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Ready, Set, Getting to Go: US Nuclear Test Readiness Posture

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Abstract

In a geopolitical environment dominated by great power competition, the stakes of maintaining a credible nuclear deterrent have returned to the forefront of national security. Yet nearly 30 years have passed since the United States conducted a nuclear test. There remains a legal requirement, with origins in hard-earned Cold War lessons, for the nation to return to underground nuclear testing if called upon to do so. However, the considerable challenges create uncertainty about how quickly the United States could resume nuclear testing if the geopolitical situation warranted it. This article overviews nuclear testing and its legal framework, outlines the challenges the United States would face to resume testing, broadly considers conditions that could prompt testing resumption, and offers recommendations on how to improve its nuclear test readiness posture.

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As the geopolitical environment has returned to one of great power competition and nearly 30 years have passed since the United States conducted a full-scale nuclear test, there is considerable uncertainty about how quickly the US could conduct a nuclear test if deemed necessary. Should a US administration decide to resume nuclear testing, significant challenges exist.[1] These include personnel and infrastructure atrophy, a complicated but necessary regulatory environment, the lack of a viable location to conduct a nuclear test, and some daunting organizational hurdles.

In the absence of underground nuclear testing, the US has developed innovative tools and methods to ensure and improve the safety, security,

This article is dedicated to all the nuclear testing experts that informed my research. While it would be easy to take a path of least resistance in retirement, you inspired me by your continued work, dedication to our nation's national security, and your passion to pass on your hard-won lessons to ensure the next generation is ready to execute nuclear tests if called upon to do so.

and effectiveness of the nation's nuclear weapons stockpile. Today's science-based Stockpile Stewardship Program (SSP) is a comprehensive effort that involves experiments, modeling and simulation; surveillance of the stockpile; and evaluation of the potential impact of any issues through design, engineering, fabrication, and testing.[2] Using state-of-the-art computational tools and engineering test facilities, the SSP has thus far functioned successfully to ensure the reliability of the nation's nuclear weapons for the past 24 years. There remains, however, a legal requirement for the nation to return to underground nuclear testing if needed.[3] This mandate is codified in former president Clinton's Presidential Decision Directive (PDD-15). Signed in November 1993, it requires the nation to be able to return to a testing footing within two to three years.[4]

The context and importance of the geopolitical forces leading to this directive are hard to overstate. The Cold War had just ended. The Berlin Wall had fallen. Both superpowers were six years into a successful arms control regime—the Intermediate-Range Nuclear Forces (INF) Treaty—and the signatories were well on their way to eliminating an entire class of medium range nuclear missiles.[5] President George H. W. Bush had implemented a nuclear testing moratorium in October 1992. Furthermore, in an effort to reassure the Russians that the US would not take advantage of their tenuous strategic situation following the collapse of the USSR, Bush directed several unilateral Presidential Nuclear Initiatives (PNI) to reduce the US nuclear alert posture vis-à-vis the former Soviet Union.[6] Building on the experience and success of the INF, the groundbreaking Strategic Arms Reduction Treaty (START) was also being negotiated to drastically cut the number of longer range nuclear weapons.[7] By the early 1990s, it looked as if history had ended, to paraphrase Francis Fukuyama's famous declaration made to mark the shift in the heretofore bipolar struggle between competing superpowers.

Within this revolutionary historical context and post–Cold War euphoria, President Clinton extended Bush's moratorium and considered pursuing a test ban treaty of limited duration and permitting a low explosive yield.[8] However, less than a year into his first term, he signed PDD-15 following a Chinese nuclear test in October 1993.[9] Two years later, in 1995, Clinton announced his support for a zero-yield comprehensive test ban treaty, conditioning his support on six safeguards.[10] These safeguards, extant since 1963, represented a set of conditions that had been deemed critical to ensuring the readiness of the entire nuclear complex to preclude any strategic or technological surprise.[11]

Weighing the merits of a resumption of nuclear testing is a complicated topic. Decision-makers must consider whether it is strategically prudent, fiscally affordable, or even necessary. Those questions are beyond the scope of this article. Instead, the focus here is on a related and less politically charged subject—whether the United States is actually *prepared*, as currently mandated, to resume nuclear testing. To be clear, nuclear test readiness is not the same as conducting a nuclear test, just as maintaining a credible nuclear deterrent is not the same as exchanging intercontinental ballistic missiles. This article first provides an overview of nuclear testing and then outlines the challenges the United States would face to resume testing. It considers some general conditions that could prompt testing resumption and makes recommendations on how to improve nuclear test readiness.

Ready: The Requirement, Spectrum, and Current Status

Even though the US hasn't conducted a full-scale nuclear test since 1992, it retains a legal requirement to be ready to do so as spelled out in PDD-15. Crafted in the wake of decisions over the course of several US administrations to reduce and eventually stop any kind of nuclear testing, the PDD and associated safeguards frame the conditions under which future US leaders would consider a resumption of testing.[12]

The origins of the current test ban began in 1991 when Soviet leader Mikhail Gorbachev unilaterally declared a moratorium on the USSR's nuclear testing. In 1992, President George H. W. Bush followed suit, declaring a US testing moratorium. This was formalized in 1996 when President Clinton signed the Comprehensive Test Ban Treaty (CTBT). After a lengthy debate in the Senate, it rejected a resolution for ratification, technically leaving the door open for the US to conduct future tests. The US has, however, continued to refrain from testing.

PDD-15 also addresses the safeguards that were codified alongside nuclear treaties in an attempt to avoid strategic and/or technological surprise by an adversary. The genesis for the safeguards was a resumption of testing by the Soviets in 1961 that surprised the US.[13] Following the Soviet test, the Joint Chiefs conditioned their support for future nuclear treaties on an ability to resume testing should geopolitical and/or technological conditions warrant it.[14]

These safeguards have evolved over time, modified as various treaties were negotiated. Generally, they stipulate that the US maintain readiness in the following areas:[15]

- Safeguard A: to conduct underground testing or stockpile stewardship
- Safeguard B: to maintain laboratories and human scientific resources
- Safeguard C: to maintain the capability to resume nuclear tests prohibited by treaties
- Safeguard D: to conduct research and development to improve treaty monitoring
- Safeguard E: to develop intelligence programs to monitor nuclear programs of other nations

While all these safeguards are important elements of nuclear deterrence, Safeguard A relates explicitly to underground testing readiness. Attempts were made in 1997 and 1999 to adjust this safeguard by removing verbiage requiring a return to an "underground nuclear test program" and replacing it with scientific assurances based on the Stockpile Stewardship Program. However, the most recent set of safeguards—which were ratified by the Senate and remain legally binding—were contained in the Threshold Test Ban Treaty (TTBT) and the Peaceful Nuclear Explosions Treaty (PNET), both entering into force on 8 December 1990.[16]

In summary, the PDD and associated safeguards were put in place to ensure that regardless of the direction of the geopolitical winds of the period, the US would remain ready to resume testing. While nuclear testing is complex and nuanced, not all nuclear tests are alike. Rather, there exists a variety of testing options the US has used over time. Each of these options has tradeoffs regarding cost and complexity, as well as their own specific purpose.

A Spectrum of Nuclear Testing

Starting with the Trinity Test on 16 July 1945, the US has conducted a total of 1,054 nuclear tests—more than any other nation.[17] These tests spanned a wide spectrum, varying greatly in scope and purpose (see fig. 1). That said, most tests aimed at advancing the collective understanding of nuclear science and weapons design generally fell into one of two categories—Department of Energy (DOE) scientific tests or Department of Defense military tests. The vast majority of these tests were accomplished under the direction of the DOE or its predecessor, the Atomic Energy Commission. These tests tended to focus on gaining a better understanding of the science behind nuclear weapons. Less frequent, the DOD tests primarily focused on understanding whether stockpile weapons met military requirements for performance and safety.

