Plutonium Pit Production

The Risks and Costs of US Plans to Build New Nuclear Weapons

HIGHLIGHTS

The United States is planning a $1.7 trillion overhaul of its entire nuclear arsenal, designing new warheads and investing in new bombers, missiles, and submarines to carry them. The new warheads, in turn, are driving demand for new plutonium "pits"—the bomb cores that begin the chain reaction in every US thermonuclear weapon—despite the fact that the United States has thousands of surplus pits in reserve.

Producing new pits would not only be expensive, time consuming, and logistically challenging, but is also technically unnecessary and politically destabilizing. It would actually decrease national security by encouraging a new arms race. In addition, a rushed program will likely increase health risks to workers and communities.

Science shows we can count on the reliability of existing plutonium pits. There are other ways to improve security without the risks and costs of producing new pits.

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Figures

Tables

Methods

Research was conducted using publicly available sources, including government documents, reports, and unclassified summaries of classified reports; peer-reviewed journals and other technical articles; news sources and books. Interviews were conducted with subject-matter experts for verification of details, implications, and other technical topics. All sources are cited where relevant.

About the Author

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List of Abbreviations

AoA	Analysis of Alternatives
ARIES	Advanced Recovery and Integrated Extraction System
CHE	Conventional High Explosive
CMR	Chemistry and Metallurgy Research
CMRR-NF	Chemistry and Metallurgy Research Replacement – Nuclear Facility
CNC	Computer Numerical Control (automated machining)
CPC	Consolidated Plutonium Center
DOD	Department of Defense
DOE	Department of Energy
DNFSB	Defense Nuclear Facilities Safety Board
DPAC	Defense Programs Advisory Committee
EA	Engineering Assessment
EBSD	Electron Backscattered Diffraction
EPA	Environmental Protection Agency
EEOICPA	Energy Employees Occupational Illness Compensation Act
EIS	Environmental Impact Statements
GBSD	Ground Based Strategic Deterrent
HE	High Explosive
HED	High Energy Density
HEU	Highly Enriched Uranium
HMX	High Melting Explosive (e.g., cyclotetramethylene tetranitramine)
ICBM	Inter-Continental Ballistic Missile
IHE	Insensitive High Explosive
JASPER	Joint Actinide Shock Physics Experimental Research
KCNSC	Kansas City National Security Campus
kt	Kilotons
kg	Kilograms
LAHDRA	Los Alamos Historical Document Retrieval and Assessment" project
LANL	Los Alamos National Lab
LEPs	Life Extension Programs
LLNL	Lawrence Livermore National Lab
MAR	Material At Risk
MIRVs	Multiple Independently-targetable Re-entry Vehicles
MOX	Mixed Oxide Fuel (facility)
MPF	Modern Pit Facility
NASEM	National Academies of Science Engineering and Medicine
NEP	Nuclear Explosive Package
NEPA	National Environmental Policy Act
New START	New Strategic Arms Reduction Treaty
NPT	Nuclear Nonproliferation Treaty
NIF	National Ignition Facility

NNSA	National Nuclear Security Administration
NNSS	Nevada National Security Site
PETN	Pentaerythritol Tetranitrate
PF-4	Plutonium Facility 4 (building 4 in LANL's Technical Area 55)
Pu	Elemental symbol for Plutonium
PULSE	Principal Underground Laboratory for Subcritical Experimentation
PUREX	Plutonium Uranium Reduction Extraction
QMU	Quantification of Margins of Uncertainties
RaLa	Outdoor explosive tests conducted at Los Alamos that employed radioactive lanthanum, referred to as "RaLa" experiments
RLUOB	Radiological Laboratory Utility Office Building
RNEP	Robust Nuclear Earth Penetrator
RRW	Reliable Replacement Warheads
RUS	Resonant Ultrasound Spectroscopy
SEM	Scanning Electron Microscopy
SLBM	Submarine-launched ballistic missile
SBSS	Science-Based Stockpile Stewardship
SRPPF	Savannah River Pit Processing Facility
SRS	Savannah River Site, South Carolina
SSP	Stockpile Stewardship Program
TATB	High explosive, triaminotrinitrobenzene
TEM	Transmission Electron Microscopy
WIPP	Waste Isolation Pilot Plant
XAFS	X-Ray Absorption Fine Structure
XRD	X-Ray diffraction

Foreword

Richard L. Garwin and Frank N. von Hippel

The plutonium-containing "primaries" of modern nuclear warheads are highly engineered and miniaturized descendants of the Nagasaki bomb.

Engineering the Nagasaki bomb was the main technical accomplishment at the Los Alamos Laboratory during 1943–45. It involved the implosion of six kilograms of plutonium metal to perhaps double its ordinary density for an instant to impede the escape of neutrons from the mass and thereby cause it to "go supercritical" with an exponentially growing fission chain reaction. That chain reaction fissioned a kilogram of the plutonium in a millionth of a second, releasing the energy equivalent of the explosion of 20,000 metric tons (20 kilotons) of chemical explosive.

The implosion mechanism around the 3.5-inch (9-centimeter) diameter sphere of plutonium included thick concentric shells of uranium and aluminum "tamper" material surrounded by an intricate array of chemical explosives designed to create the spherical ingoing shock wave that compressed the plutonium. The final bomb, including the tampers, explosives, and casing, had a diameter of five feet and weighed almost one thousand times as much as the small plutonium sphere at its center.

It was only natural that, during the Cold War arms race, the military would demand more compact weapons. Theodore B. Taylor, a legendary Los Alamos nuclear-weapon designer, recounted that, when he asked a visiting military officer what direction he would like the designers to push toward, the answer was "zero weight, infinite yield." Taylor did push the extremes of miniaturization, including an Atomic Demolition Munition with a variable yield of up to 1,000 tons of chemical explosive out of a package reportedly weighing 26.5 kilograms (0.0265 metric tons)—less than one percent as much as the Nagasaki bomb (Wikipedia n.d.a).

When today's thermonuclear warheads with tens of times the power of the Nagasaki bomb but less than one-tenth its mass were developed, miniaturized Nagasaki bombs served as their "primaries." The energy to implode their fission-fusion "secondaries" would be carried by the X-rays radiated by the hundred-million-degree temperature of the primary explosion. This energy-transfer mechanism created another reason for miniaturizing the primaries: the higher the temperature of the primary explosion, the greater the proportion of its energy that goes into X-rays.

Modern primaries are built around a "pit," a thin shell of inert metal containing a layer of plutonium.

The energy yield from the initial fission of plutonium in the pit is small by the standards of nuclear weapons—equivalent to hundreds of tons of chemical explosive—but the yield is "boosted" by fusion of a 50–50 mix of two gases, deuterium and tritium, injected into the cavity of the plutonium shell just before it is imploded. Deuterium is a stable isotope that makes up 0.015 percent of natural hydrogen, and tritium is a reactor-made hydrogen isotope that decays with a half-life of 12 years and therefore has to be periodically replenished.

When the temperature of the fissioning plutonium reaches about one hundred million degrees, the fusion reaction: D + T → helium + neutron proceeds rapidly, creating a burst of neutrons. A significant fraction of those neutrons fission additional plutonium in the imploded mass, "boosting" the yield of the primary from hundreds of tons to about ten thousand tons (ten kilotons) of chemical explosive equivalent. This increases the yield-to-weight ratio of the primary to over one hundred tons of explosive power per kilogram of weight, where the fraction of the energy going into X-rays is on the order of one half (von Hippel, Feiveson, and Paine 1987).

The plutonium pits in today's US nuclear arsenal were almost all made during the Cold War at the Rocky Flats Plant located between Denver and Boulder, Colorado. That plant was shut down in 1989 because of its releases to the environment of carcinogenic plutonium oxide from fires and outdoor waste storage, The shutdown appears to have been delayed until the conclusion of the Cold War nuclear arms race ended the demand for ever more advanced nuclear weapons.

Today, almost all of the pits in the down-sized US Cold War nuclear arsenal were produced between 1978 and 1989, i.e., 40 to 50 years ago. The warheads have been refurbished, but when the pits have been examined, their plutonium has been found to be "pristine" with no need for replacement. According to the only published estimate of the minimum longevity of the pits, the need for replacement pits still appears to be at least 50 years in the future (Hemley et al. 2007). Experiments with accelerated aging suggest that the mechanical properties of the plutonium in the pits will be good for at least another 50 years beyond that (Chung and Heller 2012), but despite repeated requests from Congress, the National Nuclear Security Administration (NNSA) has not published an updated overview of the pit-aging situation, leaving the field open for worst-case analyses.

In the meantime, the two US nuclear-weapon-design laboratories at Livermore, California, and Los Alamos, New Mexico, have been lobbying to be allowed to produce new warhead designs. The purpose of the 1996 Comprehensive Test Ban Treaty, which the United States has signed but not ratified, was to forestall the development of radically new warhead types such as the nuclear-explosion-powered X-ray laser proposed by Edward Teller, which helped inspire President Reagan's proposal to place weapons in space that could shoot down Soviet ballistic missile warheads before they could reach the United States—called "Star Wars" by its critics.

The nuclear-weapons designers' ambition today, however, is not to make new types of warheads but just primaries with additional safety and security features. They argue that these changes are within a "design space" that is well understood as a result of computer modeling based on previous nuclear testing and therefore will not require nuclear tests. They also cite their requirement to "continually exercise all capabilities required to conceptualize, study, design, develop, engineer, certify, produce, and deploy nuclear weapons" : (50 U.S. Code § 2538b). They ask, "How are we supposed to maintain that capability without exercising it?"

The main warhead safety improvement the weapon labs have been advocating is to replace those primaries in the active stockpile that contain conventional chemical explosive with primaries that contain insensitive high explosive.

The concern is not the possibility of an accidental nuclear explosion. All US warheads are already designed to not produce a nuclear yield unless the explosive is detonated symmetrically. Rather, the concern is about an accidental detonation of the chemical explosive that results in a dispersal of plutonium oxide, a powerful carcinogen if inhaled.

Plutonium dispersal accidents have occurred as a result of aircraft crashes and fires. They have never occurred with ballistic missile warheads, however, and, for more than 30 years, the US Navy resisted the redesign of its warheads because the heavier insensitive explosive would reduce the range of its missiles. Spaulding reports, however, that the Lawrence Livermore National Laboratory has developed new insensitive high explosives that have a reduced weight penalty (Pagoria 1998; LLNL 2018). Perhaps this has helped overcome the Navy's resistance.

The first new warheads the NNSA plans to produce are 800 W87-1 warheads for 400 US intercontinental ballistic missiles. US ICBMs already have enough W87-0 warheads with all modern safety features, including insensitive high explosive, for their current loading of one warhead per ICBM. The justification for producing 800 W87-1 warheads is to preserve the option of increasing the loading of US ICBMs back to three warheads, which US Minuteman III ICBMs carried during the Cold War. Maintaining that option is of interest because of the imminent expiration of the New START Treaty's limits on US and Russian nuclear warheads in February 2026 and China's nuclear buildup (CBO 2020).

Loading a larger number of nuclear warheads on US ICBMs would be a dangerous move, however, because the in-ground silos in which they are located are visible from space and therefore targetable. Increasing the number of US warheads that one attacking warhead could destroy from one to two or three would therefore increase pressure to launch on warning, an option Strategic Command adopted in the late 1970s, when it concluded (prematurely) that Soviet ICBM warheads had become accurate enough to destroy US ICBMs in their silos (Burr 2019).

George Lee Butler, the first commander of today's unified US Strategic Command (1992–1994), described the resulting pressure on the President to launch on warning if Strategic Command's leadership became convinced that there was an incoming attack on its ICBMs (Butler 1998):

> *We never said publicly that we were committed to launch-on-warning or launch-under-attack [as it is called by the Defense Department, which does not admit the possibility of false warning]. Yet at the operational level it was never accepted that, if the presidential decisions went to a certain tick of the clock, we would lose a major portion of our forces. That is, the U.S. would lose a part of the target coverage designed to limit damage or to destroy the Soviet Union. . . . Those [concerns] mattered absolutely to the people who had to sit down and try to frame the detailed guidance to exact destruction of 80 percent of the adversary's nuclear forces. When they realized that they could not in fact assure those levels of damage if the president chose to ride out an attack, what then did they do? They built a construct that powerfully biased the president's decision process toward launch before the arrival of the first enemy warhead. The consequences of deterrence built on massive arsenals made up of a triad of forces now simply ensured that neither nation would survive the ensuing holocaust.*

The assumptions on which a launch-on-warning decision would be based are likely simplistic (Steinbruner and Garwin 1976). Once a US strategic missile is launched, however, there is no way to redirect it or to command it to self-destruct. US ICBMs are provided with destruct systems when they are tested without warheads over the Pacific but not when they are armed. The reason is fear that somehow the destruct code might be stolen. This risk can be reduced to an infinitesimal level (Frankel 1990), but Strategic Command has not budged from its refusal to install a destruct system.

The danger of a mistaken launch on warning has led former Secretary of Defense William Perry and many others to argue that US ICBMs should be eliminated and that US ballistic missile submarines, hidden in the vast oceans, and strategic bombers armed with long-range cruise missiles, which could be returned to their Cold War take-off-on-warning posture in a time of high tension, provide an adequate deterrent (Perry 2016).

The leaderships of the US nuclear weapons establishment and its congressional oversight committees have a belt-*and*-suspenders psychology, and the absence of a US capability to produce new pits have made them extremely nervous. After a number of plans to build a new pit-production facility fell through, they decided to refurbish the plutonium facility at Los Alamos to produce tens of pits per year.

Then, when the NNSA's project to build a facility at its Savannah River Site in South Carolina to convert excess Cold War weapons plutonium into mixed-oxide (uranium-plutonium "MOX") fuel for reactors was cancelled by Congress due to huge cost overruns and delays, South Carolina's delegation, led by Senator Lindsay Graham, helped persuade the first Trump Administration to change the mission of the MOX building, on which $7.6 billion had already been spent, to pit production.

The cost of converting the 598-room facility into a pit-production facility has grown enormously, however, as its schedule has slipped. Spaulding reports that, in 2018, the NNSA estimated the conversion cost at $1.8 to $4.6 billion. By 2025, that cost had increased to $25 billion!

Meanwhile, the installation of pit-production equipment and the training of the workforce at the Los Alamos pit-production facility is nearing completion. The first "war-reserve" W87-1 pit was certified on October 1, 2024 (LANL 2024). Operating on a 40-hour-per-week schedule, the production line is designed to produce 30 pits per year.

Given the delay in the Savannah River production facility, the NNSA has announced that all the W87-1 pits will be produced at Los Alamos. Savannah River will produce pits for a second warhead type, the W93, a high-yield warhead that is planned to replace one of the two warhead types carried by US ballistic missile submarines—probably the relatively low-yield W76-1 (90 kiloton), which constitutes about 80 percent of the warheads currently available for US submarine-launched ballistic missiles.

The NNSA has also said that up to half of the W93 warhead pits could be recycled from dismantled Cold War warheads. If this is the case, why half and not all? The only new-design warhead with insensitive high explosive we are aware of that has been tested with a recycled pit is the W-89, a warhead for a short-range, air-to-ground attack missile that was cancelled at the end of the Cold War (Kidder 1991). No authoritative source has identified the warhead from which the pit was recycled, but an apparently knowledgeable anonymous source has identified it as the W68 (Wikipedia n.d.b), the warhead used on the Poseidon submarine, of which over 5,000 were built—more than enough to supply all the W93 pits.

Spaulding therefore questions the need for launching on a crash basis the installation of pit-production equipment in a building designed for a completely different mission and suffering extraordinary cost increases and delays as a result—a pattern that has become familiar for the NNSA. We find his argument convincing, but it may be rejected by Congress and the DOD driven by relentless pressure from the South Carolina congressional delegation to make up for the jobs lost at Savannah River due to the cancellation of the failed MOX production project.

As this report argues, what is required are a number of independent technical reviews with unclassified published summaries of:

- What the national weapons labs have learned about pit aging since 2006;
- The potential use of recycled pits;
- The prospects for retrofitting the 598-room MOX building to be a second national pit-production facility within the foreseeable future at a reasonable cost; and
- Whether moving away from tested pit designs could result in pressure to resume testing, with the other nuclear-armed states following suit, thereby losing the benefits of the Comprehensive Test Ban Treaty, described by President Clinton as "the longest sought and hardest fought prize in the history of arms control" (Clinton, 22 September 1997).

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Executive Summary

The US nuclear weapons complex is undergoing a significant transformation. Since the end of the Cold War, the core responsibility of the complex—the national laboratories and the industries that support them—has ensured the safety, security, and reliability of existing nuclear weapons. Now the United States plans a $1.7 trillion overhaul of its entire nuclear arsenal—newly designing warheads and investing in new bombers, missiles, and submarines to carry them. The new warheads, in turn, are driving demand for the weapons complex to produce new plutonium “pits,” the bomb cores that begin the chain reaction in every thermonuclear weapon in the US arsenal (see Figure 1).

The United States has not manufactured new plutonium pits in significant numbers since 1989 but has thousands of surplus pits in reserve from disassembled weapons. Not only is resuming production expensive, time consuming, and logistically challenging, but the United States clearly will not meet its ambitious goals for reviving this capability. Even more importantly, plans for nuclear modernization, associated pit production, and new nuclear warheads are technically unnecessary and politically destabilizing—and they decrease US security. Additionally, a rushed program will likely increase the risks to the workers and frontline communities who bear still unaddressed burdens from the production of nuclear weapons during the Cold War.

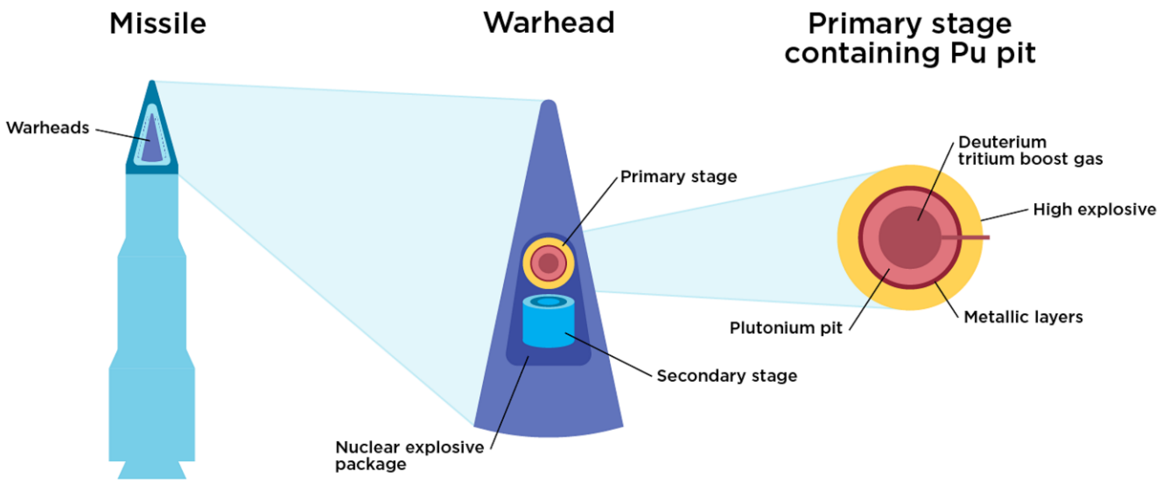
Several viable alternatives to the government’s plans would reduce risk and cost, increase safety, improve national security, and avoid fueling a new, multipolar arms race. The United States can achieve these goals without compromising the safety, security, and reliability of its existing nuclear arsenal. The scientific consensus on plutonium aging supports both the ongoing reliability and long service life of existing pits.

This report offers a comprehensive and critical examination of US plans for producing plutonium pits, including the history of pit production and a review of the current proposal to resume production. It explains the available science on plutonium aging, the rationales for the new production plan, and the potential human and environmental impacts. And it presents alternatives that would not require the proposed massive enterprise.

An Unnecessary, Unachievable Plan

Since 2015, Congress has mandated—and the Department of Energy’s National Nuclear Security Administration (NNSA) has been attempting to achieve—the production of at least 80 plutonium pits per year by 2030. Yet sustaining the current US nuclear arsenal requires no pit production at all.

Figure 1. Plutonium “Pits”: The Core of US Thermonuclear Weapons



Left: Intercontinental and submarine-launched ballistic missiles, among other delivery vehicles, can deliver one or more nuclear warheads. Center: The warhead’s nuclear explosive package contains materials that undergo nuclear fission and fusion, unleashing huge amounts of energy. Right: The plutonium pit is a hollow shell within the weapon’s primary stage. When imploded by high explosives, it drives fission reactions that set off the weapon; the nuclear chain reaction is what renders such weapons so destructive. Note: Diagram not drawn to scale. SOURCE: UCS.

While public rationales for the program often emphasize a need to replace aging pits, the national laboratories have offered no evidence that the nation’s existing pits are anywhere near the end of their service lives. Nor is the plutonium in those pits currently at risk of age-related failure that would reduce the safety, security, or reliability of present warhead designs. Moreover, the national laboratories can use existing capabilities to monitor any potential for aging effects without reviving pit production.

The NNSA has itself declared the goal of producing 80 pits per year by 2030 unachievable. Nonetheless, the United States is developing pit-production facilities at two locations: the Los Alamos National Laboratory (LANL) in New Mexico and the Savannah River Site (SRS) in South Carolina. Neither new facility is intended to sustain the existing US nuclear arsenal. Instead, the primary aim is to furnish pits for new types of nuclear warheads for deployment on land-based and submarine-launched missiles.

The barriers to the program’s success are formidable. Since the congressional mandate, Los Alamos has produced just a single pit certified for use (in 2024). Meanwhile, facility constraints, workforce issues, and a troubling accident history all challenge LANL. SRS, with an incomplete budget already surpassing $25 billion, is likely a decade away from producing even one pit.

The entire project is years into development and has a potential cost of tens of billions of dollars, yet there is no master schedule or official cost estimate. Congress has requested—but failed to require—such estimates before allocating more funding. The lack of rigorous oversight is particularly concerning because all previous efforts to revive pit production have failed and at enormous cost.

Dangerous to Communities, Dangerous for the United States

Rushing to meet an arbitrary, unnecessary deadline heightens the risks for the workforce recruited to carry out complex, hazardous plutonium processing. LANL's plutonium facility has a troubling record of recent safety violations, worker exposure to plutonium, and fires and floods. The program there appears to have prioritized expediency and cost-savings over safety. This endangers the workforce and the local community—as well as the program itself should a significant accident occur.

Pit production is resulting in LANL's largest expansion of workforce and infrastructure since the lab's inception during World War II. However, the NNSA's environmental impact assessments for the work there insufficiently address these sweeping changes, instead documenting impacts only after the fact and without adequately assessing potential future impacts. A federal court recently found the NNSA's assessment of its pit production efforts legally deficient and mandated a new analysis.

Meanwhile, frontline communities in New Mexico and South Carolina must reckon with the prospects of resumed pit production. At the same time, they continue to face the consequences of unremediated environmental contamination and harm from past activities for which there is little accountability, understanding, or reparation.

The risks extend beyond the two pit-production sites and their surroundings. Manufacturing plutonium pits increases the production and transportation of hazardous materials, waste, and weapons components (including plutonium) across the country. But the sole US repository for nuclear waste faces its own challenges and problematic safety history; it is unclear if it can accommodate the waste stream from pit production.

Nor can the true cost of new nuclear weapons be quantified solely in financial terms even considering the risks to workers and communities. The geopolitical cost of modernizing will reverberate for decades as the United States doubles down on its reliance on a nuclear arsenal, further stimulating an already accelerating arms race. Nuclear modernization is a choice, not a necessity. It is a choice that comes with substantial monetary, environmental, and geopolitical costs.

FIGURE 2. Sites Underway for Plutonium Pit Production at Los Alamos, NM, and Savannah River, SC

Left: A facility at Los Alamos National Laboratory in New Mexico is being upgraded to have the capacity to produce 30 pits per year. The 50-year-old facility has a troubling safety record and faces logistical and technical challenges to meet this mandate. Right: The Savannah River Site (SRS) in South Carolina is expected to produce 50 pits per year. It is partially completed, with a budget already exceeding $25 billion, and is likely a decade away from producing its first pit. SOURCES: Left, lanl.gov; Right; copyright © 2024 High & Low Flyer, reprinted with permission.

Alternatives for a More Secure Future

Fortunately, the nation has options that do not detract from the safety, security, and reliability of the existing nuclear arsenal—options that would eliminate the immediate need for pit production, reduce programmatic risk, and save billions. The United States could retain existing warheads, using its national laboratories' proven expertise in stockpile stewardship and in extending the lives of nuclear weapons. Without jeopardizing national security, the nation could keep to its policy of one warhead on each land-based missile or (preferably) eliminate its land-based missiles altogether. And it could reuse some of the thousands of surplus pits presently in storage. The nation could maintain pit production at an R&D level with existing infrastructure until (or even if) it becomes necessary for stewardship of the existing arsenal.

As a signatory to the Nuclear Nonproliferation Treaty, the United States is obligated to work toward nuclear disarmament. Alternatives to pit production can help the nation fulfill this obligation rather than move toward a dangerous and costly dependence on an existentially threatening technology.

Recommendations

Congress and the NNSA should limit plans for pit production to the minimum required for research and stewardship of the present stockpile. They should cancel plans for the Savannah River Site, which is still a decade away from production. The United States does not need to make any new pits to maintain a safe, reliable arsenal for decades to come, and plutonium aging is not a viable motive for resuming pit production at this time. Existing infrastructure can maintain technical capability and pit surveillance.

Before allocating additional funding for pit production, Congress should require integrated cost and schedule projections for the project, mandate a study on the reuse of existing pits, and prioritize ongoing studies of plutonium aging. It should eliminate the current goal of producing 80 pits per year.

To discourage a budding nuclear arms race and increase global security, the US should pursue alternatives to the nuclear triad of nuclear-armed strategic bombers and land- and sea-based intercontinental ballistic missiles. This would be in line with US obligations to work toward disarmament under the Nuclear Nonproliferation Treaty. Viable alternatives include eliminating the land-based missiles and cancelling programs for newly designed nuclear warheads.

The Department of Energy and the NNSA must place a higher priority on the safety and well-being of workers and frontline communities. They should remediate existing environmental harm and conduct transparent, comprehensive environmental impact studies that acknowledge the cumulative risks associated with pit production.

Chapter 1
Pit Production, Past and Present

> *"There now is no margin for further delay in recapitalizing the physical infrastructure needed to produce strategic materials and components for U.S. nuclear weapons. Just as our nuclear forces are an affordable priority, so is a resilient and effective nuclear weapons infrastructure, without which our nuclear deterrent cannot exist." – 2018 Nuclear Posture Review (Mattis 2018)*

> *"Of the few major [NNSA] projects that were successfully completed, all experienced substantial cost growth and schedule slippage." – Institute for Defense Analyses, 2019 (Hunter et al. 2019)*

Introduction

The US government is in the process of renewing the nation's capabilities for producing nuclear weapons as part of sweeping efforts to overhaul the nuclear weapons stockpile, along with the missiles, submarines, and bombers that carry those weapons. These changes, which have taken shape over more than a decade, represent a transformational change in US nuclear policy away from the post-Cold War trend of reduced reliance on the nuclear arsenal. The nuclear weapons complex—the laboratories, agencies, and contractors that study, build, and maintain nuclear weapons—is booming as activities to reestablish weapons-production capabilities take off.

This nuclear renaissance includes reestablishing the capability to manufacture all the components that make up nuclear warheads. Central to this are plutonium "pits"—the cores of modern thermonuclear weapons. Fission reactions from these cores trigger a warhead's more powerful thermonuclear yield. While many components of nuclear weapons have been routinely remade and refreshed through regular maintenance, the United States did not maintain its ability to manufacture plutonium pits in any significant quantity after the Cold War.

