national security and underpins every U.S. military operation. As Russia completes its nuclear modernization and China expands its nuclear force, the United States faces two nuclear-capable, strategic peer competitors for the first time. Unlike Russia and China, most systems in the U.S. nuclear enterprise have served far beyond their initial design life.

Across the nuclear enterprise, program offices face many common challenges. The decades between recapitalization programs require the United States to reconstitute industrial capacity and human capital to meet the growing demand. The Department of Defense must sustain legacy systems for decades as modernization proceeds on a tight schedule. This dual effort creates competition for funds, industrial capacity, and specialized labor. Nuclear weapon systems are held to the highest safety and security standards, which makes it difficult, slow, and costly to innovate or introduce emerging technology. Although there has been consistent support across presidential administrations for an effective nuclear deterrent, conflicting cost estimates are a target for opponents of recapitalization, and program offices must consider the equities of a range of stakeholders, particularly Congress.

The U.S. defense industrial base that supports the nuclear enterprise suffers from limited competition that reduces the incentive to innovate. This lack of innovation makes it more difficult to recruit and retain talent in a highly competitive labor market. As supporting industries become increasingly globalized and focused on commercial customers, it is more difficult to secure the supply chain and adopt emerging technology. Although demand conditions are strong, a growing regulatory burden and slow approval processes deter new companies from entering the market and discourage existing contractors from investing in research and development.

These challenges make it more difficult for the nuclear enterprise to innovate, manage risk, maintain acquisition schedules, contain costs, and recruit and retain talent. However, the United States also possesses historical advantages, including decades of cooperation between government, industry, and academia to develop nuclear weapon systems. Each program office takes a unique approach to address these concerns.

Effective 21st century strategic deterrence will require the United States to develop the talent and industrial capacity to employ strategic deterrence principles, exploit strategic advantages within the U.S. innovation ecosystem, and adapt to the contemporary global security environment. Although the challenges are significant, they are not insurmountable. This report provides recommendations aimed at communicating a consistent strategic narrative, developing comprehensive strategies to address cross-cutting challenges, transferring best practices across the enterprise, and improving incentives for innovation within industry. If the nation takes these steps and remains politically and financially committed to recapitalization, it will be better postured to secure itself and its allies from future threats.

Summary of Challenges:

- Chinese and Russian Modernization
- U.S. Modernization Gap Requires Reconstituting Industrial Capacity and Human Capital
- Integration of Legacy and Modern Systems
- Simultaneous Sustainment and Modernization—No Margin for Delay
- Competition Among Programs for Funds, Labor, and Industrial Capacity
- Always/Never Standard Slows Upgrades and the Introduction of Emerging Technology
- Conflicting Cost Estimates
- Budgetary Uncertainty
- Multiple Stakeholders with Competing Interests
- Limited Competition in the Industrial Base Deters Innovation
- Lack of Specialized Labor and Difficulty Recruiting and Retaining Talent
- Incorporating Emerging Technologies and Development Processes
- Securing an Increasingly Globalized and Commercialized Supply Chain
- Growing Regulatory Burden and Inefficient Approval Processes

Summary of Recommendations:

1) Communicate a Consistent Strategic Narrative to Congress, Industry, and the Public
   - Designate a Lead to Develop a Coherent Narrative Across the Enterprise
   - Ensure a Consistent Narrative to Congress to Sustain Budgetary Support
   - Convey a Consistent Narrative to Industry to Send a Clear Demand Signal
   - Communicate a Consistent Narrative to the Public to Reiterate the Importance of Modernization and Encourage Talent to Join the Nuclear Enterprise

2) Develop Comprehensive Strategies and Transfer Best Practices Across the Nuclear Enterprise
   - Embrace and Execute a Mindset of "Integrated Deterrence"
   - Build an Integrated Network of Epicenters to Bridge Gaps Between Modernization and Sustainment Efforts
   - Baseline Security and Certification Requirements and Streamline Approval Processes
   - Embrace Emerging Technologies Smartly
   - Reinvigorate Deterrence Intellectual Capital
     - Invest in the National Security Workforce and STEM Education
     - Maximize Opportunities to Create Deterrence Expertise

3) Increase Incentives for Innovation in Industry
   - Avoid the Temptation of Vertical Integration
   - Pursue Modular Open System Architectures (MOSA) to Encourage Internal Research and Development (IRAD) Expenditures and Participation by Smaller Firms
   - Develop Challenging Benchmarks for Contract Award Fees
   - Leverage All Aspects of the Adaptative Acquisition Framework and Seek New Authorities

INTRODUCTION

Nuclear deterrence is the foundation of U.S. national security. The underinvestment in U.S. nuclear capabilities after the end of the Cold War created a situation today in which all aspects of the enterprise—delivery systems, weapons infrastructure, and nuclear command, control, and communications (NC3) systems—need to be recapitalized.[1] Failure to do so could leave the United States vulnerable to nuclear aggression by peer competitors or rogue regimes, while also undermining America's conventional superiority. Emphasizing the dire nature of the situation, Admiral Charles Richard, Commander of U.S. Strategic Command (USSTRATCOM), recently said, "If strategic deterrence doesn't hold, nothing else in the Department of Defense (DoD) is going to work the way it was designed…the consequence of failure in this mission is enormous."[2]

The decades-long hiatus between recapitalization efforts created a modernization gap that presents numerous challenges for the U.S. government and industry as the nation attempts to sustain and modernize the nuclear enterprise. To manage these challenges, DoD must communicate a consistent strategic narrative, develop comprehensive strategies, transfer best practices across the enterprise, and incorporate incentives to drive innovation within industry.

Purpose and Organization: This report assesses DoD and industry's ability to simultaneously sustain and modernize all three legs of the nuclear triad and associated NC3. The report is organized into three primary sections. First, it outlines the strategic environment, context, and cross-cutting challenges that influence recapitalization efforts. Second, the authors use the Porter Diamond framework to analyze the U.S. nuclear enterprise industry's ability to meet the many demands of nuclear modernization. The report concludes by offering policy recommendations to better position the U.S. government and industry to modernize every element of the nuclear enterprise in the coming decades.

Methodology: This report summarizes information derived from engagements with government, industry, and academic experts across the nuclear enterprise.[*] Students also read a variety of reports, academic studies, and commentaries for additional background. Students participated in an Industry Analysis course that provided tools and frameworks to evaluate corporate decision-making and industry dynamics. During that course, students conducted in-depth research of four prime contractors with significant nuclear portfolios—General Dynamics, Lockheed Martin, Northrop Grumman, and Raytheon Technologies (see Appendix E: Firm Briefs). Finally, each student conducted individual research on topics related to nuclear modernization and industrial base considerations. These unique and rich information streams are synthesized to provide the assessment that follows.

Scope and Terminology: Intentionally omitted from this analysis is a discussion about the recapitalization of nuclear weapons production, storage, and testing infrastructure overseen by the National Nuclear Security Administration (NNSA) of the Department of Energy (DOE). Although DoD depends on these critical capabilities, it does not control the bulk of the funds that

[*] To encourage open and honest discussion, the students committed to abide by NDU's non-attribution policy. This accounts for the inclusion of comments without attribution throughout the report.

support them and, therefore, they are beyond the scope of this report. Nevertheless, the authors acknowledge that weapons infrastructure is equally important to the three legs of the triad and NC3 and thus forms the fifth pillar of the nuclear enterprise.[†]

The term *nuclear enterprise* includes all three legs of the triad, the weapons infrastructure, and the systems that comprise NC3. The authors consciously chose to use the term *enterprise*, rather than *triad*, to include the complex of related activities and capabilities that have the common purpose of providing strategic deterrence. This choice also highlights the reality that there is no single, central authority to manage the enterprise.

The *nuclear enterprise industry* is best described as an industry of industries. It comprises a wide variety of firms dedicated to both the sustainment of legacy systems and the development of modern replacements. Because the nuclear enterprise encompasses everything from communications equipment to solid-fueled rocket boosters, the industrial base consists of numerous firms participating in a variety of markets. However, a relatively small number of prime defense contractors generally act as integrators of the various technologies that make up nuclear systems.

[†] For an in-depth discussion of each element of the nuclear enterprise, see the 2018 Nuclear Posture Review and the 2020 Nuclear Matters Handbook.

STRATEGIC ENVIRONMENT

THE MODERNIZATION IMPERATIVE

Nuclear deterrence is the bedrock of U.S. national security and underpins every U.S. military operation. There has been remarkably consistent support across presidential administrations for a safe, secure, and effective nuclear deterrent. As Russia completes its nuclear modernization and China expands its nuclear force, the United States faces two nuclear-capable, peer competitors for the first time. Unlike Russia and China, most systems in the U.S. nuclear enterprise have served decades beyond their initial design life. The decades-long hiatus between U.S. recapitalization programs created a modernization gap that presents numerous challenges for the U.S. government and industry. Effective 21st century strategic deterrence will require the United States to adapt to the contemporary global security environment.

Nuclear Deterrence—The Bedrock of U.S. National Security: The most lethal weapon systems in history reside within the U.S. nuclear triad: a combination of nuclear submarines, long-range bombers, and intercontinental ballistic missiles (ICBMs). Each leg of the triad, supported by a multifaceted NC3 architecture, provides a unique advantage to the complex formula of strategic deterrence. The U.S. nuclear arsenal provides deterrence against strategic attacks on the U.S. homeland and also underpins every U.S. military operation around the world.[3] The nuclear triad—and the defense industry that supports it—is foundational to U.S. national defense policy.[4]

U.S. Policy Environment—Consistent Support for a Safe, Secure, and Credible Deterrent: Every presidential administration over the past sixty years has reaffirmed that "a safe, secure, and effective nuclear force remains the most credible combination of capabilities to deter strategic attack."[5] The Obama Administration initiated the modernization of all elements of the nuclear triad.[6] The Trump Administration's 2017 National Security Strategy, 2018 National Defense Strategy, and 2018 Nuclear Posture Review reiterated the need for modernization.

Although the Biden Administration's 2021 Interim National Security Strategic Guidance does not explicitly mention nuclear modernization, it asserts the United States will ensure the "strategic deterrent remains safe, secure, and effective and that our extended deterrence commitments to our allies remain strong and credible."[7] The guidance also states, "we will take steps to reduce the role of nuclear weapons in our national security strategy." Admiral Richard placed this statement within the context of arms control negotiations and said a credible nuclear deterrent reinforces U.S. negotiating power.[8] Many in industry and government await an unequivocal signal from the Biden Administration that modernization plans will continue apace.