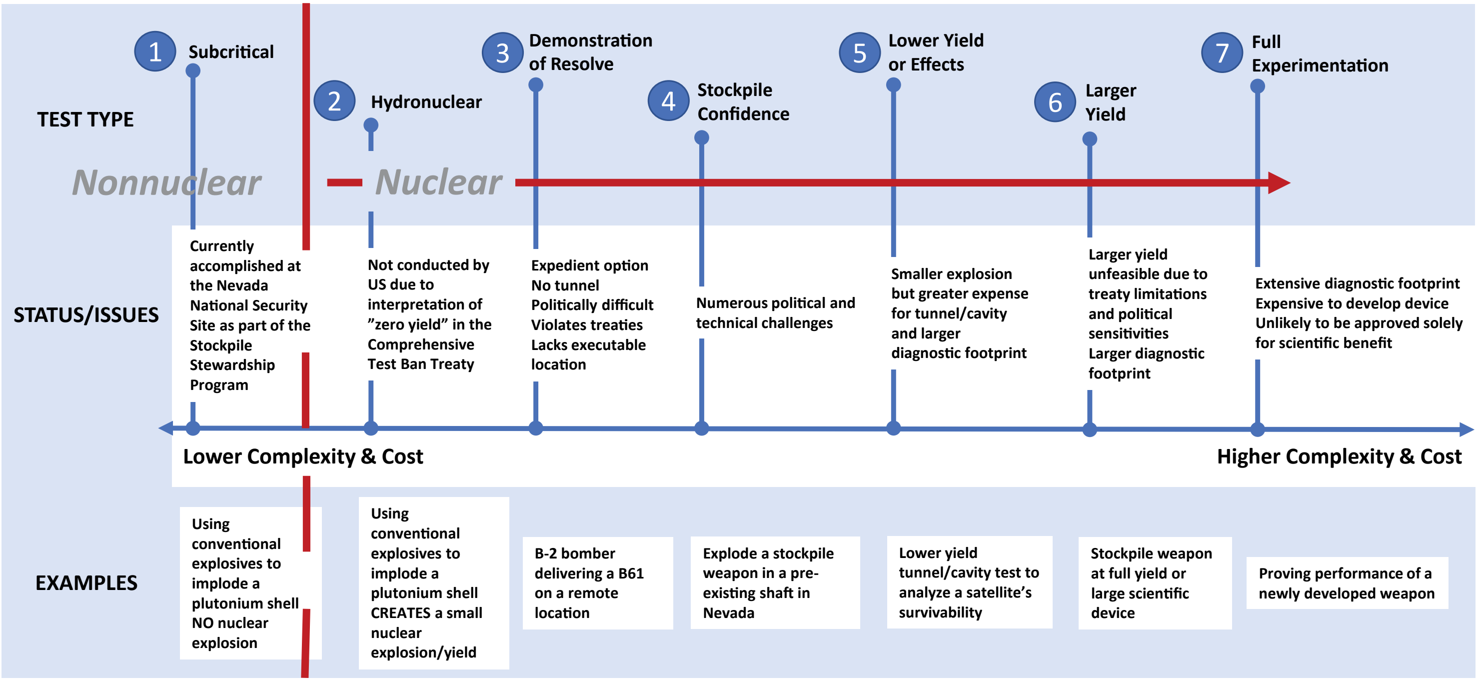

Figure 1. Testing Spectrum

The key takeaway from the testing spectrum depicted in figure 1 is that a resumption of testing involves more than simply "decide to test, conduct the test." Leaders must recognize that varying degrees of testing are available, consider what type of test is appropriate for the situation, and understand that the decision to move from left to right along the spectrum of testing requires a commensurate increase in preparedness, risk, cost, complexity, and national resolve.

Regardless of the sponsoring department or purpose, underground nuclear tests share three requirements: an emplacement site—typically a shaft, tunnel, or cavity to ensure containment of the radioactive products of the detonation, a nuclear explosive device, and a diagnostic suite capable of capturing data.[18] While all tests share these basic attributes, the complexity and cost of a given test varies greatly with the type of emplacement required, device tested, and scientific data captured.

As shown in figure 1, tests on the left end of the spectrum tend to be relatively simple and cheap to execute. Tests on the right—requiring more sophisticated devices, diagnostics, and emplacement—are generally costlier and more complex. When considering the tradeoffs associated with creating an emplacement site, drilling vertical shafts is typically less expensive than digging tunnels or hollowing out cavities in a mountain. Regardless of the type of test, any emplacement site must be designed to effectively contain its nuclear yield. Larger explosions typically require shafts, while tunnels or mined cavities are generally only able to accommodate smaller yields. Regarding the tradeoffs associated with devices, highly optimized and novel devices are more complex and costlier to test than proven designs. Finally, the costs and complexity of developing a proper diagnostic suite can vary greatly. It is difficult to develop equipment that is accurate enough to capture data transmitted over fractions of microseconds yet safe enough to ensure radiation doesn't leak into the atmosphere via the diagnostic tool.[19] A short discussion on each type of test in the testing spectrum follows.

Subcritical tests. These tests (as illustrated on the far left in the low-cost, low-complexity end of fig. 1) are still performed at the Nevada National Security Site (NNSS). Since they don't produce any nuclear yield, they don't violate any nuclear testing treaty and don't require containment.[20] These tests are key contributors to the science-based SSP.[21]

Hydronuclear tests. Increasing in complexity and cost are hydronuclear tests that generate minimal nuclear yields, typically less than the chemical energy released by the explosives used in the test.[22] These are not conducted by the US given how it interprets CTBT Article I language to preclude *any* nuclear explosion no matter how small—in other words, *zero yield*.[23] However, hydronuclear tests would facilitate an improved understanding of the behavior of plutonium relative to subcritical tests.

Demonstration-of-resolve tests. These show-of-force tests would most likely be used in response to a geopolitical event where speed of response is at a premium to deter an adversary from conducting further nuclear explosives testing, or more provocative measures. For example, a B-2 bomber could deliver a B61 thermonuclear weapon on the open ocean to demonstrate the US deterrent/assurance credibility to allies and adversaries. This kind of test would be relatively simple and comparatively cheap to conduct as it requires no emplacement site/underground footprint and little to no diagnostics, and it would likely use a stockpile weapon. Of course, the political barriers to actually conducting a test like this would be extremely high and may require the abrogation of the Limited Test Ban Treaty (LTBT), which "precludes parties to the treaty from conducting any tests outside their territory that would cause radioactive debris to enter the atmosphere."[24] Additionally, the lack of a suitable location to conduct an above-ground nuclear explosion would be extremely challenging.

Given these likely insurmountable issues, an underground test to demonstrate resolve *promptly* would be more likely. However, challenges to an underground test are hardly trivial. The major issue is location. While the NNSS offers an optimum location in terms of a preexisting holes and geographic suitability, it is no longer the relatively remote location it once was in the 1950s and 1960s. Las Vegas has grown considerably; the risks of testing in proximity to a large urban area and large military installations, such as Nellis and Creech Air Force Bases, would require considerable deliberation. Other potential underground test sites also pose significant challenges, discussed later in this article.