Past pit production has left an expensive and damaging legacy at Hanford, Washington, where the United States produced plutonium until 1987, and Rocky Flats, Colorado, where large-scale pit production ceased in 1989. Attempts to restart pit production have been chaotic: to date, all such plans have ultimately succumbed to political, financial, and logistical challenges.

The need for new pits and the associated urgency are a source of debate, and the rationales provided for new pits have varied. Concern over service life has been raised repeatedly as a justification for making new pits, yet scientific studies of plutonium aging show no indications that the current stockpile is at immediate risk. This report, which analyzes available unclassified literature on plutonium aging, concurs with the conclusion that pits should have lifespans on the order of a century or more.

Another frequently cited justification is the need for a "resilient" and "responsive" nuclear weapons complex. Many advocates for producing new pits express concern that the United States is incapable of reproducing all parts of our present arsenal, making the nation more vulnerable to potential technical deficiencies in the future.

In fact, neither concern is at the heart of new pit production. New pits are not to sustain the existing nuclear arsenal. Instead, for at least the first decade, new production is intended to make new warheads that differ from those in the existing US inventory.

To the extent possible, this report separates and distinguishes the technical issues from the political drivers behind pit production, even though these are often intertwined in the discourse around both the need and the urgency of the program.

At present, the US government is engaged in a crash program to meet a congressional mandate to produce pits at a rate that lacks justification—and that the agency responsible for the program, the National Nuclear Security Administration (NNSA), acknowledges to be unachievable. According to the Government Accountability Office, work is being pursued in parallel on two pit-production facilities without comprehensive cost projections and without a master schedule despite a decade of preparations. In addition to inhibiting sound decision-making and cost control, the current approach heightens the risks for all involved, including workers, the public, and the environment. The history of such efforts within the nuclear weapons production complex is cause for serious doubt about the possibility of successfully executing these plans.

The geopolitical ramifications of a significant investment in the infrastructure to build nuclear weapons and a return to producing new nuclear weapons may resonate for generations. As the United States doubles down on its reliance on nuclear weapons, it encourages other nations to do the same, signaling a failure of post-Cold War efforts to reduce the salience of nuclear weapons and the threat of nuclear conflict.

1.1 Background

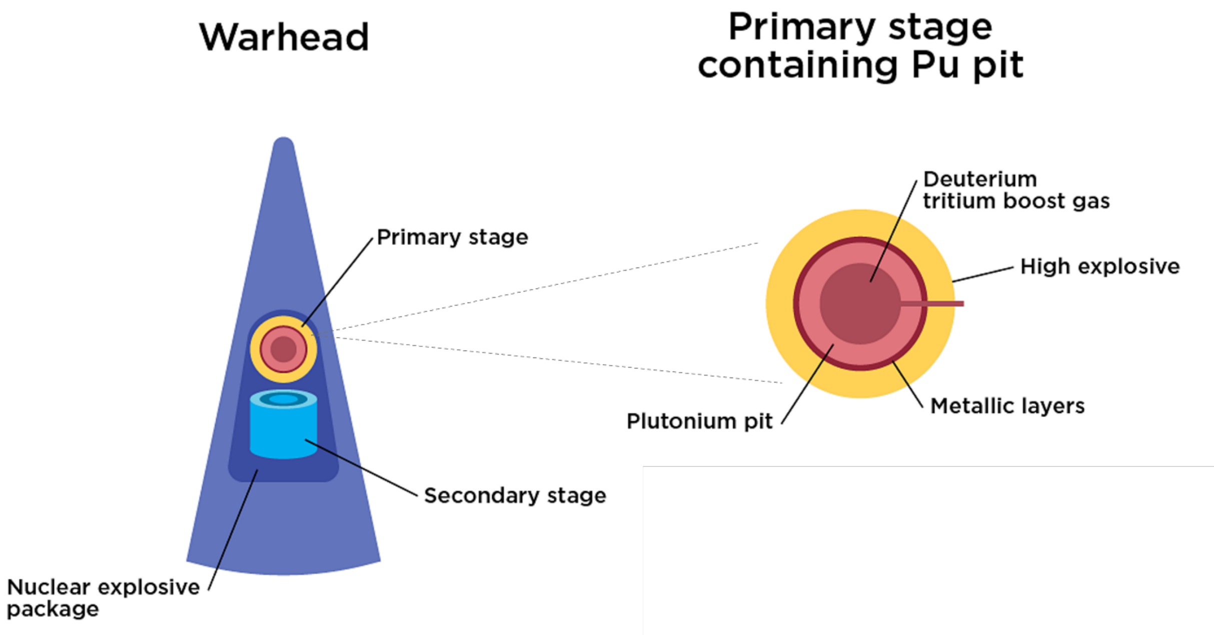
What Is a Plutonium Pit?

A plutonium pit is the nuclear component at the heart of all modern thermonuclear weapons. Often referred to as a "fission trigger" or the weapon's core, the term "pit" suggests its similarity to the pit within a stone fruit.

The pit is just one part of the primary stage of a two-stage thermonuclear weapon (Figure 1.1). It is surrounded by various other materials that may include metallic cladding and tamping layers, neutron reflective layers, a gas fill tube to introduce deuterium/tritium "boost gas," and an explosive shell that, when detonated, drives implosion of the assembly to a supercritical state and the fission of the material. The main job of the primary assembly is to generate X-rays that drive implosion of the "secondary" stage, from which most of the nuclear yield is derived via fission (about 50 to 80 percent) and fusion reactions (about 20 to 50 percent).

A diverse array of pit designs have arisen throughout the history of the US nuclear weapons program, particularly with the increasing introduction of safety and security features to the nuclear explosive package (AAAS/UCS 2012). These include design components that reduce the risk of accidental detonation or unauthorized use. For example, some measures preclude a nuclear yield should the surrounding high explosive detonate accidentally in an asymmetric manner (known as single-point safety). Other safety measures include fireproofing using vanadium coatings designed to contain the plutonium if exposed to high temperatures, which could melt it, and to reduce the risk of dispersal in the event of a severe accident during handling or transport (e.g., a jet-fuel fire following a plane crash). Further safety features outside the nuclear explosive package ensure that a nuclear weapon can only be triggered following a specific sequence of conditions during its trajectory.

Figure 1.1 A Notional Schematic of a Modern Thermonuclear Weapon



The primary stage of modern thermonuclear weapons contains plutonium. A shell of high explosive drives the hollow, spherical "pit" to a supercritical phase, generating neutrons and X-rays that implode the secondary stage, which contains uranium and fissile lithium deuteride. SOURCE: UCS.

The pits in the US stockpile are made of weapons-grade plutonium (Pu), meaning they contain more than 93 percent of the isotope ^{239}Pu alloyed with small amounts of gallium metal. The amount of plutonium in a pit varies by design but would typically be in the range of a few kilograms. The "Fat Man" bomb dropped on Nagasaki was a single-stage weapon (e.g., a plutonium primary fission weapon without a thermonuclear secondary) and contained about 6.2 kilograms of plutonium. In its relatively inefficient design, only about 19 percent of the plutonium contributed to fission, generating a yield equivalent to 21 kilotons of TNT. Modern thermonuclear weapons include primary and secondary stages, relying on both fission and fusion reactions to generate total yields ranging from several hundred to more than 1,000 kilotons (1 megaton). The primaries in modern weapons make more efficient use of plutonium; it is widely believed that many US designs contain on average about 3 to 4 kilograms.

A few older warhead designs in the arsenal employed highly enriched uranium known as "oralloy" (for "Oak Ridge Alloy") for the pit. Use of enriched uranium results in a much heavier weapon compared with plutonium designs, making it much less desirable for modern nuclear weapons, where minimization of both size and weight contributes to their capability.

The United States produced the pits in its current stockpile (weapons both deployed and held in strategic reserve) between 1978 and 1989, so they range in age from about 35 to 46 years old. Since 1989—i.e., the end of the Cold War—the United States has maintained its nuclear weapons through calculated refurbishment and life-extension programs. Thus far, these interventions have not included replacing the plutonium component; instead, they target components that have been found to degrade with time (e.g., seals, foams, batteries, certain electronic components) or, in the case of electronics, have been replaced by more modern designs.

What Is Driving the Push for New Pits?

While a number of factors drive the motivation for making new plutonium pits, the scope and urgency of the current program depend heavily on which factors dominate the choices made by the US government. Technical, political, and military motivations interact, presenting varying and often competing degrees of urgency, scope, and required timelines.

The reliability of the nuclear stockpile depends on the integrity of its components, and age-induced degradation of plutonium is a frequently cited concern that could lead to increasing uncertainty in performance margin. As Chapter 3 will discuss, this is unlikely to be a problem for many decades and can be mitigated up to a point. Other motivations include elective changes to the composition or size of the future stockpile or the production of new weapons designs. For the United States to "right-size" its approach to pit production, decisionmakers must consider a number of technical and bureaucratic choices, including whether to prioritize improving the reliability of existing weapons or the production of new designs, as well as determine how to meet the proposed demand realistically and safely while avoiding pitfalls that have crippled past large capital projects overseen by the NNSA (Hunter et al. 2019).

At present, the NNSA acknowledges that the purpose of new pit production is not to sustain the existing arsenal but rather to meet demand for two newly designed, newly manufactured warheads, the first since the end of the Cold War. Producing pits to replace those in existing weapons would not occur within at least the first decade of production, and those produced thereafter are expected to serve further new designs rather than to refresh existing ones.

Beginning in 2010, as part of the domestic political deal for Congress to approve the New START treaty, the United States embarked on a new era of nuclear modernization: replacing and upgrading the nuclear-capable bombers, missiles, and submarines that constitute the "nuclear triad." The NNSA plans for each of these delivery systems to receive a new warhead in the coming years. A warhead conceived for the ground-based intercontinental-range ballistic missile force is slated to receive only new pits, while another new warhead destined for submarine-based missiles may rely on a combination of new and reused pits. The United States has a reserve of between 15,000 to 20,000 pits from retired and disassembled weapons, many of which may be suitable for reuse, and which could potentially meet much of the demand. Production of all new warheads represents a significant change in strategy from that followed since the Cold War, which relied on maintaining warhead designs that had been created and tested prior to 1992.

It is well accepted that plutonium's natural radioactive decay results in some degree of physical degradation at the atomic scale, yet much of this damage reverses itself naturally. Even though the degree to which such changes may compromise a weapon's performance margins is debated, it seems unlikely that plutonium is the life-limiting component in any modern warhead. The NNSA argues that we can no longer wait to reestablish plutonium-pit production due to concerns over the service life of the current stockpile, but that implied urgency contradicts studies by expert panels commissioned by the US government and statements from the national laboratories charged with studying plutonium aging (Kramer 2023; Hemley 2006; Heller 2007).

Several such independent analyses of plutonium aging have been carried out, most recently in 2018 and 2019 by the Defense Programs Advisory Committee and the JASON committee (JASON 2019). Both assessments are classified, but it is known that both concluded that the NNSA had not adequately prioritized studies of plutonium aging since a first JASON assessment in 2006, which concluded that "most primary types have credible minimum lifetimes in excess of 100 years as regards aging of plutonium" (Hemley 2006; Bawden 2024a). This Union of Concerned Scientists (UCS) analysis concurs with that conclusion based on the available unclassified literature. Based on what is understood about plutonium aging, no new plutonium pits should be needed for the purpose of ensuring the reliability of the existing stockpile for decades to come.

However, the NNSA is charged with both ensuring reliability of the current stockpile *and* with positioning itself to meet future demand according to the US nuclear posture. The 2015 National Defense Authorization Act states, "Timelines for creating certain capacities for production of plutonium pits and other nuclear weapons components must be driven by the requirement to hedge against technical and geopolitical risk and not solely by the needs of life extension programs" (Levin and McKeon 2014). That statement echoes a concern that the United States has failed to maintain a sufficiently responsive nuclear infrastructure, regardless of the demands generated from stewardship of existing weapons.

Restarting plutonium-pit production carries significant implications, however. In particular, it would confirm the reversal of post-Cold War moves away from a reliance on nuclear weapons. By signaling that the nation intends to maintain its nuclear arsenal as a key part of its national security posture well into the future, the United States appears to contradict its obligations under the Nuclear Nonproliferation Treaty, which binds parties to not only a cessation of a nuclear arms race but also disarmament. Currently, all the states possessing nuclear weapons are expanding or modernizing their nuclear arsenals, heading to an incipient arms race limited only by international appetite for spending on increasingly deadly weapons. Current efforts to modernize nearly every part of the US nuclear triad are projected to approach $2 trillion dollars over the next 30 years and these costs are rapidly accelerating (Weiner 2024; Reif and Guzmán 2019; CBO 2017).

Restarting pit production at an unnecessarily demanding pace is putting enormous stress on the US nuclear enterprise, which does not bode well for successful execution. The NNSA will not meet its target on time, and to reach it at all—let alone to do it safely—will likely incur a ballooning price tag, additional time, and will require far greater oversight than has been the case to date. Proposals to renew plutonium-pit production have come and gone before—and they have always been deemed unnecessary, premature, too costly, or too complex. As with past efforts, current plans may face revisions, changes in scope, or even cancellation as choices are made to adjust the pit-production strategy to meet financial, logistical, technical, and public pressures. What is clear is that the current strategy faces severe risks and hurdles and is likely to prove oversized, premature, and destabilizing at home and abroad.

1.2 NNSA's Plans for Resuming Pit Production

A Two-Site Solution

Current US plans to achieve the capacity to produce 80 plutonium pits per year call for production at two sites—but not necessarily because it is impossible to produce that many pits at one site. More pits were produced per year at Rocky Flats during the Cold War, and previous efforts laid out plans to expand production at the Los Alamos National Laboratory (LANL) to make up to 450 pits per year (DOE 2003). A key rationale for having two sites is for reasons of redundancy. This is not a compelling argument for several reasons, and it almost certainly adds expense, given what we know from past studies and about the NNSA's ability to execute large projects.

The 2015 National Defense Authorization Act formalized requirements for the current pit-production effort. The act stipulated that the NNSA develop the capacity to produce no fewer than 80 pits per year by 2030, starting with 10 pits in 2024 and increasing the goal for each year thereafter (Carl Levin and Howard P. "Buck" McKeon National Defense Authorization Act for Fiscal Year 2015). The NNSA had stated in 2017 that the 80-pits-per-year requirement is "based on pit aging and directed military requirements" (NNSA 2017). However, the figure has been floated for more than 20 years in various documents, independent of specific programmatic requirements.

In May 2016, in response to the congressional mandate, the NNSA began an Analysis of Alternatives (AoA) for reconstituting pit-production capability, simultaneously preparing to produce up to 30 pits per year at LANL (NNSA 2017). The AoA considered numerous strategies for meeting the 80-pit goal, ultimately recommending further analysis of two possibilities, either of which would individually be capable of meeting the 80-pit mandate. One was to construct a new facility at Los Alamos, New Mexico; the other was to repurpose a partially constructed facility at Savannah River, South Carolina. In 2018, huge cost overruns and delays of the Savannah River facility had led to the cancellation of its previous mission after the investment of more than $7.6 billion (Box 1.1) (Sonne and Mufson 2018).

The Analysis of Alternatives was followed in 2018 by a mandatory, independent Engineering Assessment to analyze possibilities at both LANL and the Savannah River Site (SRS) stemming from the AoA (Parsons 2018). Notably, this assessment, operating under the assumption that LANL's existing facility would reliably produce 30 pits per year, considered how best to produce 50 pits per year by other means. Therefore, production of 30 pits per year at LANL was considered a foregone conclusion despite the fact that the AoA had not recommended this just months prior. In fact, *none* of the scenarios considered in the AoA relied on LANL's existing plutonium facility for long-term production; the AoA actually advised *against* it as well as against splitting production between LANL and another site. The AoA noted that doing so would “add long-term production risk and surveillance costs due to multiple production lines” (NNSA 2017).

The 2018 Engineering Assessment noted that LANL’s “preferred option” was indeed to rely on its existing facility as a “bridge” until the completion of new plutonium process modules adjacent to the existing facility (Parsons 2018). Nonetheless, the assessment concluded that repurposing the partially completed Savannah River facility provided the least risk and lowest cost when combined with production at LANL’s existing facilities. This split approach contradicted most of the reasoning in the AoA, which cited limitations with regard to the age and size of LANL’s facility as being disqualifying. Moreover, the approach contradicted LANL’s own proposal to construct newer pit-production modules to overcome these shortfalls.

In May 2018, the NNSA provided Congress with its chosen path forward, largely following the advice of the Engineering Assessment. The agency opted for a “two-site solution” for pit production: LANL would produce 30 pits per year with upgrades to its existing facility, and the partially built facility at Savannah River would be repurposed to produce 50 pits (Lord and Gordon-Hagerty 2018). The Nuclear Weapons Council deemed this decision consistent with the 2018 *Nuclear Posture Review*, which stated, “There now is no margin for further delay in recapitalizing the physical infrastructure needed to produce strategic materials and components for U.S. nuclear weapons” (Mattis 2018).

Each of the two chosen sites presents challenges and risks, however. Even as the benefits of redundancy and the impacts on future pit production capacity are yet to be realized, it is clear that the two-site approach must overcome severe obstacles if it is to provide the expected “enduring” capability.

Los Alamos PF-4 Facility, New Mexico

> *“The best analogy I can come up with is that we are overhauling and upgrading a plane during flight with a load of passengers on board” – Mark Davis, Associate Lab Director for Weapons production, Los Alamos National Laboratory (Carrier 2024)*

The Los Alamos National Lab produced the first pits to enter the US stockpile, starting with the one for the Trinity test in 1945 and including all pits produced until 1952, when production moved to the Rocky Flats plant located in Colorado between Denver and Boulder. Rocky Flats carried out industrial-scale pit production until 1989, when contamination of the environment with plutonium and other pollutants forced its closure and left the United States without the capability.

In 1996, the Department of Energy (DOE) issued a Record of Decision that assigned LANL sole responsibility for limited-scale pit production at its plutonium facility, called “PF-4” (for “Plutonium Facility, building 4”) in LANL’s technical area 55 (DOE 1996a). A modest “Plutonium Sustainment Program” there was intended to maintain functional expertise in plutonium handling and processing at a rate of no more than 20 pits per year. In actuality, this rate was never required, nor was it ever achieved. LANL did not produce a war-reserve pit (e.g., one that meets all specifications to be certified for the stockpile) until 2007; it produced a total of 31 pits between 2007 and 2011.

A combination of factors limited the scope of LANL's pit production, including not only a lack of demand but also the existing facility's several competing missions. The PF-4 building, which dates from 1978, is a 233,000 square-foot, two-story structure with a basement. The interior is divided into many smaller rooms, most of which are assigned to other tasks, so pit production can only occupy a fraction of the total space. At present, two other major plutonium missions occur at the facility: preparation of ^{238}Pu thermal batteries for space missions and ARIES (the Advanced Recovery and Integrated Extraction System), a process responsible for extracting 26.2 metric tons of surplus plutonium in various forms, including retired pits, for dilution and disposal by 2045 (a goal that will not be met based on current performance) (GAO 2019).

In 2018, the NNSA issued a conceptual plan to expand ARIES within PF-4 contemporaneously with expanded pit production, suggesting that up to 50 percent more space would be required, along with 200 new staff (NNSA 2021a). The Government Accountability Office (GAO) reported that ARIES had processed no more than 242 kilograms in a single year, and LANL reported that it hoped to produce 100 to 150 kilograms in 2022—much less than required to meet the 2045 target (GAO 2019; LANL National Security Science 2022). With pit-production needs likely stymieing any expansion of ARIES, that program faces an uncertain future. The idea of relocating ARIES has been floated; however, this would incur additional cost and the need to replicate engineering and administrative safety controls, which are immense for a plutonium facility.

Floorspace is not the only limited resource when trying to accommodate pit production alongside the ongoing ^{238}Pu work and ARIES. Nuclear criticality safety dictates that only limited quantities of plutonium be co-located (when stored or while being handled). Different isotopes (^{238}Pu vs. ^{239}Pu) present different health-physics risks for workers, often requiring different monitoring and different safety precautions. Storage and processing capacity in vaults and gloveboxes with limited space introduces further administrative and practical complications for adherence to nuclear criticality safety limits and safe operating procedures.

Scenarios in which pit production, ARIES, and ^{238}Pu heat-source work would all remain at PF-4 were deemed "high risk" in the 2018 Analysis of Alternatives due to the limited resources and inability for further physical expansion at the facility (NNSA 2017).

Nearby buildings in the same technical area, including the adjacent Radiological Laboratory Utility Office Building (RLUOB), do provide additional space for analytical chemistry and materials characterization but only on small quantities of plutonium. The maximum handling limit was recently revised from 38.6 grams up to 400 grams to satisfy requirements for pit production. To ensure that chemical and metallurgical standards are met requires a number of scientific capabilities—including radiochemistry, mass spectroscopy, electron microprobe, and other techniques—for both fundamental research and quality control throughout the production of pits. However, the RLUOB does not provide an alternative for expansion to relieve the competing processes within PF-4, nor can it become a production facility in the future. Other structures totaling 80,000 square feet are being constructed at LANL's TA-51 to provide additional staging and assembly workspace to prepare gloveboxes and other equipment for installation at PF-4 (LANL 2023).

Over the past 20 years, the NNSA has invested over $5 billion in PF-4 to upgrade the aging facility (Bawden 2023a). Many of these improvements were required to address safety issues and modernize capabilities for analytical chemistry and waste handling. Nonetheless, significant concerns persist about the building's ability to accommodate a significantly expanded, "enduring" (i.e., multi-decadal) mission. The building will be about 50 years old when it is projected to achieve its target rate of pit production. Further upgrades would represent challenging retrofits and, indeed, the NNSA has foregone some recommendations of the Defense Nuclear Facilities Safety Board for engineered safety systems. In other words, PF-4 will be unique in carrying out multiple hazardous processes, while lacking what are considered best-practices for modern nuclear facility design.

As early as 20 years ago, a LANL report recognized the complications of an aging facility. That study covered the potential expansion of PF-4 for a past proposal for pit production that was ultimately cancelled: "[T]he physical constraints of the existing facility limit the upgrade options, increase the cost of needed improvements (material handling, storage, ventilation, shielding, and power) and inhibit the introduction of improved manufacturing technologies. These constraints also reduce the opportunities for inclusion of new facility design approaches that can enhance production efficiency, reduce worker radiation exposures, and minimize safety and security risks" (DOE 2003). The same study noted, "[M]ajor modifications to an operational nuclear facility increase the risk of significant safety, contamination, or safeguards and security events during the transition period."

The 2017 Analysis of Alternatives eliminated PF-4 from further consideration as an "enduring" pit-production facility for many of the same reasons, stating "that continuing to rely on PF-4 for the Nation's enduring pit production capability presented unacceptably high mission risk" because "it will be problematic for PF-4 to support additional changes in nuclear safety risk tolerance, increased pit manufacturing activity, and higher capacity for [other plutonium missions]" (NNSA 2017). Such activities would require increasing the amount of plutonium considered at risk within the facility at any given time, and they would increase the potential for offsite dispersal of plutonium oxide in the event of a severe accident such as a fire following a seismic event.

Seismic events are indeed a potential hazard at Los Alamos, located in a region crisscrossed by numerous faults resulting from interacting geologic processes (Yellowstone Volcano Observatory 2023). The town and laboratory are situated on mesas formed from volcanic flows and ash that emanated from a large volcanic complex that now forms the Jemez Mountains and Valles Caldera. The region is sometimes referred to as the Yellowstone of New Mexico. Geologically known as a "super-volcano," its most recent eruptions occurred less than 100,000 years ago (exceedingly recent by geologic standards). Adjacent to Los Alamos sits the Rio Grande Valley, a rift valley.

Retrofits to PF-4 have improved its seismic resiliency, but the construction style lacks redundant structural safeguards. Failure of one component (e.g., roof girders, pillars) could trigger failure of adjacent ones, so there may be little margin between damage and collapse (Keilers 2014). Previous seismic analyses of the structure found that further retrofitting would be required were the facility expected to carry out a nuclear mission well into the future (Whittaker et al. 2015).

Some retrofits have been or are being completed, but, given the inherent hazards, the challenge of doing so in an active nuclear facility without interrupting the ongoing missions is extremely fraught. Mark Davis, Associate Lab Director for Weapons Production at LANL, said in 2023, “The best analogy I can come up with is that we are overhauling and upgrading a plane during flight with a load of passengers on board” (Carrier 2024).

Despite these many complications and concerns, the fact remains: as of 2024, LANL’s PF-4 was still the *only* US facility with any capacity to handle plutonium and to produce pits. The facility’s shortcomings appear to be outweighed by its uniqueness in this regard, and it has been accelerating its productivity in recent years. It produced four development pits in 2018 (NNSA 2022) and 14 in 2023 (Hruby 2024a); the first war-reserve pit was announced in October 2024 (NNSA 2024a). Tradespeople working on overnight shifts continue to install equipment, while day-shift plutonium workers continue with pit production—a scenario deemed “very high risk” in a 2019 independent assessment (Hunter 2019). Ongoing installation of equipment and an increasing production rate are expected over the next several years.

The NNSA qualified the risks at PF-4 as a potential “single point of failure for the majority of defense-related and nondefense plutonium missions within the United States” in 2020, given the facility’s age and physical limitations (NNSA 2020). The apparent concern over a single point of failure has no doubt contributed to the choice to pursue a two-site approach, but even that approach continues to rely on LANL for 30 pits per year (with all of its faults and associated risks) into the indefinite future.

Figure 1.2. Sites Underway for Plutonium Pit Production at Los Alamos, NM, and Savannah River, SC

Left: A view of the Plutonium Facility, building 4, at Los Alamos, known as PF-4 where the NNSA is striving to make 30 pits per year. Right: A view of the former MOX facility at Savannah River, South Carolina, now being refurbished to produce 50 pits per year. SOURCES: Left, lanl.gov; Right; copyright © 2024 High & Low Flyer, reprinted with permission.

Savannah River Site, South Carolina

The NNSA’s second site to achieve the remainder of the 80-pit-per-year mandate is a similarly (if not more) challenging facility at the Savannah River Site (SRS), in South Carolina, a DOE facility that covers 310 square miles along the Georgia border. Ground was broken for the Savannah River Pit Processing Facility (SRPPF), in 2007—but for an entirely different purpose.

Often referred to as the “MOX Plant” (for Mixed Oxide Fuel), what is now known as the SRPPF was originally conceived to convert excess US plutonium into fuel for commercial power generation in nuclear power plants, making use of the radioactive legacy of the Cold War for energy rather than weapons (Box 1.1). The MOX project faced delays and huge cost overruns before its cancellation in 2018—after the investment of more than $7 billion in a structure originally estimated to be completed in 2007 at a cost of $1 billion. This decision came just as the NNSA was being tasked with identifying how and where to produce 80 pits per year.

The NNSA justified the choice to repurpose the MOX plant based on its design, which includes the seismic qualifications required of a nuclear facility. The site also benefits from existing infrastructure and support facilities at the SRS, which produced plutonium in reactors through much of the Cold War. However, unlike Los Alamos, the SRS has no history of producing plutonium components for weapons, no associated workforce, and no facilities for analytical chemistry or materials characterization. Moreover, the project is starting with an extremely complex, partially constructed building that was designed for a different purpose. Because of these deficits, particularly the lack of prior experience with plutonium foundry (casting) or machining, a 1998 report considered the SRS a “weak candidate” to assume responsibilities for pit production when the Department of Energy was considering how or whether to replace Rocky Flats (Moniak 2023).