An Evolving Threat: The aging U.S. nuclear force was designed for a Soviet-era threat that no longer exists. According to Admiral Richard, "for the first time in our history, the nation is on a trajectory to face two nuclear-capable, strategic peer adversaries at the same time."[9] In addition to these peers—Russia and China—the United States must also deter nuclear threats from North Korea and Iran as well as non-state actors seeking nuclear material.

Russia's Nuclear Modernization: The dissolution of the Soviet Union and the emergence of the Russian Federation as a successor state did not reduce the role of nuclear weapons in Moscow's security policy.[10] In the late 1990s, Russian officials began planning a modernization program to replace aging Soviet conventional and nuclear weapons, but a lack of funds limited execution. As the Russian economy grew, the Kremlin began allocating significant funds to defense modernization in 2008. Since then, the defense ministry has focused its attention and funding on nuclear weapons. Consequently, Russia's nuclear modernization has outpaced efforts to improve its conventional forces.[11]

Russia intends for its investments in nuclear systems to offset weaknesses in its conventional forces. Russian doctrine envisions potentially threatening or using limited nuclear strikes to achieve favorable outcomes or "to thwart ballistic missile defenses, challenge deterrence, and target [U.S.] capabilities."[12]

USSTRATCOM assesses Russia's recapitalization of its nuclear triad is "roughly 80 percent complete."[13] Russia is deploying a new generation of silo and road-mobile ICBMs, a new submarine, and a new submarine-launched ballistic missile. For the air leg of its triad, Russia has outfitted its Soviet-era heavy bombers to carry a new nuclear-armed cruise missile.[14]

Russia is also developing a new generation of nuclear-armed "novel" weapons, which are not subject to limitations of the 2011 Strategic Arms Reduction Treaty (New START).[15] It has already deployed the nuclear-armed *Avangard* hypersonic glide vehicle. It is developing a nuclear-powered/nuclear-armed underwater vehicle, a nuclear-powered/nuclear-armed cruise missile, and multi-role hypersonic anti-ship missile.[16] Russia also maintains a non-strategic nuclear arsenal of 2,000 weapons and invests heavily in nuclear-conventional intermediate range missiles.[17] Finally, the defense ministry is modernizing both its Soviet-era early attack warning system and its NC3 network.[18]

China's Nuclear Modernization: China's rapid economic growth has enabled it to modernize the People's Liberation Army. Its 2019 Defense Strategy reiterated China's goal of achieving a complete modern military by 2035 and a "world-class" military by 2049.[19] To this end, China continues to invest heavily in both its human capital and military capabilities. Stockholm International Peace Research Institute (SIPRI) estimates China's military spending increased from approximately $22.9 billion in 2000 to $260.9 billion in 2019.[20] China now has the second-highest defense budget globally, behind the United States (~$700 billion). Simultaneously, China is attempting to build a competitive advantage through a concerted effort to recruit highly skilled military and civilian talent.[21]

Within China, the highest levels of government provide explicit strategic direction to national security priorities, including nuclear deterrence. Furthermore, a network of state-owned enterprises (SOEs) supports the regime's modernization and expansion efforts. Although SOEs are inefficient, this vertical integration allows for quicker acquisition from one or two prime contractors within each of the five major Chinese defense sectors.

The nuclear force is an area of focus for China's growing military budget. Notably, it plans to expand from a nuclear dyad to a triad by adding air-launched ballistic missiles to its arsenal. China's shipbuilding industry is contributing significantly to the expansion of the sea leg

of the triad. China has more than 1,000 shipyards, and their capacity far exceeds the capacity of the U.S. defense industrial base.[22]

SOEs are achieving significant advances in China's land-based conventional ballistic and cruise missile programs. Engineers can quickly transfer advancements from these conventional missile programs to China's ICBM and its submarine- and air-launched cruise missile programs. Perhaps more concerning, China might be applying its technological gains to pursue tactical-level nuclear-capable air-launched ballistic missiles and nuclear-capable cruise missiles that complicate U.S. strategies.[23] This situation led the Director of the Defense Intelligence Agency to conclude that China is likely to double the size of its nuclear stockpile over the next ten years.[24]

The U.S. Modernization Gap: Unlike the systems in Russia's and China's nuclear enterprises, most U.S. systems have served decades beyond their initial design life. They are increasingly aged, antiquated, and reliant on obsolete parts. After the Cold War, the United States repeatedly postponed replacement plans to achieve a peace dividend, pay for counterterrorism operations and wars in Iraq and Afghanistan, and comply with the Budget Control Act.[25]

The decades-long hiatus between U.S. recapitalization programs created a modernization gap that presents numerous challenges for the U.S. government and industry. Many systems within the nuclear enterprise are difficult to maintain and face parts obsolescence, materiel shortages, and diminishing manufacturing sources for critical sustainment supplies.[26] Recapitalization "requires reinvigoration of certain industrial capabilities," including reconstituting a specialized workforce.[27] As a result, sustainment and modernization are more complex and expensive.

The U.S. government now plans to concurrently refurbish or replace most elements of the nuclear enterprise over the next 20 years.[28] The Nuclear Matters Handbook provides a detailed description of each modernization program.[29] In short, this vast undertaking includes:

- Columbia-class submarines replacing Ohio-class submarines, which have been life-extended to 42 years (five years beyond any other submarine);
- B-21 long-range bombers replacing the B-2 and the B-52, which will be more than 80 years old when the B-21 reaches full operational capability;
- Ground Based Strategic Deterrent (GBSD) replacing the Minuteman III (MMIII) ICBM, which will be 60 years old at retirement;
- Long-Range Stand-Off missiles replacing AGM-86 air-launched cruise missiles;
- NC3 next-generation efforts to replace systems that were last overhauled in the 1980s before the digital age; and
- Plutonium pit production, warhead modernization, and DOE/NNSA infrastructure upgrades.

CONTEXT AND CROSS-CUTTING CHALLENGES

The industry study identified common contextual factors and cross-cutting challenges across the nuclear enterprise. Nuclear programs must consider the equities of various stakeholders, including Congress, industry, DoD, other federal agencies, and U.S. allies. The United States holds its nuclear weapon systems to the highest safety and security standards, making innovation difficult, slow, and costly. DoD must simultaneously sustain legacy systems for decades as modernization proceeds on a tight schedule. Total costs for such complex programs are difficult to estimate and could exceed $1 trillion over decades, creating a target for opponents. The U.S. government needs to re-cultivate an intellectual base skilled in conceptualizing and executing integrated and effective deterrence for the current security environment. Each program in the nuclear enterprise operates within a unique governance structure, and each has developed a unique acquisition strategy to manage these challenges. Enterprise-wide communication is infrequent, and programs would benefit from additional opportunities to share best practices.

The industry study identified several contextual factors and cross-cutting challenges that affect the U.S. nuclear enterprise's ability to manage risk, innovate, contain costs, maintain acquisition schedules, and recruit and retain talent. These contextual factors and challenges shape DoD's acquisition strategies and industry's business strategies. Each element of the enterprise is affected differently, and each program takes a unique approach to manage these challenges.

Stakeholders: Given the strategic and budgetary implications, numerous stakeholders are involved in modernization of the nuclear enterprise. All three parties of the iron triangle (Congress, DoD, and the defense industrial base) have significant equities. For commercial companies, billions of dollars are on the line to support steady profit margins and continuous production for the next 20 years. The military's acquisition offices manage each program's cost, performance, and delivery schedule. As the budget authority, Congress must navigate the interests of political parties, interest groups, and constituents while considering the implications for the U.S. debt and the broader national budget. Concurrently, Congress must conduct appropriate oversight as the military speeds acquisition through new and innovative authorities Congress has provided. Beyond the stakeholders in the iron triangle, many other agencies are involved in formulating U.S. nuclear policy and budgets: DOE/NNSA, the Department of State, and the Office of Management and Budget, among others. The United States must also consider the implications for allies and partners who rely on U.S. extended deterrence or industrial cooperation for their nuclear programs. Appendix A further explains the stakeholders and competing forces within the U.S. innovation ecosystem that affect nuclear modernization.

Always/Never—The Highest Standard: The unique destructive power of nuclear weapons requires the highest standards of safety, security, reliability, and control. The nuclear enterprise operates according to the always/never principle: "a nuclear weapon must *always* detonate on an intended target when authorized by the President, and *never* detonate in any other environment or for any other reason."[30] This exacting standard reinforces the credibility of the U.S. nuclear force and its deterrent effect. However, the always/never standard complicates efforts to sustain, modernize, and secure the nuclear enterprise. Changes are generally slow, methodical, and based on mature technologies. Thus, it is particularly challenging to introduce

emerging technologies, adopt agile development processes, and establish cyber and other security standards.

Sustaining the Old While Producing the New: One critical feature of nuclear modernization is the need to sustain legacy systems as the production of replacement systems occurs over decades. Many replacement systems will need to integrate with legacy systems, creating competition for funds between new systems and "their nonnegotiable predecessors."[31] This dual mandate also introduces complexity that increases costs and schedules. However, the 2018 Nuclear Posture Review asserts that there is no longer any margin for delay in the recapitalization schedule.[32] Failure to balance these competing demands could reduce the deterrent effect of the U.S. nuclear force, increase U.S. vulnerability to aggression by peer competitors and rogue regimes, undermine the benefits of U.S. conventional superiority, and hurt the nation's ability to assure allies and partners through extended deterrence.[33]

Conflicting Cost Estimates—A Target for Opponents: The simultaneous recapitalization of nearly the entire nuclear enterprise over decades is a massive undertaking, and it is difficult to accurately project costs. In the past, similar DoD projects exceeded budget estimates.[34] DoD hopes to contain costs and shorten schedules by using mature technology and new development processes.