Stockpile confidence tests. These tests, designed to prove the performance of an aging stockpile weapon, would be similar to the underground demonstration-of-resolve test described above. A preexisting hole would be needed as would a stockpile weapon. However, to capture the required performance data (not a necessity when simply demonstrating resolve), a sophisticated diagnostic suite would be essential. These tests would also pose the same locational challenge described in the previous paragraph.[25]

Lower yield or effects tests. These tests would likely be conducted in a preexisting shaft or tunnel at the NNSS and require a larger diagnostic footprint than the stockpile confidence tests. Counterintuitively, lower yield tests may pose a higher risk of an unplanned release of radioactive gasses and thus a danger to nearby populations as they can be harder to contain than larger yield tests.[26] Effects tests tend to be lower yield and are usually exploded in a cavity or tunnel near an object of interest such as a satellite, aircraft, or another nuclear warhead. The scientific purpose is usually to determine how a nuclear explosion affects an object's (e.g., a satellite, an aircraft, etc.) survivability in a nuclear environment. Effects tests necessitate more sophisticated diagnostics and more expensive tunnels or cavities. Historically, these were usually conducted by the DOD utilizing a DOE supplied device.

Larger yield tests. For numerous reasons, these tests would have significant political constraints. Policy makers must not only consider whether to violate or abrogate treaty obligations to achieve a higher yield but also choose a test site with less risk of creating negative effects (e.g. environmental).

Full experimentation tests. Finally, on the far-right spectrum of testing, full experimentation tests could be the most expensive and complex of all testing options. Used to test a new device, they require a sophisticated diagnostic suite and possibly drilling a specialized hole to accommodate the test.

Leaders may find that given the current challenges within the nuclear enterprise, supporting and conducting any of the more complex, costly tests further to the right of the relatively simpler tests (e.g., the subcritical ones) could prove extremely difficult within the legally defined timelines of two to three years specified in PDD-15. And as with any major program involving significant organizational, technical, and political challenges, the costs are likely to be much higher than initial estimates. Table 1 shows a representative sample of historical tests that highlight some of the issues described in this section.

Table 1. Historical nuclear tests

Testing Spectrum	Test/ Event	Date	Type/ Location	Description
Subcritical	Rebound	2 July 1997	Underground at U1a, NNSS	First subcritical experiment after testing moratorium announced in 1992.[a]
Hydronuclear	Multiple series of tests	12 Jan 1960[b]	Underground at Los Alamos	First of eight tests in a series ending 11 February 1960. Tests were a series of safety experiments that identified then extant one-point safety problems and drove remedial action for the stockpile's safety features.[b]

Table 1 (*continued*)

Testing Spectrum	Test/ Event	Date	Type/ Location	Description
Demonstration of resolve	First operational combat use	6 Aug 1945 9 Aug 1945	Airdrop at Hiroshima, Japan Airdrop at Nagasaki, Japan	While not considered tests, one could argue that the two atomic bombings to end the war with Japan fit the definition. Two nuclear weapons that the US exploded over Japan ending WWII were not "tests" in the sense that they were conducted to prove that the weapon would work as designed (as was the first test near Alamogordo, New Mexico, on 16 July 1945), advance nuclear weapon design, determine weapons effects, or verify weapon safety—as were the more than 1,000 tests since 30 June 1946.[c]
Stockpile confidence	Multiple series of tests	1979–86*	Underground at various locations, NSSS	Seventeen tests (*including four tests from the early '70s, now called Stockpile Confidence Tests) were conducted on each weapon type; there were no catastrophic failures.[d]
Lower yield or effects	Huron King	24 June 1980	Underground at U3ky, NSSS	Tested radiation hardness of the then new DOD Defense Satellite Communications System. It was a combination Los Alamos-DOD test.[e]
Larger yield	Handley	26 Mar 1970	Underground at U20m, NSSS	One of the largest detonations conducted at NSSS. Test was part of 52 tests in Operation Mandrel, 1969–70.[c]
Full experimentation	Grabel	25 May 1953	Airburst at Area 5, NSSS	Test of Mk9 nuclear weapon from a 280 mm cannon.[c]

[a] "Nuclear Weapon Hydronuclear Testing," Global Security, Weapons of Mass Destruction, accessed June 2020, https://www.globalsecurity.org/.
[b] Robert N. Thorn and Donald R. Westervelt, *Hydronuclear Experiments*, Report LA-10902-MS (Los Alamos, NM: Los Alamos National Laboratory, February 1987), https://www.osti.gov/.
[c] US Department of Energy, National Nuclear Security Administration Nevada Field Office, *United States Nuclear Tests: July 1945 through September 1992* (Oak Ridge, TN: US Department of Energy, Office of Science and Technical Information, 2015), https://www.nnss.gov/.
[d] Kent Johnson et al., *Stockpile Surveillance: Past and Future*, Sandia Report SAND95-2751 (Albuquerque, NM: Sandia National Laboratories, 1996), https://www.osti.gov/.
[e] Glenn McDuff, *Underground Nuclear Testing: A Primer*, LA-UR-18-24015 (Los Alamos, NM: Los Alamos National Laboratory, 2019), https://permalink.lanl.gov/.

The Current State of Nuclear Test Readiness

Before examining the obstacles associated with being prepared to resume underground nuclear testing, it is important to review the positive attributes of the current testing posture with regard to the safety, security, and effectiveness of the nuclear stockpile. This status is best understood through the lens of the Stockpile Stewardship Program.

The SSP was authorized by Congress in response to the 1992 nuclear testing moratorium "to ensure the preservation of the core intellectual and technical competencies of the US in nuclear weapons."[27] Absent a program of underground testing, the nuclear enterprise had to leverage science in a novel way to gain a deeper understanding of "weapons design, system integration, manufacturing, security, use control, reliability assessment, and [*ultimately*] certification [*of the device*]."[28] Embracing its mandate forcefully, the SSP pioneered numerous scientific inventions and tools, some of which are one of a kind, to ensure the safety, security, effectiveness, and reliability of stockpile via "a combination of weapons surveillance (i.e., disassembly and identification of mechanical problems), nonnuclear tests, and computer modeling."[29]

The surveillance program. A major concern of the SSP is to address the advanced age of stockpile weapons. Given that the current stockpile weapons are considerably older than their initially designed shelf life, a cornerstone of the SSP is the surveillance program that monitors a weapon's health. This program employs some of the world's best scientists to better understand the effects of aging on all components within a weapons system—nuclear and nonnuclear. A main focus of surveillance is to understand how plutonium, one critical fissile material used to drive a nuclear reaction, would age and how this aging could affect a weapon's performance. Periodically, stockpile weapons are returned to the national laboratories to perform "weapons autopsies" to look for aging and other defects.[30]

Nonnuclear testing. Another fundamental component of the SSP is the requirement to conduct nonnuclear testing. These tests are primarily performed at the NNSS and national laboratories within the nuclear enterprise (i.e., the National Nuclear Security Administration) using some of the nation's most unique facilities and novel instruments. Test readiness events are a critical component within the nonnuclear testing arena. Scientists, on a fairly regular basis, engage in these events in Nevada to sharpen their skills.[31] These test readiness events are often guided by retired scientists, many of whom are the last of their discipline with firsthand nuclear testing experience. These events offer younger scientists a unique and fleeting opportunity to learn from true experts.