According to the NNSA, the SRPPF is a particularly challenging candidate for refurbishment. While the main process building is sizeable—a 500,000 square-foot, three-story structure with thick, reinforced concrete walls—none of its 598 rooms are large enough on their own to contain the entire pit-production line (Dayani 2010). Because plutonium must remain within the confines of specially designed gloveboxes through most of the pit-production process, systems of conveyors and dollies move material between workstations along the glovebox line. The complicated architecture of the MOX plant means that process lines will be segmented, with operations occurring on multiple floors, requiring an elaborate version of dumbwaiters and conveyors to move material up, down, over, and through the thick, already constructed and reinforced concrete walls and floor slabs. According to the 2018 Engineering Assessment that recommended the SRPPF, “[C]onveyance will have to connect all process areas and the operations support areas,” which were envisioned at the time to reside on three separate floors (Parsons 2018). The LANL’s PF-4 facility also requires conveyance systems between gloveboxes, but its pit-production line is relatively consolidated on a single level.

The conceptual design phase for the SRPPF ended in 2021. By the summer of 2024, contractors had stripped out 2,535 gross tons of equipment, materials, and building components, including duct work, previously installed gloveboxes, tanks, conduit, and other building systems incompatible with pit production. None of the material had ever been used for its intended purpose (Nuclear Newswire 2024). In October 2024, project officials claimed that design for the pit-production facility was about 60 percent complete and indicated that construction could begin as early as December 2025, pending approvals (ExchangeMonitor 2024a). The Defense Nuclear Facilities Safety Board, an independent agency responsible for monitoring conditions at DOE facilities, has expressed concerns that some choices do not adequately prioritize worker safety. The board cited the assertion of personnel overseeing the project that human senses can adequately protect against the invisible, odorless, and tasteless effects of radiation rather than following conventions for what constitute “safety significant controls” (Connery 2023).

The fact that facility design and construction are occurring simultaneously results in considerable uncertainty regarding both the schedule and cost estimates, both of which already deviate wildly from the estimates used for site selection. Such practices have led the Government Accountability Office (GAO) to include the NNSA’s acquisition and project management on its “high risk” list (GAO 2023a). Nearly 10 years after the 2015 pit-production mandate, the NNSA has produced neither an integrated schedule nor a cost estimate for the overall endeavor (GAO 2023b). The complexities involved in refurbishing the SRPPF are one of the dominant contributors to this ongoing lack of transparent forecasting.

Jill Hruby, NNSA administrator from 2021 to 2025, has stated that the agency is working aggressively to finish construction of the SRPPF by 2032 (Hruby 2024b). However, the FY2023 performance evaluation report for the Savannah River Site criticized the contractor, Savannah River Nuclear Solutions, LLC, for “less than adequate design integration, management and quality design outputs that continued to impact the schedule” and “untimely resolution of . . . technical and project management deliverables,” resulting in the project’s falling further behind schedule (NNSA 2023).

Worker shortages, both for construction and for eventual plutonium processing, is another complication that is especially acute for the SRPPF. Throughout the US nuclear weapons complex, there is an urgent shortage of skilled trades, resulting in competition for staff qualified to work in nuclear facilities; this contributes heavily to schedule uncertainty (Edelson 2021). Construction of new nuclear reactors at Plant Vogtle (12 miles away from the SRS) required 9,000 workers at the peak of construction, creating its own local competition (Cline 2020). In 2023, the GAO noted that only about 75 percent of the planned number of engineers were assigned to the SRPPF, compounding delays in design and construction (Bawden 2023b). As for production processes, workers trained in plutonium metallurgy, specialized machining, and associated analytic work are virtually nonexistent. Those who conducted such work during the Cold War are, for the most part, no longer in the workforce; therefore, a new workforce must be cultivated.

In response, both LANL and the SRS sponsor training at local community colleges. These programs offer certificates in radiation technology, health physics, and “nuclear fundamentals,” the latter of which involves an eight-month program and apprenticeship to become a “production operator” (Carter and Cox 2024; ExchangeMonitor 2024b; NSS Staff 2021; Northern NM College 2024). At the SRS, training includes the Savannah River Plutonium Modernization Program, which is intended to foster workforce development for an estimated 1,800 employees and provide ongoing training once the facility is operational (SRS n.d.). Part of the construction includes an onsite Training and Operations Center where trainees can manipulate non-radioactive samples in “cold” gloveboxes.

These programs are not without controversy, including the question of whether the minimal academic preparation they provide is sufficient for the risks assumed by would-be employees (Guzmán 2023). Long-term retention of a newly minted workforce will be key to the project’s success, but this has been a challenge for the NNSA and its contractors responsible for operating its sites (Bawden 2024b). This is partly due to increasing competition from private industry and the burgeoning tech industry, as well as a fundamental lack of training in associated areas in most academic environments.

Thus, despite the fact that the cancelled MOX facility, a structure designed for a plutonium mission, may have seemed superficially attractive for producing plutonium pits, it faces many cumulative challenges to being fit out for that purpose. The inability of the NNSA to successfully execute the building's originally proposed mission to produce MOX fuel adds an additional degree of doubt as to whether pit production is on track for a similar fate.

Box 1.1. The Mixed Oxide Fuel (MOX) Plant: The Plutonium Facility That Wasn't

Aerial photography showing construction of the MOX Fuel Fabrication facility in September 2012. SOURCE: Wikimedia Commons.

The proposed pit-production facility at Savannah River, South Carolina, will occupy a building originally constructed to produce "Mixed Oxide" (MOX) fuel—a process that was intended to blend excess plutonium in the US stockpile with uranium and yield fuel suitable for energy production in commercial nuclear reactors (Toevs 1997). In an about face from this "swords-to-ploughshares" approach, the facility is now slated to convert legacy plutonium pits into weapon-ready pits for new nuclear weapons.

Formerly known as the MOX plant, the facility is a source of significant controversy. Ground was broken in 2007 for the building, and it was expected to begin its mission by 2016 at a cost of $4.9 billion. In 2016, the DOE estimated completion could take until 2048 at a potential cost of $17.2 billion (DOE 2016). Up to 25 percent of the construction work was done incorrectly, requiring rework by the contractor (Rogers et al. 2015; Lyman and von Hippel 2015). The life-cycle cost of the facility had risen to an estimated $47.5 billion by this time—up 60 percent from just a year before and 25-fold since the project's 2002 approval (UCS 2015).

Hobbled by these difficulties, the program was cancelled by the Trump administration in 2017 after more than $7.6 billion had been invested in the incomplete carcass of a building (Sonne and Mufson 2018). Tons of plutonium were left stranded at Savannah River, becoming the source of a lawsuit between the Department of Energy and South Carolina.

Meanwhile, the benefits of the MOX program had been continuously called into question on numerous grounds, cost being only one. Other means of disposing of excess plutonium were deemed less expensive (*World Nuclear News* 2018) and to pose less risk of proliferation through loss or theft of material (Lyman 2014; Lyman and Von Hippel 2015). There was also a lack of commercial customers willing to accept the fuel.

Shortly after the cancellation of the MOX project, the decision was made to repurpose the partially complete facility to produce plutonium pits. The projected cost for the new mission was $3.7 billion (NNSA 2017). Retrofitting the incomplete building for another purpose is an extremely difficult task and its construction makes it difficult to accommodate different types of equipment, including new gloveboxes and safety and security systems. In July 2024, the Department of Energy announced that demolition and removal of billions of dollars of equipment installed for MOX (2,535 gross tons of unused materials) had been completed (*Nuclear Newswire* 2024), allowing retrofit to proceed to the next stage. The NNSA expects the facility to begin handling plutonium in the early 2030s, but the projected cost has already grown from $3.7 billion in 2017 to as much as $25 billion as of 2024 (NNSA 2017; Hruby and Granholm 2024), seemingly repeating the same ill-fated history that doomed the MOX project.

At the same time, the fate of excess plutonium remains undecided (GAO 2019; Moniak 2024). Dilution-and-disposal seems the most likely method of getting rid of it, but the process has yet to find a definite home among the possible DOE facilities. This raises a further issue: any plutonium disposition likely competes with the pit-production mission for space, funding, and workers, either at Los Alamos (where the ARIES project has been doing this work on a limited basis) or at Savannah River, perhaps as part of a future pit-production plant (Moniak 2023).

Regardless of how or when excess plutonium is treated for disposal, it then adds to the considerable waste stream that must be accommodated at the nation's only nuclear waste repository, the Waste Isolation Pilot Plant in southern New Mexico.

A Cross-Complex Effort

Although the NNSA's chosen approach to pit production is often discussed as a "two-site solution," it actually involves most of the DOE nuclear weapons complex in some way (Figure 1.3). Production of the pits themselves is expected to occur at LANL and the SRS, but the plutonium that will be recycled into new pits is stored at the Pantex Plant near Amarillo, Texas (Box 1.2, "The Pit Production Process"). The Lawrence Livermore National Lab (LLNL) in California plays a role in certification as the principal design lab for the warhead that will receive LANL pits. Meanwhile, the Kansas City National Security Campus provides non-nuclear components for primary assembly, and the Nevada National Security Site conducts laboratory and subcritical experiments as part of pit qualification and design. New Mexico's

Waste Isolation Pilot Plant is the nation's sole repository for transuranic waste generated by pit production.

This cross-complex effort will entail transporting legacy plutonium, primarily between Pantex and the two production sites and then back to Pantex for warhead assembly. Thus, plutonium will regularly be on roads across the southern United States. Work at the LLNL and the Nevada National Security Site requires smaller quantities of material. Back-and-forth transportation of weapons-relevant quantities of plutonium comes with its own logistical and regulatory hurdles. While the NNSA is equipped for such transport, spreading work among multiple sites raises risks for security that would be avoided or reduced by consolidating workflow to a minimum number of sites.

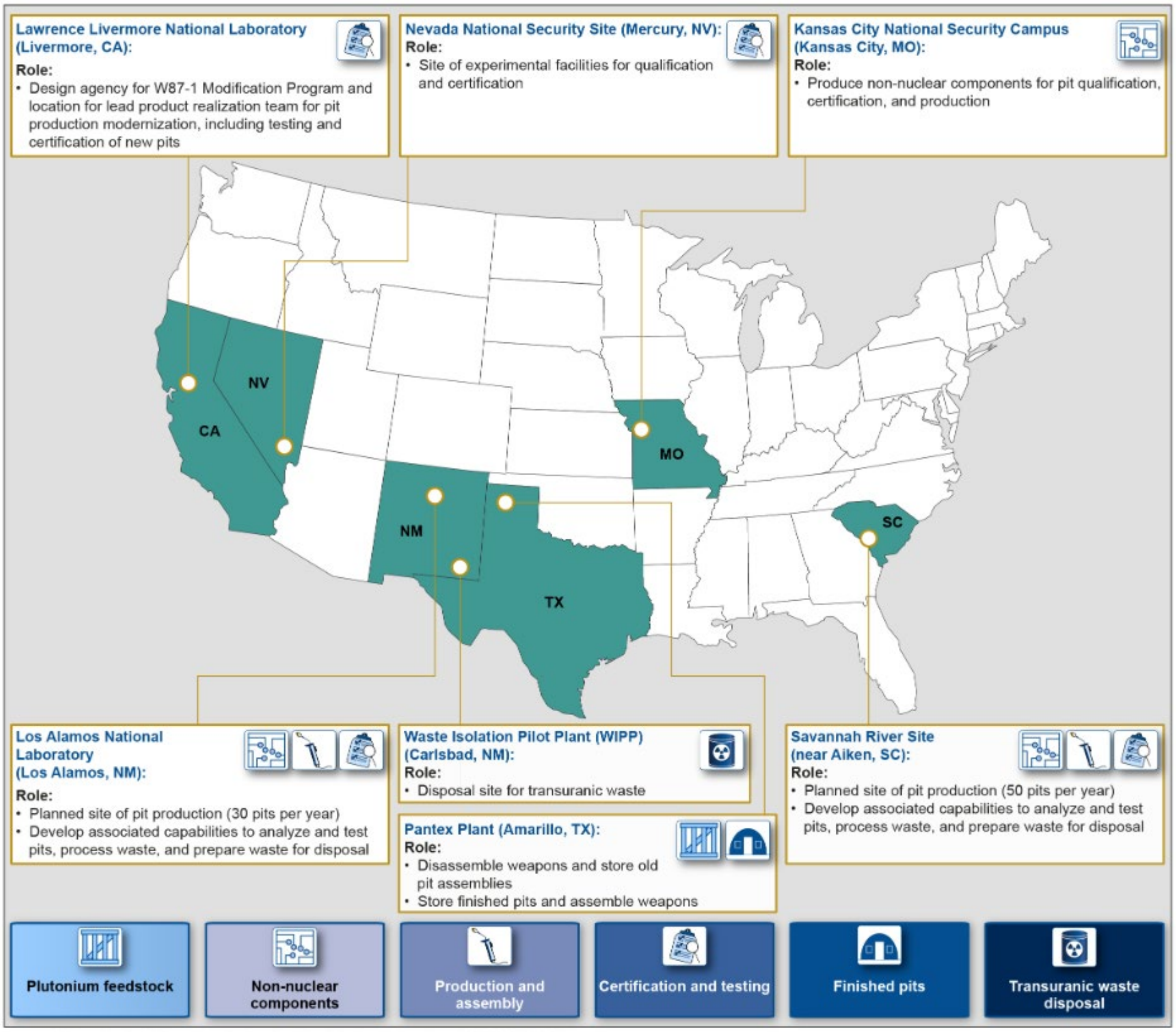
The Costs and (Questionable) Benefits of Redundancy

The 2018 decision to pursue two sites touted the potential for "resiliency, flexibility, and redundancy" within the nuclear security enterprise and was deemed "the best way to manage the cost, schedule and risk of such a vital undertaking" (Lord and Gordon-Hagerty 2018). The NNSA's decision contradicted the studied alternatives described above as well as public statements made the same month by NNSA staff acknowledging that reliance on multiple facilities could increase operational risk at LANL as well as overall life-cycle costs (Cummins 2018).

The concept of "resiliency" appears throughout documents outlining plans for pit production, echoing language from the 2018 *Nuclear Posture Review*, which called for "an effective, responsive, and resilient nuclear weapons infrastructure" (Mattis 2018). Testimony from the NNSA's then-administrator Lisa Gordon-Hagerty used similar language to justify the two-site approach: "Even though this approach will require NNSA to fund activities at two sites, any interruption or delay to pit production in the future due to the lack of resiliency will have huge cost increases across the entire Nuclear Security Enterprise" (Gordon-Hagerty 2019). The 2020 Environmental Impact Statement for pit production at Savannah River mentions that "each site would have the capability to produce 80 pits/year . . . [enabling] NNSA to meet national security requirements if one facility became unavailable" (DOE 2020).

Earlier analyses noted the risk inherent in relying on multiple facilities, including increased cost and workforce challenges, transportation and safety challenges, and the need for on-site analytical capabilities, as well as increased operational risk for workers. It now seems clear that LANL may not be able to produce more than 30 pits on its own without additional equipment, according to laboratory director, Thom Mason, despite a 2019 directive in the National Defense Authorization Act to be able to do so should Savannah River face delays (which is now the case) (Wyland 2024; John S. McCain National Defense Authorization Act for Fiscal Year 2019). An independent 2019 report concluded that *neither* site would be capable of producing 80 pits on its own, meaning the annual production rate will always depend on both facilities being operational (Hunter 2019).

Figure 1.3. The Production of Plutonium Pits Relies on Collaboration that Spans the US Nuclear Complex



Source: GAO analysis of National Nuclear Security Administration information. | GAO-23-104661

Although the two pit-production facilities are located at Los Alamos National Laboratory and the Savannah River Site, every major Department of Energy site listed here contributes to the endeavor by supplying non-nuclear components (Sandia National Lab and the Kansas City Plant), conducting materials testing and certification (Lawrence Livermore National Lab and the Nevada National Security Site), or receiving and assembling components (Pantex Plant). Legacy plutonium is stored at the Pantex Plant and shipped cross-country to the other sites. Y-12, at Oak Ridge, Tennessee (not shown), is primarily responsible for producing secondary stage components. SOURCE: Graphic from (Bawden 2023A), GAO-23-104661.

Moreover, having two sites does not make them independent of one another in terms of possible interruptions to production. Inevitably, the two will share closely related safety and production protocols, in which case a serious accident or discovery of deficiency in a production process will likely result in interruption at both facilities as processes are reviewed and revised. Several other single-point failure modes also persist in the network of sites that play a role in pit production (Figure 1.3). Most notably, the United States has only a single radioactive waste repository, and it has suffered a years-long shutdown due to recent accidents. Further, Pantex remains the sole origination site for all pit-production stock and the sole site for assembling warheads.

Indeed, almost *none* of the rest of the US nuclear enterprise has redundant capabilities. The nuclear complex has historically been managed in such a way that each individual site produces and certifies specific components—tritium from Watts Bar, uranium from Oak Ridge, neutron generators from Sandia Laboratory, other non-nuclear components from the Kansas City Plant, and so on. A two-site approach for pit production is therefore a means of redundancy but not resiliency; the complex remains dependent on numerous other single points of failure for critical components in the weapons supply chain. The degree of specialization required for many of these components precludes complete redundancy, and it also limits the ability to rapidly shift work from one site to another. This makes the argument for multiple pit-production sites questionable with regard to building a resilient nuclear complex.

Indeed, the choice to pursue two production sites (contrary to the recommended alternatives) is likely more political than technical and may suggest a lack of trust in Los Alamos to carry out the pit-production mission on its own. As alternatives were being studied, the PF-4 facility at LANL had only just emerged from a multiyear shutdown following mishandling of plutonium. The modest rate of pit production that was demonstrated at LANL between 2007 and 2011 also took longer than expected and is reported to have added to military frustration over LANL's repeated failures (Weiner 2020). This history may have contributed to the 2018 Engineering Assessment's conclusion that PF-4 represented a high risk of single-point failure (Cummins 2018).

While LANL's history raises cause for doubt, it remained the only facility capable of processing plutonium as of 2024. It will remain so until the completion of the SRS, projected for the early 2030s. In other words, the NNSA had to either accept these shortcomings or wait nearly a decade for an alternative site.

Also, multiple facilities are not required to produce 80 pits per year if a single site were properly resourced. Past proposals that did not go forward (described below) were envisioned to provide up to 450 pits per year using a new facility at LANL, while the vastly larger Rocky Flats industrial-scale plant produced 1,000 to 2,000 pits per year during the peak of the Cold War. As outlined in the 2018 Engineering Assessment, LANL's preferred option for achieving 80 pits per year was an onsite expansion to allow production of that many pits with single-shift operations (Parsons 2018). It is clear that a single facility could eventually be capable of producing 80 pits, and that neither a lack of feasibility nor cost considerations drive the two-site approach. In fact, because the choice to develop two sites has been made, the costs have quickly outpaced original expectations and easily exceed past estimates for larger pit production capacity at a single site.

1.3 A Brief History of Past Pit Production: Boom and Bust

Revisiting past production processes, as well as several recent proposals that ultimately failed, sheds light on the present proposal for pit production, including how it compares in terms of cost, schedule, and potential international reaction. Previous efforts have failed due to various circumstances, including impracticality, cost, and perceived lack of need. Controversies surrounding the urgency and required scale of production are not new and have varied over time as both domestic and international politics have swung in new directions.

The Cold War Plutonium Industry: Hanford and Rocky Flats

The production of nuclear weapons following World War II and until the end of the Cold War was fraught with risk and costs, including consequences to human health and the environment that persist decades later. For some observers, these risks were justified at the time as the cost of national security, while others were unaware or unable to consent to the effects of working or living in proximity to the industrial pipelines that fed the nation's nuclear stockpile. Production of plutonium in reactors and the manufacture of plutonium pits left some of the heaviest environmental scars now afflicting the United States. Although the proposed resumption of pit production, if done properly, could avoid most of the historic harms, history nonetheless offers an important reminder of hazards and potential consequences, as well as a reminder of why the general public remains extremely wary of the resumption of pit production.

Plutonium, a human-made element, was first synthesized in 1940 at University of California at Berkeley using a cyclotron, a type of particle accelerator that had only just been developed. By 1942, scientists had managed to make small quantities of plutonium, barely visible to the naked eye. By 1944, a dedicated nuclear reactor running at Hanford, Washington, produced the quantities required for the first nuclear device tested at Trinity in New Mexico and the bomb used over Nagasaki, Japan, in 1945. (The Hiroshima bomb was powered by highly enriched uranium, not plutonium). Production of plutonium increased exponentially thereafter at industrial scale.

Hanford's B reactor was built in less than one year to meet the urgent demand for the wartime Manhattan Project. By 1953, Hanford had six operational reactors, with another coming online at Savannah River, South Carolina. By the mid-1950s, the United States had created thousands of kilograms of plutonium destined for the rapidly growing weapons stockpile (DOE 1996b).

Starting in 1952, plutonium metal created in these reactors went to the Rocky Flats plant situated between Denver and Boulder, Colorado, and operated by Dow Chemical (later Rockwell International). There, it was formed into pits using a wrought process that annealed the plutonium metal and rolled it into sheets, which were then shaped using dies to form the halves of a pit (CRS 2014; Chung and Heller 2012). These halves were welded around the equator to form a spherical or ovoid shape before being coated in a more fire-resistant cladding material and before being sent for assembly.

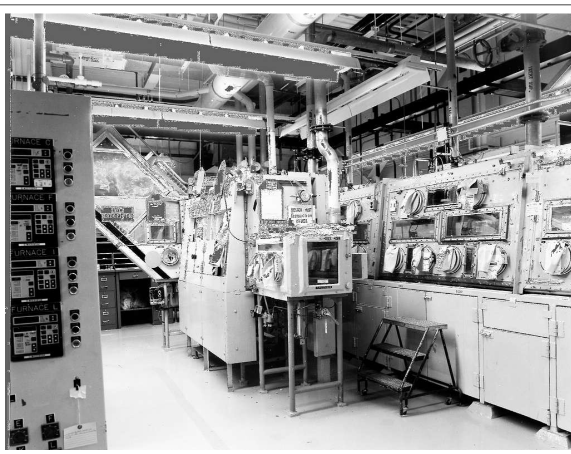
At its peak, Rocky Flats produced 1,000 to 2,000 pits a year between 1953 and 1989 (roughly five pits per day), for a total of roughly 70,000 pits (DOE 2020; Obmascik 2000). At its peak in the mid-1960s, the United States possessed 31,255 nuclear warheads (Kristensen 2024).

The speed and scale of production at the height of the Cold War had serious environmental and occupational consequences. As of 2024, Hanford ranked as one of the most contaminated superfund sites in the United States, hosting over 54 million gallons of radioactive liquid waste in tanks, some of which are leaking and for which there is no easy remediation. It is estimated that it will cost $528 billion to clean up what remains at the site, but it may never be completely remediated (Vartabedian 2023).

At Rocky Flats, major fires occurred in 1957 and 1969. Both began as a result of the pyrophoric (spontaneously flammable) nature of plutonium, particularly shavings, in the presence of oxygen. In both cases, fire quickly consumed the protective gloveboxes in which work was carried out. In the 1957 event, the fire burned through a HEPA filtration system designed to control emissions from the facility, and the resulting plume of radioactive smoke spread over hundreds of square miles (Till et al. 2002). The 1969 event was deemed the costliest industrial accident in the United States up to that time (Jonuska 2022); despite more than two years of cleanup, affected areas have never been fully remediated, and some of the most heavily contaminated equipment was simply embedded in concrete on site at the time (Obmascik 2000).

The 1969 fire drew attention to safety at the facility, where it was also revealed that drums containing waste from plutonium machining stored on an outdoor pad had leaked more than 5,000 gallons over several years (Siegel 1993; Jonuska 2022). Other hazardous materials, including beryllium, volatile organic compounds, americium, tritium, nitrates, plutonium, and depleted uranium, are now known to have contaminated the area, some from illegal spray irrigation from ponds for holding waste (Kaltofen 2019; Till et al. 2002).

FIGURE 1.4. Views of the Rocky Flats Facility



Left: A molten-salt-extraction line used for material preparation at Rocky Flats. Right: An aerial view showing the extent of the facility in 1995. Situated between Denver and Boulder, Colorado, the site covered 6,500 acres. The central, industrialized portion of the site covered approximately 385 acres and included more than 800 structures. SOURCES: (DOE Legacy Management 2020); pycril.com (public domain).

In 1989, following an unprecedented raid by FBI agents, Rocky Flats became the first federal facility to be subject to a criminal environmental case. Three years later, the managing contractor pleaded guilty and paid $18.5 million in fines—the largest to date for environmental crimes, but a tiny fraction of the $36 billion that was initially estimated for cleanup that was thought could take up to 65 years (Buffer 2003). Ultimately, the site was cleared in only 10 to 15 years at a cost of $7.3 billion, but critics of the Department of Energy attribute the difference in speed and cost to “cutting corners” (DOE Legacy Management 2020; Ben David, Herzfeld, and Gayner 2024).

Demolition of the facilities was inordinately challenging. At the time of the shutdown, more than 3,000 kilograms of plutonium were onsite in more than 20,000 discrete packages spread across many buildings (DOE 1996c). Up to 1,100 pounds (roughly 500 kilograms) of plutonium were reported lost in ductwork and gloveboxes (Obmascik 2000), and much of the leftover radioactive waste was in the form of mixed residues. Contaminated material was shipped to locations in New Mexico, Nevada, and Utah (*Deseret News* 1995). Cleanup was deemed complete in 2005. Much of the land was transferred to the US Fish and Wildlife Service in 2007 to create a refuge, but the most heavily affected areas where pit production occurred remain closed to the public. Contentious and prolonged legal battles over the status of the land have been ongoing, as is persisting environmental damage (Elliott 2016).

The legacy of Rocky Flats has undoubtedly played a significant role in public perceptions of nuclear weapons production, despite the fact that recent proposals for producing pits have been much more modest; they come nowhere near approaching the scale of what was carried out there, much less with such reckless practices. Present plans would replicate neither the risks of Rocky Flats nor the environmental devastation of Hanford, but they do represent one of the largest investments in the nuclear complex since the Manhattan Project. Moreover, some risks associated with pit production are inherent to the material itself and to human fallibility—factors that have not changed and cannot be eliminated. (Chapter 4 explores these risks further.)

Reviving the Industry: Previous False Starts

The shutdown of Rocky Flats in 1992 marked a significant transition in the US nuclear complex by eliminating a key production capability for which there was no alternative. At the same time, the Cold War was drawing to a close with the fall of the Soviet Union, leading to dramatic reductions in the size of the US stockpile. The cessation of US nuclear testing in 1992 eliminated another source of demand for domestic plutonium processing and new pits.

In 1996, the Department of Energy decided to study options to resume making plutonium pits. An environmental assessment considered producing pits at the Los Alamos National Laboratory, the Savannah River Site, or both. A scenario without pit production was also considered. The decision, to proceed at Los Alamos, was driven not by a need to make new weapons, but rather to replace pits that are destroyed annually as a part of the stockpile stewardship and surveillance programs. The DOE deemed a capacity of up to 50 pits per year, produced in a single shift of operations, sufficient (DOE 1996).

In 1999, the Department of Energy followed up with an environmental assessment for production at Los Alamos, concluding that a nominal capacity to make just 20 pits per year would suffice at least through 2007. This decision was driven largely by delays in initial efforts to restart pit production and “operational constraints” at the Chemistry and Metallurgy

Research Building, where plutonium samples were tested and analyzed. Notably, the decision declared, “This postponement does not modify the long-term goal announced in the [1996] Record of Decision for the Stockpile Stewardship and Management Programmatic Environmental Impact Statement of 50 pits per year (up to 80 pits per year using multiple shifts)” (DOE 1999; DOE 2008a).