According to the 2018 Nuclear Posture Review, DoD is spending two to three percent of its base budget to maintain and operate the current nuclear force.[35] In 2018, DoD estimated it would spend 6.4 percent of its budget on the nuclear enterprise at the peak of modernization ($230-290 billion between 2018 to 2040, not including funds for NNSA).[36] Outside experts estimate the cost will be much higher, with the Congressional Budget Office projecting the combined cost for DoD and NNSA would reach $494 billion between 2019 and 2028.[37]

DoD Nuclear Enterprise Funding[38]

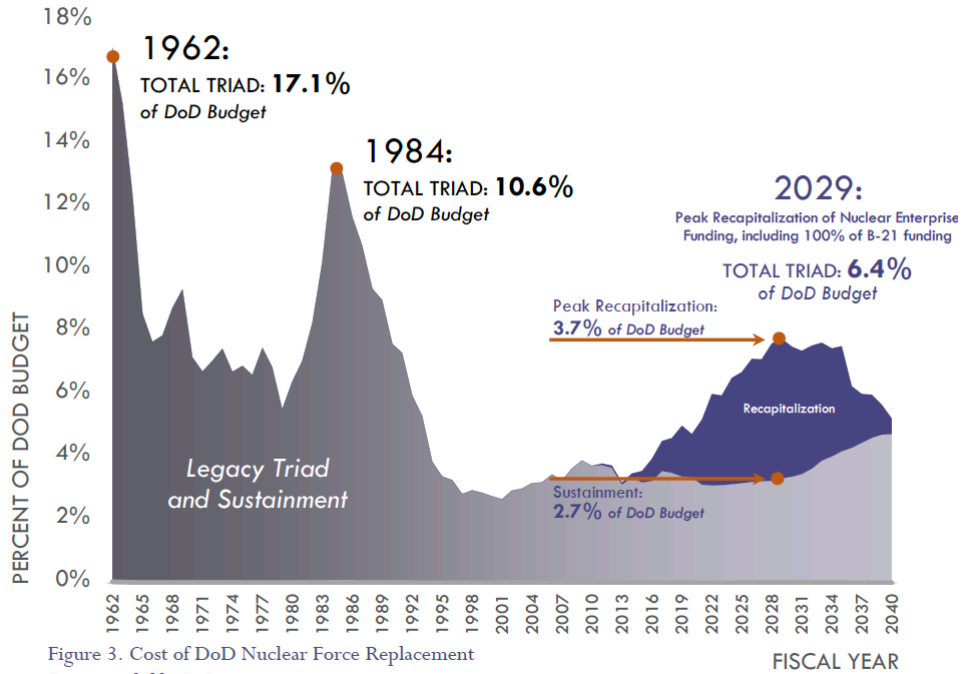


Figure 3. Cost of DoD Nuclear Force Replacement
Data provided by DoD

One expert notes the differing estimates exist because "the United States does not maintain a single, unified budget for nuclear weapons and other nuclear activities."[39] This expert estimates the United States will spend an average of $30-40 billion per year to sustain and modernize the nuclear enterprise for a total of at least $1-1.2 trillion over the next 30 years. Although DoD asserts nuclear modernization is "both necessary and affordable," there are vocal opponents who disagree and advocate for deferring modernization, reducing the size of the nuclear force, or downsizing to a dyad to save money (among other reasons).[40]

Human Capital in Government: In addition to the human capital challenges in industry, the government has a relative deficit of expertise in strategic deterrence compared to the Cold War era. The fall of the Soviet Union, the rarity of arms control negotiations, and the focus on counterterrorism operations in recent years contributed to a decline in the number of U.S. service members, civilians, and academics focused on deterrence. As nuclear enterprise modernization programs ramp up, the U.S. government needs to cultivate an intellectual base skilled in conceptualizing and executing integrated and effective deterrence in the current geopolitical environment. Recognizing that "deterrence in the 21st century is an interdisciplinary problem requiring interdisciplinary derived solutions," both the Chairman of the Joint Chiefs of Staff and the Commander of USSTRATCOM identified a need to reinvigorate a strategic deterrence intellectual complex.[41] While investment in nuclear recapitalization supports deterrence by ensuring a credible capability, the study and application of strategic deterrence theory to the contemporary strategic environment will better inform military plans and support the ultimate goal of "avert[ing]…large-scale warfare and winning the nation's peace."[42]

Unique Acquisition Strategies for Each Program: Programs within the nuclear enterprise have developed unique acquisition strategies to manage the challenges described above. Enterprise-wide communication among program offices appears infrequent with few mechanisms to share best practices. Most modernization programs use mature, proven technologies to lower risk, protect schedules, and meet cost goals. In addition, the three major delivery platforms are leveraging concepts such as iterative innovation and open system architectures. Some programs are using the traditional approach to acquire major capabilities (GBSD), and others are taking advantage of newer acquisition pathways or special authorities (B-21 and Columbia).

The B-21 program is using unorthodox acquisition techniques to help reach initial operational capability within ten years of contract award. With per unit costs as a key performance parameter, the total program budget is currently below government estimates.[43] The Air Force assigned the program to its Rapid Capabilities Office (RCO), which uses streamlined decision-making, prioritized funding, and hiring flexibilities. The B-21 program uses Other Transaction Authorities in development. Combined with the use of mature technology and measures intended to prevent requirements creep, these decisions help ensure the program stays on schedule and within budget. Northrop Grumman, a proven builder of this design type, is incentivized to remain on schedule and find cost savings during the early life of the program to encourage additional production after delivery of the minimum order quantity of 100 aircraft.

In contrast, the GBSD program is progressing along the traditional major defense acquisition pathway. Cost and schedule risks are higher due to interdependence with activities currently beyond the control of the GBSD program office, including the dismantlement of

MMIII. Northrop Grumman and the program office expect digital engineering to reduce risk in schedule and increase performance during the engineering and manufacturing development phase (EMD). Despite these steps, some critics argue the ground-based leg of the triad is neither necessary nor worth the cost.[44]

The Columbia-class submarine is the Navy's top procurement priority. Congress's creation of the National Sea-Based Deterrence Fund (NSBDF) in the FY2015 National Defense Authorization Act (NDAA) and subsequent updates provide the program an unusual amount of flexibility to fund long-lead items and design, construction, purchase, and alteration of the system.[45] These authorities help address supply chain and industrial base concerns. Also unique to this program is the industrial duopoly for U.S. submarine production by Electric Boat (EB)/General Dynamics (GD) and Huntington Ingalls Industries (HII). The Navy created the Integrated Enterprise Plan (IEP) to help maintain a U.S. shipbuilding capability and establish priorities. The IEP calls for the Columbia submarines to be built jointly at EB/GD and HII, much like the Virginia-class attack submarine.[46] The demand for the simultaneous delivery of two Virginia-class and one Columbia-class submarine adds additional stress to the industrial base.[47] The Navy, through the IEP, can set priorities by adjusting the division of work between the two programs and protect the schedule of the Columbia program. The program office appears to have a successful approach to strategic communications and engagement with Congressional staff.

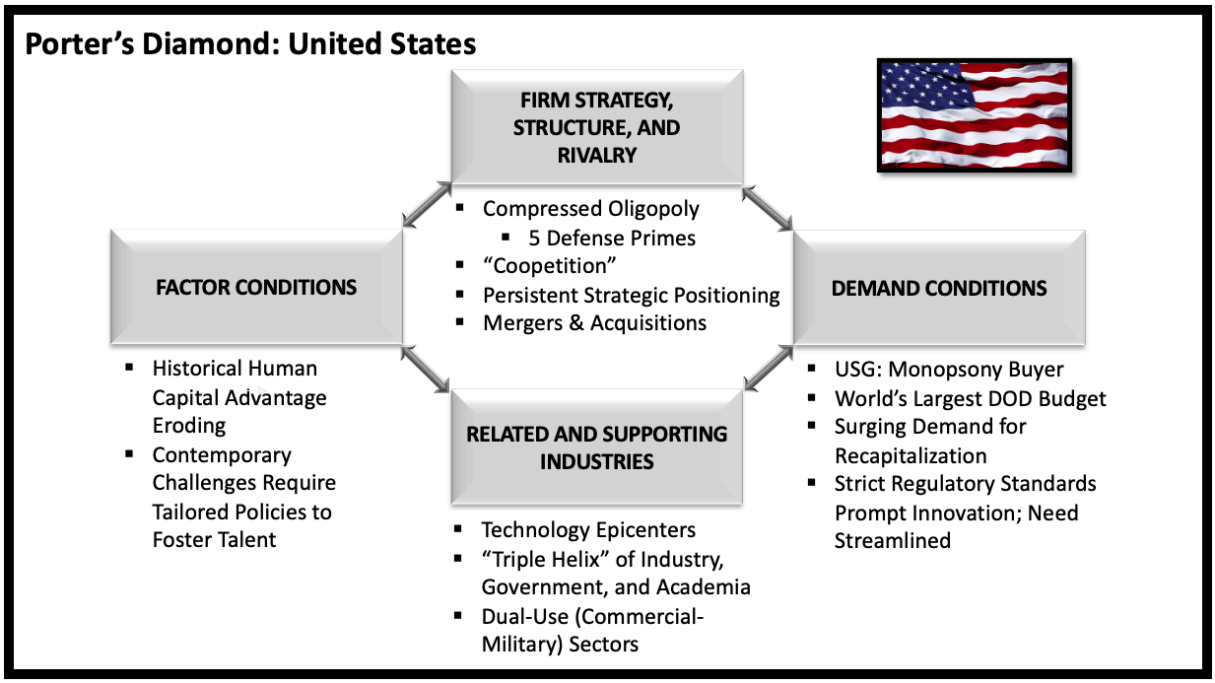
The Commander of USSTRATCOM is the single requirement holder for NC3, although the supporting services determine funding priorities. Modernization efforts intend to reduce the total number of system components.[48] Admiral Richard has said NC3 "is not a product or a 'thing' with a long service life like a delivery platform or warhead; rather it is a process of rapid, continuous, incremental network capability improvements."[49] This approach requires the adoption of innovative techniques that are not certified yet for use in nuclear systems. It also involves the entry into the market of new companies that often lack personnel with security clearances. Classification at the lowest appropriate level is crucial to controlling costs. DoD is attempting to leverage innovation hubs at government laboratories, universities, and corporations to develop more straightforward requirements that will create a more resilient NC3 architecture.

Inconsistent Governance Structures: As with acquisition strategies, there is no single governance structure across the enterprise. To an extent this is logical—the intricacies of each program call for unique approaches. However, students identified instances in which DoD could replicate governance practices in other parts of the enterprise with positive effects. For example, the Navy's integrated approach to delivering conventional and nuclear submarines at shipyards with limited capacity could be modified and applied to the ICBM leg, where program stovepipes for MMIII and GBSD complicate GBSD's critical path to initial operational capability. DoD has demonstrated a willingness to update governance structures in the past, as it did with NC3 in 2018. It must acknowledge that further improvements across the enterprise may be needed to streamline modernization efforts.