Recognizing that these experienced scientists will not be around forever, Los Alamos National Laboratory has created the National Security Research Center (NSRC) with the mission to archive, digitize, catalog, and make available 75 years of classified research materials. These include films, drawings, scientists' notes, and other documents to aid future generations' understanding of how to execute a nuclear test as well as a host of other information related to weapons design and so forth.[32]

Subcritical tests. "Subcrits" are another essential feature of the SSP. Conducted at NNSS underground facility U1a, these tests use high explosives to dynamically compress plutonium and model its behavior. To be clear, per executive order and in accordance with congressional direction, these tests never produce a critical mass.[33] In addition to the improved understanding gleaned from these experiments, these tests, like the nuclear test readiness exercises, serve as "the primary method of training the next generation of diagnosticians while at the same time exercising many of the fielding capabilities that would be used for an underground nuclear test."[34]

Dual-Axis Radiographic Hydrodynamic Test (DARHT). Complementing the subcritical experiments is Los Alamos National Laboratory's DARHT facility. The DARHT is a high-tech invention that provides a "rich suite of diagnostic measurements," allowing scientists to model the microseconds during a "weapon's crucial triggering phase" when the conventional explosives that surround the nuclear fuel are detonated. Aside from being one of the world's most powerful X-ray machines, the advanced data DARHT provides is second only to an actual nuclear test in understanding an implosion's progress.[35]

National Ignition Facility (NIF). Another important contributor to nonnuclear testing is Lawrence Livermore National Laboratory's NIF. The NIF has the distinction of being the world's "largest and most energetic laser facility ever built." Goals of the NIF mission are to pursue fusion ignition, improve scientific understanding across numerous disciplines, and help ensure the reliability of the nation's nuclear stockpile—without testing, which is of course fundamental to the SSP.[36]

Los Alamos Neutron Science Center (LANSCE). The LANSCE facility provides a linear accelerator producing neutron and proton beams and detector arrays for industrial and defense research.[37] A portion of those beams function in a uniquely developed science known as proton radiography (pRad), which "uses protons to take images of many of the materials in the physics package at pertinent times with high contrast. Proton radiography is especially well suited to studies of the movement of waves inside the explosives themselves." Proton radiography offers an enhanced capability (e.g., beyond X-ray radiography) to understand the underlying physics of what drives a nuclear explosion.[38]

Electromagnetic Environments Simulator (EMES) and the Z machine. Sandia National Laboratory is home to two unique machines that are able to test objects in extreme environments. The EMES is used to conduct susceptibility testing by sending electromagnetic waves through objects of interest and, to some degree, explores some of the same vulnerabilities as nuclear effects tests.[39] Likewise, the Z machine "provides the fastest, most accurate, and cheapest method to determine how materials will react under high pressures and temperatures."[40]

Supercomputing. Scientists use data from past nuclear tests, coupled with data supplied by SSP's surveillance and nonnuclear test programs, to simulate and hopefully verify results from extremely sophisticated computer codes used to model the behavior of nuclear weapons. These simulations run on some of the world's largest and fastest computers.[41] Programs such as Los Alamos's Advanced Simulation and Computing (ASC) Program develop simulation capabilities and deploy computing platforms to "analyze and predict the performance, safety, and reliability of nuclear weapons and to certify their functionality in the absence of nuclear testing." The codes developed by the scientists and processed by these computers serve as a key component to certifying effectiveness of the nation's nuclear stockpile.

The facilities, programs, and technology described above represent only a fraction of the numerous scientific tools used throughout the nuclear enterprise to support the SSP. The ability to model the extraordinary complexity of nuclear weapons systems is absolutely essential to the SSP, which is, after all, reliant on science and numerical simulation absent actual nuclear testing.

Interestingly, as explained by senior Los Alamos scientist Joseph Martz, it is somewhat ironic that the inability to test weapons and produce a nuclear yield has, in certain aspects, actually led to a better scientific understanding of how the weapons work. In the past, having a testing capability meant scientists did not need to understand all the details of a nuclear weapon to assess weapon performance. Dr. Martz also noted that while nuclear testing was a "unique and wonderful tool, it was also the world's biggest shortcut. The SSP has forced today's scientists to do their homework and model a device's physics and engineering at a much greater level of detail than in the past."[42] Since 1996, every director of each of the national nuclear security laboratories has signed 24 annual assessment letters to the Secretaries of Energy and Defense and the chair of the Nuclear Weapons Council. Every letter to date has reported that there was no need to conduct nuclear testing to maintain the certification of the warheads/bombs for which each laboratory is responsible.[43]

Set: Challenges to Resuming Testing

Referring to the testing spectrum in figure 1, the challenges generally become more complex for tests farther right on the spectrum. These challenges involve location, personnel, equipment, the regulatory environment, and organizational complexities.

A Suitable Location

This is certainly the most significant challenge in any decision calculus regarding a resumption of underground nuclear testing. On the surface, a return to the NNSS—with its dry soil, porous rock, and deep water table—seems the obvious choice as the deserts of southern Nevada are perhaps the world's best environment for conducting underground nuclear tests.[44] However, Nevada now has considerable disadvantages that didn't exist during the nuclear testing heyday. Specifically, the region's population boom makes the effects of testing potentially much more damaging and potentially hazardous than before. The greater Las Vegas metropolitan area, which had a population of 25,000 in 1951, blossomed to 700,000 inhabitants by 1992 when it hosted its most recent nuclear test. Since then, this growth has intensified as the area has transformed into one of the world's premier tourist destinations with a population of 2.7 million.[45]

In the past, tourists flocked to Las Vegas hotels and casinos to witness and feel atomic explosions. The DOE put seismometers on high-rise buildings, checked building plans, and maintained extensive files on buildings throughout the valley to monitor structural resiliency.[46] However, since the apex of Las Vegas "nuclear tourism" in the 1950s and 1960s, casinos have grown significantly taller, and the distance between the highly populated Las Vegas metropolitan area and the NNSS has shrunk considerably.[47] Given these factors, any further nuclear testing operations in southern Nevada, other than perhaps small (hydronuclear) or no-yield tests that reside on the left side of the spectrum in figure 1, are probably highly unlikely.

For many of the same reasons, other alternative locations would also likely be off limits. Historical test locations such as New Mexico, Alaska, Mississippi, and Colorado pose many of the same challenges to host testing as Nevada. Some experts view Amchitka Island in Alaska's Aleutian Island chain as a possible site given its past testing history and remote location. However, as the decades have passed since the last tests conducted there in the 1960s and 1970s, its infrastructure has decayed. The significant distance from the mainland would likely make test operations expensive, not to mention inconvenient.[48] The political challenges are probably even more formidable than the logistical ones. Amchitka Island is part of the Alaska National Maritime Wildlife Refuge, and the island still bears the scars from its 1971 nuclear test.[49] Given the known difficulties of performing activities like offshore drilling in nationally designated wildlife refuges, it is highly likely that any suggestion to conduct a nuclear test there would be politically dead on arrival.

Personnel

Given that the last underground nuclear test was performed over 25 years ago, the US lacks personnel—specifically geophysicists, physicists, and engineers with hands-on experience—to perform not only these tests but also some of the essential associated experimentation. At its peak, Los Alamos had approximately 4,000 people contributing to the test program, while the test site in Nevada employed 7,000 individuals.[50] With the reduced scope of nonnuclear tests, the number of people devoted to testing is a fraction of what it once was. According to Wendee Brunish, retired Los Alamos Containment Group leader and current chair of the Containment Evaluation Review, the most crucial loss impacting test preparedness is that "the expertise that allowed us to produce and evaluate containment designs has greatly diminished and will soon be almost non-existent."[51]

Equipment and Infrastructure

While 33 predrilled holes exist that could be used for an immediate test assuming they are still open and stable, the equipment required to safely conduct underground testing has atrophied severely.[52] The ability to emplace a rack or canister has been compromised as the large crane capable of handling this load was salvaged and the wire ropes and pipes required to lower the test device need pull testing to ensure viability.[53] While the remaining unused racks and canisters are helpful for instructional purposes, they may be of limited utility to conduct an immediate test as racks are developed specifically for each test and aren't interchangeable. The specially designed gas-blocked cables that prevent radioactive material from releasing into the atmosphere have been baking in the Nevada desert for almost 30 years, and there is no longer a manufacturer to supply replacements.[54]

Furthermore, the ability to manufacture the specialized expansive grout and epoxies used to form the plugs for the shaft that block rising debris would need to be reconstituted along with some of the diagnostic instruments used for ground motion analysis.[55] A major question would be whether to invest in new technology to aid in testing or whether it is more prudent to reconstitute proven, but antiquated, testing methods. In either case, a two- to three-year timeline to test would be a significant challenge given these issues.