Despite that statement, the figure of 80 pits per year does not appear in the 1996 decision. However, since the 1999 decision, first 50 to 80 pits and later solely 80 pits per year became the goal for pit production, but without any clear explanation for how that number was derived. The math may have been a simple “back of the envelope” result in which approximately 4,000 warheads were estimated to be refreshed over a period of about 50 years, resulting in a need for about 80 pits per year. Regardless, the number became the accepted standard, independent of assessments of the arsenal or Department of Defense requirements.

In 2001, the NNSA unveiled a focused “Pit Manufacturing and Certification Campaign” to produce a limited number of pits for the W88 submarine-based warhead, which the shutdown of Rocky Flats had left incomplete (Medalia 2004). Because the production run for the W88 was incomplete, the NNSA lacked the usual supply of extra pits required for stockpile surveillance, which can involve destructive testing of specific components to assess aging. Without additional pits, the US Navy would eventually have to sacrifice deployed warheads for surveillance, not always getting them back. Building new W88 pits would solve that problem and, as the designated production facility, LANL’s PF-4 began efforts to produce the first certified post-Cold War pits.

Somewhat remarkably, in 2003, just two years after launching the pit-manufacturing campaign, Los Alamos produced a single “war reserve” pit and the first produced since 1992 (Henry 2023). To be certified, a war-reserve pit must undergo an array of tests, including detailed physical and chemical analyses. Pits that pass the tests are “diamond stamped”—a surface stamp using indelible ink—to indicate their readiness for the stockpile (NSS Staff 2021).

Four years later, in 2007, Los Alamos resumed production at a significantly increased pace. Though sources vary, according to the GAO, the NNSA produced 11 W88 pits in 2007, eight of which were diamond-stamped and put in the US nuclear stockpile to replace ones that would be used in destructive tests under the stockpile stewardship program. Two more were to be used for a shelf-life program that studies the lifetime of plutonium pits, and one was set aside for destructive testing (GAO 2008). Over the next three years, Los Alamos produced 20 more pits, for a total of 31 W88 pits between 2007 and 2011 that were either war-reserve quality or close enough to allow use in stewardship surveillance and testing.

The cost of the effort to produce the 31 pits was significant: $3.2 billion (in constant 2024 dollars, taking inflation into account) were invested in pit production at LANL from 2001 to 2008. Then the program moved to a budget line item called “Directed Stockpile Work,” and the budget increased significantly thereafter. Without an explicit directive from the NNSA or the Nuclear Weapons Council to continue, it seems that no pits were produced in 2012 or 2013, when PF-4 faced a safety shutdown.

Somewhat ironically, shortly after that production phase began, in 2008, the Bush Administration established a requirement that the NNSA develop the capacity to produce 50 to 80 pits per year (GAO 2016). The requirement was set by the Nuclear Weapons Council, the joint

Department of Defense/Department of Energy body responsible for oversight of the US nuclear weapons program. The requirement was not to *produce* 50 to 80 pits in a year, but rather to have the *capacity* to do so, suggesting that demand and capacity were not strictly related.

In 2013, a Department of Defense official explained how the number "50 to 80" was derived (Medalia 2015):

> *We established that requirement back in 2008 for a capability to produce in the range of 50 to 80 per year. That evolved from a decision to basically not take the path that we originally were taking with the Modern Pit Facility, but to go and be able to exploit the existing infrastructure at Los Alamos to meet our pit operational requirements. The capability at Los Alamos was assessed to be somewhere in the range of 50 to 80 per year that they could get with the modernization program they anticipated. The Nuclear Weapons Council looked at that number. It's a capacity-based number, and said it's probably good enough. We'll have to accept some risk, but it's probably good enough.*

The Nuclear Weapons Council therefore agreed to a *capacity* to produce 50 to 80 pits annually, deriving not from a military requirement but from an assessment of what would be possible at the PF-4 facility.

Contemporaneous with LANL's previous production of a small number of pits, other proposals were brought forward to significantly increase production capacity. Entirely new facilities have previously been proposed, including the Modern Pit Facility, the Consolidated Plutonium Center, and the Chemistry and Metallurgy Research Replacement Nuclear Facility. Some of these mirror LANL's "preferred alternative" from the 2018 Engineering Assessment in which new modules would have been constructed adjacent to PF-4 to meet a quota of 80 pits per year. Ultimately, none of these proposals got very far; all were judged unnecessary, too expensive, or impractical based on other resource-allocation considerations.

Modern Pit Facility

The first significant, post-Cold War proposal for a dedicated pit-production facility at LANL was for the Modern Pit Facility (MPF). It was initiated by the George W. Bush administration whose classified 2001 *Nuclear Posture Review* included a push for new pit-production capacity (DOD 2002). The MPF would have been newly constructed at Los Alamos, separate from PF-4, and was originally projected to operate from about 2018 through 2070.

A congressional panel, tasked with studying the reliability and safety of the US stockpile, cited the lack of a "firm resource commitment" to build such a facility but emphasized that a pit-production facility "adequate for national needs" be established "with urgency" (Foster et al. 2002). Meanwhile, concern had been mounting that the schedule for producing pits at LANL had slipped by five years, from 1998 to 2003, creating a credibility problem for LANL management (APS 2004).

To fulfill the direction from the *Nuclear Posture Review*, the Bush administration asked in 2003 for initial funding for a new facility. The initial request was quite modest, $4 million, and would ramp up relatively slowly. Later that year, the Department of Energy's draft environmental impact assessment for the large-scale facility projected a production capacity of 125 to 450 pits per year (DOE 2003). The initial estimate for the facility's cost was $2 to $4 billion (Medalia 2004). This is in stark contrast to the projected $18 to $25 billion cost for the currently proposed 50-pits-per-year capability at Savannah River (Hruby 2024a), up from $8 to $16 billion in 2021 (Edelson 2021).

The MPF enjoyed support from three of four congressional committees with jurisdiction over its future: the House and Senate Armed Services committees and the Senate Energy and Water Development Subcommittee. However, it met opposition from Rep. David Hobson (R-OH), chair of the House Energy and Water Development Subcommittee. While the other committees raised questions about feasibility and schedule, Hobson challenged not only the very need for new pits but also proposals for a new "bunker-busting" nuclear weapon known as the Robust Nuclear Earth Penetrator (Sterngold 2008). Consequently, his committee voted to appropriate only $7 million of the $30 million requested by the administration (DOE 2005; DOE 2004).

In Rep. Hobson's view, the Bush administration had not presented a strong case for making new nuclear weapons, and he deemed excessive the capacity that DOE had studied—for as many as 450 pits per year (CRS 2014). Hobson pointed out that potential adversaries like North Korea, Russia, and China might respond by accelerating their nuclear programs were the United States perceived to be doing so. He also was concerned that the United States could not afford such a facility, particularly when nuclear stockpiles were far lower than during the Cold War and the nuclear weapons laboratories certified that US nuclear weapons were safe, secure, and reliable on an annual basis without such production (Sterngold 2008).

The following year, Rep. Hobson's opposition to the MPF hardened based on the lack of justification. Language his subcommittee declared that it would approve no money for the facility until "capacity requirements tied to the long-term stockpile size are determined." While Senate counterparts approved MPF funding, the final appropriations bill eliminated it (Behrens et al. 2007). Unable to overcome Rep. Hobson's opposition, the Bush administration submitted a 2007 budget with no funding for the MPF, ending the first significant proposal for resuming pit production.

A 2004 report on the MPF noted that LANL's existing PF-4 facility was expected to be capable of producing 80 pits per year in a single shift, but that the NNSA had rejected the possibility because it was assumed that the minimum required capacity was at least 125 pits per year (APS 2004).

Consolidated Plutonium Center

With the failure of the Modern Pit Facility, the NNSA quickly launched a new attempt to resume pit production. In January 2008, it unveiled plans for a Consolidated Plutonium Center (CPC) capable of producing 125 pits a year with a single shift of work (i.e., 40 hours per week) and 200 pits with multiple shifts or weekend work. The lower-end production capacity was identical to the goal for the MPF, while the upper end was less ambitious.

The CPC was part of a much larger proposal for the entire US nuclear weapons infrastructure, initially known as Complex 2030 and later as Complex Transformation. The goals of the Complex Transformation proposal were to maintain core nuclear weapons competencies, create a responsive, cost-effective nuclear weapons infrastructure for all aspects of the complex, and consolidate nuclear materials at fewer sites (DOE 2008b). The current pit-production proposal clearly has abandoned that ambition.

The draft environmental assessment for the Complex Transformation proposal considered five sites for pit production: Los Alamos, the Savannah River Site (where plutonium was produced and tritium is still packaged for use in nuclear weapons), the Nevada Test Site (where explosive testing of nuclear weapons was conducted, now the Nevada National Security Site), the Pantex Plant in Texas (which assembles and disassembles nuclear weapons and stores a reserve of pits), and the Y-12 National Security Complex in Tennessee (where weapons-related uranium work takes place).

The draft assessment also considered an option to increase production at Los Alamos without building a new, dedicated pit-production facility, instead using existing and other planned facilities, including the proposed Chemistry and Metallurgy Research Building Replacement-Nuclear Facility. That approach was expected to be able to produce 50 to 80 pits per year. The assessment noted that PF-4 at Los Alamos was the "only existing plutonium facility" that could achieve that level of production without major construction (DOE 2008b).

Plans for the Consolidated Plutonium Center were short-lived. In September 2008, Secretary of Energy Samuel Bodman and Secretary of Defense Robert Gates issued a joint paper declaring that the "best alternative, for all potential pit production capacities, is to increase the existing production facilities at Los Alamos to its estimated maximum capacity of 50-80 pits per year" (Bodman and Gates 2008).

Even this recommendation, made by the top officials of the Departments of Energy and Defense, did not lead to a move to increase production at Los Alamos. The following month, October 2008, the NNSA and the Department of Energy released a final environmental assessment for Complex Transformation. It declared that, until the next administration established its own *Nuclear Posture Review*, the NNSA would limit production of plutonium pits to "a maximum of 20 pits per year," as had been authorized since 1996 (DOE 2008b).

Chemistry and Metallurgy Research Building Replacement-Nuclear Facility

The Chemistry and Metallurgy Research Replacement Nuclear Facility (CMRR-NF), although not intended directly for pit production, was to serve to increase analytical capabilities at Los Alamos in support of plutonium work. It would have provided laboratory capabilities required to certify that pits and other components meet the rigid requirements for addition to the US nuclear stockpile. This work involves analyzing and characterizing the plutonium's chemical and material properties, including its chemical composition, physical and structural attributes (including metallic texture, atomic-scale defects), and micro- and macroscopic characteristics of assembly, including such things as weld quality (GAO 2012).

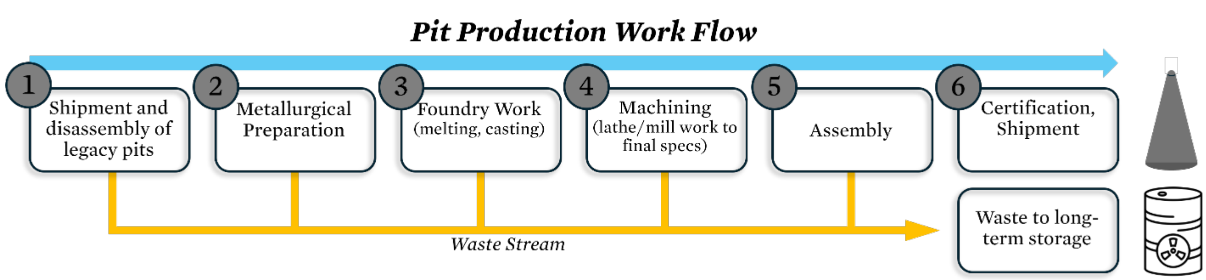
First proposed in 2005, the CMRR-NF was initially estimated to cost $745 to $975 million, with its completion scheduled for some time between 2013 and 2017. Five years after that proposal, in 2010, the NNSA estimated that the facility would cost $3.7 to $5.8 billion (almost six times more) and not be completed before 2020 (three to seven years later). In 2012, the NNSA delayed CMRR-NF by at least five more years because of financial pressure from other projects, particularly the Uranium Processing Facility at the Y-12 plant in Tennessee (GAO 2012).

Two years later, in 2014, the NNSA cancelled the CMRR-NF permanently, after spending roughly $800 million (2014 dollars) on it (GAO 2016; DOE 2012). That left the NNSA with a problem. The proposed work for the CMRR-NF—pit testing, in particular—still needed to be done. Therefore, the NNSA developed a two-fold plan. First, it proposed to enhance the capabilities of a new Los Alamos building, the Radiological Laboratory Utility Office Building, so it could handle larger quantities of plutonium after the installation of more equipment for that work. Second, LANL would remove contaminated equipment that was no longer in use in PF-4 and install new plutonium analysis equipment. However, PF-4 is already quite crowded and carries out plutonium work unrelated to pit production, and the RLUOB had not been initially designed to take on the full scope of analytical needs required for pit production.

When announced in 2014, the estimated cost for those two projects was $1.5 billion to $2.0 billion, and the work was projected to be completed by 2024. According to the GAO, the RLUOB is now expected to be completed between 2026 and 2028 and the PF-4 upgrade to be finished between 2026 and 2029, for a total cost of $1 billion to $1.3 billion (Bawden 2023a).

These three cases—the MPF, the CPC, and the CMRR-NF—share a common theme. When confronted with a need for a particular capability, the NNSA first chose to build a brand-new, large-scale facility. In each case, as actual budgets far outstripped expectations, and often after spending hundreds of millions or even billions of dollars, the NNSA accepted an alternative that could meet the requirements using existing facilities that cost far less and that would have been the most economical route had they been pursued from the start.

Box 1.2. The Pit Production Process



SOURCE: UCS, modified after (Bawden 2023a).

Pit production involves much more than plutonium. In fact, the process for recycling old pits, purifying the metal, and remaking new ones is complicated, involving chemical procedures, mechanical processing, high-temperature processes, machining, welding, and precise characterization. Most, if not all, of these processes must be carried out in specially designed gloveboxes designed to separate workers from hazards, contain contamination, and, in some cases, protect the material from oxidation in air. As an enclosed trolley system moves material down the production line, plutonium never leaves the connected gloveboxes unnecessarily. Some of the process can now rely on automation, but many steps still require delicate, hands-on work.

New pits will be made from existing pits that have been removed from retired weapons, meaning new plutonium does not need to be produced in reactors, as was done historically. The Pantex Plant near Amarillo, Texas, stores legacy pits. These are typically older than the pits in the deployed stockpile, so they can be expected to have higher levels of accumulated decay products (^{235}U and ^{4}He), as well as americium from the decay of the minor plutonium isotope, ^{241}Pu. These daughter products are separated from the ^{239}Pu using pyrochemical processes including electrorefining—high-temperature processing that separates plutonium metal through oxidation/reduction in molten salt, chemically separating impurities in the process. The original material may be broken down through conversion to an oxide/hydride form, which flakes apart in preparation for subsequent chemical processing and purification. Resulting salts can be further separated by dissolution in nitric or hydrochloric acid to extract remaining plutonium metal and americium from electrorefining residues. Americium has a number of commercial applications (home smoke detectors use it, for example) and has historically been supplied from the Russian market (Gardner, Kimball, and Skidmore 2016). Purification of legacy plutonium produces significant quantities of radioactive liquid waste and precipitates that must be disposed of.

Following separation, purified plutonium metal must be reconstituted, which means the correct proportions of gallium must be alloyed to stabilize the metal in a desirable form, and the feedstock must be checked for purity. Once this is achieved, the material can be melted in an induction furnace and cast into hemishells that are near their final dimensions (referred to as “near-net casting”). The hemishells then move on for traditional machining to achieve precise dimensions and surface quality.

Plutonium is especially tricky to machine. Not only must the machining take place in a glovebox (now made easier with the advent of Computer Numerical Control processes, or CNC), but coolants must be chosen and used judiciously because contamination with shavings renders them radioactive. Considerable effort has gone into reducing or eliminating the use of coolants whenever possible, but the localized (frictional) heating that arises from machining must be carefully controlled because the metal’s chemical stability is sensitive to temperature, and phase changes (changes in crystal structure) can result from high temperature (see Chapter 3). Dust and contact with organic solvents are also undesirable for plutonium’s surface chemistry. Finally, plutonium cuttings are notorious for being pyrophoric, which means they can ignite spontaneously in the presence of oxygen. This has led to glovebox fires at both Rocky Flats and Los Alamos, including recently.

Following detailed characterization and assurance of specifications, the hemishells move on to be joined using a specialized welding process in a walk-in glovebox (Hennigan 2023). The plutonium components also receive external metallic claddings as part of the integrated pit assembly (which includes non-nuclear components) before being packaged and returned to Pantex for assembly within a warhead.

Throughout the process, cleanliness and the preservation of the surface quality are important. All rags, wipes, solvents, single-use tools, and personal protective equipment become part of an ever-growing waste stream. This waste, along with associated chemical waste, is prepared for temporary storage onsite before being transported to the Waste Isolation Pilot Plant near Carlsbad, New Mexico, for permanent storage.

1.4 Costs and Schedule

Advancing Without a Plan

One of the most perplexing aspects of efforts to produce new plutonium pits is the NNSA's inability or, perhaps, unwillingness to provide a complete schedule or official cost estimate for the project (GAO 2023b). Even a decade after the original congressional directive to resume pit production, the prospects for completion remain undefined. Although billions of dollars have been spent already, the future costs have huge uncertainties. That alone should be a cause for concern about the viability of the endeavor.

In 2014, Congress mandated that the NNSA produce 10 plutonium pits in 2024, 20 in 2025, and 30 in 2026. By 2027, the NNSA was to demonstrate production fast enough to produce 80 war-reserve pits annually (Carl Levin and Howard P. "Buck" McKeon National Defense Authorization Act for Fiscal Year 2015). As of November 2024, a single war-reserve pit was announced complete at LANL—the first since 2011.

The 2014 legislation did not specify what types of pits to produce, where the NNSA should produce them, or how much the US government should be willing to pay to achieve the goals Congress set. The legislation merely declared broadly that a "modern, responsive nuclear infrastructure" was a "national security priority," that delaying such infrastructure was "an unacceptable risk," and that pit production must be "driven by the requirement to hedge against technical and geopolitical risk and not solely by the needs of life extension programs." Neither the rate of pit production nor the absolute quantity were directly tied to a programmatic need. As noted, a quota of 80 pits per year appears to have been inherited from earlier proposals, not from the warhead programs these new pits were intended to supply. That goal was deemed unfeasible as early as 2017 when the NNSA studied its options for meeting the congressional mandate (NNSA 2017). 2033 was deemed the earliest possible target date for any option studied.

It became clear that even a three-year extension would not be enough for the NNSA to meet the production deadline, as the 2017 analysis had predicted. During her confirmation hearing in 2021, incoming NNSA administrator Jill Hruby testified that because of delays at the Savannah River Site, it would be "between 2030 and 2035" before the NNSA could produce 80 pits a year (US Senate 2021).

The NNSA sent Congress an outline of its plan for pit production in June 2021 (Hruby 2021). That report said that producing 80 pits in a year "is achievable in the 2032–2035 timeframe contingent upon the potential for both implementation and technical options to accelerate both project completion and transition to [war reserve] pit production." That convoluted language seems to imply that the agency itself was not confident it could meet its proposed 2035 goal unless a number of contingencies were satisfied and efficiencies could be found.

Also in June 2021, the NNSA sent Congress its plan to develop a comprehensive schedule for the pit-production project. The document sought to explain how the agency was responding to a congressional mandate to produce such a schedule. It stated that the NNSA started working on a comprehensive schedule in 2018, immediately after the NNSA administrator selected the two-site plan. The report indicated that the NNSA would have such a plan by September 2021, just a few months after this report had been sent to Congress (Verdon 2021).

Neither of the 2021 reports contained insight into the costs of the pit-production plans. And the schedule delivered to Congress in October 2021 was far from comprehensive.

No Horizon for Expanding Budgets

In addition to planning uncertainty, budgets appear to be unconstrained. In 2003, a LANL study for the NNSA concluded that with only 3,000 additional square feet within PF-4, it could reliably produce all pit types in the US stockpile with single-shift work at a rate of 50 to 80 pits per year and at a cost of less than $1 billion (Fetter and Von Hippel n.d.; Boertigter, Kornreich, and Barkman 2003). By today's standards, this now appears wildly optimistic. Two decades later, the projected construction cost for a 50-pit-per-year capacity at the Savannah River facility alone may reach $25 billion, outstripping common national indices for construction costs by more than an order of magnitude over the same period.

In 2021, the NNSA announced that the pit-production projects at Los Alamos and the Savannah River Site had completed the project-definition and conceptual-design phases. For the Los Alamos project, the preliminary construction cost estimate was $2.7 to $3.9 billion, with an expected completion date of 2027 to 2028. Final cost and schedule estimates were expected in 2023 (NNSA 2021b). For the Savannah River Site, the preliminary cost estimate was $6.9 to $11.1 billion (up from $1.8 to $4.6 billion in 2018), with completion estimated to take place between 2032 and 2035, adding two years to the optimistic figure cited in the NNSA administrator's confirmation hearing the month before.

Life-cycle cost estimates—which include design and construction, operating the facility for 50 years, and decommissioning—vary even more wildly. Repurposing the abandoned MOX plant at Savannah River was projected to cost $5.7 to $22.9 billion over its entire life cycle, whereas a new facility at LANL was anticipated to cost $6.8 to $27.4 billion. Remarkably, the construction costs *alone* at Savannah River are now projected to be higher than the initial life-cycle cost estimate at up to $25 billion just to reach operational status (therefore not including 50 years of operational cost and decommissioning) (NNSA 2024b). Over $7 billion had already been spent on the empty structure at Savannah River prior to cancellation of the MOX project in 2018 (Box 1.1).

The estimate to expand production at PF-4 temporarily was significantly less than for reworking the MOX plant. The contractor estimated that life-cycle cost to be $14.8 billion; however, the demands of the aging facility are likely to inflate that value. When combined, the cost of achieving a capacity of 80 pits per year is therefore still largely undefined and likely subject to change.

Based on NNSA budget documents, the agency spent over $10 billion on plutonium pit production between 2020 and 2024. That includes almost $800 million in 2020 and over $2.9 billion in 2024. For 2025, the NNSA requested over $3 billion, and it projects it will need $3.5 billion in 2026 and over $4 billion in 2027 (NNSA 2024b). This is despite the fact that LANL is unlikely to have achieved its capacity of 30 pits per year by then, and Savannah River will still be roughly a decade away from production.

The official estimates for cost and schedule were expected in 2023 or 2024 (NNSA 2021c) but had yet to be produced 10 years after the original congressional mandate for the project.

Outside Reviews Confirm Uncertainty

Two significant external reviews have scrutinized the NNSA's management of the project and the potential fidelity of existing cost projections. The first was conducted by the Institute of Defense Analyses (IDA) in 2019 and the second by the Government Accountability Office in 2023 (one of several GAO reports related to pit production).

In 2019, Congress directed the NNSA to hire a consultant to review the agency's plans for pit production. The IDA's assessment was scathing: "[E]ventual success of the strategy to reconstitute plutonium pit production is *far from certain*" (emphasis added) (Hunter 2019). While noting that success was possible—"although not on the schedules or budgets currently forecasted"—all options were "extremely challenging," and "pursuing an aggressive schedule *creates major risk* to achieving an 80-ppy production capability under any option" (Hunter et al. 2019).

The IDA based its findings on an assessment of the NNSA's previous attempts to develop major projects, all of which were significantly over budget and behind schedule, and several of which—like the Modern Pit Facility and the Chemistry and Metallurgy Research Replacement Nuclear Facility—had been cancelled after the spending of hundreds of millions of dollars. Every major project undertaken by the NNSA that cost more than $700 million took at least 16 years to complete. The IDA thus concluded that it "could find no historical precedent" suggesting that the NNSA could meet its target of 80 pits per year by 2030 (Hunter et al. 2019).

In January 2023, the GAO issued its own detailed report, *NNSA Does Not Have a Comprehensive Schedule or Cost Estimate for Pit Production Capability* (Bawden 2023a). It notes that "[re]establishing pit production likely represents NNSA's largest investment in weapons production infrastructure to date." The report sharply criticizes the program and the NNSA's apparent reluctance or inability to adhere to best practices for major project management.

The GAO report notes that the NNSA acknowledged the value of a schedule and cost estimate but wanted to wait to have more complete information before producing one, specifically for the Savannah River Site. Yet significant work was underway at both sites already. The GAO strongly recommended that the NNSA should still complete a preliminary master schedule and cost estimate using GAO best practices because failing to do so would increase the likelihood of disruption and delay. Even if preliminary, such planning "could improve NNSA's decision-making, the efficiency and effectiveness of their efforts, and the quality of information provided to Congress" (Bawden 2023a). Instead, the report notes, the NNSA "will have spent billions of dollars without having an overall idea of total program costs, or when program objectives, to include the capability to produce 80 pits per year, will be reached."

The GAO report thoroughly reviewed the NNSA's October 2021 attempt to produce the schedule cited above. The GAO found the schedule to be largely incomplete, including only some details for the Los Alamos and Livermore labs' parts of the project and only through 2024—and it included almost nothing for the Savannah River Site. When the report reached 2027, there were no details or milestones even for the two national labs. It was also not "resource loaded"—i.e., it did not identify the resources required to complete the plan (Bawden 2023a). It was, in short, neither the comprehensive schedule nor the cost estimate that Congress had requested and that the GAO strongly recommended, and it fell short of basic expectations for managing a project on this scale.

Further, the GAO noted, the NNSA intended to have a comprehensive schedule and life-cycle cost estimate by September 30, 2025, a delay of one to two years after the projected timeline cited in 2021. On the cost estimate, the GAO report found “at least $18 billion to $24 billion in potential costs” for the 80-pit-per-year project in the NNSA’s fiscal year 2023 budget request—yet the agency still would not pull those figures together to provide an official cost estimate.

In April 2024, NNSA Administrator Hruby revealed a new—but still unofficial—cost estimate of $28 to $37 billion for acquisition costs for the project (Hruby 2024c). In an online update to its 2023 report, the GAO authors noted that this figure included construction and recapitalization spending but not annual program costs. Incorporating those figures would add $1 billion per year for almost a decade (GAO 2023b). The GAO’s update also noted that the NNSA now expected to finish the life-cycle cost estimate and comprehensive schedule in 2026, two to three years later than it had estimated in 2021.

Thus, Congress continues to fund a program that is already more expensive than alternatives that had been rejected on a cost basis—a program with an unknown schedule, unknown costs, and production goals that do not derive directly from the program needs they are intended to fulfill.

1.5 Potential Geopolitical Costs and Risks

The financial and logistical challenges involved in pit production may not be where the greatest costs lie. The building of new, modernized nuclear weapons, as embodied by not only the massive investments in the plutonium-pit production plan but also plans for new nuclear delivery systems (ICBMs, submarines, and bombers), signal that the United States has no intention of following through on its legal commitments to cease engaging in a nuclear arms race and also to work for global nuclear disarmament. These are not just legal commitments; they are imperative for keeping the United States and the world safe. Simply put, nuclear weapons are incompatible with a secure future.

The US choice to overhaul its nuclear arsenal and resume Cold War production activities are not a response to actions by potential adversaries. They have been planned or advocated for over a decade, before the most significant geopolitical circumstances now used to justify US policy.

The transition from stewardship of the existing arsenal toward developing and modernizing the infrastructure for producing nuclear weapons is inconsistent with US commitments to nuclear disarmament under Article VI of the 1968 Non-Proliferation Treaty (NPT) to which the nation is legally bound: “Each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament, and on a treaty on general and complete disarmament under strict and effective international control” (United Nations 1968).