The size and scope of many programs make an overarching governance structure for the whole enterprise impractical. No single office or organization can effectively integrate the efforts of numerous "megaprojects" valued at nearly $1 trillion. This creates a situation in which seams can develop between programs, which might lead to problems fielding new capabilities on time, on budget, and with the necessary level of interoperability with other parts of the enterprise.

THE NUCLEAR ENTERPRISE INDUSTRY: CHALLENGES AND OPPORTUNITIES

Within the strategic environment and context described above, the U.S. industrial base supports nearly every element of the nuclear enterprise. Economist Michael Porter asserts that the four determinants of national competitiveness are 1) firm strategy, structure, and rivalry; 2) factor conditions; 3) related and supporting industries; and 4) demand conditions.[50] This report uses this "Diamond of National Advantage" as a framework to analyze the challenges and opportunities for the U.S. nuclear enterprise industry. The analysis concludes with an assessment of U.S. national advantages vis-à-vis China and Russia.



FIRM STRATEGY, STRUCTURE, RIVALRY, AND COMPETITION

The nuclear enterprise industry suffers from subdued market competition and limited innovation. These conditions increase costs for government, extend cycle times, and weaken the national technological advantage. Given the speed at which Russia and China are advancing their nuclear triads, this structure presents a degree of risk to U.S. national security.

The Role of Firm Strategy, Structure, Domestic Rivalry, and Competition: Porter contends that a nation's environmental context strongly influences firms competing in an industry. Nations value specific activities that attract capital and human resources to the firms that compete in those activities. Competing firms attempt to carve out a niche and differentiate themselves to sustain a competitive advantage. Fierce domestic rivalry pressures companies to innovate to maintain or gain a superior strategic position.

Challenges and Opportunities in the Nuclear Enterprise Industry: The nuclear enterprise is an industry of industries. Its competitive structure has compressed over time into a collection of oligopolies. A mixture of market and government failures concentrated the individual sectors of NC3, shipbuilding, long-range bombers, and ICBM production down to five competing prime contractors: Boeing, Lockheed Martin, General Dynamics, Northrop Grumman, and Raytheon. As the singular customer for much of the nuclear enterprise, the U.S. government forms a monopsony/compressed oligopoly structure with the five prime contractors.

Nuclear enterprise prime contractors determine where to compete based on their corporate and business strategies. Over decades, each contractor cornered the market on a particular technology by investing in research and development (R&D) and building expertise to extend their competitiveness in a specific market sector. Firms have found niches where they tend to achieve monopolies or, at best, duopolies. Mergers and acquisitions further compress the industry, stifling competition. Firms may compete head-to-head for certain DoD contracts, but they often start joint ventures or serve as subcontractors for one another on sole-source contracts. This "coopetition" influences DoD's approach to procurement, transforming acquisition strategies typically based on vigorous competition into something closer to a negotiation.

This structure conveys bargaining power to the prime suppliers.[51] In the nuclear enterprise industry, however, the bargaining power of suppliers is balanced by the power of the monopsonist customer, the U.S. government, which imposes its influence on industry. The government establishes demand, controls information, and sets pricing. As experts explain, "inefficiencies remain as the seller of weapon systems still face a buyer who is a monopsonist."[52] To exacerbate these inefficiencies, Eric Lofgren highlights, "exerting that [monopsonist] power creates long term consequences. The industry reshapes itself into an oligopoly/monopoly structure to balance the power."[53]

High barriers to entry maintain the compressed competitive structure. These include restricted access to intellectual property and proprietary technology, steep competition for human capital, knowledge of U.S. policies, rent-seeking, and forces at play within the iron triangle. Larger, more established firms have the capital to hire lobbyists and spread influence across multiple Congressional districts. Prime contractors further restrict new entrants in the market by abjuring software solutions and advocating for significant hardware upgrades that preclude smaller competitors due to their complexity.

Based on interactions with the prime contractors, the nuclear enterprise industry operates on a demand system. Firms follow the direction of leaders in DoD and Congress to meet minimum system requirements. This contrasts with a supply system, where industry leads the charge on designing new products and then convinces the customer it has the best solution. Additionally, some suppliers appear focused on producing incrementally improved variants of Cold War nuclear armaments. It is unclear whether the demand-based, incremental approach is the lowest cost and least risky approach. Regardless, it requires the lowest level of innovation and proactivity by prime contractors.

FACTOR CONDITIONS: HUMAN CAPITAL

The availability of specialized labor is one of the most significant factor conditions affecting the competitiveness of the U.S. nuclear enterprise industry and its ability to innovate. Human capital challenges are eroding what has historically been a competitive advantage for the United States. The U.S. government should develop and implement policies tailored to the enterprise to create an environment that will foster talent and maintain a competitive advantage.

The Role of Factor Conditions: Michael Porter argues a "nation's position in factors of production, such as skilled labor or infrastructure," is one critical determinant of an industry's capacity to innovate.[54] This innovation drives both industry and national competitiveness. Human capital is arguably the most important factor condition within the nuclear enterprise, as it offers the best opportunity to positively influence innovation, thereby increasing national competitiveness. Efforts to improve human capital, however, will require targeted and sustained resourcing.

Human Capital Challenges and Opportunities in the Nuclear Enterprise Industry: As Porter argues, "in the sophisticated industries that form the backbone of any advanced economy, a nation does not inherit but instead creates the most important factors of production—such as skilled human resources or a scientific base."[55] As the nation commits to modernization of the nuclear enterprise, however, it is struggling to reinvigorate the relevant specialized labor force that, like much of the enterprise itself, has atrophied over the last several decades.

The nuclear enterprise workforce is composed of personnel from an array of disciplines executing diverse functions within the "nuclear enterprise infrastructure."[56] Many of these individuals come from science, technology, engineering, and mathematics (STEM) backgrounds, but key talent also includes highly skilled production personnel with specialized manufacturing expertise. [57] Collectively, this workforce is responsible for every facet of the enterprise from sustaining today's nuclear capabilities and ensuring their safety and reliability to designing, developing, and producing future capabilities.[58] In both technical and production arenas, the enterprise is in constant competition for talent. This challenge is well documented, and multiple engagements with relevant sectors during this industry study corroborated this premise.[59]

On the technical side, the nuclear enterprise suffers from a shortage of qualified STEM personnel. This problem is not unique to the enterprise; rather, it reflects a more significant problem affecting the national security innovation base.[60] Several aspects of the nuclear enterprise—such as stringent security clearance requirements, sub-optimal pay and duty locations, and uncertain future demand—exacerbate competition.[61] Within the enterprise, industry competes for top talent between sustainment and recapitalization programs. Externally, it competes for talent with cutting-edge global technology companies, many of which offer opportunities to work with advanced future technologies like augmented reality and quantum computing that will be increasingly relevant and lucrative in the future. Nuclear recapitalization efforts, conversely, are grounded in mature technology. Although this construct reduces program risk, it affords fewer opportunities to innovate or exercise advanced skills. This trade-off has implications. The one organization encountered within this industry study that did not report problems recruiting or retaining qualified STEM talent was Johns Hopkins Applied Physics Laboratory. The organization attributes much of its success in recruitment and retention to a

diverse workforce and to the fact that its work is directly linked to national security and incubated in an environment that cultivates innovation.[62]

On the manufacturing side, the nuclear industrial base also competes for scarce talent, especially in critical skill sets like specialized welding.[63] This trend is especially evident among shipbuilders who support the sea leg of the triad. Generally, this industry sector is challenged by "too few replacements for retiring workers, insufficient labor mobility, the perception of unattractive physical working conditions, and the cyclical nature of shipbuilding."[64] Here too, security clearance requirements limit an already scarce labor pool.[65]

RELATED AND SUPPORTING INDUSTRIES

As related and supporting industries become increasingly globalized and focused on commercial customers who demand the latest technological advances, it is more difficult for the nuclear enterprise industry to secure its supply chain and balance the risks and benefits of innovation. Emerging technologies, agile software development, and other innovations offer advantages that U.S. adversaries are eager to attain. To maintain the U.S. competitive advantage, modernization programs must find ways to exploit innovation while mitigating risk and securing supply chains.

The Role of Related and Supporting Industries: Porter asserts that internationally competitive suppliers and other related industries provide a competitive advantage because they "deliver the most cost-effective inputs in an efficient, early, rapid, and sometimes preferential way."[66] A close working relationship between the primary industry and supporting industries results in a constant exchange of information and rapid learning. This dynamic accelerates the pace of innovation and creates a competitive advantage.

Challenges and Opportunities in Related and Supporting Industries of the Nuclear Enterprise Industry: Nuclear modernization is at an inflection point as emerging technologies, agile software development, and other innovations become increasingly important and prevalent in industries that support the nuclear enterprise. These innovative technologies and processes can improve the nuclear enterprise, but they have risks that government and industry must carefully weigh to ensure nuclear surety and a credible deterrent.

Quantum computing has the potential to transform data encryption, enhance the understanding of nuclear physics, and create new materials that extend the lifecycle and survivability of components in nuclear systems.[67] Artificial intelligence and machine learning could improve situational awareness, expand decision space, and improve cybersecurity within the nuclear enterprise.[68] The race to dominate these advanced technologies is a critical component of great power competition. As former Secretary of Defense Esper said, "artificial intelligence will change the character of warfare. I believe whoever masters it first will dominate the battlefield for many, many, many years."[69]

Several studies indicate that agile software development, compared to the traditional waterfall development process, can reduce costs, development time, and product defects.[70] Given the quick pace of technological change and the length of the traditional development process,

upgrades following the traditional method can be out of date before the services deliver them to the warfighter.[71] Agile software development, however, is based on modular and iterative software development that focuses on collaboration, customer feedback, and small, rapid releases. Agile development, modular systems, and digital engineering can make it easier to upgrade systems in the future and reduce sustainment costs. The GBSD program has incorporated these techniques for these reasons.

Given the always/never standard, some in DoD are understandably hesitant to incorporate agile software development and emerging technology, particularly autonomy, into the nuclear enterprise.[72] The strict standards for nuclear programs contribute to the lengthy, cumbersome, and expensive certification processes. On the other hand, some DoD leaders are passionate about delivering capability faster using the newest techniques. This innovative spirit helps recruit and retain STEM experts in the nuclear enterprise who want their skills to keep pace with the commercial sector.