Regulatory Environment

Known in DOE parlance as "authorization basis," the regulations that ensure worker, public, and environmental safety have expanded considerably since the early 1990s when the most recent nuclear test occurred. To resume nuclear testing in a timely fashion, these regulations would need to be thoroughly reviewed to ensure compliance or to determine areas requiring changes. Would the responsible parties be able to navigate this complicated but necessary regulatory environment within the time constraints posed by PDD-15?[56]

Organization

While the issues described so far are challenging in their own right, the organizational problems posed in planning and conducting a nuclear test are equally daunting. In nuclear testing, the sum of the parts required to execute a test is not equal to the whole of actually executing a test. According to the NNSA, functional test readiness is broken into at least 15 specialized areas: containment, security, assembly, storage and transportation, insertion, emplacement and stemming, timing and control, arming and firing, diagnostics, test control center activities, post-shot drilling, nuclear design, weapons engineering, test integration, and nuclear chemistry.[57] All these specialized areas either complement or are in addition to the aforementioned challenges in that they represent a unique level of complexity. In the words of one experienced Los Alamos nuclear tester, "a successful test requires developing the nuclear design, organizing the porta-potties for the test site, and everything in between!"[58]

While each of these entities can and does maintain its own capabilities through a variety of day-to-day work activities, exercises, and such, it's important to appreciate the organizational challenges that must be overcome to integrate these 15 specialties as part of an entire system to conduct an underground nuclear test. As explained by a Sandia National Laboratory scientist:

> By exercising all of the skills and capabilities required to design, test, qualify, and produce complete systems on a regular basis, those skills are ready and available to address higher-priority problems on a moment's notice. The complex must exercise all of the skills required, not just the science, modeling, and simulation skills, to have them available. These skills include but are not limited to a strong scientific foundation, systems analysis, engineering analysis, design definition, systems engineering, component design, test and evaluation, component production, and weapon assembly and disassembly. Like an athlete, you cannot exercise

> 20 percent of the skill base and expect to function at 100 percent on game day. You have to practice all parts of your craft or you will not be able to perform up to expectation when a problem arises unexpectedly.[59]

Questions of whether or not to resume underground nuclear testing are largely political and driven by geostrategic conditions. After almost 30 years since the end of the Cold War, and the consequent hiatus from conducting nuclear tests, the US has become desensitized to any situation that could warrant a return to Cold War–style nuclear competition. Moreover, the global war on terror consumed much of the United States' strategic thinking such that concepts like nuclear deterrence and assurance fell by the wayside for many years. Today it is difficult for America's senior leaders and the general public to imagine an environment where the nation might be compelled to conduct a nuclear test.[60] That said, history and surprise offer two broad areas to consider in thinking about the potential resumption of nuclear tests.

Getting to Go: Recommendations to Improve Test Readiness

Although the geostrategic environment is much different than it was during the Cold War, it provides some examples of periods when the US had to play catch-up in the world of nuclear science to maintain and/or ensure parity and consequent strategic stability with the Soviet Union. The Soviets first discovered that a high-altitude electromagnetic pulse (EMP) could have a catastrophic effect on electronics and were the first to develop special alloys in their weapons to counter those effects.[61] The US, previously unaware, was forced to quickly follow suit. Additionally, Soviet scientists were the first to recognize that the intense X-rays emitted from a nuclear explosion could be used to destroy a warhead's heat shield. Again, the US had to move expeditiously to return to the drawing board to protect its weapons from a phenomenon an adversary had discovered.[62] And perhaps the most compelling example of a historical lesson learned is the Soviets' sudden withdrawal from the testing moratorium in 1961. The Soviets went on to accomplish 57 tests in the remaining three months of the year, to include the history's largest detonation—the 55 megaton Tsar Bomba. The great difficulty the United States faced in the aftermath to generate a timely and equivalent response formed the basis for today's test readiness safeguards.[63]

Surprise comes in many varieties and, as the Cold War examples above illustrate, can catch a nation and its leaders off guard and unprepared. Black swans, grey rhinos, and pink flamingos are terms to characterize what former defense secretary Donald Rumsfeld called unknown unknowns (black swans), known unknowns (grey rhinos), and known knowns (pink flamingos). Furthermore, the adversary "gets a vote," and according to Nassim Nicholas Taleb who coined the term in his book by the same title, a black swan is perspective dependent. In other words, a black swan event may be "a surprise for a turkey but not a surprise for the butcher"—so the object should be to "avoid being the turkey."[64] The nuclear weapons certification process is highly complex, and although the national laboratories have not encountered a significant issue to call the viability of the stockpile into question, the US is still learning about the science behind plutonium aging and its associated impact on weapons components. In short, when it comes to the safety, security, and effectiveness of the nation's nuclear deterrent, the United States must have a plan to not suffer the same fate as the turkey. The US has several opportunities to improve its nuclear testing posture and at the same time prevent unexpected surprises.

Take Inventory

First, the US needs to assess exactly where it stands with respect to its test readiness posture (i.e., capabilities and deficiencies) and develop a plan for success. As discussed earlier, much of the material infrastructure, human capital, and specific organizational experience needed to resume testing has deteriorated or disappeared. While a lot of the hardware (cables, cranes, diagnostic equipment) no longer exists or needs refurbishment, more troubling is that the limited number of experienced scientists available to help develop, advise, and support the execution of a nuclear tests is diminishing with each passing year. Additionally, reviewing the regulatory environment's must-do's in advance could rapidly improve the timeline to return to testing. Finally, scientists and policy makers must work together to identify the "least bad" of all available testing site locations to avoid paralysis should a test become required. Taking this inventory of extant capabilities sooner rather than later, and developing a plan, will help mitigate the natural degradation of material, people, and experience over time.

Capture Corporate Knowledge

Perhaps the most time-critical aspect of developing an effective test readiness plan is to take measures to ensure that the hard-earned corporate knowledge on how to accomplish testing is effectively captured and cataloged. Some efforts, like the Los Alamos National Security Research Center's endeavor to digitize and catalogue the over 10 million historical documents in its archive, are a step in the right direction. Efforts like this should be copied and accelerated across the enterprise. Additionally, steps should be taken to interview the last generation of nuclear testing scientists to capture their technical expertise and lessons learned. Fortunately, many of these scientists, like the ones that took the time to inform this paper, are still passionate about their experience and national security. They are eager and honored to pass on lessons learned to the next generations. Adequately capturing today's corporate knowledge is critical—especially leveraging the human knowledge capital of older scientists and engineers with nuclear testing experience.