Plans for new nuclear warheads and investments in the massive infrastructure to support their production encourage arms racing, and they are inconsistent with the commitment to pursue nuclear disarmament. Instead, they represent a commitment to nuclear weapons for decades to come—and US adversaries will perceive them as such. The choice to remanufacture plutonium pits represents a clear intention to continue relying on the nuclear arsenal as a deterrent against adversaries as part of a much larger renewal of US nuclear forces. By choosing to introduce new weapons, the United States threatens to participate in a multipolar arms race rather than to continue progress toward disarmament following the end of the Cold War.

The United States has by far the largest, most capable conventional military in the world, and it is part of NATO and other significant military alliances that augment that military power. That the United States continues to pursue nuclear weapons and deems them a critical part of its strategic defense policies demonstrates a stubborn adherence among US decisionmakers to a Cold War mentality. This makes achieving the third pillar of the NPT, nonproliferation, more challenging, and it diverts resources from a more sustainable path to peace. Clearly, we see pressures in Eastern Europe, the Middle East, and East Asia for nations to get their own weapons in such an environment. The associated dissolution of arms-control measures, partly at the behest of US administrations, makes this more likely. Accelerated weapons production represents a failure of the post-Cold War movement toward a less dangerous world.

Findings and Recommendations

The requirement to produce 80 pits per year has no clear anchor in established military or technical need, but if that is to be the goal, past proposals and scrutiny of associated costs and risks reveal that two production sites for pit production would not be required. The objective of creating "resiliency" and "redundancy" for pit production carries little relevance given the lack of redundancy elsewhere in the nuclear complex and the NNSA's stated reliance on having both facilities operate at capacity in order to achieve its goal.

Congress should require the NNSA to provide an integrated master schedule and complete cost estimate for pit production, including a credible life-cycle cost estimate per the GAO's recommendation and suggested best practices.

Despite the challenges at PF-4, that facility is already beginning to produce certified pits, whereas the Savannah River facility is at least a decade away from production and likely to incur further cost increases. The NNSA should therefore rely on PF-4 to maintain pit-production capability at the minimum level required to maintain expertise. Alternatives are available that reduce the need for pits from both PF-4 and the SRS (see Chapter 2) until they are required to sustain the present stockpile.

A resumption of weapons production comes with an associated geopolitical cost and may serve as a block to nuclear disarmament.

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Chapter 2
The New Nuclear Arsenal

> *"We cannot advocate for nuclear nonproliferation around the globe, while pursuing more usable nuclear weapons options here at home" – Ohio Republican Congressman David Hobson, in 2004 (Ackland 2006)*

> *"Creation of the stockpile of the future will require the vision and will to unleash the creative energy of the workforce. . ." –Former Los Alamos Director, Terry Wallace, in 2018 (Spivey 2021)*

Introduction

The rush to manufacture new plutonium pits represents one of the largest US investments in its nuclear complex since the Manhattan project. Following the end of the Cold War, the United States reduced the size of its nuclear stockpile due to successive arms control agreements. The national laboratories were tasked principally with maintaining the US arsenal through a highly successful, science-based "stockpile stewardship" program that has ensured the safety, security, and reliability of the nation's nuclear weapons without nuclear testing.

At the same time, the technical capabilities made possible by the stockpile stewardship program have proven to be a double-edged sword, allowing interest in new nuclear warhead designs to flourish. Since 2003, there have been a number of such proposals, all of which ultimately failed in Congress—until 2010. That year, as a result of domestic political negotiations to renew the new START arms control treaty, Congress agreed to efforts to replace and upgrade US nuclear weapons and delivery systems. The current push to restart production of plutonium pits is emblematic of this transition from maintenance to the design and production of a new nuclear arsenal.

Interest in designing new nuclear weapons and restarting plutonium pit production far predates current strategic developments such as the Russian invasion of Crimea, its war in Ukraine, and the reported expansion of China's nuclear arsenal. Although new weapons neither significantly enhance US nuclear "deterrence" nor provide solutions to these geopolitical circumstances, advocates for designing new nuclear weapons nonetheless cite those global events as rationales.

Driving current plans for renewing plutonium-pit production are plans for two new nuclear warheads: the W87-1, which would be carried on a modernized intercontinental ballistic missile (ICBM) called Sentinel, and the W93, which is destined for the submarine-launched Trident missile. Both programs have experienced extreme budget overruns and lack direct coordination; as a result, they face significant uncertainty. Rather than use these questionable programs as rationales, several alternatives can reduce or even eliminate the need for renewed pit production over the coming decade—alternatives that are cheaper, safer, and more sensible—while helping the United States to meet its national security needs.

2.1 That Was Then, This Is Now: A Paradigm Shift in the Nuclear Complex

Stockpile Stewardship: Ensuring "Safety, Security, and Reliability"

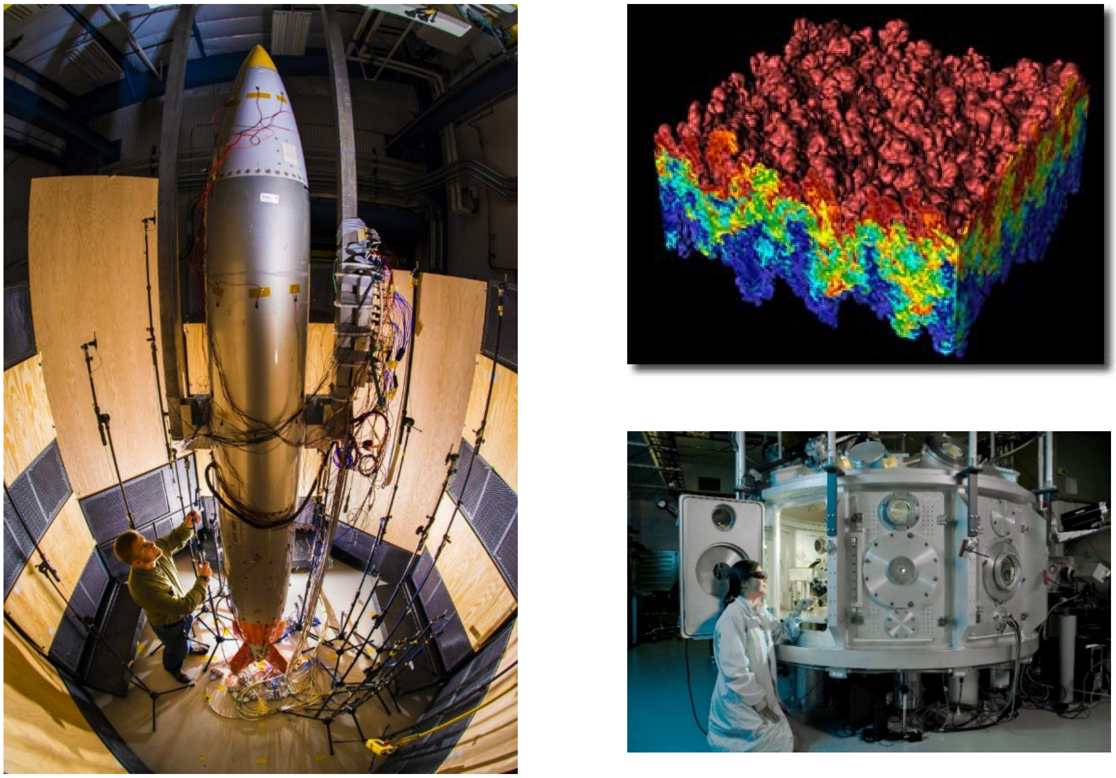
With the 1992 cessation of underground explosive nuclear testing, the United States could no longer use such tests to certify the functionality of stockpile designs. The 1994 Defense Authorization Act directed the Department of Energy (DOE) to establish the science-based Stockpile Stewardship Program to maintain both US nuclear weapons and the capabilities required to produce and certify weapons. Under this program, laboratory experiments and computational modeling have replaced explosive nuclear tests to refine the understanding of weapons' performance, design, and any age-related changes. The program has been extremely successful in meeting its goals, and laboratory directors have relied on it since 1995 to annually certify the safety, security, and reliability of the stockpile to the President of the United States.

Safety, security, and reliability, in this context, refer to ensuring that nuclear weapons cannot detonate accidentally (safety), that they are not vulnerable to unauthorized access or control (security), and that, if used, they will perform within 10 percent of their design yield "at the target" following an expected sequence of actions (reliability). Among other factors, this mandate requires understanding how various components and materials age so that the national laboratories can make high-fidelity estimates of the weapons' longevity and performance margins over time. To preserve or update performance margins accordingly, interacting points of failure must be understood so that accumulated uncertainties can aid in planning required interventions for limited-life or aging components.

While that challenge may seem difficult, science-based stockpile stewardship has proven extremely effective (Figure 2.1). Success has been made possible in part by rapid advancements in computational capabilities. Just as important has been the development of a number of sophisticated experimental facilities, across the nuclear weapons complex, designed to probe extreme conditions of temperature and pressure in a controlled, precise manner. Underground explosive nuclear tests often served to validate a specific nuclear explosive package, but laboratory and subcritical experiments now do much more. They elucidate specific aspects of weapons physics and system performance with a higher degree of precision and fidelity and over a wider range of conditions than would typically be possible with an explosive nuclear test. Stockpile stewardship also includes extensive reanalysis of nuclear-testing data using the best available methods to iteratively improve the understanding of those tests and benchmark computer models against known performance metrics (Reis, Hanrahan, and Levedahl 2016; Jeanloz 2000).

Facilities such as the National Ignition Facility (at Lawrence Livermore National Laboratory) or Z (at Sandia National Laboratories) use lasers and electromagnetic acceleration, respectively, to compress materials, including plutonium, to conditions akin to what they might encounter in a weapon. In particular, these facilities can characterize possible changes in the performance of plutonium as a function of age. Such experiments have elucidated subtle differences in plutonium's compressive behavior under previously inaccessible states of temperature and pressure, and with very high precision. Similarly, experimental facilities that generate neutrons and X-rays can be used to conduct detailed non-destructive surveillance of many age-related changes within weapons components. Results from such experiments can be fed into or compared with sophisticated computational models that rely on some of the world's

FIGURE 2.1. Scientific Tools and Computational Modeling: Predicting, Monitoring, and Remediating Aging in Nuclear Weapons



The stockpile Stewardship program combines detailed experimental studies in the lab with ever-advancing computational capabilities to understand the properties of nuclear weapons, from the atomic scale up to complete assemblies. Left: An acoustic testbed at Sandia National Laboratory. Top right: Computational modeling of microscopic instabilities in a moving surface. Bottom right: Trident laser facility at Lawrence Livermore National Lab, for materials science and plasma physics experiments. SOURCES: DOE n.d.; LLNL n.d.; LLNL 2009.

fastest supercomputers, enabling scientists to test and tune many variables from the macro- to micro-scale and improve models of weapons performance. The end result of these laboratory and modeling efforts is a much more nuanced and detailed understanding of the underlying physics than was possible in the past.

Along with stockpile stewardship, the national laboratories and the Pantex plant examine weapons withdrawn from the arsenal (Table 2.1). This enables the labs to identify required maintenance intervals for components with limited life spans and monitor a given design for unexpected changes. Limited-life components include tritium boost gas reservoirs, neutron generators, thermal batteries, and other materials (e.g., foams or seals) that may degrade in the presence of radiation or temperature fluctuation.

TABLE 2.1. The US Stockpile as of 2024 and Recent Life Extensions

	Weapon	Delivery System	Total Number Available	First Production Unit	Last Life Extension
Land	W78	Minuteman III ICBM	600	1979	Cancelled 2018
	W87-0	Minuteman III ICBM (slated for Sentinel)	540	1986	2004
Sea	W76-1	Trident II SLBM	1,511	2008	N/A
	W76-2	Trident II SLBM	25	2019	N/A
	W88	Trident II SLBM	384	1989	2022 (Alt 370)
Air	W80-1	Bomber	500	1982	2027 (W80-4)
	B61 (5 versions)	Bomber	488	1968–2021	2021 (B61-12)
	Retired/Awaiting Dismantlement	-	1,336	-	-
	Total		5,384		

Of the 5,384 nuclear weapons in the US stockpile, about 1,370 are deployed on ballistic missiles (400 on intercontinental ballistic missiles and 970 on submarine-launched ballistic missiles), 300 are kept at heavy bomber bases, and 100 nonstrategic bombs are deployed in Europe. The B61 has been produced in 13 variants, starting in 1968. Currently deployed variants include the -3, -4, -7, -11 and -12. A new design (-13) is in production.
SOURCE: Data courtesy of Federation of American Scientists (Kristensen et al. 2024).

When interventions are deemed necessary, the laboratories often conduct what is called a "Life Extension Program" (LEP). This major endeavor, spanning multiple years, gradually refreshes the entire inventory of a given design to ensure that it can remain deployed with confidence within its performance margins. LEPs are intended to replace "like-with-like" or to replace components (reusing existing inventory or using new components of the same "form, fit, and function") to preserve the weapons' design characteristics without introducing any new performance capabilities. Exceptions to this, in which more modern components have been introduced, include cases to enhance safety and security or to replace specific components with versions less vulnerable to aging or physical damage. Therefore, LEPs require some degree of production capability within the nuclear complex to replenish or supply refurbishment efforts. Such efforts have not included replacing plutonium pits, nor is this planned in the coming years.

Most weapons in the US arsenal were not originally designed to remain in the active stockpile for as long as they have, but the combination of improved scientific understanding and periodic LEPs has made this possible with high confidence in their continued reliability. A 2009 evaluation of LEPs by the JASON technical advisory group concluded that the programs could continue "for decades, with no anticipated loss in confidence, by using approaches similar to those employed in LEPs to date" (JASON 2009). This has proven to be the case, and the laboratories' capabilities for effective stockpile stewardship have only improved in the succeeding years. In recent years, those capabilities have made possible life extension for all the designs in the current stockpile. The result is a nuclear arsenal that is relatively "fresh" (with one exception), despite the time since they were first designed and produced.

Indeed, stockpile stewardship has exceeded the capabilities originally envisioned for its required success. The facilities and scientific tools have become *so* advanced over the past three decades that they introduce a challenging dilemma. As designs in the stockpile have aged, the materials and technology around which they were designed have become increasingly antiquated compared with those that today's weapons scientists have at their disposal. The confidence instilled by improved technical understanding leads to the temptation to introduce design modifications made possible by improved materials, processes, and technology. This is especially the case to the degree that using modern materials and technology can enhance safety, security, and reliability.

Pushing the Limits of Stewardship

A 1994 expert review of the DOE's plans for science-based stockpile stewardship foresaw the dilemma created by the ever-improving technical capability (Drell 1994). The authors warned that implementing the Science-Based Stockpile Stewardship program "must avoid the appearance that, while the U.S. is giving up nuclear testing, it is as compensation introducing so many improvements in instruments and calculational ability that the net effect will be an enhancement of our advanced weapons design capabilities." That statement was prescient. The scientific and computational infrastructure developed as part of stockpile stewardship has made possible the successful maintenance and life extension of the US arsenal; it has also, by virtue of its success, enabled designers to modify and certify changes to warhead designs without resorting to nuclear tests.

How much change can be introduced to a design while retaining confidence in its safety, security, and reliability has long been a subject of debate. Some changes may become necessary if original materials or components are no longer easily obtained or available at all. Or they may be elective—for instance, if a new manufacturing technique can eliminate the use of hazardous materials or allow for better reproducibility. In other cases, it may be possible to reproduce a component in a way that reduces its vulnerability or increases its longevity. Such changes can help increase safety, security, and reliability. However, their cumulative effect is to gradually shift the design away from its original parameters. Historically, such changes have involved components exterior to the nuclear explosive package (which contains the plutonium and other nuclear materials) and that can therefore be repeatedly tested to failure in the laboratory with high confidence.

More controversial are changes that are not necessary to extend a weapon's life and which lead to new performance capability. One recent example is the life-extension program for the B61-12 gravity bomb: it included installing a new tail-kit assembly that gave digital guidance capability to this formerly ballistic weapon, thereby improving targeting accuracy. The National Nuclear Security Administration (NNSA) claims that this enhancement resulted in "no overall change in military requirements or capabilities" because it could be accompanied by a reduction in nuclear yield (NNSA 2018a). However, it is reasonable to expect that the enhancement changes potential scenarios for using the weapon, which may result in changes to military strategy.

In recent decades, the US government has explicitly explored building new weapons to introduce new capabilities, although it has cancelled all such programs so far. Both the Robust Nuclear Earth Penetrator (RNEP) proposed in 2003–2005) and the Reliable Replacement Warheads (RRW 1 and 2, 2004–2009) were conceived as weapons to strike deeply buried or hardened targets (Medalia 2004; Medalia 2009).

While the RNEP was projected to reuse the nuclear explosive package from the largest-yield weapon in the US arsenal (the 1.2 megaton B83), the RRW-1 was partly conceived as a feasibility study for certifying a weapon with a new pit design and manufacturing process (NNSA 2008). The RRW-2 proposal would have reused existing pits for an air-carried warhead. These were the first proposals since the inception of stockpile stewardship to suggest going beyond maintaining the existing stockpile and toward potential certification of new designs using existing components (including previously tested nuclear explosive packages).

Ultimately, bipartisan opposition killed both programs. Funding for the RNEP program was eliminated in 2005 with the Republican chair of the House Appropriations Energy and Water Development subcommittee, David Hobson (R-OH), stating, "We cannot advocate for nuclear nonproliferation around the globe, while pursuing more usable nuclear weapons options here at home" (Ackland 2006). By 2009, funding for both RRW proposals was on the chopping block, and the move to build new weapons for the US arsenal appeared momentarily stalled. Comments by President Obama in April of that year appeared to reinforce this trend, calling for concerted efforts toward disarmament and a reduction in the role of nuclear weapons in US national security strategy (Office of the Press Secretary 2009).

This rhetorical shift away from nuclear reliance would prove fleeting. To gather Republican support for ratification of the New Strategic Arms Reduction Treaty (New START) with Russia in 2010, the Obama administration agreed to funding for nuclear modernization efforts that would ultimately begin a significant shift in the nuclear complex (Hewitt 2019). Around the same time, concern over perceived changes taking place in other nuclear states increased the sense of urgency within the national laboratories to exercise if not bolster US capabilities.

A Paradigm Shift: Out with the Old, In with the New

Advocates touted the 2010 decision to increase funding for modernizing the nation's aging nuclear infrastructure as consistent with arms control and US efforts toward disarmament; their logic was that a strong nuclear complex could be a hedge against a leaner nuclear arsenal. Commitments made by the administration at the time included plans for new bombers and new nuclear-capable submarines. The utility of ICBMs, the third leg of the nuclear triad, was debated at the time, but the administration agreed to maintain them, partly at the behest of the Senate ICBM coalition, composed primarily of members from states hosting or maintaining the missiles (Conrad et al. 2009; Knight 2024a).

This commitment to invest in nuclear delivery systems and infrastructure was closely followed in 2012 by plans from the Nuclear Weapons Council and the NNSA to significantly reshape the composition of the nuclear arsenal itself: consolidating the number of warhead types by fielding three new "interoperable warheads" (IW-1, IW-2, and IW-3) that could be used on multiple delivery systems. This was referred to as "3+2," referring to the intent to have three interoperable warheads for the ground- and sea-based legs of the triad and two for the air-based leg (MacDonald 2013).

To satisfy the requirements of the 3+2 strategy, a scheduled life-extension program for the W78 ICBM warhead, the oldest weapon in the deployed stockpile, was renamed the W78/88-1 LEP. This marked the intention to make the warhead "interoperable" on the Minuteman III ICBM *and* the Trident II D5 submarine-launched ballistic missile (SLBM). The program was soon renamed IW-1, consistent with the interoperable warhead strategy.

The evolution of the naming convention is suggestive of the fact that interoperability would require mixing and matching primary and secondary components in new configurations, resulting in nuclear explosive packages distinct from any previously tested. Despite the obvious novelty, the administration claimed that interoperable warheads would not constitute new nuclear weapons because the design of those components was not new. By this logic, 3+2 was deemed consistent with 2010 US *Nuclear Posture Review*, which stated, "The United States will not develop new nuclear warheads" and would, instead, prioritize refurbishment and reuse (DOD 2010). A 2015 analysis of 3+2 by the Union of Concerned Scientists (UCS) had criticized the rather distorted semantics used to justify this approach; the product would obviously differ from warheads already in the arsenal (Gronlund 2015).

New or not, the proposal for interoperable warheads signaled a willingness to introduce significant changes to weapons designs under the auspices of life extension.

In 2014, the Nuclear Weapons Council temporarily suspended the IW-1 program, partly due to growing costs, but the 2018 *Nuclear Posture Review* resurrected it (Mattis 2018). The program was renamed the W87-1 without the potential for interoperability, but with the intention of being entirely newly manufactured rather than refurbishing or reusing components from the W78 that it would replace (Bawden 2020a). The NNSA stated at the time that life extension of the W78 would not meet military requirements, meaning the land-based leg of the triad would require a new warhead (NNSA 2018b). Although the newly proposed warhead has "87" in its name, it is not a life extension of the W87-0-, another change in the nomenclature traditionally used that somewhat obfuscates the program's novelty.

The choice to build a new warhead has had significant implications for the production capacity of the US weapons complex. Most important is the increased need to produce new plutonium pits. Previous LEPs had mainly reused the weapons' primary stages, updating other components around it. Manufacturing new weapons requires either reusing existing pits or making new ones. Numerous other manufacturing capabilities are also required, including the increased need to synthesize new high explosives, manufacture reentry vehicles, develop electronics for firing and fusing systems, and make a host of other items that the national labs and associated industry did not have to produce under the stewardship model. Furthermore, there is an important distinction between remanufacturing to original design specifications (replacing "like with like") and remanufacturing with modernized (presumably improved) components that introduce new capabilities.

The choice to manufacture a new weapon thus represents a significant paradigm shift. It appears to mark the end of the era of stockpile stewardship and life extension, and it anticipates a commitment to new nuclear weapons for decades to come (Figure 2.2). This transition would appear to move the United States away from its obligations under the Nuclear Nonproliferation Treaty: "Each of the Parties to the Treaty undertakes to pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament" (United Nations 1968).

The transition from stockpile stewardship to fully embracing modernization has been reflected in the evolving use of official language to describe US strategy, from the 2010 pledge to refrain from developing new nuclear warheads, to the 2024 Stockpile Stewardship and Management Plan, which states, "At a time of rising nuclear risks, a partial refurbishment strategy is no longer adequate to meet mission needs" (DOD 2010; NNSA 2023a). The latter document describes stockpile stewardship in the past tense, adopting the more recent "Stockpile Research, Technology, *and Engineering*" (SRT&E) terminology, with the stated goal of "enabling the *future* nuclear deterrent [emphasis added]."

Rising global nuclear risks are often cited to justify modernization, as exemplified in a 2023 report of the Congressional Commission on the Strategic Posture of the United States (Creedon et al. 2023). However, as the history briefly described here shows, the W87-1 program stems from decisions and conceptual designs that predate most of the geopolitical circumstances discussed today. Interoperable warheads were first conceived nearly a decade before reports that China was constructing its own ICBM silos (2021) or enlarging its nuclear arsenal, before Russia annexed Crimea (2014) and invaded eastern Ukraine (2022), and when North Korea had conducted only two of its six known nuclear tests (Warrick 2021; Park 2023). Pressure to modernize the US arsenal predates these circumstances and has significant domestic motivations.

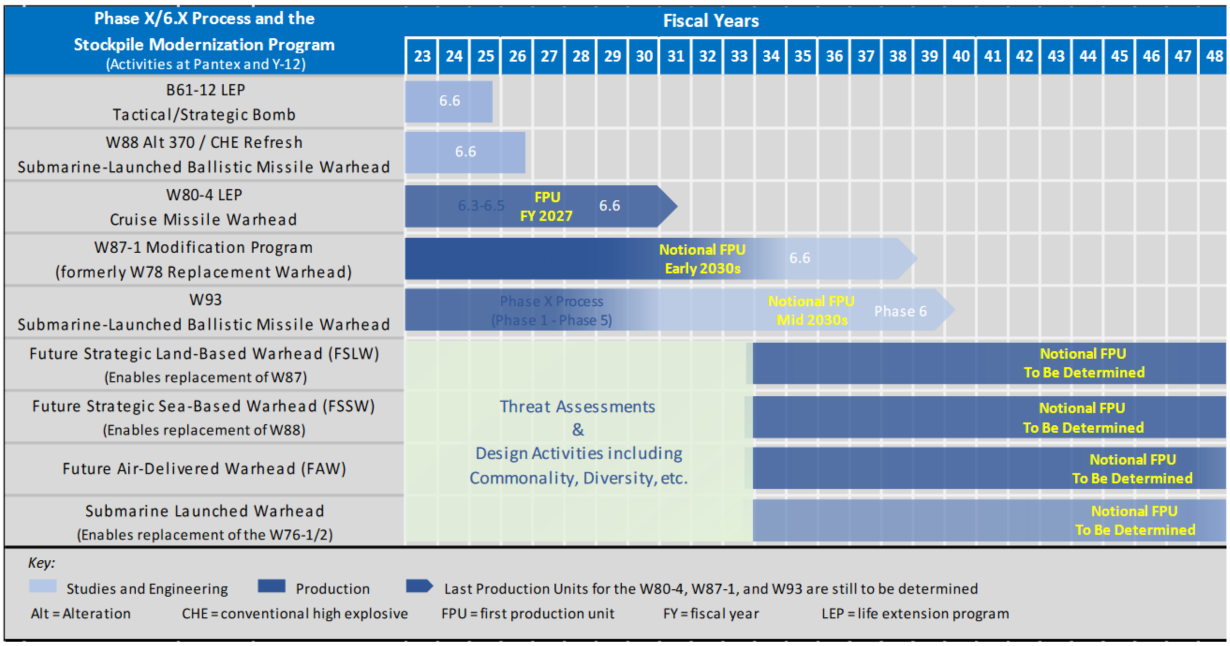
Reinvigorating the Enterprise

> *"Creation of the stockpile of the future will require the vision and will to unleash the creative energy of the workforce. . . . Sustainment of the existing stockpile through [life extension programs] has been necessary but not sufficient . . . I have seen what Los Alamos scientists and engineers can accomplish, and it has been impressive. Nurturing and empowering the intellectual capital to design and certify a modern nuclear weapon, when needed for the future stockpile, is the next step." –Former Los Alamos Director, Terry Wallace, in 2018 (Spivey 2021)*

US champions of nuclear modernization have long expressed concern over a perceived loss of capability in the nuclear complex, a loss that, they argue, endangers the nation's ability to respond to changing defense requirements. While stockpile stewardship has proven extraordinarily capable in maintaining the post-Cold War arsenal, critics contend that it does not create what the Bush administration termed a "responsive infrastructure" that can nimbly address changing needs. On the other hand, modernization presents an opportunity to reconstitute knowledge and infrastructure that nuclear proponents claim have atrophied.

Plans for new nuclear warheads, along with the associated research, manufacturing, and certification, shift the mission of the national labs from stewardship back to production, and that comes with the largest historic investment in the complex since the Manhattan Project.

FIGURE 2.2. Planning for the Future Nuclear Stockpile



US plans for the future of its nuclear arsenal include ongoing development of newly conceived warheads and preservation of a nuclear triad late into this century. The FY2024 Stockpile Stewardship and Management Plan foresees imminent production of two new nuclear warheads—the W87-1 and W93—and several future warheads for all legs of the triad. With first production units foreseen in the 2040s, this assumes continued reliance on the nuclear arsenal until late in the century. The numbers in each bar indicate a project's phase of development according to NNSA's project management nomenclature. Phase 6 indicates full-scale production and sustainment. SOURCE: NNSA 2023b.

Lawrence Livermore National Laboratory, which maintains responsibility for designing and certifying the W87-1, has hailed the project as "invigorating the enterprise" (Weldon and O'Brien 2022).

Since the last American underground nuclear explosive test in 1992, weapons designers and physicists involved in developing the current arsenal have left the workforce, and the practice of weapons production has given way to a more academic type of science in the labs. While significant investment has been made in facilities to support stockpile stewardship in the absence of such testing, other infrastructure across the nuclear complex is showing its age.