U.S. adversaries are pursuing emerging technologies to attain a strategic advantage over the United States.[73] A nuclear adversary willing to employ autonomous command and control to accelerate the employment of nuclear weapons and gain speed in decision-making would threaten global nuclear stability and the current U.S. nuclear deterrence strategy. To remain competitive, DoD must understand both the promises and the perils of innovative development methods and emerging technology, particularly when U.S. adversaries might be more willing to accept the benefits over the risks. Balancing the risks with the benefits of innovation is one of the biggest challenges facing DoD leaders in the nuclear enterprise.

Supply chain security is another significant challenge for the nuclear enterprise industry. Legacy systems rely on older technology that is less interconnected and often isolated from other systems. Modern versions of these systems will necessarily be more connected and reliant on technology that is ubiquitous in the commercial sector, creating supply chain and security vulnerabilities that U.S. adversaries will seek to exploit. An interagency task force on supply chain security identified the following vulnerabilities in the nuclear enterprise: a lack of trusted sources of microelectronics, software design tools, and data management systems; an increasingly global and untrusted supply base for analytical and test equipment; and sole sources for certain critical materials.[74]

DoD and industry must assess the entire weapon system holistically from design through sustainment to anticipate threats to the supply chain, avoid them, and adapt as necessary. Digital design, engineering, mapping, and predictive analytics are critical tools that provide advantages for supply chain security.

DEMAND CONDITIONS

Overall demand conditions in the nuclear enterprise industry are strong. Strict standards often prompt innovation, although the regulatory burden is growing. Given the importance of steady demand for industry and innovation, the U.S. government should consider taking steps to stabilize demand further and decrease the regulatory burden without lowering standards.

The Role of Demand Conditions: According to Porter, the fourth factor affecting an industry's competitiveness is the presence of demanding buyers who "pressure companies to innovate faster and achieve more sophisticated competitive advantages."[75] From industry's perspective, stable demand is important "to justify investments in the productive capacity required to fulfill contracts and…compete for future awards."[76] Without consistent demand, production lines shut down and personnel with specialized skills leave the industry.[77] Because the government is the primary customer in the nuclear enterprise industry, Congressionally approved budgets for nuclear programs are an important demand signal. Stable funding is also important for strategic deterrence. As the nuclear enterprise ages, adversaries may question its effectiveness and credibility. Inconsistent funding levels send mixed messages about the United States' willingness and ability to maintain a capable nuclear force.

Challenges and Opportunities for Demand Conditions in the Nuclear Enterprise: Recent budgets and engagements with stakeholders in the nuclear enterprise indicate that overall demand is strong and most nuclear modernization programs enjoy support from Congress. However, some experts believe Congress might delay programs or cut funding for nuclear modernization because of opposition to certain programs, the growing national debt, or competing priorities within the military and among agencies.

Current plans to simultaneously recapitalize nearly all elements of the nuclear enterprise resemble the conditions of a military surge. The tight schedules for most programs contribute to the surge conditions. While recapitalization occurs over decades, the government will also need industry to sustain increasingly antiquated legacy systems. Conventional weapons programs, such as the Virginia-class submarine, further increase the demands on many companies in the nuclear industry. The growing commercialization of space and dual-use technologies also increases demand. For example, HII describes the company's $46 billion backlog of work as an "unprecedented" indication of strong demand.[78]

Congress and the military have taken steps to provide more consistent funding. The Columbia submarine program uses authorities in the NSBDF for advanced construction, advanced procurement, and multi-year shipbuilding. The Air Force's RCO manages the B-21 program, ensuring access to streamlined decision-making, stable funding, tailored acquisition strategies, hiring flexibility, and the ability to request military construction funds directly. Several programs described innovative contracting strategies that provide earlier profits to companies to prepare for production, meet schedule targets, and reduce costs. The Columbia and B-21 programs prioritize strategic communication with Congressional staff to maintain funding. In some cases, however, program offices seemed unaware of existing options that could help stabilize demand.

Regulatory Environment for the Nuclear Enterprise: The unique destructive power of nuclear weapons requires the highest standards for safety, security, reliability, and control.[79] Strict standards reinforce the credibility and deterrent effect of the U.S. nuclear force. These standards have pushed the industry to innovate. For example, the policy decision to stop nuclear explosive testing led to "the development of new scientific, computational, and technical tools" to simulate the effects of nuclear weapons.[80] Labor shortages and tight schedules prompted HII to design a new specialized manufacturing fixture to construct the Columbia submarine more quickly and with less labor.[81]

Porter emphasizes that "strict standards, however, must be combined with a rapid and streamlined regulatory process that does not absorb resources and cause delays."[82] The 2021 NDAA concluded that the political and regulatory environment for the defense industry was regressing, which creates barriers to entry, increases costs, and reduces profits.[83] Industry and government representatives in the nuclear enterprise assessed these problems are driven, in part, by risk aversion within government and frequent changes as military and civilian staff rotate.

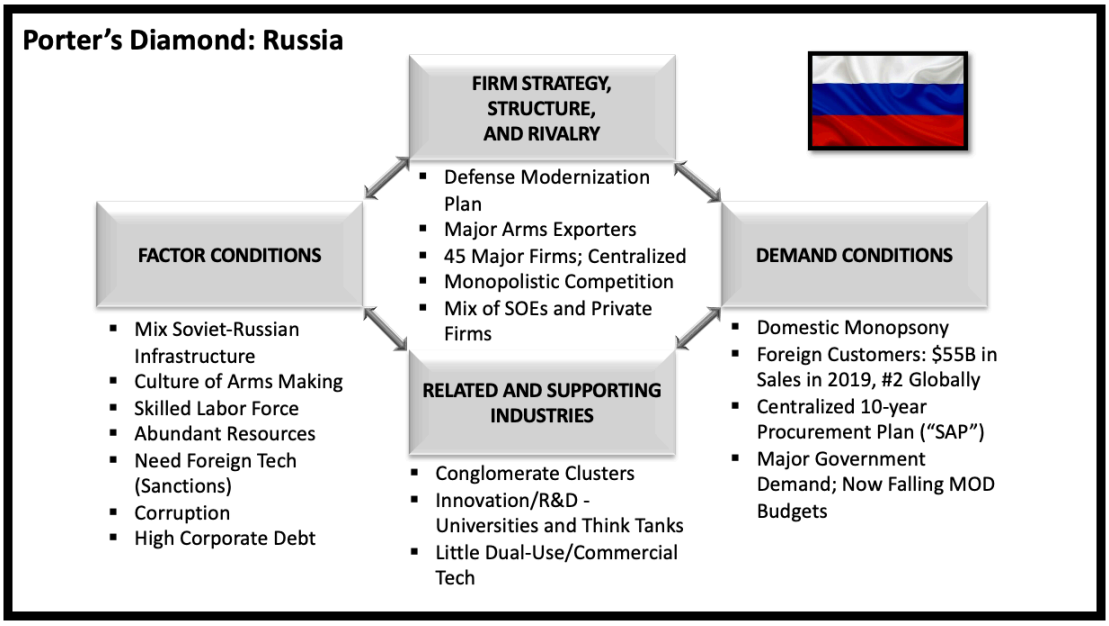
Industry and government representatives cited many iterative, inconsistent, and frequently changing regulations that constrain modernization. For example, there are thousands of pages of cybersecurity standards issued by different DoD entities; however, there is no integrated approach, and it is unclear which standards will apply across the services. Industrial security standards and security clearance processes prompted similar concerns.

Industry experts working on Navy and NC3 programs criticized the lengthy process for qualifying and certifying new technologies, such as 3D printed components. Lengthy, uncertain certification processes reduce companies' return on investment and decrease their incentive to invest their own funds in research and development. A 2017 DoD report to Congress recognized that the military could not realize the potential of additive manufacturing until it developed procedures for certifying components.[84]

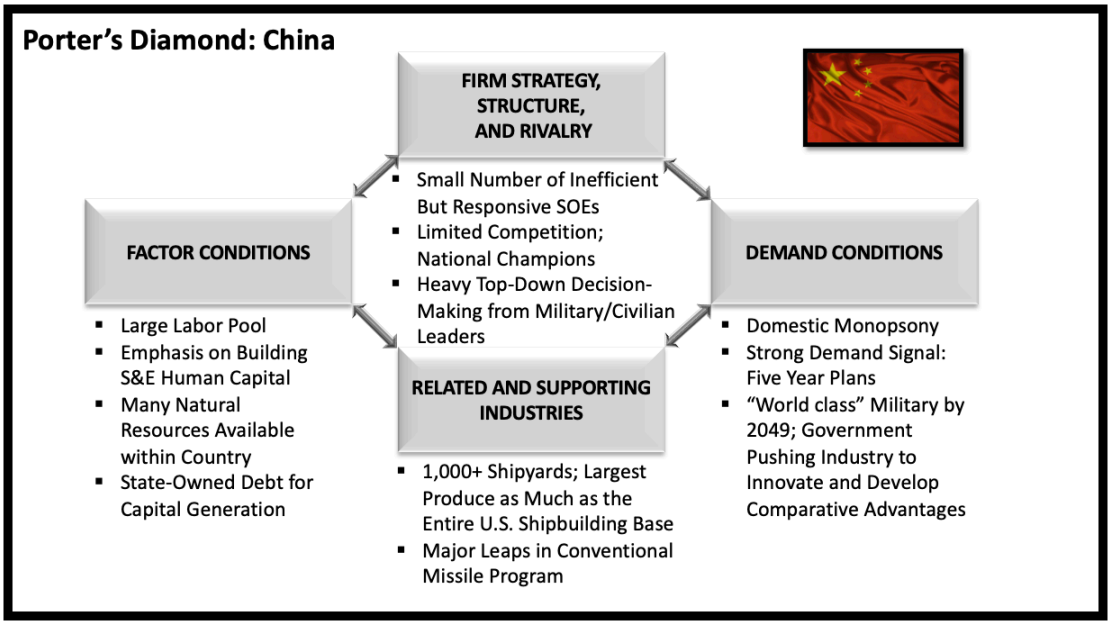
COMPARATIVE ANALYSIS OF THE NUCLEAR ENTERPRISE INDUSTRY IN CHINA, RUSSIA, AND THE UNITED STATES

Russia and China are modernizing both their conventional and nuclear forces. Russia's nuclear modernization program is approximately 80 percent complete, and China is expected to field a complete strategic triad of nuclear weapons soon.[85] As a result, Russia and China are eroding traditional U.S. comparative advantages in nuclear deterrence. The figures and analysis below illustrate how the nuclear industries in China and Russia compare to U.S. industry.