Leverage the Stockpile Responsiveness Program

As outlined in the 2018 *Nuclear Posture Review*, the Stockpile Responsiveness Program (SRP) is a congressionally mandated program "that explicitly directs that the US ensure the responsiveness and flexibility of our nuclear weapons infrastructure."[65] The SRP's goal is to improve resiliency and responsiveness "via the full life-cycle spectrum of nuclear weapons conceptualization development, design, manufacture, and retirement to face technological surprise and potential geopolitical shifts in the future."[66] One of the main ways the SRP accomplishes these objectives is to expose early-career staff to challenging problems under the guidance of experienced mentors. While the scope of the SRP is vast, if the program is properly funded and includes a sufficient focus on test readiness, the SRP will, according to Michael Bernardin, at that time the Los Alamos associate lab director for weapons physics, "provide the opportunity to grow the needed expertise to mitigate risk to national security."[67]

Rethink and Refresh the Arms Control Environment

Somewhat counterintuitively, a new look at arms control treaties may provide an opportunity to improve test readiness posture, avoid a "testing arms race," and enhance deterrence/assurance confidence. If major powers like Russia and China share similar concerns about weapons reliability, rather than "cheating" on existing treaties, they might find it advantageous to collaborate on an agreed-upon testing protocol.[68] For example, a relook at and fresh interpretation and specification of language in the CTBT could provide the opportunity to engage both Russia and China on arms control around an issue of mutual concern.[69] While unlikely, perhaps the nuclear powers might agree to a construct that would allow for a limited number of tests, under scripted scenarios, during a defined time horizon, and within a very specific definition of allowable yield (e.g., an extremely small, underground hydronuclear test). Doing so could allow participants a transparent and predictable option to gauge and reassess stockpile confidence and improve safety (nuclear surety). Additionally, this approach could reduce the risk of a "rogue defector" possibly triggering an all-out nuclear testing resumption. Reengaging collaboratively in an arms control environment with the major nuclear powers may further concrete steps to reduce stockpiles while retaining the proven concept of strategic stability as a bedrock to prevent a nuclear exchange of any kind.

Consider Hydronuclear Testing

The capability to conduct an extremely small yield (e.g., < 100 tons) nuclear test—a hydronuclear test—may offer the US advantages in several areas. Perhaps most importantly, it would provide a means to improve the safety, security, and effectiveness of the stockpile. As explained by a retired Los Alamos testing expert, "a little bit more yield can be a lot more useful" and may provide some reassuring insights into weapons performance.[70]

By allowing hydronuclear tests, other nuclear states—namely, Russia and China—might be induced into a new or revised arms control agreement. Advantages accrued to the parties in any potential agreement could relevel the playing field in terms of stockpile confidence and security. Parties would also have a transparent mechanism to avoid the geopolitical downsides of abrogating existing agreements and/or getting caught doing so.[71] This transparency will help to negate any asymmetric advantages that may currently exist (e.g., if, in fact, Russia and China have been cheating on existing treaties or understood nuclear testing norms). Furthermore, undertaking hydronuclear tests could be a key to opening some, but not all, of the "black boxes" that challenge the best science of the SSP. That is, it could eliminate or mitigate the black swans and/or grey rhinos that might otherwise remain unknown until a crisis occurs.

There is some historical precedent regarding the benefits of hydronuclear testing when it comes to safety. In fact, scientists conducted a series of hydronuclear safety tests in the late 1950s to clarify some of the puzzling results regarding one-point safety of certain stockpile weapons already deployed to the field.[72] These tests occurred during a critical time in the Cold War—a test moratorium initiated by the Eisenhower administration in late 1958. Calculations and hydrodynamic experiments were unable to resolve these problems, which turned out to be reflective of a critical safety design flaw for four weapon systems that had become operational in 1958.[73] The military halted production, and weapons handling procedures were severely constrained.[74] Los Alamos responded quickly with a proposal for a series of extremely small yield tests (i.e., hydronuclear) that could be conducted to help inform a solution to the safety problem. The administration approved; the series was conducted (within the constraints imposed by the testing moratorium); and within four months, the most urgent safety questions had been answered. Without these tests, the likelihood that the nation would field weapons that weren't one-point safe was much higher. In fact, had the nation mistakenly fielded nontested one-point safe weapons on the B-52 that crashed in Palomares, Spain, scientists estimated the chance of an accidental nuclear yield to be 1,000 times greater.[75]

Finally, if the Russians and the Chinese have been conducting their own hydronuclear experiments (that would violate the US understanding of language in the CTBT), a return to some kind of regime within which the US could conduct these tests would go a long way to eliminating any technical advantages (i.e., strategic superiority) our adversaries may have accrued by cheating.

Coordinate and Collaborate

During the period when the US conducted nuclear tests, the national labs—Los Alamos, Lawrence Livermore, and Sandia—were permitted wide discretion in determining how to perform them. This meant that each lab often took a different approach and adopted different specifications for racks, canisters, test hole dimensions, and other methodological differences. The labs could revive and review recommendations from the now defunct Joint Testing Organization to ensure coordination and collaboration if necessary. This would prevent unnecessary slowdown in the event that PDD-15, with its two- to three-year timeline, is executed. Related to lab-to-lab coordination (that should be easier today due to the establishment of the National Nuclear Security Administration), an assessment of the regulatory environment would help planning and improve timeliness. Given the more stringent and necessary safety and environmental concerns since 1992, a menu of options, key regulatory must-do's, and challenging issues could be identified and resolved ahead of time—avoiding paralysis should an administration order testing resumption.

Conclusion

The United States has continued to abstain from nuclear testing since 1992. Regardless of one's position on the merits or lack thereof when assessing a resumption of nuclear testing, the act of actually performing nuclear tests should not be confused or conflated with the nation maintaining a capability to do so as stipulated by presidential decision directive.

As nearly three decades have passed since the country's most recent nuclear test, it is easy to forget the origins and context that drove PDD-15 and the safeguards. Both were crafted and agreed upon by the executive and legislative branches of government to ensure that conditions to resume nuclear testing were maintained even under the most favorable of geostrategic conditions. Hard lessons from the Cold War were learned, and the safeguards were modified over time to reflect those lessons. As time has passed, these guideposts have faded from the collective consciousness. Yet these hard-earned lessons of past presidents, statesmen, and military leadership remain important reminders with respect to national security.

So too, in some sense, have the aspirations of global collaboration faded as nation-states return to mimic, in many ways, the great power competition of the late 1800s and post–World War I. A nuclear-armed Russia is challenging the European order, and China is attempting a revision to the rules-based international norms that have existed since the end of World War II. Both of these competitors have modernized their nuclear forces in earnest while the US capability aged and, in some respects, atrophied. Their aggressive modernization programs—conventional, nuclear, and nonconventional—that are underway across multiple domains threaten to upset the strategic stability prevailing since the end of the Cold War. These threats became clearer as events unfolded in Ukraine and the South China Sea, through destabilizing actions regarding US domestic politics, and with the creation of organizations that upset and offset long-standing international norms in the economic and technology sectors—to name just a few examples.

As a result, the US, specifically the DOD and DOE, have engaged in a massive effort to reconstitute the nuclear enterprise. Through the creation of Air Force Global Strike Command, a reinvigoration of the ICBM force, and a national security strategy that gives nuclear forces a seat at or near the head of the table, the nation's nuclear deterrent is on the road to recovery. Funds are being allocated to modernize the three legs of the triad, and a renaissance of strategic deterrence thinking is underway across government institutions, private sector think tanks, and in academia. The partnership between the DOD and DOE that can trace its roots to the Manhattan Project is being revitalized as both organizations collaborate even more deliberately on key nuclear national security programs like the SSP, SRP, Life Expectancy Program, Alts (alterations), gaming, modeling, and personnel exchanges such as the Air Force Fellows program across the national laboratories.

Many challenges remain as the US works to rebuild and improve the health of its nuclear enterprise and infrastructure. The DOE and DOD will deal with competing priorities as they attempt to modernize all legs of the triad and simultaneously rebuild and improve the material and personnel resources of the critical national laboratories. Test readiness posture may not make the cut in terms of the lengthy list of wicked problems facing the enterprise. However, the longer the nation waits, the more intractable this problem becomes.

The United States is at a crossroads on how to address its nuclear test readiness deficiencies. Perhaps the simplest path to remedy issues regarding test preparedness is to change the law. Replacing, revising, or rescinding the requirement for the US to be ready to resume nuclear testing could obviate the need for the enterprise to be prepared to test in a given time horizon. Taking this path would be akin to the Ford administration removing the costly requirement for the US to be ready to resume atmospheric nuclear testing. However, any decision to change the legal requirements for test preparedness should carefully consider the geopolitical, national security, and fiscal implications.