Meanwhile, the labs suffer from a recruitment-and-retention problem. For younger scientists, work on nuclear weapons may not appear as salient or attractive compared with the dynamic, often lucrative software and technology industries and other rapidly advancing academic fields that attract people with many of the desirable technical skill sets. For the labs, modernization presents an opportunity to reverse this attrition. Indeed, Los Alamos hired over 2,500 new employees in 2023—a 14 percent year-over-year increase, primarily to support the production of plutonium pits (Wyland 2024). However, these workers lack the experience of retiring employees who contributed to the existing stockpile.

An important domestic driver of modernization is the opportunity to reverse trends that weapons proponents fear have weakened US readiness, as well as to regrow infrastructure and workforce seen as necessary to ensure plans for what the NNSA calls the "future nuclear deterrent" (NNSA 2023b). These plans also ensure a robust future for the defense contractors who manage the national labs through limited-liability consortia and who represent one of the most powerful lobbying forces in Washington, DC (Aboukhater and Hartung 2024; Munoz 2024).

Current US plans for nuclear modernization project a continued reliance on nuclear weapons for security well into the late 21st century. This undoubtedly plays a role in military planning by other nuclear powers that have observed US interest in modernization over the past 20 years, and as hard-won arms control agreements have simultaneously eroded, partly due to decisions by the US government (Landler 2018; Lopez 2019).

2.2 New Warheads Are Driving the Rush for New Pits

The W87-1 is the first warhead program since the end of the Cold War that will be completely newly manufactured, rather than extending the life of an existing design. The W93 SLBM warhead is expected to follow it closely (Figure 2.2). Together, these two warhead designs are driving the demand and schedule for plutonium-pit production.

The W87-1 Warhead

As a replacement for the W78, the W87-1 would join the W87-0 on the ground-based ICBM leg of the triad. It would be deployed on the Sentinel ICBM, which is under development as a replacement for Minuteman III missiles. The cost of the W87-1, estimated at $14.8 billion in 2020, is likely to rise due to insufficient planning or assessment of cost and scope at its outset (GAO 2020). This figure excludes the cost of required pit production.

As its name suggests, the W87-1 will closely resemble the W87-0, one of the last weapons added to the stockpile before the end of the Cold War. It is expected to have a similar nuclear yield (about 300 kilotons, which could possibly increase to about 475 kilotons by modifying the weapon's newly manufactured secondary stage) (NNSA 2018b). This is equivalent to 20 to 30 times the yield of the bomb dropped on Hiroshima in 1945. The NNSA has stated that the nuclear components are closely based on a previously tested design (NNSA 2019). However, some changes to pit design, likely involving the fill tube for tritium boost gas, were recently accepted to facilitate manufacture. It is claimed that the W87-1 will neither provide new military capability nor require nuclear explosive testing because its primary design is sufficiently close to tested configurations (ExchangeMonitor 2024).

Historically, defense strategists have considered it important to have redundant warheads for every leg of the triad. The idea is to avoid the unprecedented situation in which a technical defect rendered one leg ineffective, thereby undermining deterrence. Given the apparent similarity in design between the W87-1 and W87-0, the benefits of redundancy may not be as strong in this case, nor as significant given the possible use scenarios for the ICBM fleet.

The rush to reach full pit-production capacity for the W87-1 is tied to anticipated (but highly uncertain) schedules for the Sentinel ICBM on which it would be deployed. In 2024, then-NNSA administrator Jill Hruby stated that Los Alamos would produce new pits for the W87-1, anticipating a capacity of 30 pits per year by around 2028. The second pit-production site, at Savannah River (which is significantly further behind), is scheduled to produce pits for the other newly proposed warhead, the W93, beginning in the mid-2030s (Hruby 2024a; Hruby 2024b). The Los Alamos National Laboratory (LANL) produced the first W87-1 pit to meet full qualification standards (termed "diamond stamped") in October 2024; the laboratory reportedly produced at least 14 developmental pits to various stages of completion in 2023 (Hruby 2024c).

The production schedule for new pits is urgent *only* if the United States seeks to deploy more than one warhead on Sentinel ICBMs, using multiple independently targetable reentry vehicles (MIRVs)—something the United States has not done since 2005. The United States currently has an estimated 540 W87-0 warheads available (Kristensen et al. 2024). This is more than enough to provide one for each ICBM in the entire fleet (present or future) without developing new warheads, even if the W78 were retired immediately. The Air Force acknowledges that the Sentinel missile will initially deploy with the existing W87-0 until the progressive rollout of the W87-1.

Re-MIRVing the ICBM fleet would have strategic consequences. It would increase first-strike incentives for an adversary—a single warhead could destroy multiple US warheads—which leads to a decrease in nuclear stability. Re-MIRVing is also likely to hamper future arms-control negotiations, however bleak the prospects for such diplomacy may appear in 2025. Continued reliance on the W87-0 as the sole warhead for the ICBM fleet should be possible given it is one of the newest designs in the US arsenal and includes modern safety and security features such as insensitive high explosive (IHE) and a fire-resistant pit.

The W87-1 Will Use a New Explosive

The NNSA has claimed that one of the biggest benefits of retiring the W78 in favor of the W87-1 is its ability to use IHE in place of the conventional high explosive (CHE) (NNSA 2018b). The high explosive drives the plutonium in the primary stage of a nuclear weapon into a supercritical configuration, triggering fission. The W78 warhead currently deployed on Minuteman III ICBMs still relies on CHE, as do the W76 and W88 warheads deployed on submarines.

Although all early weapons designs relied on CHE, it is sensitive and therefore vulnerable to accidental detonation. In a number of historical incidents, CHE detonations dispersed plutonium without generating a nuclear yield (Outrider n.d.). IHE is less vulnerable to detonation that would result from a physical insult (e.g., shock or high temperature) and hence the term "insensitive." This increases safety and security, particularly during transport, assembly, and disassembly and for air-carried weapons, which are more vulnerable in deployment than those that sit in silos or submarines.

Some arguments in favor of replacing the W78 with the W87-1 have focused on the increased efficiency and cost savings of going to an IHE design. Safety requirements for handling IHE are significantly less restrictive than for conventional high explosives, particularly at the Pantex Plant where assembly and disassembly take place (NNSA 2018b). However, such efficiencies could be gained in the ground-based leg of the triad simply by eliminating the W78 and relying on the existing W87-0, which already contains IHE. Development of the W87-1 is not required to achieve this goal.

The W87-1 would use a relatively new formulation of IHE developed by the Lawrence Livermore National Laboratory. Called LLM-105, its detonation performance reportedly approaches that of CHE but with the increased safety of IHE (LLNL 2018; NNSA 2015). New variants of High Explosive (HE) are being developed around the LLM-105 chemical composition for future use. The choice to use new rather than existing IHE formulations presumably comes with volume and weight savings that benefit payload considerations for the future Sentinel missile. At the same time, the ability to produce and qualify new high explosives in large quantities is an area that has been considered "at risk of atrophy" within the nuclear complex; the W87-1 presents an opportunity for renewal (Bawden 2020b; US Senate 2019). A new facility at Pantex for synthesizing advanced explosives began full production in 2019 and was reportedly operating at levels exceeding Cold War era productivity as of 2023 (Pantex 2019; Meyers 2023).

. . . and a New Aeroshell

The aeroshell (or housing) of the W78 warhead has also been cited as a reason not to pursue life extension because size and volume constraints would preclude the use of IHE in the existing Mk12 reentry vehicle (NNSA 2018b). Despite this, for deployment on Sentinel, the W87-1 will also require a new aeroshell, dubbed the Mk21A. The new aeroshell development includes the arming and fuzing assembly and radio frequency subsystem with antennas, spin subsystem, and electrical cables and disconnects (Pincus 2023). The new aeroshell comes with its own complex challenges and a cost of at least $1 billion (Harpley 2023).

Direct replacement of CHE with IHE is often not possible due to their differences in performance and the associated mass and volume requirements. Design constraints elsewhere in the primary, including requirements for compression of the pit itself, are also likely to restrict possibilities for direct replacement. It is thought that the new Mk21A aeroshell will be similar to the existing Mk21 used for the W87-0 warhead, presenting similar available volume but likely with some weight savings enabled through using modern materials and production techniques.

Aeroshell production is another of several challenging manufacturing bottlenecks that must be addressed for the W87-1. The certification of new aeroshells includes costly flight tests, the first of which failed in 2022 (Starr 2022). Test launches, conducted using Minotaur rockets, take advantage of decommissioned motors from retired Peacekeeper and Minuteman missiles, making each test expensive and increasingly precious due to limited resources. A 2024 flight test apparently succeeded, although few details have been released (Hadley 2024).

The cumulative financial costs and effort required to produce and qualify new pits, new explosives, new reentry vehicles, new firing and fuzing systems, and other associated components are far less than those to extend the life of an existing design. Reproducing an existing design (including the tested W87-0) would also likely introduce fewer requirements and instill greater confidence in performance. At present, the United States maintains enough W87-0 warheads to increase their deployment on ICBMs without the W87-1, even though, as noted, the choice to upload more than one warhead per missile (MIRV) would prove destabilizing geopolitically.

It would appear that the primary benefit of these activities is neither cost effectiveness nor increased capability. Rather, they offer the opportunity for the nuclear weapons complex to maintain relevance and capability, and for the investment in infrastructure that enables it.

The W-93 Warhead

Close on the heels of the program to develop the W87-1 is that for the W93, a new warhead conceived for either a new submarine-launched missile that would replace the Trident II D5 missile or (more likely) on a life-extended version of the Trident II (Leone 2024; Woolf 2021). The W93 is at an earlier stage of development than the W87-1, but its evolution bears many similarities. Just as the W87-1 derives from the Interoperable Warhead 1 (IW-1), the W93 closely descends from the previously cancelled IW-2, also reincarnated without the requirement for interoperability across delivery systems. Projected costs to develop the W93 have ballooned, from $14 billion in March 2022 to $22.9 billion in November 2023 (NNSA 2023b; 2022).

The W93 is expected to be a high-yield warhead (more than 400 kilotons), but there is speculation that a lower-yield option may also be considered. As a lightweight warhead, the W93 would add capability to future Columbia-class submarines; the NNSA and the Pentagon have argued that the lighter weight would help compensate for the fact that the submarines will carry fewer warheads than the existing Ohio-class due to having fewer missile tubes. A lighter, relatively high-yield (or variable yield) warhead would provide the Navy with the ability to "hold all targets in current plans at risk," implying that it would make possible strikes from a greater distance against hardened targets (Donnelly 2020).

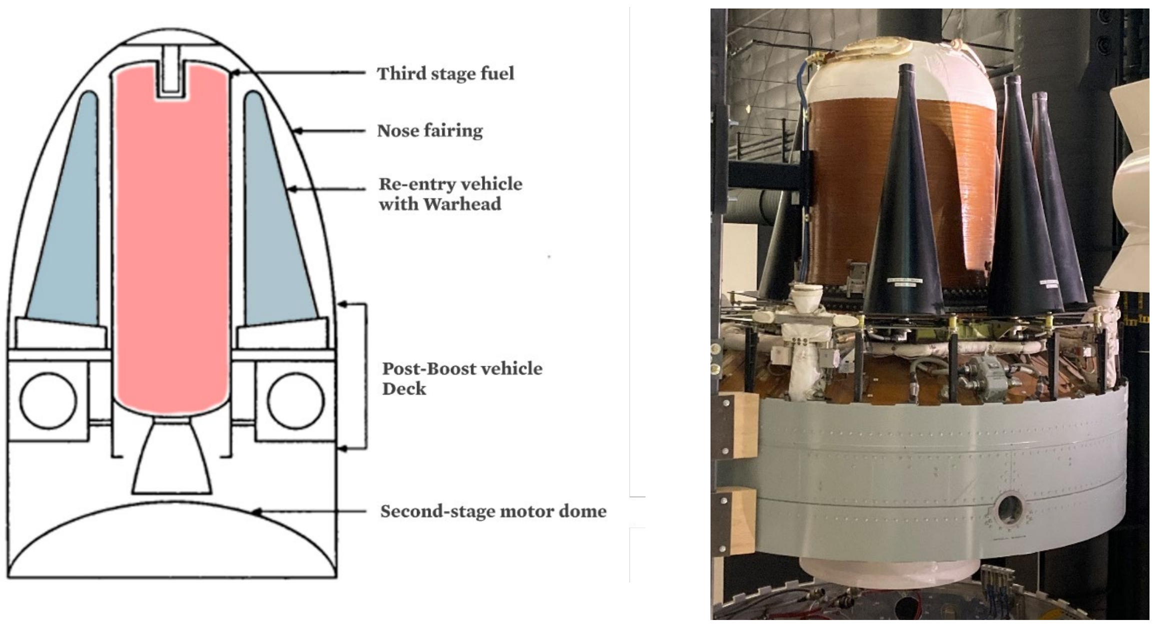
The W93 would supplement the existing W76-1 and W88, two recently introduced or refurbished members of the submarine-based leg of the triad. Given their recent production, both warheads should have multi-decadal lifespans, calling into question the true need for a third submarine-launched warhead (W93) with a yield similar to the W88.

According to an unclassified 2020 whitepaper from the Pentagon and the NNSA for Congress, the W93 was expected to replace other warheads (DOD/NNSA 2020). However, how the W93 would be integrated and what it would replace were left undecided, making its integration seem anything but strategic. Because the Columbia-class subs will enter service one by one, with the first expected in 2031 (at the earliest), the W93 may need to be made compatible with both current and upcoming generations of submarine, creating awkward timing with respect to the turnover in the Navy's fleet.

Due to the recent refurbishment of both the W76 and W88 warheads, it is not clear whether or how either would be phased out in favor of the W93 if current deployment levels are maintained. Notably, the DOD/NNSA whitepaper justified funding the submarine-based W93 by criticizing land-based ICBMs for increasing risk: "hedging with fixed intercontinental ballistic missiles would increase reliance on a launch under attack posture" (DOD/NNSA 2020). Given that the Pentagon and NNSA are also developing the new Sentinel ICBM and the W87-1 warhead, it's rather surprising to use the apparent vulnerability of that system to justify the need for the W93.

Like the W87-1, the W93 would employ IHE, despite the Navy's history of reticence to adopt it and the fact that IHE provides less safety benefit for warheads deployed on SLBMs (Gronlund 2015). Because of space constraints, Trident II SLBM warheads are arrayed around the fuel for the missile's third stage. That presents an explosion risk of its own, potentially negating most of the IHE benefit except during manufacture, transport, and disassembly (Figure 2.3) (Drell, Foster, and Townes 1990).

FIGURE 2.3. The Configuration of Submarine-Based Warheads Negates Much of the Benefit of Insensitive High Explosive



Left: Because the multiple warheads on the Trident II D5 SLBM are arrayed around the (explosive) fuel for the missile's third stage, the use of IHE carries less benefit than for weapons deployed on bombers or ground-based missiles, where the incremental safety and security are greater. Right: An example of multiple warheads arrayed around the fuel (orange cylinder) on an older Trident I C4 SLBM is on display at the National Museum of Nuclear and Atomic History in Albuquerque, New Mexico. SOURCE: Left, modified after Harvey and Michalowski 1994; right, author photo.

In addition to adding unnecessary pressure on the pit-production schedule, the W93 will also require a new aeroshell, called the Mk7. This would further strain the complex to produce and qualify several new aeroshells when the manufacturing capabilities are barely revived. The new aeroshell will also require flight testing.

A unique constraint driving requirements for the W93 is close cooperation with the United Kingdom. Under a Mutual Defense Agreement, the UK receives a good deal of nuclear technology from the United States for its own sea-based nuclear arsenal (LANL 2023). In particular, both nations rely on the Trident II D5 SLBM, and it is reported that the United Kingdom will use the new Mk7 reentry vehicle (to be provided by the United States) for its own variant of the W93 (MOD 2021). The two nation's versions of the W93 warhead are expected to bear many similarities, as is already the case with the British Holbrook warhead and the US W76.

Compatibility of components for the new British Dreadnought submarines (which use US propulsion plants) and the future US Columbia-class submarines thus significantly constrain the design space. Continued reliance on a shared missile design thus makes life-extension of the US Trident II D5 missile much more likely. That the Trident II D5 is considered reliable enough under life extension for the foreseeable future calls into question why a similar LEP is deemed unacceptable for the land-based counterpart, the Minuteman III.

2.3 The Sentinel Intercontinental Ballistic Missile Program

Sentinel: A Replacement for Minuteman III

The United States deploys 400 Minuteman III ICBMs in silos spread across large expanses of Colorado, Montana, Nebraska, North Dakota, and Wyoming (principally around the Minot, Malmstrom, and F.E. Warren air force bases). An additional 50 silos sit empty but are maintained in a “warm” condition, ready to be recommissioned. Each missile carries either a 300-kiloton-yield W87-0 or a 335-kiloton-yield W78 warhead. Each missile can carry up to three independently targetable W78 warheads (or two W87-0 warheads) and did so prior to de-MIRVing, which took place between 2001 and 2014, leaving a single warhead per missile.

The United States now plans to replace all Minuteman III missiles with a new “ground-based strategic deterrent,” referred to as Sentinel. Sentinel, which would carry the existing W87-0 warhead as well as the new W87-1 warhead, is therefore closely linked to the immediate rush to produce plutonium pits. However, the incremental military value provided by the Sentinel program is questionable. Moreover, its costs are soaring, and it will require the United States to overhaul not only the silos but also the vast communications-and-launch infrastructure spread across thousands of square miles of the Northern Plains.

As with plans for the W87-1 and W93, the push to replace Minuteman III began more than a decade ago under very different geopolitical circumstances than those used to justify its urgency today. The Air Force began to consider replacing existing ICBMs in 2013, and it produced a classified Analysis of Alternatives in 2014 examining possible paths forward. The conclusion was that Sentinel would be preferable and more cost-effective than life-extending the fleet of Minuteman III missiles—a routine practice that has kept them reliably deployed since the 1970s.

Plans call for producing 659 Sentinel missiles—enough to conduct routine flight tests and fill currently empty silos. The new missiles will also require refurbishing or replacing the 450 launch silos and modernizing more than 600 facilities to “like new conditions” per the Air Force Global Strike Command (Flatoff 2024).

The Department of Defense (DOD) claims that Sentinel will provide enhanced capability—specifically better accuracy, better “probability to penetrate” an adversary’s defenses, better range and payload capacity (with a larger “bus,” which is the final stage that delivers the payload), increased flexibility for targeting (including improved guidance), and better physical safety. Its rebuilt command-and-control infrastructure will be updated to respond to modern cybersecurity risks (Dalton et al. 2022). Sentinel is said to be designed to ease future upgrades, enabling the Air Force to integrate new technology as it becomes available and with components more easily accessible than is the case for Minuteman III (Losey 2024).

Despite these proposed improvements, many experts have criticized the program. It does not alleviate many of the current system's technical or strategic vulnerabilities, and its increases in performance do not necessarily overcome real-world challenges. Despite having better range and payload, it would still likely be incapable of striking targets in China or North Korea without flying over Russia, which could easily lead to a dangerous miscalculation. An analysis by Hans Kristensen and his colleagues from the Federation of American Scientists points out that the ability to evade an adversary's hypothetical missile defense lies with the warhead itself, not the missile; typically, the two have separated by the time interception is possible (Kristensen et al. 2024). Therefore, the analysis questions why *any* capability beyond Minuteman III would be required. Minuteman III can already potentially be uploaded with more warheads, and Sentinel will not increase US capacity to do so (not to mention that doing so would be politically destabilizing). Whether or not "modern" is better is therefore not entirely clear.

It's Not Just the Missiles

One of the greatest complications besetting the Sentinel program is the associated need to overhaul completely not only the silos but also the massive command-and-control structure that makes it possible for geographically dispersed missiles under different commands to be launched within seconds of one another. Sentinel would be larger than the Minuteman III, requiring the replacement of aging silos. Also, more than 7,500 miles of cabling between facilities would need to be replaced with modern fiber optic for secure communication; much of this would depend on easements across private land, only a third of which have been tentatively secured (Decker 2024a; Cameron 2024).

Undoubtedly, the launch facilities and command-and-control infrastructure associated with US ICBMs are dangerously outdated. The facilities are famously known for relying on 5¼" floppy disks and other almost comically antiquated analog systems from the Cold War era (Fung 2016). More seriously, the facilities may be contributing to increased cancer rates among missile operators, potentially due to high levels of polychlorinated biphenyls (PCBs) in the facilities where the Air Force stations staff for long periods in cramped, underground quarters (Copp 2023; Luna et al. 2024). While original plans for Sentinel called for reusing and partially modifying the silos, some may require total replacement (Cameron 2024). The full scope is yet to be determined, raising the question of whether ambitions for replacement are feasible—or even necessary.

Soaring Costs

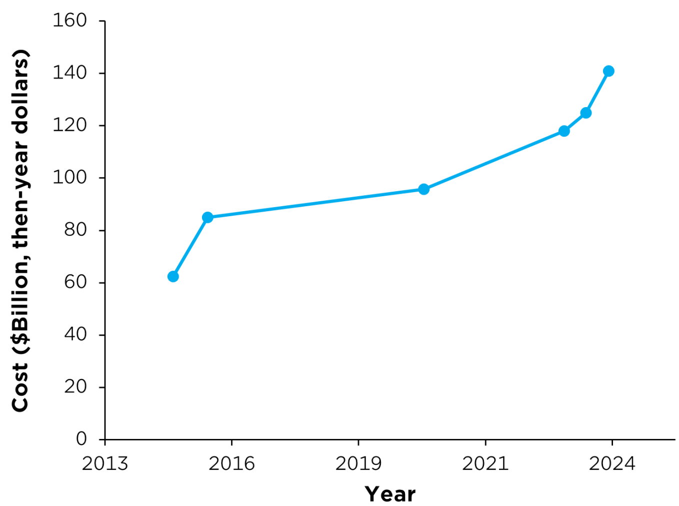
The required facility upgrades are separate from the design and development of the missiles themselves, but they fall under the same contract and are partly responsible for the program's soaring costs.

The economics of the Sentinel program have been controversial since its inception when the DOD awarded the contract to Northrup Grumman without competition (Erwin 2020). Although Boeing intended to compete, it effectively had to drop out when Northrup acquired a critical company with facilities in Utah that produces solid-fuel rocket engines, giving it control of a key part of the supply chain (Barnes 2024). Reliance on a single contractor has led to predictable risks, including delays due to staffing problems, supply-chain disruptions, and other management issues. All these have been noted by the Government Accountability Office (GAO) and criticized by the ranking member of the House Armed Services Committee, Rep. Adam Smith (D-WA), as "gross malfeasance . . . both by the people who oversee the project and the contractor" (GAO 2023; Capaccio 2024).

In 2023, the GAO warned that the Sentinel program "entered development without fully maturing its critical technologies, increasing risk of costly and time-intensive rework if problems emerge later in development." It noted that the program's large scope made it particularly complex and therefore at risk of cost overrun (Pincus 2023; GAO 2023).

Indeed, costs for the program have increased rapidly (Figure 2.4). Sentinel's initial price tag of $60 billion in 2015 increased to $85 billion the following year. After award of the contract, it jumped to $95 billion in 2020. In July 2023, the Congressional Budget Office estimated that Sentinel could cost $118 billion between 2021 and 2030 (CBO 2023). In early 2024, the Air Force announced a two-year delay in the program due to the aforementioned difficulties, accompanied by a 37 percent cost increase (Decker 2024b). By August 2024, the potential delay had reached five years (Cameron 2024), and the cost had skyrocketed to $141 billion (Copp 2024). Estimates of the lifetime cost come in at more than twice that amount ($315 billion through 2075), *not* including the cost of either the W87-1 warhead or the plutonium-pit production required to fabricate it (Taxpayers for Common Sense 2024).

FIGURE 2.4. The Rising Costs of Replacing US ICBMs



Originally estimated to cost $60 billion when analyses of alternatives were studied in 2014, the projected cost of the Sentinel program ballooned to $141 billion as of 2024, triggering a congressional review due to a violation of the Nunn-McCurdy Act. SOURCES: Data from Kristensen et al. 2024; Knight 2024b; Taxpayers for Common Sense 2024.

Accountability?

When the cost of a DOD program increases by 25 percent or more over the current baseline estimate or 50 percent or more over the original baseline estimate, the Nunn-McCurdy Act requires the department to report the increase to Congress (Peters and O'Connor 2016). Sentinel triggered what the act describes as a "critical breach" in 2024, requiring justification for the program's continuation, including whether it is essential to national security, whether future cost control could be managed, and whether the program had a higher priority than other programs whose funding would be reduced to cover this program's increased cost.

In the lead-up to Sentinel's Nunn-McCurdy review, several members of Congress expressed concern that the review was not being conducted in the manner required by law and that the DOD was approaching the issue with a clear bias in favor of continuation. The group also noted that four years after the contract's award, there was still no master schedule, anticipated timeline, or resource phasing for all of the work involved (Garamendi et al. 2024). Similar critiques were applied separately to the pit-production mission.

Following review and despite the program's cost, Congress allowed it to proceed in July 2024. The details of the review remain classified, so it is unclear what justifications the DOD gave. The Air Force acknowledges that cuts to other programs will eventually offset the increases, but reportedly most of the increases will fall beyond the next five years (Copp 2024). This suggests that the true fiscal consequences for other Air Force programs are undecided and yet to come, contrary to the Nunn-McCurdy Act, which requires identifying how financial balance will be achieved. The inevitability of future cuts to other programs should be considered as part of the cumulative cost of Sentinel, particularly as they may affect conventional forces that would likely be deemed more essential to Air Force capability than ICBMs.

Facing the Consequences of Cost and Delay

While the consequences of rising costs appear to be deferred, other practical consequences of the multiyear delay to Sentinel will resonate through other programs in the near term. In March 2024, the Air Force confirmed that initial Sentinel flight tests (originally scheduled for December 2023) will not take place until February 2026 (Decker 2024a). The Air Force attributed this to increased lead times for components in the missile's guidance system. In August 2024, it was reported that silo construction could take years to begin (Cameron 2024). This will lead to at least some increased cost to keep existing Minuteman III missiles deployed with at least partial life extension. The Air Force originally justified Sentinel as less expensive than extending the life of Minuteman III. However, there are reports that, due to delays with Sentinel, Minuteman III missiles may need to remain in service until 2050 while still producing the new missile, thus compounding the costs of both systems and effectively resulting in the scenario that the 2014 Analysis of Alternatives rejected (Capaccio 2025).

Separate delays with plutonium-pit production complicate the synchronization of the warhead and delivery-system upgrades. It is expected that Sentinel will initially be fielded with existing W87-0 warheads until the W87-1 can be introduced incrementally as pit-production efficiency allows. If the W87-1 is ready before Sentinel is deployed, it is highly improbable that temporary deployment on the Minuteman III would be considered. Doing so would require costly flight testing as well as other modifications required for compatibility of the new warhead and Minuteman III's post-boost system. Delays with either W87-1 production (dependent on LANL's pit-production rate) or Sentinel's deployment (currently uncertain) affect each other, and the perceived benefits of a new missile and new warhead might not be realized for years to come. At present, neither timeline is easy to predict and both are over budget.

Meanwhile, delays to new Columbia-class submarines led the Biden administration to announce that some of the existing Ohio-class subs would likely need to have their life extended to maintain some capability until other modernization programs across the triad, including Sentinel, catch up (Liang 2024). This means that modernization delays to the ground-based leg will potentially have repercussions for other legs of the nuclear triad and introduce the need to extend other programs to avoid gaps in capability.