Russia modernized its nuclear forces by investing heavily to reconstitute its nuclear weapons research, development, and production capabilities. Russia's key advantages are its culture of developing military hardware, a labor force skilled in math and science, and a large, mature defense industrial base. However, Russia's overall defense industrial base faces significant long-term challenges.[86] Key disadvantages include dependency on foreign technology, an industrial base that is heavily indebted, low levels of innovation, declining government funding, a shrinking pool of skilled labor, and corruption.[87]



China's key advantages are its high-tech development plans, steady investment, access to critical materials, a large labor pool, and responsive state-owned enterprises. Estimates suggest China now produces more than twice the number of science and engineering (S&E) graduates than the United States each year. In recent years, Chinese nationals earned as many as 25 percent of the S&E doctorate degrees awarded in the United States.[88] China's key disadvantages are dependence on the global economy and foreign technology, adherence to centralized and inflexible decision making, inefficiency, and slow innovation.



Although the United States faces the challenges described above, the nation also possesses key advantages such as an entrepreneurial society where innovation resides across government, academia, and industry. Ultimately, the United States has major long-term competitive advantages that should leave it well positioned to catch up with Russia and stay ahead of China. However, the United States must acknowledge and address the challenges above. If the nation remains committed to pursuing modernization and harnesses its national advantages, Washington can enhance its deterrence capabilities relative to Moscow and Beijing.

POLICY RECOMMENDATIONS

1) COMMUNICATE A CONSISTENT STRATEGIC NARRATIVE TO CONGRESS, INDUSTRY, AND THE PUBLIC

Based on interactions with stakeholders, there does not appear to be a single entity within DoD responsible for coordinating strategic communications about nuclear modernization and its costs across the enterprise. Inconsistent information from leaders across government attracts Congressional scrutiny, disincentivizes industry, undermines public support, and deters talent from joining the enterprise. An enterprise-wide strategic communications plan is necessary to ensure consistent funding, support, talent, and interest from industry. These recommendations are resource neutral, but they require consensus among the military services, policy entrepreneurship, and possibly organizational changes that could require Congressional approval.

A. Designate a Lead to Develop a Consistent Narrative Across the Enterprise: DoD should designate a lead office to coordinate strategic communication and advocate for modernization across the nuclear enterprise. This office should also focus on capturing the total costs across the enterprise, including efficiency measures, to increase confidence in DoD's cost estimates. Under the current OSD structure, the Deputy Assistant Secretary of Defense for Nuclear Matters falls under the Office of the Assistant Secretary of Defense for Nuclear, Chemical, and Biological Defense Programs. Given the evolving strategic environment and the magnitude of modernization efforts, the department should re-examine the current organizational construct. Elevating nuclear matters to an independent Assistant Secretary would send a public signal of the importance of modernization and deterrence. More important than redrawing lines on an organizational chart, however, this move should empower the new Assistant Secretary and his or her staff to perform the various integrating functions across the enterprise that are critical to its success during this period of modernization.

B. Ensure a Consistent Narrative to Congress to Sustain Budgetary Support: Some program managers have excellent relationships with Congressional staff, but others have less interaction and face greater scrutiny. Across programs, the narrative is not always coordinated or consistent. Inter-service and intra-service competition for funds exacerbates this problem. Programs should seek to learn from each other's best practices to deliver a more consistent and compelling narrative.

In addition, enterprise-wide strategic communication must acknowledge common criticisms and better articulate the ways recapitalization programs promote efficiency, innovation, and cost savings. Some critics in Congress argue that concerns about budget uncertainty are overblown and perhaps a disingenuous effort to prop up industry or avoid difficult trade-offs. However, most programs are adopting innovative technical approaches, acquisition strategies, contracting methods, and other techniques to reduce production and sustainment costs over the decades-long lifecycle of the systems. DoD must identify a better narrative for communicating this fact to Congress and the public. For example, each program should have a similarly formatted chart that compares the relative costs of sustaining legacy capabilities to buying modern systems and explains the assumptions that informed the calculations.

C. Convey a Consistent Narrative to Industry to Send a Clear Demand Signal: Effective strategic communication can help convince industry that nuclear modernization programs will continue to receive funding over the long term. A steady demand signal gives companies the confidence to invest their own money in R&D relevant to the nuclear enterprise. Consistent demand also entices new companies to enter the market, thus increasing competition, lowering costs, and spurring innovation. Effective strategic communication can also attract companies with expertise in emerging technologies to compete for contracts in the nuclear enterprise. Studies demonstrate that the STEM workforce can contribute significantly to innovation, which drives economic growth and creates national competitive advantages.[89] A strategic communications plan must also leverage university affiliated research centers (UARCs) and federally funded research and development centers (FFRDCs). These critical incubators for technology development are a venue to expose young talent to the economic opportunities and national security benefits of joining the nuclear enterprise industry.

D. Communicate a Consistent Narrative to the Public to Reiterate the Importance of Modernization and Encourage Talent to Join the Nuclear Enterprise: Clear and coordinated strategic communications—backed by support from Congress and industry—should reiterate the importance of strategic deterrence to the public to garner broader support for nuclear modernization. The end of the Cold War brought about a decline in public attention on the nuclear enterprise. Today, most of the U.S. general population is probably unaware of Russian and Chinese nuclear modernization efforts. Strategic communication can remind the public that strategic deterrence underpins national security. Further, a general societal decline in familiarity with the roles and missions of the armed forces combined with the inherently clandestine nature of nuclear operations makes recruiting to support the enterprise intrinsically challenging.[90] A more compelling narrative to the public and industry can encourage STEM experts and those with specialized skills to join the nuclear enterprise industry. Amid stiff competition for human capital, engineers, developers, and welders will not specialize in a nuclear field unless they are confident there will be a stable pipeline of work.

2) DEVELOP COMPREHENSIVE STRATEGIES AND TRANSFER BEST PRACTICES ACROSS THE NUCLEAR ENTERPRISE

Across the nuclear enterprise, government and industry face multiple common challenges. These cross-cutting challenges include effectively sustaining legacy systems while producing new capabilities; balancing smart risk with the always/never nuclear mandate; conveying requirements to industry; and overcoming funding uncertainty and a lack of specialized labor. These challenges have significant implications for recruiting and retaining talent, supply chain security, competition, acquisition strategies, technical approaches, costs, and schedules.

To better understand and manage these challenges, DoD must comprehensively review the industry as a holistic portfolio across the enterprise. The initiatives proposed below offer a starting point to address some of these cross-cutting issues. As initiatives succeed, DoD should ensure there are appropriate mechanisms to capture and share best practices across the enterprise. Apart from additional R&D investments to support human capital development, much of which needs to happen at the national level, the recommendations that follow are resource neutral. They

will, however, require organizational and cultural changes, policy entrepreneurship, and consensus among the services.

A. Embrace and Execute a Mindset of "Integrated Deterrence:" Secretary of Defense Austin envisions a whole-of-government approach to deterrence, a concept he calls "integrated deterrence." In a recent speech, he urged the military services to eliminate stovepipes and incorporate capabilities across DoD, other federal agencies, and the nation's allies. He heralded the need for advanced weapon systems featuring the latest technologies—to include artificial intelligence and quantum computing—across all domains.[91] Accordingly, as the nation invests in recapitalization across the nuclear enterprise, it must consider this holistic approach to deterrence.

B. Build an Integrated Network of Epicenters to Bridge Gaps Between Modernization and Sustainment Efforts: Modernization and sustainment programs would benefit from greater coordination with each other. Modernization programs could learn lessons from sustainment programs to reduce costs and risk. Sustainment programs would benefit from exposure to the innovative techniques common in modernization programs. Greater coordination requires breaking down the artificial divide between sustainment and acquisition communities and establishing mechanisms by which the two sides can learn from each other.

DoD should build a formal structure of epicenters across the nuclear enterprise, to include civilian and DoD labs and DOE facilities, to promote an innovation-friendly ecosystem and a culture of collaboration between procurement and sustainment programs. These epicenters could also drive efforts to integrate emerging technologies while mitigating risk and supply chain vulnerabilities that frequently arise much later in the lifecycle of a system.

C. Baseline Security and Certification Requirements and Streamline Approval Processes: Demanding buyers and strict standards can encourage companies to innovate and build competitive advantages. However, regulatory, security clearance, and certification processes must be streamlined, consistent, and rapid.[92] Speedier security clearances for the nuclear industry would help ease labor shortages in the short term and remove a burden that deters specialized labor and new companies from entering the industry. Certification, industrial security, and cybersecurity standards should remain high, but there must be common standards and more efficient processes across the nuclear enterprise to accelerate companies' return on investment and encourage new companies to enter the market, which promotes innovation and competition. These standards must be easily adaptable as policy and technology change.[93]

D. Embrace Emerging Technologies Smartly: Nuclear modernization efforts should apply emerging technologies, such as artificial intelligence (AI) and machine learning (ML), where they will improve capabilities at an acceptable level of risk. There is significant reticence in the nuclear enterprise to introduce automation into human decision-making; however, as the technology matures and confidence in these technologies increases, DoD should consider opportunities for greater integration of AI/ML into the areas of situation monitoring, planning, and force direction. AI/ML can improve the speed of execution within NC3, thereby expanding decision space and increasing operational and strategic advantages. To better understand the benefits and risks of incorporating emerging technology into the nuclear enterprise, DoD should establish an Advanced Technologies Enablers Board. Such an organization, comprised of

scientists and nuclear enterprise experts, could help DoD study and understand emerging technologies and the associated risks and conflicts across all nuclear modernization efforts.

Additionally, embracing emerging technology within the nuclear enterprise will help recruit and retain qualified personnel. Government and industry representatives cited the slow speed and lack of innovation in the DoD acquisition process as problematic for recruiting and retaining top talent. Alternatively, work environments that fostered diversity, innovation, and a personal connection to development efforts reported significantly better retention. Accordingly, DoD should encourage greater innovation in program execution with defense contractors through appropriate risk-taking and "smart" failures. The GBSD program's use of digital engineering and cloud-based program management capabilities illustrates just such an effort. Further, organizations should consider revamping personnel incentives to better align with a culture of innovation and encourage greater personal investment in outcomes.