The alternate path is to resource nuclear test readiness appropriately and adopt the recommendations outlined here. Should the US choose this course, it must address the shortcomings surrounding current nuclear test readiness with a plan to conduct a test if directed. In a world defined by great power competition, the next emergency is likely just around the corner. The effects of black swans, grey rhinos, and pink flamingos become more consequential the less prepared the nation is for a surprise. The longer nuclear testing atrophies, the more the problem will have to be reframed as reinventing testing rather than resuming it. SSQ

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Notes

1. *Nuclear testing* refers to any test that would generate a nuclear yield, however small.

2. Los Alamos National Laboratory, "Nuclear Deterrence and Stockpile Stewardship," 6 April 2018, https://www.lanl.gov/. In 1994, Congress established the science-based Stockpile Stewardship Program, which combines advanced scientific and experimental capabilities with high-performance supercomputing to help scientists and engineers understand and resolve issues in the nation's nuclear deterrent. Los Alamos National Laboratory, "Nuclear Deterrence."

3. The Senate also passed 98-1, S. 1050, the FY2004 National Defense Authorization Bill, sec. 3133, directing the Secretary of Energy to achieve the ability to conduct a nuclear test within 18 months of a decision to test.

4. Randolph D. Moss, "Legal Effectiveness of a Presidential Directive as Compared to an Executive Order," Memorandum Opinion for the Counsel to the President, Office of Legal Counsel, Department of Justice, 29 January 2000, https://www.justice.gov/. Both an executive order and a presidential directive remain effective upon a change in administration unless otherwise specified in the document, and both continue to be effective until subsequent presidential action is taken.

5. The INF Treaty was signed in 1987 and was a landmark arms control agreement eliminating both the Soviet SS-20 and the US Pershing II mobile medium-range ballistic missiles.

6. Susan J. Koch, *The Presidential Nuclear Initiatives of 1991–1992*, Center for the Study of Weapons of Mass Destruction, National Defense University, Case Study Series 5 (Washington, D.C.: National Defense University Press, 2012), https://ndupress.ndu.edu/. The PNIs were declarations made by President Bush in the 1991–92 timeframe. While unilateral in nature, they were intended to seize the initiative in arms control and elicit reciprocity from his Soviet/Russian counterparts.

7. START built upon the INF in the sense that similar reductions of weapons were planned—in this case, ICBMs, SLBMs, and strategic nuclear-capable bombers. Additionally, components like the verification framework and counting rules were refined based on the INF experience.

8. Jonathan Medalia, *Comprehensive Nuclear-Test-Ban Treaty: Issues and Arguments,* CRS Report RL34394 (Washington, D.C.: Congressional Research Service, 2008), https://www.everycrsreport.com/.

9. National Security Council and National Security Council Records Management Office, "PDD-15 – U.S. Policy on Stockpile Stewardship Under an Extended Moratorium and a Comprehensive Test Ban, 11/3/1993," *Clinton Digital Library*, https://clinton.presidentiallibraries.us/. Signed by President Clinton on 3 November 1993, PDD-15 stipulates that the US must maintain a capability to resume testing and "a capability to conduct a nuclear test within 2–3 years . . . will be assumed by the Department of Energy."

10. Medalia, *Issues and Arguments,* CRS-6.

11. Jonathan Medalia, *Comprehensive Nuclear-Test-Ban Treaty: Updated "Safeguards" and Net Assessments*, CRS Report R40612 (Washington, D.C.: Congressional Research Service, 2009), https://www.everycrsreport.com/.

12. It is important to point out that a president can issue a new executive order or presidential decision directive with different stipulations that would supersede PDD-15.

13. Thomas Kunkle, *A Short History of the United States Nuclear Treaty Safeguard Program* (Los Alamos, NM: Los Alamos National Laboratory, 2004).

14. Medalia, *Updated "Safeguards" and Net Assessments*, app. A, 3. According to Medalia, "during the 1963 debate on the ratification of the LTBT [Limited Test Ban Treaty], the Joint Chiefs of Staff expressed concern that the treaty would lead to 'euphoria' and cause the United States to let down its guard against the Soviet Union," Medalia, 3 and app. A.

15. Medalia, app. A, 21.

16. Kunkle, *Nuclear Treaty Safeguard Program, 11*.

17. US Department of Energy, National Nuclear Security Administration Nevada Field Office, *United States Nuclear Tests: July 1945 through September 1992* (Oak Ridge, TN: US Department of Energy, Office of Science and Technical Information, 2015), xiii, https://www.nnss.gov/. This number is 50 percent more than the next closest country, the former Soviet Union with 715 tests. For a quick summary of tests, see Arms Control Association, "The Nuclear Testing Tally," fact sheet, accessed July 2020, https://www.armscontrol.org/.

18. Dr. Michael R. Furlanetto (deputy program director for the Office of Experimental Sciences, Associate Laboratory Directorate for Weapons Physics, Los Alamos National Laboratory, Los Alamos, NM), interview by author, 26 September 2019.

19. Wendee Brunish, *Containment of Underground Nuclear Tests: A Primer* (Los Alamos, NM: Los Alamos National Laboratory, 2014).

20. Test devices don't reach critical mass, which is the minimum amount of nuclear material needed to realize a self-sustaining chain reaction. Thus, while fissions occur because there is a convergent chain, these don't multiply because the system is subcritical and a self-sustaining chain reaction isn't possible. These tests conform with the US interpretation of language in the Comprehensive Test Ban Treaty, discussed later in this article.

21. Joseph Martz, "Detonation from the Bottom Up," *National Security Science Magazine*, July 2014, 3–14, https://www.lanl.gov/.

22. Furlanetto, interview.

23. US Congress, Senate, Committee on Foreign Relations of the United States, *Final Review of the Comprehensive Test Ban Treaty: Hearings before the Senate Foreign Relations Committee*, Statement by Ambassador Stephen J. Ledogar (Ret.), 106th Cong., 1st sess., 7 October 1999, https://www.govinfo.gov/. In testimony, Ambassador Ledogar, the chief US negotiator, stated unequivocally that zero yield meant exactly zero yield and that at the time, the negotiating parties to the treaty, including Russia, understood that language.

24. US Department of State, Treaty Banning Nuclear Weapons Tests in the Atmosphere, in Outer Space, and Underwater, 10 October 1963, https://2009-2017.state.gov/.

25. Kent Johnson et al., *Stockpile Surveillance: Past and Future,* Sandia Report SAND95-2751 (Albuquerque, NM: Sandia National Laboratories, 1996), 4, https://www.osti.gov/. Beginning in 1970, the DOD and DOE agreed to a formal series of underground tests of weapons withdrawn from the stockpile, called stockpile confidence tests. They differed from development nuclear tests in that the weapon was from actual production, had experienced stockpile conditions, and had minimal changes made to either the nuclear or nonnuclear components prior to the tests. Johnson et al., 4.

26. Wendee Brunish (retired Los Alamos Containment Group Leader and current chair of the Containment Evaluation Review, Los Alamos, NM), interview by author, 29 October 2019. The Baneberry test accident was an example of such a containment failure

that occurred in part due to its smaller yield, but also due to the test's proximity to fault lines and other geological features. See US Department of Energy, *United States Nuclear Tests.*

27. US Congress, House, Fiscal Year 1994 Defense Authorization Act, sec. 3138, 103rd Cong., 1st sess., 5 January 1993, https://www.congress.gov/.

28. Medalia, *Updated "Safeguards" and Net Assessments,* 5.

29. Los Alamos J-Division (Weapons Experiments), "Dual Axis Hydrodynamic Radiographic Test (DARHT): Validating Weapons Performance without Nuclear Testing," November 2018, 2.