2.4 Available Alternatives for the Triad without Pit Production

> *"If nuclear deterrence rather than reproducing the status quo or expanded pit replacement is the goal, current pit production plans are not a requirement but one option of many." —Sharon K. Weiner, Arms Control Today, 2020 (Weiner 2020)*

As delays and budget increases spread across so many programs, it seems clear that the scope of US nuclear modernization efforts exceeds what the complex can currently support. Furthermore, past performance suggests that cost and delay in these major acquisition programs are likely to worsen in the decade (or more) before today's efforts can or will come to fruition. The Pentagon will likely need to explore alternatives that respond to real-world constraints and allow an achievable path forward. These include what can reasonably be accomplished financially with the available workforce, supply chain, and infrastructure.

Several options are possible, all of which either reduce or eliminate the need for pit production and ICBM modernization in the near term. All would significantly reduce costs and logistical pressures on the complex, while allowing better oversight of programs for which modernization may be deemed more critical.

According to the NNSA, the first decade or more of plutonium-pit production at Los Alamos and Savannah River is devoted to the new W87-1 and W93 warheads, respectively. Jill Hruby, NNSA administrator from 2021 to 2025, clearly stated, "The W87-1 and W93 programs are setting the quantity and schedule of pit production now" (Hruby 2024a). That view drives what some have described as an unachievable crash effort to reestablish pit production capability (Asplund and von Hippel 2023). Looking to the future, the NNSA's forecasts for several other new warheads (Figure 2.2) would create an ongoing need for new pit production.

Because new pits are not intended to extend the lives of existing nuclear weapons through stockpile stewardship or LEPs, pit production will not contribute to the safety, security, or reliability for the 1,770 weapons in the active stockpile (Table 2.1). Furthermore, given what is known about plutonium aging (see Chapter 3), a program to replace pits in existing weapons could be carried out at a much more modest and achievable pace since they would not be required for decades to come.

The requirement of 80 pits per year is not only unachievable but tremendously expensive, and it places a tremendous burden on the US nuclear infrastructure and its workforce. A more measured approach is important for the safety of workers and communities, for calculated prioritization of resources, and to avoid repeating costly failures that have characterized other large NNSA projects.

These issues should be of concern to both advocates and opponents of nuclear modernization. Trying to accomplish too much and failing may ultimately prove more harmful to foreign perceptions of US capability than a more modest, more measured approach that addresses technical weaknesses where they exist, and that is also more conducive to international dialogue and arms-control efforts. Should US ambitions prove untenable, the costs may prove to be more than just economic.

The Feasibility of Reusing Pits for the W87-1 and W93

> *"It's always easier to reuse existing SNM [special nuclear material] than to produce new components. Thus, the capacity of existing resources to conduct pit reuse always exceeds the capacity to produce new pits." —Brett Kniss & Drew Kornreich, Los Alamos National Laboratory, November 2009 (Kniss and Kornreich 2009)*

Should the United States refrain from producing new nuclear weapons designs, several scenarios would enable the United States to scale back plutonium-pit production, or even place it on hold until required.

The United States maintains a large inventory of plutonium pits from retired nuclear weapons. Held at the Pantex Plant near Amarillo, Texas, many of these pits may be eligible for reuse based on their age, condition, and design. While the number of viable pits is not publicly available, the NNSA has stated that up to half of the W93 production may rely on reused pits (Hruby 2024d). Moreover, it has previously explored this option for the W87-1 (NNSA 2018b). If reusing pits is, indeed, possible for either or both of the proposed warhead designs, that could alleviate the need for two pit-production sites, potentially avoiding the need for an expensive retrofit of the Savannah River facility and make possible a much more modest program at Los Alamos.

A Plentiful Inventory

At the height of the Cold War, the United States possessed 31,255 nuclear weapons, a number reduced to 3,748 today (Kristensen 2024; NNSA 2024). Weapons no longer in the stockpile have been dismantled or await dismantlement. From 1994 to 2023, the United States dismantled 12,088 nuclear warheads; another 2,000 awaited dismantlement as of 2024 (NNSA 2024). Consequently, the United States reportedly has 61.5 metric tons of "excess" plutonium (NNSA 2023b). Much of this material is still in the form of pits because the United States has so far failed to execute plans to convert at least 34 metric tons of what is deemed excess into other forms such as Mixed Oxide Fuel (MOX) or to "dilute and dispose" of it in a down-blended (non-weapons usable) form (Lyman 2014; US State Department 2010). This has created a tremendous inventory of plutonium pits at Pantex, and as much as 9.5 metric tons of plutonium in unspecified form remain at Savannah River, awaiting treatment and risking violation of a settlement between the federal government and South Carolina (Moniak 2024a).

The Pantex facility is authorized to store up to 20,000 plutonium pits, but it has reportedly approached (GAO 2014; Moniak 2024b) or even exceeded (Paltrow 2018) this limit. Some 4,000 to 5,000 of these pits are believed to be held in strategic reserve for potential reuse and could be considered for use in place of new pit production. In most cases, their age is not yet a reason to exclude them.

Precedents for Reusing Plutonium Pits

Reuse of existing pits is not a radical proposition. Rather, the national laboratories have extensively explored the idea in the past. Both the Reliable Nuclear Earth Penetrator and Reliable Replacement Warhead 2 proposals would have relied on pit reuse had they gone forward. As noted at the time, some older pits can be modified to improve performance margin and reliability (NNSA 2008). As of 2024, the PF-4 facility at Los Alamos had reestablished much of the infrastructure, tooling, and physical requirements to do so.

Pit reuse has been considered more recently as well. According to the 2015 Stockpile Stewardship and Management Plan, "Pit reacceptance and reuse functions will augment pit production to ensure necessary quantities are readily available to satisfy future stockpile requirements"(DOE 2014). In 2018, the NNSA suggested that the W87-1 could, if unforeseen circumstances require it, "deploy with a re-used pit" (NNSA 2018b). As recently as 2020, Lawrence Livermore was working with production sites to "broaden pit reuse options to respond to emerging needs," according to its performance review (NNSA 2020).

While new pits may increase performance margins and, arguably, lifespans, most pits in the strategic reserve are still too young for plutonium aging to be of great concern over the average projected deployment of a warhead design (about 30 to 40 years) (Hemley et al. 2006; Chapter 3). Reused pits can be qualified and margins understood through non-nuclear explosive testing. Furthermore, other means can compensate for reduced margins, including replacing the explosive and increasing the amount of "boost gas" (in which tritium gas helps produce neutrons during implosion of the primary stage). Finally, much of the yield in modern thermonuclear weapons comes from the secondary stage, not the primary (which contains the pit). Modifications to the secondary subassembly may also be possible to help compensate for reduced margin in the primary, helping broaden options for pit reuse from the thousands available. In general, secondary performance is well understood, and the United States has the ability to produce "canned sub-assemblies" (containing the secondary stage) with existing infrastructure at the Y-12 facility in Oak Ridge, Tennessee.

A proven case study for pit reuse, one that likely informs current efforts for the W93, was the cancelled W89 warhead project. Development of the W89 was underway when the United States shut the Rocky Flats plutonium facility in 1989, ending large-scale US pit production and leading to a short-lived plan for pit reuse at Pantex. The W89 was designed to reuse pits from the retired W68, of which 5,250 were produced—a staggering number by today's standards. The W89 was designed to have a yield in the range of a few hundred kilotons, use IHE and modern safety and security features, and render the reused pits fire-resistant by adding vanadium cladding. Because explosive nuclear testing was underway until 1992, the new configuration is believed to have been proven with a full-scale underground test (Harvey and Michalowski 1994; Leopold 1992). The W89 program was terminated shortly thereafter, so all these pits presumably remain available and are proven compatible with modern requirements, including IHE.

Pit Storage May Compromise Reuse Options

A possible limitation to pit reuse is the physical condition of the many thousands stored at Pantex. Plutonium is highly reactive and susceptible to oxidation in the presence of ambient atmosphere and moisture. In addition, because some pits produce more heat than others, the heat load within storage containers must be considered and sometimes managed.

The need for hermetically sealed containers for pit storage capable of preventing incursion of moisture and contact with organic materials has long been understood (DOE 1994). Pantex enacted an "Integrated Pit Storage Program Plan" in the 1990s to facilitate proper packaging, but, in 1999, the Defense Nuclear Facilities Safety Board (DNFSB) reported that the program was failing to carry out planned work. The board cited delays of up to five years, lack of funding, and the ongoing presence of incompatible materials that could lead to chemical corrosion (Dwyer and Waugh 1999). Fiberboard inserts from the Celotex™ company were used to position and protect many pits within their containers, but that material is composed of sugar cane, paper, starch, and wax—organics that can be a source of moisture and chlorides, which can accelerate degradation of the exposed pit surface (Connery 2021; Defee, Landsberger, and Iskander 2001).

Unfortunately, a recent review of pit-storage conditions suggests that the situation may not have improved in the nearly 30 years since these issues were identified. While no public information is available about the condition of pits, one can infer that the quality of some reserve pits stored in unsealed containers could have been compromised by negligent storage practices. In 2022, the DNFSB found that the number of pits stored in unsealed containers had risen from 8 percent in 2014 to 14 percent in 2021, citing a "relaxation in requirements to preserve pit quality and integrity" (Connery 2021). This was true not only for older pits but also for current stockpile program pits. The contractor at Pantex, Consolidated Nuclear Security, LLC, cited "a lack of funding and priority" to explain why so few pits were being moved to sealed containers annually (Connery 2021).

Other conditions, including the quality of climate control in bunkers where pits are stored and least one flood that resulted in stormwater infiltrating a storage area, illustrate the challenges facing pit storage (ExchangeMonitor 2017). Because of these uncertainties, the NNSA should be required to provide a lifetime assessment of pit condition and inventory for reuse as part of its justification for further pit production. On the basis of inventory alone, reuse should be feasible, and it is certainly preferable given the costs, complications, and risk inherent in new production.

Pit Reuse for the W87-1 and W93

As noted, in 2018 the NNSA suggested a scenario in which the W87-1 could be deployed with a reused pit (NNSA 2018b); in 2024, NNSA administrator Jill Hruby testified that up to half of the W93 production could reuse pits (Hruby 2024d). In other words, there are possible reuse avenues for both warheads. These should be explored more fully *and* exhausted to alleviate the requirement to produce 80 pits per year. To the extent that reuse can reduce pressure on production, a more measured, cost-effective, and appropriately scaled approach can be pursued.

Options for reusing pits may be more extensive in the case of the W93 than for the W87-1, in part because of the Navy's historic acceptance of conventional high explosives on board its submarines. Also, many more pits designed for CHE were produced for the US stockpile. The Navy's reasoning is not entirely tradition-bound but practical: warheads on submarine-launched Trident missiles are arranged tightly around the explosive fuel of the missile's third stage, negating many benefits of IHE (Figure. 2.3). It seems likely that the tested W89 pits with IHE also constitute a possibility for reuse; they exist in abundant quantity.

The NNSA has stated that the Savannah River facility would produce W93 pits (Hruby 2024d; Leone 2024). Should the W93 go forward, pit reuse would alleviate the immediate need for a second production facility and allow consideration of more efficient, lower-cost approaches. As discussed, the Savannah River plant faces construction challenges and is projected to cost $18 to $25 billion, according to NNSA's own (historically inaccurate) estimates (Hruby 2024a; Hunter 2019).

Therefore, pit reuse offers a means to scale back production to a sustainable level that is commensurate with immediate needs and priorities. Although the PF-4 facility at Los Alamos is not ideal as a long-term, sole-production facility, it could maintain the capability already established there while a more sensible and achievable plan is devised that increases the likelihood of successful execution with much lower risk.

Maintain a Single Warhead on Ground-Based Missiles

The primary motivation for pit production at Los Alamos is to provide pits for the W87-1, which will accompany the existing W87-0 on the new Sentinel ICBM. Production of the W87-1 is only required if the United States should choose to upload more than one warhead per ICBM. Currently, each Minuteman III is armed with a single W78 or single W87-0 warhead. Originally designed to carry up to three warheads each, ICBMs have been limited to one warhead with the 2010 implementation of the New START treaty. This standard could be maintained with the existing W87-0 warhead, alleviating the need for roughly the first decade of pit production at Los Alamos and with minimal impact on capability or reliability. Declining to MIRV would have significant security benefits as well as economic benefits.

While the W87-1 undoubtedly would improve upon the safety and security of the W78 (currently one of the oldest designs in the stockpile), its improvement relative to the W87-0 is unclear, given its expected similarity in design. Along with the W88, the W87-0 is one of the newest, most modern designs in the stockpile, containing some of the most recent pits produced. It already includes IHE, a fire-resistant pit, and among the most modern safety and security features. Furthermore, it has undergone a life-extension program, which could presumably be repeated if necessary (Heller 2012). The United States has 540 W87-0 warheads, enough to place one on every ICBM with a significant reserve.

In 2023, the Congressional Commission on the Strategic Posture of the United States suggested that the nation consider putting multiple warheads on the future Sentinel system or even fielding them in "road mobile" configurations, among other recommendations for a broad nuclear buildup (Creedon et al. 2023). These recommendations have been widely criticized as "doomsday thinking" (Nelson 2023). Many of the committee's proposals could prove tremendously destabilizing, diplomatically counterproductive, and expensive, and they could elicit a similar response from adversaries, significantly increasing the nuclear risk (Drozdenko 2023).

Should the United States choose to maintain a nuclear triad, whether with Minuteman III or the planned Sentinel replacement, it can do so with the existing W87-0 warhead, while demonstrating restraint from slipping back into the disproven Cold War mentality that deterrence is a question of numbers. If uploading is deemed essential, it can be done on existing Trident II SLBMs, using existing W76 and W88 warheads or the future W93. These warheads would be less vulnerable to attack, and they are capable of striking targets globally without the same risk of territorial overflight inherent to the land-based ICBMs.

Cancelling the W87-1 and relying solely on the existing W87-0 would eliminate the need for at least the first decade of plutonium-pit production at Los Alamos. Also, a single production site could proceed more responsibly than is now the case.

Extending the Life of the Existing Minuteman III

Along with maintaining the W87-0 warheads currently deployed on Minuteman III, the United States could choose to life-extend the missiles themselves rather than pursue the troubled Sentinel program.

Minuteman III was first deployed in 1970, and some proponents of Sentinel cite that as reason for replacement. In fact, the missiles have been life extended as recently as 2015 at a cost of more than $7 billion. Life-extension efforts have improved the accuracy and survivability of its design and modernized its flight controls, the guidance system, propellant, and engines. The Air Force has described the result as "basically new missiles except for the shell" (Fetter and Reif 2019; Pampe 2012). Indeed, the Minuteman III is a well understood and thoroughly flight-tested design. Experts agree that it is technically possible to maintain it well into the future.

Relative Cost and Questionable Logic

Because Minuteman III has proven so capable, the Air Force has, indeed, considered life extension on multiple occasions, including as recently as 2022 (Dalton et al. 2022). In 2014, 2014, the Air Force conducted an Analysis of Alternatives for the Sentinel program (then called the Ground Based Strategic Deterrent) and concluded that the most cost-effective approach was to build a new missile rather than extend the life of the existing one. This conclusion relied on a cost comparison that required the current system to remain in operation through 2075 and assumed then-current deployment levels of 450 missiles—logic that has been criticized as arbitrary and intentionally favoring Sentinel (Shrager 2024; Korda 2021). The 2014 analysis remains classified, despite calls from Congress and others to release it, precluding further information on its rationale (Dress 2024).

Another 2014 study, conducted by the RAND corporation and commissioned by the Air Force, directly contradicted the Air Force's decision on how to proceed. It concluded that extending the life of Minuteman III would be two to three times cheaper than building a new missile and could meet the country's needs for several more decades (Caston et al. 2014). High-level officials, including Linton Brooks, former head of the NNSA, disagreed at the time with the need for a new weapon, saying that life extension of Minuteman III was not only feasible but eminently sensible (Young 2014). Subsequent analyses have repeatedly confirmed that life extension of Minuteman III would not only be possible but significantly more cost effective, even if the 2075 lifetime requirement were upheld (Fetter and Reif 2019; Korda 2021).

Given the increases in the projected cost of Sentinel since 2014, this is almost undoubtedly true. However, the Air Force maintains that "there is no backup plan for Sentinel," claiming that the window for upgrading Minuteman III has now passed, in part because it has now waited too long to do so (Heckman 2023; Dalton et al. 2022). Ironically, delays to Sentinel are now likely to necessitate maintaining Minuteman III until at least 2050, with as yet unknown cost implications (Capaccio 2025).

Statements from the Department of Defense and conclusions from the 2014 RAND analysis are consistent in noting impending supply issues for Minuteman III components, including missile bodies and motors. Regularly conducted test flights using reserve missiles contribute to a dwindling supply. While it would seem that the industrial challenges to renewing the US supply of tested components should not prove significantly more difficult than developing entirely new ones that require qualification, there are other simple solutions to this problem. One is to temporarily reduce the number of annual test flights until production capability can compensate. Another is to further reduce the number of deployed missiles. A smaller number of deployed ICBMs would make life extension of Minuteman III even more cost effective by comparison, while providing a strategic reserve of components from retired missiles until reproduction can meet demand. Adam Smith (D-WA), Democratic leader and recent chair of the House Armed Services Committee, suggested that this scenario is not considered to significantly detract from US defensive capability given the relative vulnerability and strategic utility of land- and sea-based missiles, respectively (Smith 2024).

Eliminate the Ground-Based Leg of the Triad

The most forward-thinking approach—but also the simplest—would be to eliminate deployed ICBMs completely, not just to reduce their number. The absence of the bloated Sentinel program would eliminate the need for pit production for the W87-1, and the United States could progressively phase out Minuteman III when it reached the end of its service life. Eliminating the land-based leg of the triad would do away with "launch on warning" posture. This would significantly improve global security, while providing significant cost savings by eliminating future life-extension and maintenance of the missiles and associated infrastructure.

Coupled with pit reuse for the W93, eliminating ICBMs would allow the United States to maintain pit production at a research level until pit lifetimes dictate their replacement. That time is not imminent for the existing stockpile.

Over the years, the Union of Concerned Scientists has addressed in detail the rationale for eliminating the ground-based leg of the nuclear triad (Wright, Hartung, and Gronlund 2020; Negin 2024; MacDonald 2024; Knox 2024). And this idea comes not only from nongovernmental organizations and outside analysts; it has also come from senior officials formerly responsible for the weapons themselves, including former Secretary of Defense William Perry, former US Strategic Command director and Joint Chiefs of Staff vice chair General James Cartwright, and former head of US strategic nuclear forces General Lee Butler. All have advocated in recent years for eliminating ground-based missiles based on their diminished relevance and destabilizing nature (Wright, Hartung, and Gronlund 2020; Perry and Cartwright 2017; Cartwright and Blair 2016; Butler 2015).

ICBMs Are Vulnerable and Make the US Population Vulnerable

The literature on the rationale for eliminating ground-based missiles is vast, so the following only briefly distills why that path should be considered in order to reduce or eliminate much or all of the immediate pressure to produce plutonium pits.

During the Cold War, ICBMs were known as the “nuclear sponge,” so-called because some strategists believed they would “soak up” a Russian first-strike while preserving other legs of the triad for retaliation. The fixed locations of the 450 US silos are known to the nearest inch; thus, they are the most vulnerable to attack of any part of the arsenal.

It is well known that upon receiving warning of an incoming attack, the US President (who maintains sole authority to authorize a nuclear strike) has about 10 minutes to assess the validity of the warning, decide on a response, and execute that decision (Wright, Gronlund, and MacDonald 2016; Blair 2020). Were the United States to detect an incoming nuclear attack (whether real or, as has occurred, false), the only way to avoid destruction of US ICBMs is to launch them, at which point they cannot be recalled or retargeted. What is referred to as a “launch on warning” posture is an outdated, dangerous holdover from the past and one that is unique to the ICBM fleet. Dozens of close calls in the past have driven both the United States and Russia to begin preparations to launch (UCS 2015).

Should the United States be first to launch missiles in a conflict, it is expected that a retaliatory strike would soon follow, killing tens of millions of Americans. A recent study demonstrated that up to 300 million Americans, as well as most populated areas of Canada and northern Mexico, are vulnerable to nuclear fallout from a hypothetical attack on US silos (Gault 2024; Phillipe and Berman 2023). Furthermore, missile silos are likely to be increasingly at risk from precision non-nuclear weapons—and likely before the end of life of the proposed Sentinel fleet (Dalton et al. 2022).

ICBMs Are Not Necessary: Submarines Provide Sufficient Capability

In contrast to fixed, land-based ICBMs, the submarine-based leg of the triad is invulnerable to detection, highly mobile, and significantly more powerful. The planned Columbia-class submarines are expected to be even less vulnerable than their predecessors, the Ohio-class submarines (Korda 2020).

Under current treaty limits, a single Ohio-class sub carries 20 Trident II ballistic missiles. This corresponds to 100 warheads, each with a yield of 90 kilotons or more. A single sub carries a destructive potential roughly 600 times greater than the bomb dropped on Hiroshima in 1945. The United States maintains eight to ten submarines at sea at all times (Kimball 2024; Kristensen et al. 2024).

When the United States was first developing its nuclear arsenal, land-based ICBMs were more powerful and accurate than submarine-launched ballistic missiles, and commanders were less confident in their ability to maintain secure communication with submarines at sea. This is no longer the case. SLBMs are now at least as accurate as ICBMs, and the Navy is confident that communications with its submarines are reliable and secure. This has been true for decades (Wright, Hartung, and Gronlund 2020; Negin 2024).

Even if the United States wishes to maintain or increase the number of deployed nuclear weapons (which is discussed, given the precarity and anticipated expiration of New START), submarines allow for this possibility and can carry even more warheads than they do now. The Congressional Budget Office has argued that relying on this capability is a means of saving tens of billions of dollars without reducing the number of fielded warheads (CBO 2018).

Political Pressure vs. National Security

Given the myriad changes from the geopolitical circumstances that led the United States to create its ICBM fleet, it is increasingly clear that the preservation of the triad's land-based leg is not solely a question of its contribution to national security (e.g., through the inherently dangerous ability to be launched quickly). It is also driven by political considerations and economic factors.

The Senate's ICBM coalition, composed primarily of members from states that host or produce the missiles, has lobbied vigorously to keep them, and it has been influential in the decisions determining the path of US nuclear modernization over the past decade (Conrad et al. 2009; Knight 2024a). The three bases that host the 450 silos cumulatively support thousands of jobs in rural states. In addition, the top 11 companies benefiting from the industrial recapitalization related to Sentinel spent more than $119 million on lobbying in 2019 and 2020, eclipsing the capabilities of opposing voices (Aboukhater and Hartung 2024; Hartung 2021). As noted, Northrup Grumman received the contract for Sentinel without competition and on a "cost-plus-incentive" basis, which allows for the originally negotiated amount to be adjusted but does not guarantee cost control.

Historic competition between the Air Force (which controls the land-based missiles) and the Navy (which operates the submarine-based leg) has also long been a factor in advocacy for the nuclear triad. Both branches of the military are keen to maintain their parts of the nuclear arsenal and the funding and jobs that come with it (Wright, Hartung, and Gronlund 2020).

As with the production of plutonium pits, the technical and strategic justification for replacing the ground-based leg of the triad is lacking—overshadowed by the perceived political and economic benefits of modernizing the nuclear complex. Eliminating ICBMs can be done without diminishing nuclear deterrence, thereby enabling tremendous cost savings and diminishing the need for pit production until absolutely required for the present stockpile.

Findings and Recommendations

The US nuclear complex is increasingly transforming its mission away from the highly successful practice of science-based stockpile stewardship and moving, instead, toward applying the scientific and technical advances the program has enabled toward designing and producing new nuclear weapons. This choice predates geopolitical events now used to justify it, including Russia's invasion of Crimea and subsequent war in Ukraine, as well as reports of China's nuclear expansion. The W87-1 and W93 warhead proposals are the latest of several attempts to introduce new warhead designs over the past 20 years. While previous proposals, including the Robust Nuclear Earth Penetrator, Reliable Replacement Warhead, and various interoperable warheads, were cancelled, they demonstrate a longstanding willingness to modernize and improve US nuclear capabilities that is inconsistent with the obligation to pursue disarmament under the Nuclear Nonproliferation Treaty.

The national laboratories could demonstrate and maintain enough pit-production capability to support future stewardship of the existing stockpile with a single production site and without rushing to achieve a quota of 80 pits per year for new nuclear warheads. Smaller production at a single site would be cheaper, safer, and more sensible, while giving the nuclear complex the ability to respond to the most urgent technical needs within the stockpile, should any be discovered.

The currently proposed program of plutonium-pit production is both unachievable and unnecessary to sustain the existing US arsenal. Available options would provide a safe, secure, and reliable nuclear arsenal for the foreseeable future, while reducing the near-term need for plutonium-pit production, reducing programmatic risk, and enabling cost savings. These options include:

> *Cancel plans to build the new W87-1 and W93 nuclear warheads:* The Trident II SLBM already carries two recently refurbished warheads. Moreover, while the W93 may provide additional military capability, its utility may not be worth the economic and logistical costs of outfitting the Savannah River Site (which is dramatically over budget, ill-suited for retrofit, and potentially able to produce only half of the required pits for the W93). Because the W87-0, the current ICBM warhead and one of the most modern in the US arsenal, cannot be MIRVed on the new Sentinel missile, the W87-1 may introduce additional capability but only for this new missile. Instead, the existing Minuteman III missiles could be refurbished and equipped with W87-0 warheads.
>
> *Refrain from MIRVing the land-based ICBMs*: Declining to put multiple warheads on land-based missiles would reduce the need for new pits and contribute positively to US and international security, given that MIRVed land-based missiles increase first-strike incentives. US land-based missiles could be armed with single warheads; this could be done with the existing, refurbished W87-0 warheads for decades to come.
>
> *Eliminate land-based ICBMs entirely:* This cost-effective approach would alleviate pressure to produce pits and would also eliminate the need to spend tens or hundreds of billions of dollars to life-extend the Minuteman III or build Sentinel. It would also yield security benefits, given the key role that the vulnerability of missile silos plays in pressure to keep a prompt-launch capability.
>
> *Prepare and implement plans to reuse existing pits whenever feasible*: Congress should mandate a comprehensive study of the inventory of existing pits stored at the Pantex Plant, with the goal of fully evaluating the availability and condition of pits for modification and reuse. While some pits may have been stored improperly, pit reuse for the W93 warhead would likely eliminate the requirement for a second pit-production facility at the Savannah River Site. This could save up to $25 billion.

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Chapter 3
Assessing the Lifespan of Plutonium Pits

> *"Producing no fewer than 80 [war reserve pits per year] as close as possible to the 2030 date remains a high priority, particularly considering uncertainties associated with performance due to the aging of plutonium in existing pits and meeting new safety and security requirements." —NNSA Administrator Dr. Jill Hruby (Hruby 2021)*

Introduction

According to the National Nuclear Security Administration (NNSA), concerns about the lifespan of plutonium pits in the US nuclear stockpile are central to the decision to reestablish production capability. The United States has not made new plutonium pits in large numbers since violations of environmental laws had forced the closure of the Rocky Flats Plant in Colorado in 1989. Although the Los Alamos National Laboratory has been authorized to produce up to 20 pits per year at its PF-4 facility since 1996, it produced only a limited number between 2007 and 2011 to finish production of the W88 warhead and for specific research and development purposes.

The Rocky Flats Plant produced some 70,000 plutonium pits at a rate of 1,000 to 2,000 pits per year between 1952 and 1989. Except for the last few W88 pits, it produced all pits in the current US stockpile in the late 1970s and through the 1980s, so all are 35 to 47 years old. Plutonium is susceptible to surface corrosion, self-induced radiation damage, and long-term chemical change, as well as temperature-induced changes in its physical state. In particular, radioactive decay causes more than half the atoms in ^{239}Pu to be displaced in any 10-year time period.