E. Reinvigorate Deterrence Intellectual Capital: No single technological capability affords the same strategic advantage as the collective capability of expert human capital. Effective strategic deterrence requires comprehensive investments in the people who enable capabilities across the nuclear enterprise. As a former commander of USSTRATCOM said, "achieving strategic deterrence in the 21st century requires continued investment in strategic capabilities and [a] renewed multi-generational commitment of intellectual capital."[94] Achieving strategic deterrence in the contemporary global security environment requires a comprehensive, resourced strategy to recruit, cultivate, and retain the technical, manufacturing, and intellectual capital that underpins the nuclear enterprise and the nation's deterrence. The recommendations that follow are intended to reinvigorate this complex.

1. Invest in the National Security Workforce and STEM Education: Although outside the explicit realm of DoD, the U.S. government must fund key areas of education and R&D. This mandate aligns with President Biden's Interim National Security Strategic Guidance imperative to invest in the national security workforce.[95] Federal R&D funding supports higher education, especially STEM, by providing opportunities for students to engage in cutting-edge research through associated universities, FFRDCs, and UARCs. DoD should attempt to maximize nuclear enterprise R&D efforts. Such investments provide a unique opportunity to orient students to the nuclear enterprise while educating them on how their efforts directly support national security.

2. Maximize Opportunities to Create Deterrence Expertise: DoD should view investments in future intellectual capital as analogous to investments in capabilities. The complex nature of 21st century deterrence requires individuals who are experts in the study of both the physical and cognitive aspects of deterrence. Creating this capability requires a significant investment now in anticipation of a greater return later. To build this intellectual workforce, DoD should prioritize funding for internships and academic opportunities, such as scholarly paper writing competitions, that enable direct engagement with university students. Additionally, DoD should encourage engagement with students on enterprise problems posed to UARCs and FFRDCs.

To improve awareness of the role of deterrence in national security, DoD should widely promote educational opportunities such as USSTRATCOM's Annual Deterrence

Symposium. Opportunities to formally study strategic deterrence are growing (see Appendix C). In 2015, the Air Force stood up the School of Advanced Nuclear Deterrence Studies, and each year the Air Force sends officers to fellowships across the nuclear enterprise to include the national nuclear laboratories and DOE. The Center for Strategic and International Studies launched the Project on Nuclear Issues to cultivate emerging thought across the full range of nuclear issues and communities.[96] Finally, several universities have developed Ph.D. programs, master's degrees, and graduate certificates in the area of Strategic Studies. DoD leadership should prioritize support for these programs, channel top talent into these programs, and ensure graduates fill deterrence-related positions upon completion. This emphasis on creating and effectively employing the right talent will help create a sustained pool of strategic deterrence experts.

3) INCREASE INCENTIVES FOR INNOVATION IN INDUSTRY

Program offices across DoD seek to develop platforms with proven technologies to lower risk, protect schedule, and meet cost goals. However, in a once-in-a-generation nuclear modernization program, these steps do not necessarily help sustain the U.S. nuclear industrial base for the future or encourage innovation within industry. For these reasons, DoD and its stakeholders should consider the following recommendations to ensure the viability of the defense industrial base (DIB) in 2050 and beyond. To be successful, the government and industry need to develop acquisition strategies and craft contracts that drive agility and flexibility into the system and incentivize innovation and program goals.

A. Avoid the Temptation for Vertical Integration: The DIB will succeed with competitive innovation, not vertical integration. Accordingly, the Federal Trade Commission should consider restricting mergers and acquisitions for the niche industries involved in the nuclear enterprise. While vertical integration, as seen in places like China, may speed acquisitions, it does so at the expense of innovation, particularly when applied to the limited corporate space of the U.S. defense industry.[97] Vertical integration also increases long-term sustainment costs.

One example of the stifling effect of vertical integration on competition is Northrop Grumman's acquisition of Orbital ATK. Over the past two decades, the number of U.S. companies producing rocket motors has fallen from six to two—Orbital ATK and Aerojet Rocketdyne.[98] Although the Federal Trade Commission firewalled Orbital ATK as a supplier during the GBSD competition by allowing competitors to bid against Northrop Grumman and use ATK as a supplier, the acquisition had a chilling effect on the competition. Ultimately, Northrop Grumman was the sole bidder. Lockheed Martin's proposed vertical integration with Aerojet Rocketdyne will further limit competition in the U.S. DIB.

B. Pursue Modular Open System Architectures (MOSA) to Encourage Internal Research and Development (IRAD) Expenditures and Participation by Smaller Firms: Larger firms are often more risk-averse regarding innovation than smaller ones. Despite evidence that leadership in disruptive innovation pays dividends, larger firms often fail to lead innovation because they believe they will earn steadier profits by sustaining technologies for their existing customers.[99] The Government Accountability Office reports that about 80 percent of prime contractors spend IRAD funds on incremental technologies that add to their near-term

profitability, leaving just 20 percent for disruptive innovations.[100] Defense contractors typically spend about two percent of revenue on IRAD, meaning they spend less than half of one percent of revenue pursuing truly disruptive innovations. Contracts must allow flexibility and encourage industry to fail fast and often through contract incentives that encourage IRAD investments.

Unlike larger companies, new entrants and small firms are often more flexible and can make strategic commitments to develop emerging market applications.[101] Thus, industry should do more to incorporate small businesses and build incentive structures that value innovation. An innovation-friendly ecosystem would integrate the use of MOSA into the weapon system. MOSA allows multiple vendors and contract winners to compete for smaller-scale, lower-cost upgrades, thereby promoting innovation, creating more consistent demand, and providing more opportunities for industry. At the sub-level, the suppliers of prime contractors can compete on their own for follow-on contracts directly with DoD, introducing more competition into the nuclear industry and significantly reducing sustainment costs while increasing future innovation.

C. Develop Challenging Benchmarks for Contract Award Fees: Modernization efforts within the nuclear enterprise benefit from meaningful incentives for industry to innovate and perform. Program offices must work to understand the motivations of their industry and associated companies. Challenging yet realistic goals for award fees are critical to contract performance as the B-21 program demonstrated when it linked cost savings to incentives. Further, realistic and dependable delivery schedules, including on-time delivery of government-funded supplies, support revenue streams for companies and help them meet their yearly and quarterly projections. Early and firm DoD commitments to order a certain quantity provide a consistent demand signal and allow companies to benefit from economies of scale, which reduce costs for the government. DoD can also leverage Title III of the Defense Production Act to incentivize industry to produce or sustain material essential to national security. The right mix of incentives will prompt companies to innovate to meet nuclear modernization requirements, find efficiencies, reduce costs, increase speed, and invest in next-generation technologies.

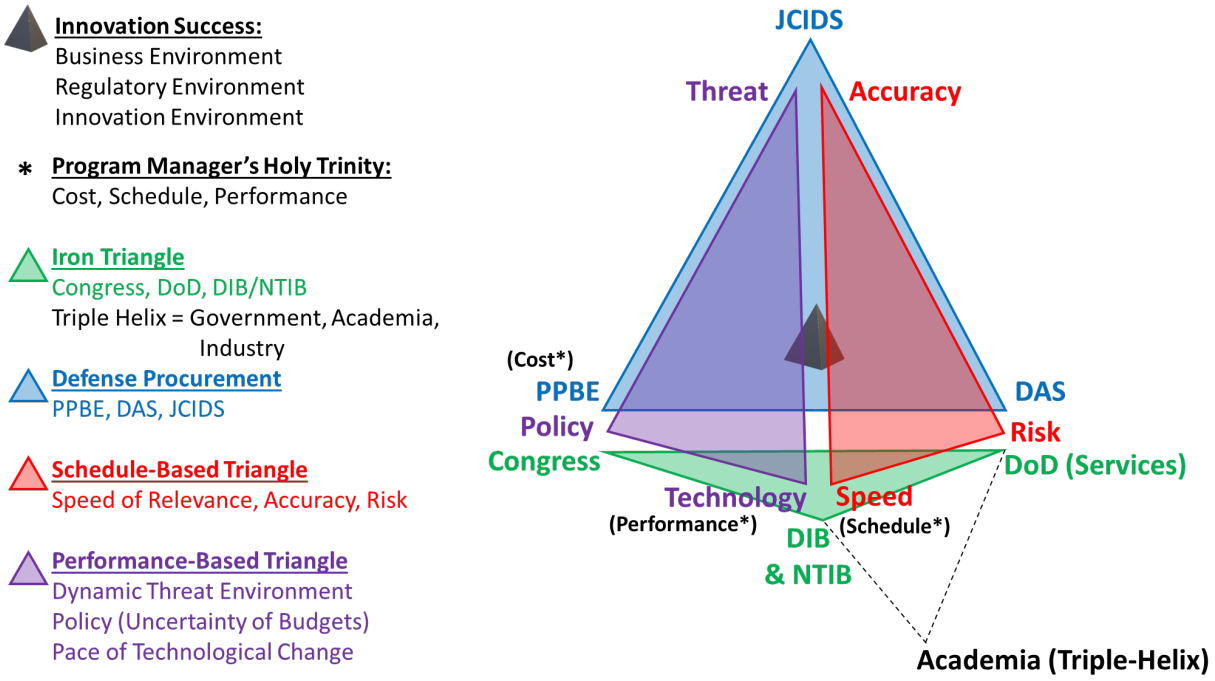
D. Leverage All Aspects of the Adaptative Acquisition Framework and Seek New Authorities: Acquisition frameworks and organizational decisions in certain program offices offer promising concepts that could be replicated with success in other programs. The Air Force's RCO structure and the authorities in the NSBDF are two examples of approaches that incentivize industry. Continuing to develop flexible procurement options within the adaptive acquisition framework will push policies to support strategic acquisitions of the future. DoD should request Congress establish a working capital fund or another mechanism similar to the NSBDF to set aside dedicated funding, provide multi-year budget consistency, and authorize special procurement authorities. The fund could potentially be a part of the Biden Administration's proposed infrastructure plan.[102] Expanding the NSBDF model across the nuclear enterprise would provide further authorizations for economic order quantity contracts, advanced construction, advanced procurement of high value/long lead components, and multi-year production of critical components.[103] If an enterprise-wide solution is infeasible, then individual programs could request dedicated funding and procurement authorities to manage shortages of critical materials and services. For example, centrally funded block buys of testing hours at laboratories would incentivize industry to expand capacity for survivability testing, which is a constraint for sustainment and modernization.