30. Martz, "Detonation from the Bottom Up," 3–14.

31. Chris Bradley (senior scientist and Los Alamos member of the Containment Evaluation and Review Panel, Los Alamos, NM) and Garrett Euler (Los Alamos containment scientist, Los Alamos, NM), interviews by author, 5 December 2019. Scientists, on a fairly regular basis, engage in testing preparedness events in Nevada such as UNICORN (2005), SPE Phase I in Granite (2011–16), and SPE Phase II in Alluvium (2018–19) to sharpen their skills.

32. With an expert staff of research librarians and archivists, the NSRC houses the largest collection of national security and nuclear weapons documents in America. The center's collections encompass work produced not only at Los Alamos but across the nuclear enterprise in the DOE and DOD. Rizwan Ali (director, Los Alamos National Security Research Center, Los Alamos, NM), interview by author, 6 April 2020.

33. Martz, "Detonation from the Bottom Up," 11.

34. US Department of Energy, National Nuclear Security Administration, Nevada Operations Office, *Enhanced Test Readiness Cost Study*, DOE/NV-828 (Las Vegas, NV: DOE, National Nuclear Security Administration, 1 July 2002), 15.

35. Los Alamos J-Division, "Dual Axis Hydrodynamic Radiographic Test."

36. "What Is NIF?," Lawrence Livermore National Laboratory, accessed 22 January 2020, https://lasers.llnl.gov/.

37. "Los Alamos Neutron Science Center [LANSCE], Weapons Neutron Research Facility," Los Alamos National Laboratory, accessed 21 April 2020, https://lansce.lanl.gov/.

38. Martz, "Detonation from the Bottom Up," 12.

39. "Electromagnetic Environments Simulator (EMES)," Sandia National Laboratories, accessed 8 April 2020, https://www.sandia.gov/.

40. "Z Pulsed Power Facility," Sandia National Laboratories, accessed 8 April 2020, https://www.sandia.gov/.

41. Fred Mortensen (Los Alamos Fellow and Design Leader, Los Alamos, NM), interview by author, 25 April 2020.

42. Joseph Martz (senior staff scientist, Los Alamos National Laboratory, Los Alamos, NM), interview by author, 15 October 2019.

43. Sieg Shalles (director, Office of Stockpile Assessment, Los Alamos, NM), interview by author, 26 February 2020.

44. Bradley, interview.

45. John C. Hopkins, "Nuclear Test Readiness: What Is Needed? Why?," *National Security Science Magazine,* December 2016, 10, https://www.lanl.gov/; and "Las Vegas, United States Population, Population Stat, accessed 6 July 2020, https://populationstat.com/.

46. John C. Hopkins (former Los Alamos Laboratory associate director, responsible for Nuclear Weapons Program, Los Alamos, NM), interview by author, 8 October 2019.

47. Glen McDuff (Los Alamos research scientist, retired, Los Alamos, NM) and Keith Thomas (Los Alamos research scientist, Los Alamos, NM), interviews by author, 1 October 2019; and Glenn McDuff, *Underground Nuclear Testing: A Primer*, LA-UR-18-24015 (Los Alamos, NM: Los Alamos National Laboratory, 2019), https://permalink.lanl.gov/.

48. Hopkins, interview.

49. The 1971 Cannikin Test was one of the largest underground nuclear tests and, according to Greenpeace's website, was the impetus for its formation. Kieran Mulvaney, "A Brief History of Amchitka and the Bomb," Greenpeace, 25 August 2007, https://www.greenpeace.org/.

50. Hopkins, interview.

51. Brunish, *Containment of Underground Nuclear Tests*.

52. DOE, *Enhanced Test Readiness Cost Study*, 7, 16.

53. Hopkins, "Nuclear Test Readiness," 9.

54. All retired testing experts interviewed for this research highlighted the importance of gas-blocked cables and expressed concerns about the viability of the aged inventory and the ability of the nation to remanufacture replacements.

55. DOE, *Enhanced Test Readiness Cost Study*, 9.

56. DOE, app. E, 37.

57. DOE, app. F.

58. McDuff, interview.

59. Joseph Medalia, *Nuclear Warheads: The Reliable Replacement Warhead Program and the Life Extension Program* (Washington, D.C.: Congressional Research Service, 2007), CRS-31, https://fas.org/.

60. Nina Tannenwald, "How Strong Is the Nuclear Taboo Today?," *Washington Quarterly* 41, no. 3 (2019): 89–109, https://doi.org/10.1080/0163660X.2018.1520553. Tannenwald's idea of the "nuclear taboo" is related.

61. Houston T. Hawkins, "Rethinking the Unthinkable," *National Security Science Magazine*, December 2014, 14, https://www.lanl.gov/.

62. Hawkins, 14; and Office of the Under Secretary of Defense, *The Nuclear Weapons Effects National Enterprise: Report of the Joint Defense Science Board/Threat Reduction Advisory Committee Task Force* (Washington, D.C.: Defense Science Board, 2010), https://www.airforcemag.com/. In this 2010 study, the authors point out the need for renewed attention to nuclear weapons effects (e.g., EMP) vis-à-vis our nuclear enterprise. As pointed out in this report, weapons effects testing was a major portion of our underground nuclear testing program. The task force report suggests nuclear survivability (e.g., defensive measures to ensure continued operations in radiation environments) has declined.

63. Notable Los Alamos engineer and scientist Robert Osborne stated that "within 6 months of the moratorium the staff had dispersed to such a point that we had *completely* lost our ability to perform a comprehensive test (emphasis added)." McDuff, *Underground Nuclear Testing*, slide 66.

64. Nassim Nicholas Taleb, *The Black Swan: The Impact of the Highly Probable* (New York: Random House, 2007), 93–94.

65. Office of the Secretary of Defense, *Nuclear Posture Review, 2018* (Washington, D.C.: Department of Defense, 2018), 63, https://media.defense.gov/.

66. National Nuclear Security Administration, *Fiscal Year 2020 Stockpile Stewardship and Management Plan: Report to Congress* (Washington, D.C.: Department of Energy, 2019), 4-4, https://www.energy.gov/.

67. Michael Bernardin, Los Alamos associate lab director for weapons physics, *Review of the Hopkins-Sharp Paper on Stockpile Stewardship without Nuclear Testing*, Report LA-UR-18-29194 (Los Alamos, NM: Los Alamos National Laboratory, September 2018), 7.

68. The Defense Intelligence Agency (DIA) reported that there were concerns that Russia was cheating with regards to the CTBT by conducting hydronuclear tests. See "DIA Statement on Lt. Gen. Ashley's Remarks at Hudson Institute," Defense Intelligence Agency, 13 June 2019, https://www.dia.mil/.

69. Note the US (and others') CTBT status and "interpretation" of nuclear explosion in Art. 1 of the treaty.

70. Brunish, interview.

71. A State Department report asserts Russia has conducted nuclear tests and has concerns about China adhering to a "zero yield" standard. Department of State, *Executive Summary of Findings on Adherence to and Compliance with Arms Control, Nonproliferation, and Disarmament Agreements and Commitments* (Washington, DC: Department of State, April 2020), 7–8, https://www.state.gov/.

72. Robert N. Thorn and Donald R. Westervelt, *Hydronuclear Experiments,* Report LA-10902-MS (Los Alamos, NM: Los Alamos National Laboratory, February 1987), https://www.osti.gov/. "One-point" safety implies a nuclear detonation may not start "at any single point on or in the explosive components." In other words, if a bullet hits the weapon, it should not explode. Thorn and Westervelt, 3.

73. Thorn and Westervelt, 2.

74. Thorn and Westervelt, 4.

75. Thorn and Westervelt, 5.

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