CONCLUSION

Modernization of the nuclear enterprise is a titanic undertaking that will span decades and may cost U.S. taxpayers upwards of $1 trillion. If this recapitalization effort is to be successful, government and industry must address several challenges that threaten the nation's ability to field the capabilities it needs for a robust and relevant strategic deterrent. After a thorough investigation of the nuclear enterprise and its industrial base, this report finds that although the challenges are significant, they are not insurmountable. The three lines of policy recommendations outlined above can mitigate many of these challenges. First, DoD must develop and communicate a consistent strategic narrative about nuclear modernization. Next, it must develop comprehensive strategies and transfer best practices across the entire enterprise. Finally, it must create incentives for industry to innovate. If the nation takes these steps and remains politically and financially committed to recapitalization, it will be well positioned to secure itself and its allies from future threats.

APPENDICES

Appendix A:
The Innovation Environment (Six Trinities and the Triple Helix)[104]



Robert Atkinson describes his concept of a "national innovation system" as a triangle with three forces that strongly influence innovation within the United States. Atkinson says,

> One way to conceptually organize all the factors determining innovation in a nation is to think of an innovation success triangle, with business environment factors along one side of the triangle, the trade, tax and regulatory environment along another, and the innovation policy environment along the third. Success requires correctly structuring all three sides of the innovation triangle.[105]

Within the environment of defense procurement, many triads accompany Atkinson's innovation success triangle. As Atkinson explains, policymakers must understand the interrelationships between the sides of these triads to navigate the defense procurement environment successfully. Moreover, I.B. Holley teaches, "the procurement process itself is a weapon of war no less significant than the guns, the airplanes, and the rockets turned out by the arsenals of democracy."[106] In today's great power competition, the defense procurement process provides policymakers a powerful international platform on which to compete when deployed successfully. Holley further explains that because defense procurement generates national economies, it possesses substantial political influence, and "to ignore or even to minimize the frankly political aspects of military buying is to be less than candid and, at the very least,

unrealistic."[107] Within the defense procurement environment, economic, political, and technological forces exist, requiring keen policymaking to harness and manipulate their strengths properly.

When considering innovation for defense, one must account for the formal forces that make the sides of the iron triangle (Congress, DoD or military services, and the DIB and national technology innovation base (NTIB). The iron triangle represents politically charged organizations that hold Congressional authority over innovation costs provided by the Constitution, legal authority to procure defense technologies offered by the NDAA, and constituent authority for the DIB to preserve jobs in Congressional districts. Policymakers must also account for academic organizations, which reside as a sub-organization to DoD and the DIB/NTIB. Government, industry, and academia represent Henry Etzkowitz's "Triple Helix Model of Innovation."[108] This model considers the entrepreneurship of universities working with government and industry and receiving funds for their innovative research.[109] When these universities work with the government and industry, they indirectly affect the innovation ecosystem. However, academic organizations also directly influence the ecosystem through their ability to produce STEM expertise. Because political influence drives the forces within the iron triangle, policymakers must understand the political interests that motivate these forces to influence innovation.

The additional forces depicted in the figure above and Etzkowitz's Triple Helix Model represent the powers affecting the innovation ecosystem. When expressed two-dimensionally, policymakers can organize these forces into separate triangles to understand their triadic effects. Etzkowitz explains in a dyad, "you either come together or split apart."[110] This duality represents a fundamental relationship between two forces. However, in a triad, a third element exists moderating the relationship between the other two forces. Etzkowitz warns, "the way that some look at things in dichotomies meant they couldn't see the effect of the triadic element."[111] Once policymakers understand the effects of each force individually across a two-dimensional area, they must then evaluate their integrated effects in a three-dimensional volume or tetrahedral. Within this tetrahedral, one sees the four apexes' alignment, which provides policymakers key focus areas to target the interrelationships within the innovation ecosystem.

An additional triangle exists adjacent DoD, directing innovation and technology developments within the defense procurement system comprised of the Defense Acquisition System (DAS) or Adaptive Acquisition Framework (AAF); the Joint Capabilities Integrated Development System (JCIDS); and the Planning, Programming, Budgeting, and Execution (PPBE) process. This Defense Procurement Triangle embodies formal processes that drive the execution of defense technology developments, establish joint requirements, and communicate the cost of innovation across the DoD and to Congress. Similarly, innovation's success within these triangles requires correctly navigating within all three sides of this system.

Two additional triangles further make up this ecosystem. Contrary to the iron and defense procurement triangles, the schedule-based and performance-based triangles provide little formality but contribute to the U.S. ability to compete with adversaries. The schedule-based triangle reflects the speed of innovation necessary to compete against China in delivering the latest technology advancements in AI and 5G. However, the faster one makes decisions on technology investments, the less time there is to study the second and third-order effects.

Unfortunately, more deliberate planning slows innovation. Speed and accuracy balance each other as two sides of this triangle. The faster one tries to execute innovation, the more risk one accepts in less accuracy. The more methodically one plans to increase accuracy, the more risk one accepts in performing slowly. Risk makes up the last side of this schedule-based triangle. As with the formal triangles, innovation's success depends on maintaining balance within this triangle.

Similar to the schedule-based triangle, the forces within the performance-based triangle strongly affect the ability to innovate and compete with China in today's environment. Technology represents the critical aspect of this triangle. Overestimating the maturity level of a particular technology results in cost overruns, schedule delays, and the technology's inability to counter the threat effectively. The threat generates the need to innovate and develop technology, which makes up the second side of the triangle. As the threat advances, the need to further advance technology increases. Working with allies and partners offers the United States enhanced capabilities to counter global threats more efficiently and effectively. More stringent policies hinder the DIB and NTIB's ability to share sophisticated technology, negatively affecting overall costs and international interoperability of the system. Less stringent policies run the risk of exposing advanced technology but enhance interoperability and capability to counter a global threat. Overall, to counter emerging global threats with allies and partners, policymakers must balance the forces within the performance-based triangle.

These six trinities, along with Triple Helix Model, form the three-dimensional ecosystem within which innovation occurs. When aligning the corners of each triangle, these apexes form a tetrahedral that provides policymakers further insight into how best to manipulate these forces. Within this tetrahedral, one sees the alignment of the four apexes. The first apex between the DoD, DAS, and risk annotates the DoD's execution of the defense acquisition system to manage risk across cost, schedule, and performance, which exist as forces within an opposing apex. The second apex addresses the function of the JCIDS process to generate formal joint warfighting requirements to address the threat. Accuracy within this apex reflects the need to study the threat extensively to generate the right capabilities needed to counter global threats. Defense professionals often criticize the length of this process and argue for reform. The third apex aligns Congress with policy and the PPBE process. Congress establishes policies that govern innovation. Congress also controls the budget and passes the NDAA, which follows the PPBE process. The fourth apex associates DIB/NTIB with technology and speed. This apex represents the driving forces behind the need for the DIB/NTIB to innovate the most advanced technology at the speed of relevance. These apexes provide policymakers key focus areas to manipulate the interrelationships within the innovation ecosystem.

Appendix B:
Deterrence Education Programs in the United States

The list below is a sample of efforts to improve and expand deterrence education in the United States.

Services:
Air Force Institute of Technology:

- Graduate Certificate: Nuclear Weapons Effects, Policy, and Proliferation
- Nuclear Engineering Master's and PhD programs
- Strategic Deterrence Courses: Nuclear 150, Nuclear 200, Nuclear 300, Nuclear 400

Professional Military Education:

- Nuclear Lab Fellowships
- SANDS
- Mahan Scholars Research Program at the Naval War College

Deterrence and Assurance Working Groups (DAWGs)
ROTC scholarships for 13Ns
USAF Center for Strategic Deterrence Studies
USSTRATCOM Deterrence Symposium
U.S. Strategic Leadership Fellows Program

Think Tanks:
Nuclear Scholars Initiative/PONI—CSIS
Deterrence in Southern Asia – Stimson Center

USSTRATCOM Academic Alliance:
Air University
American University
Bellevue University – *Strategic Deterrence Certificate*
Coastal Carolina University
Colorado School of Mines
Command and General Staff College
Columbia University in the City of New York
Creighton University
Defense Nuclear Weapons School
Georgia Tech
Georgetown University
Harvard University – *Nuclear Deterrence Graduate Certificate*
Hamilton Lugar School of Global and International Studies
Iowa State University
John Hopkins APL & School of Advanced International Studies
Louisiana Tech University – *Louisiana Tech Research Institute*
Missouri State University – *Defense and Strategic Studies Master's and PhD*
Naval Postgraduate School
National Defense University
North Dakota State University

Norwich University
Nuclear Policy Working Group
Pedagogical University
Penn State ARL & Brandywine
Project on Nuclear Issues
Purdue University
Royal Danish Defence College
Stanford University
Texas A&M University
United Kingdom Deterrence & Assurance Academic Alliance
United States Studies Centre, University of Sydney
U.S. Air Force Academy
U.S. Army War College
U.S. Naval Academy
U.S. Naval War College
University of Arizona
University of Denver
University of Kansas
University of Miami
University of Nebraska – *National Strategic Research Institute*
University of Northern Iowa
University of Notre Dame
University of Pittsburgh
University of California, San Diego
University of Tennessee
University of Texas
Utah State University
University of Wisconsin
West Point
Yale University

Appendix C:
Glossary of Acronyms

AAF	adaptive acquisition framework
AI	artificial intelligence
DAS	defense acquisition system
DIB	defense industrial base
DoD	Department of Defense
DOE	Department of Energy
EMD	engineering and manufacturing development phase of an acquisition program
FFRDC	federally funded research and development centers
GBSD	Ground Based Strategic Deterrent (the successor to the Minuteman III)
GD	General Dynamics
HII	Huntington Ingalls Industries
ICBM	intercontinental ballistic missile
IEP	integrated enterprise plan
IRAD	internal research and development
JCIDS	Joint Capabilities Integrated Development System
ML	machine learning
MMIII	Minuteman III intercontinental ballistic missile
NC3	nuclear command, control, and communications
NDAA	National Defense Authorization Act
NNSA	National Nuclear Security Administration
NSBDF	National Sea-Based Deterrence Fund
NTIB	national technology innovation base
PPBE	planning, programming, budgeting, and execution
R&D	research and development
RCO	Air Force Rapid Capabilities Office
SOE	state-owned enterprise
STEM	science, technology, engineering, and mathematics
UARC	university affiliated research centers
USSTRATCOM	U.S. Strategic Command

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