At present, the national laboratories have provided no evidence to suggest that pits in the stockpile are at or near the end of their service lives. However, some scientific questions remain over how to assess the service life of pits for different weapon designs such that age-induced changes do not compromise the potential performance of the US stockpile.

Research to understand pit aging began in 1997, when the NNSA initiated a program at the Lawrence Livermore and Los Alamos national labs to quantify changes in plutonium's physical properties over time. These efforts were part of the then newly launched Stockpile Stewardship Program, which has sought to assess and maintain the "health" of US nuclear weapons in the absence of full-scale underground testing. The NNSA released results of these first aging studies in 2006, and the independent JASON advisory committee reviewed them. The review concluded that "most primary types have credible minimum lifetimes in excess of 100 years as regards aging of plutonium [and] those with assessed minimum lifetimes of 100 years or less have clear mitigation paths" (Hemley 2006).

A 2012 public report from Lawrence Livermore confirmed and even extended these forecast lifetimes. It concluded that plutonium was "aging gracefully" at an effective age of 150 years, with no evidence of detrimental changes to its physical properties (Heller 2012).

Expecting that the additional years of experimental and theoretical work would improve insight, the JASON committee was asked to reevaluate pit lifetimes in 2019. However, the committee expressed concern that "in general, studies on Pu aging and its impacts on the performance of nuclear-weapon primaries have not been sufficiently prioritized over the past decade" (JASON 2019). In other words, too little experimental work had been carried out over the preceding decade to provide significant new information about the aging process, its quantification, or its uncertainties. While the updated assessment did not indicate "any impending issues for the stockpile," it nonetheless recommended reestablishing pit manufacturing capabilities "as expeditiously as possible."

While the 2019 JASON recommendation was no doubt influential in securing support for renewed pit production, in fact, plans to produce 80 pits per year originated as early as 2009 and 2010 (Kniss and Kornreich 2009; McConnell 2010). In 2015, Congress mandated this quota (Carl Levin and Howard P. "Buck" McKeon National Defense Authorization Act for Fiscal Year 2015). Also, it was included in the 2018 *Nuclear Posture Review* (Office of the Secretary of Defense 2018) and the 2020 National Defense Authorization Act (Public Law 116–92. 2019).

The apparent lack of prioritization in the national laboratories for aging studies over the same period, as noted by JASON, suggests that renewed calls for pit production were not clearly coupled to a demonstrated scientific need. Indeed, only in 2021 did the Senate Appropriations Committee direct the NNSA to develop a "comprehensive, integrated ten-year research program for [nuclear warhead] pit and plutonium aging that represents a consensus program among the national laboratories and federal sponsors"(US Congress 2021). Those plans, if they have been produced, remain classified.

Because pit aging has been cited as a core motivation for the present effort to produce 80 pits per year by 2030, stakeholders should understand what is known about the science of plutonium aging and what questions remain.

3.1 Plutonium Aging vs. Primary Aging

What is referred to as a "pit" is actually an assembly that includes not only plutonium but also various other materials that may themselves degrade over time. While most conversations around pit production focus on efforts to recycle and recast the plutonium component of the primary stage (the pit itself), other parts of the primary may define a shorter lifespan for the assembly than aging effects within the plutonium alloy would dictate. Thus, how plutonium ages is only one of several factors determining the primary's acceptable service life, but it is key to determining the required rate and scope of pit production if the nation intends to maintain the current stockpile. As noted, the immediate motivation is to supply pits for new weapons, not to maintain the current stockpile.

The pit is assembled along with an explosive shell that drives its implosion; together, these make up the primary stage of a modern thermonuclear weapon. Determining the reliability of a given design depends on how confidently weapons designers can combine these uncertainties and understand their interactions (Box 3.1). A major role of the science-based Stockpile

Stewardship Program is to understand *all* the required material properties needed to inform such estimates and determine required maintenance intervals and priorities for refurbishment.

Surface effects due to corrosion and signs of thermo-mechanical stress in components can be monitored forensically, given that weapons of each type are routinely dismantled for surveillance as part of the Stockpile Stewardship Program. For some pit designs, termed "non-bonded," the plutonium can be mechanically separated from the rest of the pit. Aging of any life-limiting, non-plutonium components can be addressed independently through refurbishment, allowing reuse of the plutonium core. Conversely, the plutonium in some pits may be bonded to adjoining metallic layers (i.e., beryllium, steel, or uranium); in these cases, precision machining and/or chemical processes may be required to separate the components (Toevs 1997).

Corrosion or chemical reactivity at metallic interfaces may affect surface properties in the presence of contaminants (e.g., hydrogen, tritium, chlorides, moisture). This could affect both plutonium and any associated cladding (beryllium, aluminum, or steel) or heat-protective (vanadium) layers. Pits in weapons are sealed and therefore at relatively low risk of exposure to corrosive conditions from moisture, oxygen, or hydride formation. Pits from disassembled weapons kept in unsealed containers at the Pantex Plant may have been subject to damage as a result of exposure to incompatible packaging, water vapor from the air, and temperature fluctuations in their storage facilities.

The explosive shell surrounding the pit may also degrade over time. The current US arsenal contains both conventional high explosive (e.g., cyclotetramethylene tetranitramine, known as HMX or High Melting explosive, or pentaerythritol tetranitrate, known as PETN) and insensitive high explosive (typically triaminotrinitrobenzene, TATB) and a polymeric (e.g., plastic-based) binder. Both explosives and binder may be subject to gradual decomposition, a process that may be exacerbated by thermal stress, radiation from the pit, or chemical exposure. Decomposition could also cause outgassing, which could expose neighboring materials within the primary. Also, thermal or mechanical stress may lead the explosive, cladding, or reflector to crack, which would alter the detonation efficiency and the properties of the wavefront that reaches the plutonium to drive implosion, with a deleterious effect on performance. Modern explosives are more robust than earlier formulations and can be separated from the rest of the pit during assembly, disassembly, or surveillance.

The shortest-lived component in the assembly dictates the operational life of the primary stage. Only two cases require recycling and recasting plutonium for new pits :

- If the plutonium itself is the life-limiting factor within the primary due to radiation-induced damage or other physical or chemical aging mechanisms; or
- If a new weapon design requires a pit with specifications that do not exist in the current stockpile, as is apparently the case for the W87-1 ICBM warhead.

In certain cases, it may be possible to reuse the plutonium component of the primary should age-related issues arise with other components. Issues with non-fissile components, including explosives, can be handled largely with existing facilities and capabilities, including life-extension programs, which have a well-established precedent.

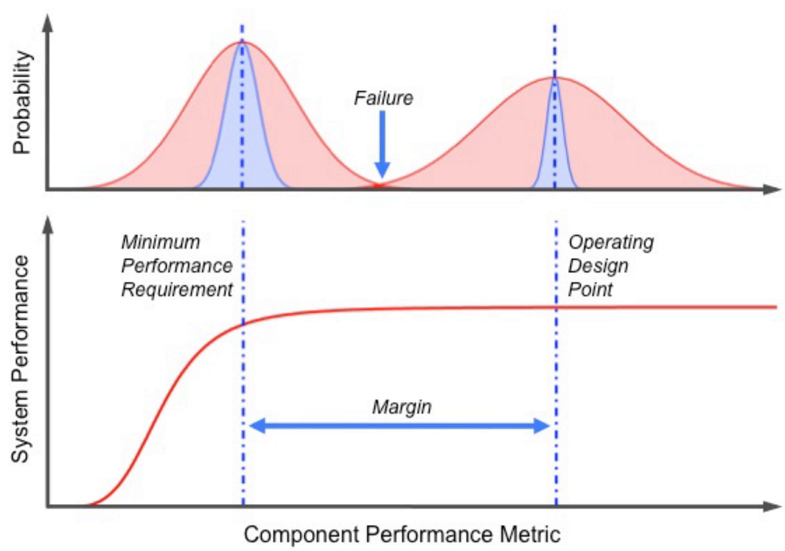
Based on early assessments of plutonium aging, former NNSA administrator Linton Brooks stated in 2006 “It is now clear that although plutonium aging contributes, other factors control the overall life expectancy of nuclear weapons systems” (Pincus 2006).

Here, we focus on the possible impacts of plutonium aging rather than on other factors external to the pit since much of the infrastructure and cost of NNSA’s current plans involve the plutonium itself and efforts to purify, cast, and fabricate new plutonium components.

Box 3.1. Quantifying Margins of Uncertainties

To assure the reliability of the nuclear stockpile on an annual basis, it is necessary to understand whether critical components are in danger of failing to perform as designed. To address that need, since 2001, the national laboratories have been developing and refining a method called Quantification of Margins of Uncertainties (QMU) in weapons performance.

Based on engineering practices, QMU is intended as a common language, applicable across the national laboratories, for identifying possible failure modes and assisting in prioritizing work and directing investment to ensure stockpile reliability. In addition, QMU can be applied to define risk/benefit assessments for the possible introduction of new components and to estimate how weapons may perform in untested configurations.



QMU seeks to identify how cumulative uncertainties interact so that confidence in a given component’s performance can be reasonably estimated. When components can be tested repeatedly, performance metrics can be understood statistically. If uncertainties in the design point and minimum performance requirement are of similar magnitude to the acceptable performance margin (scenario shown red), failure may occur. If uncertainties are tightly constrained relative to performance margins (as shown in blue), then performance can be assured with higher confidence. Source: UCS, after National Research Council, 2009.

For the purposes of QMU, reliability is distinct from safety and security. A reliable system is one in which the accumulated performance uncertainties are tightly characterized and the margin to failure is as large as possible. QMU refers to the characteristics of a system as metrics. The difference between the minimum operational threshold for a given metric and the point at which it is designed to operate is the performance margin. Below this critical threshold (or cliff), the performance of the system will be severely degraded or fail. Uncertainties exist in calculating the margin, and these may be systematic or random (intrinsic) uncertainties that originate due to variations in manufacturing, materials, or test-to-test variability.

To operate reliably, the calculated margin (M) must be larger than the total uncertainty (U), such that the ratio M/U >>1. If M/U is about 1 or less, it indicates a danger that a metric may not perform as required; therefore, efforts should be directed to increasing the performance margin, reducing uncertainties, or both. Modifying components within a weapon may be attractive as a means of increasing the margin, but doing so can also increase uncertainty relative to tested designs.

In the case of pit production, quantifying the effects of aging on the performance of plutonium in pits reduces uncertainties and allows an improved determination of the margin for a given metric (e.g., the weapon's yield). In some cases, margins can be increased to compensate for growing uncertainty. For some pit designs, changing the properties of the boost gas may increase the ratio M/U and thus mitigate any age-related effects in the plutonium up to a point.

Unfortunately, most QMU evaluations are not limited to a single component. The complexity of weapons means that there are many failure modes—hence, many potentially interactive margins and cliffs. If increased tritium loading requires increased mass or a new reservoir, this may decrease margins or introduce uncertainty elsewhere. Any changes incurred through life-extension or redesign must be considered carefully to ensure that the propagation and interaction of failure modes are understood. This is particularly true of proposals for radically new designs that rely on untested combinations of components.

3.2 Plutonium: A Uniquely Complex Metal

"Plutonium is so unusual as to approach the unbelievable. Under some conditions it can be nearly as hard and brittle as glass; under others, as soft as plastic or lead. It will burn and crumble quickly to powder when heated in air, or slowly disintegrate when kept at room temperature. It undergoes no less than five phase transitions between room temperature and its melting point. Strangely enough, in two of its phases, plutonium actually contracts as it is being heated. It has no less than four oxidation states. It is unique among all of the chemical elements. And it is fiendishly toxic, even in small amounts." —Atomic Energy Commission Chair Glenn T. Seaborg, 1968 (AEC 1968)

Plutonium is a metal, but its behavior is far from our common understanding of more familiar metals like aluminum, copper, or iron. Virtually nonexistent in nature, plutonium was first synthesized in nuclear reactors in 1940, only five years before its use in the Fat Man device dropped on Nagasaki, Japan—an explosion that used a significant fraction of the world supply of plutonium at the time. Scientists had little time to understand its physical and chemical complexity, let alone how to overcome its metallurgical mysteries. This was, of course, overcome with empirical testing when the Trinity device demonstrated the feasibility of a plutonium implosion design.

Because plutonium has only existed since 1940, naturally aged samples with controlled and documented histories are scarce, if available at all from early periods. This results in a need for theory, modeling, and experiments to understand how plutonium evolves with age.

The complex behavior of plutonium and its stability over time are largely due to its unique place on the periodic table. Plutonium sits in the middle of the actinide series, with electrons perched precariously between competing states. This means that subtle perturbations (e.g., due to pressure, temperature, or impurities) can lead to dramatic changes in behavior.

Furthermore, weapon performance relies on understanding how plutonium transforms during detonation, not just at the ambient conditions under which it is stored. These conditions include shock compression as the surrounding explosive drives the plutonium to a nuclear supercritical state (runaway nuclear chain reaction), as well as interaction with the deuterium/tritium boost gas used in modern weapons. Manufacturing new pits introduces the risk that changes in production processes could lead to changes in the properties if the complexities in the chemistry and materials science are not sufficiently understood. Thus, the intricacies of plutonium's physical and chemical properties are relevant to both new and old pits, as well as for forecasting future changes in the arsenal.

The apparently fickle chemical, physical, and radioactive behavior of this metal is largely why its long-term stability is more difficult to understand and predict than is the case with most materials. Yet while plutonium presents many surprising properties for metallurgists, chemists, and materials scientists, this very complexity turns out to have several beneficial side effects when it comes to aging.

A Man-Made Element

With extraordinarily few exceptions, plutonium does not occur naturally and cannot be mined or extracted from the Earth. Instead, it was an early product of the twentieth-century revolution in atomic physics and the very first element to be artificially synthesized in any appreciable quantity.

Plutonium is produced from uranium, which occurs naturally in a variety of geologic settings. Both plutonium and uranium can exist in the form of numerous isotopes. All isotopes of a given element contain the same number of protons (which determines their atomic number or place on the periodic table), but they have different numbers of neutrons within the nucleus, and therefore different atomic masses. While some isotopes are stable, others are not; unstable configurations lead to radioactive decay.

Approximately 99.3 percent of naturally occurring uranium is in the form of oxides of ^{238}U (a non-fissile isotope containing 92 protons and 146 neutrons). About 0.71 percent is ^{235}U, a fissile isotope with 143 neutrons, meaning it is less stable than ^{238}U and can undergo a nuclear fission chain reaction by releasing neutrons to its environment, triggering further fission. The power of nuclear weapons comes from these chain reactions, which is why modern weapons use the fissile isotopes ^{235}U and ^{239}Pu.

To produce plutonium, surplus neutrons from ^{235}U fission chain reactions are used to bombard ^{238}U in a nuclear reactor. This makes ^{239}U (a heavier isotope), which then undergoes a two-step beta decay (giving off electrons and neutrinos), transforming one neutron into a proton in each step to yield ^{239}Pu.

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{92}U \xrightarrow[\text{23.5 min}]{\beta^-} ^{239}_{93}Np \xrightarrow[\text{2.35 d}]{\beta^-} ^{239}_{94}Pu$$

The process of turning ^{238}U into ^{239}Pu is known as breeding. It is now known that plutonium has 20 isotopes ($^{228\text{-}247}$Pu). The most common ($^{238\text{-}242}$Pu) are all “fissionable” (able to split into lighter nuclei and hence radioactive) but their half-lives differ depending on their relative stability. US weapons-grade plutonium contains more than 93 percent ^{239}Pu, largely to avoid unwanted neutron emission from other shorter-lived isotopes (e.g., ^{240}Pu) that are generated along with ^{239}Pu in the reactor. The relative amounts of each isotope depend in part on how long it resides in the reactor.

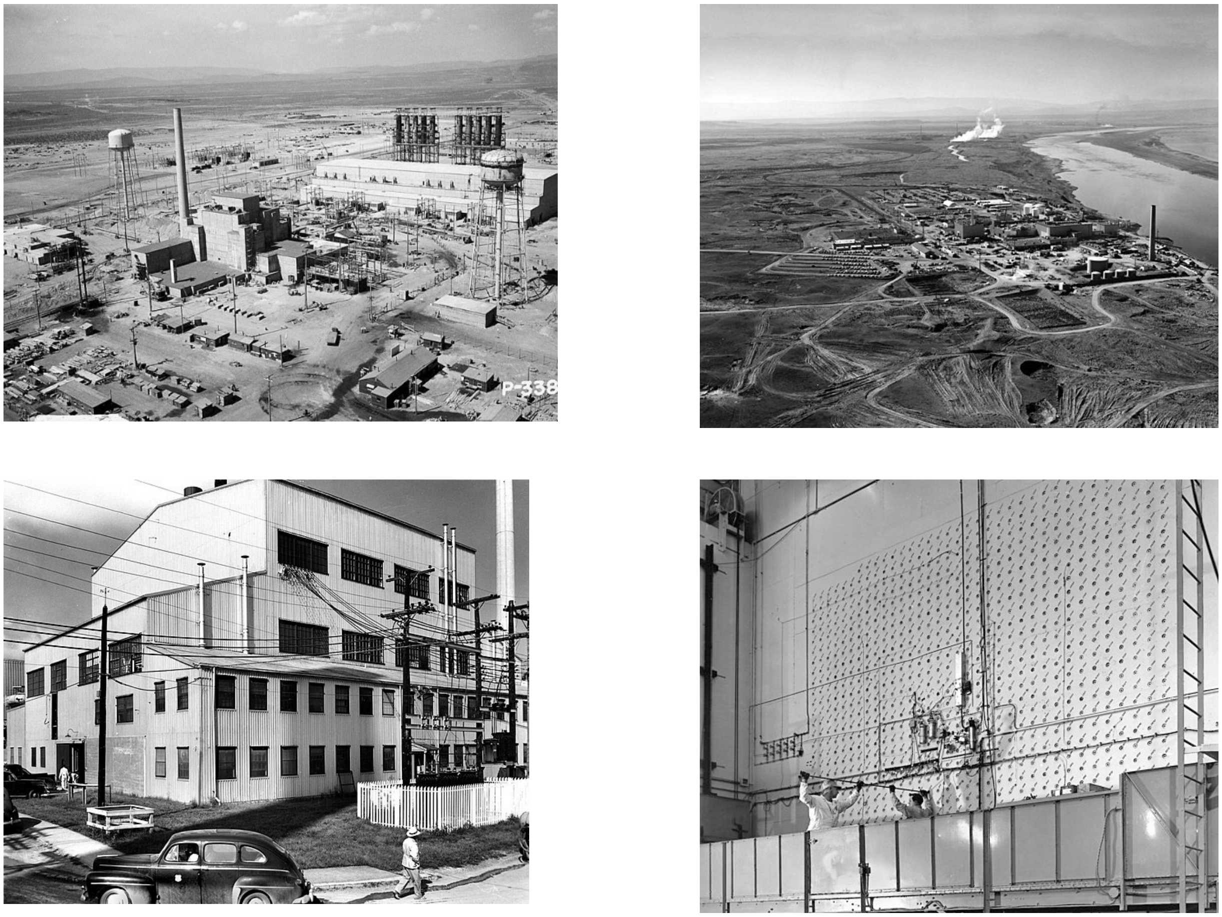
The Manhattan Project used uranium mined from Navajo lands in the southwestern United States, as well as the Shinkolobwe mine in what was then the Belgian Congo (present-day Democratic Republic of the Congo). Plutonium for the project was produced in reactors at the Hanford Site near Richland, Washington, on the Columbia River (1944 to 1989) and at Savannah River, South Carolina (1953 to 1988). Uranium isotopes were separated at Oak Ridge, Tennessee, to provide fuel for the reactors, and plutonium was laboriously separated from the irradiated uranium fuel, gram by gram, until the necessary quantity was obtained for the Trinity test and the Nagasaki device (about six kilograms each). As of 2023, it was estimated that the United States had just over 87 tons of separated plutonium, 79.7 tons of which was considered military stock (IPFM 2023).

A Complex Actinide Metal

Electrons in a Balancing Act

The structure of its nucleus drives plutonium’s fissile characteristics, but the organization of electrons around the nucleus drives its chemical and physical behavior. The outermost (valence) electrons of an element typically determine interactions with neighboring atoms and chemical bonding. In a metallic solid, nuclei form a crystalline lattice in a jungle-gym-like structure, and the atoms’ outermost valence electrons swarm through the structure being shared among the atoms. In most metals, these “delocalized” electrons give rise to such properties as the electrical conductivity, thermal conductivity, ductility, and even reflectivity.

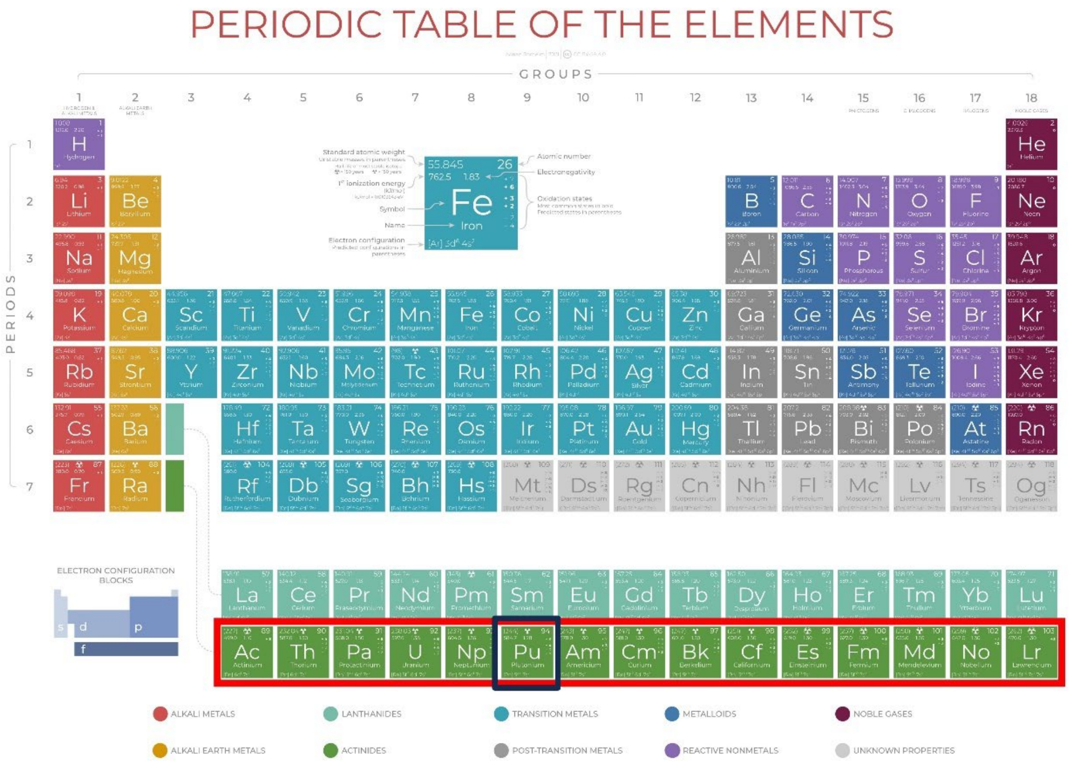
FIGURE 3.1. Former Plutonium Production Sites for Nuclear Weapons



The United States produced plutonium for weapons initially at Hanford, Washington, and Oak Ridge, Tennessee, and later, Savannah River, South Carolina. Top: Aerial view of the Hanford Site, including the B reactor (top left, c. 1944) and N Reactor sites (top right, c. 1960s), showing the close proximity to the Columbia River in eastern Washington state. Bottom: The exterior and interior of the X-10 graphite reactor at Oak Ridge, c. 1950. X-10 was the first proof-of-concept production reactor following demonstration of the concept by Enrico Fermi and his colleagues at the University of Chicago. SOURCE: Wikimedia Commons n.d.a, b, c, d

Plutonium is unlike most metals, and its place on the periodic table explains its fickle character. Sitting near the middle of the actinide series of elements, it finds itself torn between the chemical properties of its neighbors to either side (Figure 3.2, bottom row, containing metallic, radioactive elements 89 to 103). Elements to the left of plutonium tend to allow their electrons to “roam” in a delocalized (or shared manner); elements to the right tend to hold onto them in a localized (or unshared manner) (Boring and Smith 2000; Moore and van der Laan 2009).

FIGURE 3.2. Plutonium: The Middle Child of the Actinides



Plutonium is an actinide metal with its electrons perched between localized (bonding) and delocalized (itinerant) states. With many of these states close in energy, the material shifts easily from one state to another. SOURCE: Modified from Wikimedia Commons n.d.e.

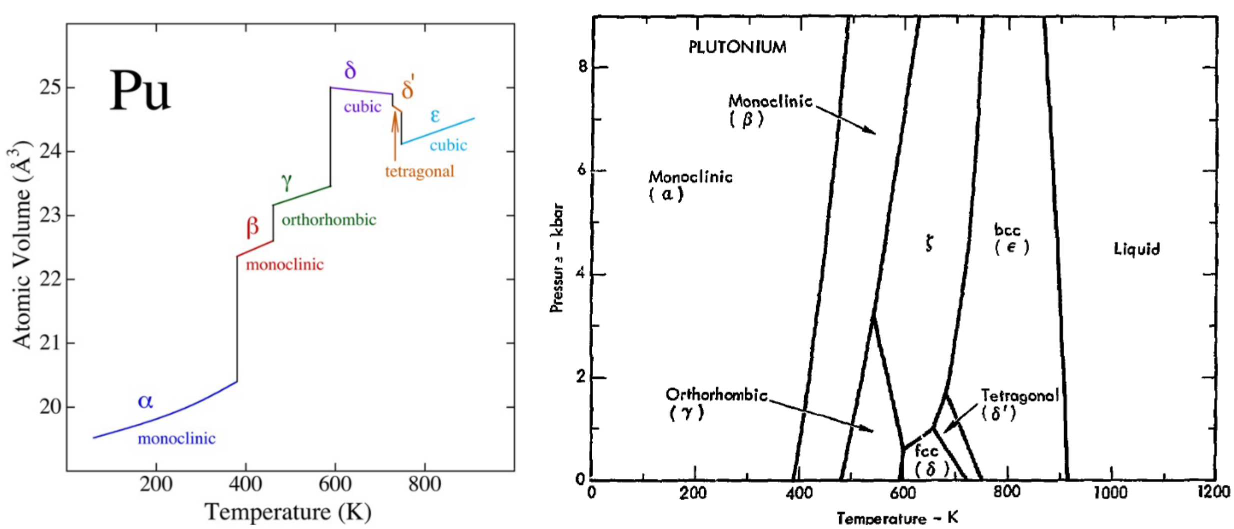
The electrons that determine plutonium's chemical behavior also have very similar energies to their neighbors, which allows them to "tip" easily into different bonding configurations with relatively little persuasion. Minor perturbations in pressure or temperature or the introduction of atoms of another element can easily nudge plutonium into a new state of chemical bonding, crystal structure, or both. This electronic precarity makes theoretical and computational approaches for predicting plutonium's behavior especially difficult, and it emphasizes the need for careful empirical studies (Kemsley 2015; Hecker, Harbur, and Zocco 2004).

The Many Unusual Faces (and Phases) of Plutonium

The fact that plutonium readily transitions between states, combined with the possibility that such transitions could compromise its physical properties, has practical implications for pit aging that may determine the reliability of a weapon design over time. Understanding this science is important and begins by understanding the stability of different forms of plutonium (known as phases) as a function of pressure and temperature.

Crystalline solids, including metals, have specific periodic structures at the atomic level, much like a jungle gym or construction scaffolding. Raising the temperature or applying pressure to the atomic lattice can induce the atoms to seek a new crystal structure (or "phase") that is energetically favorable. The actinides are capable of forming a large number of solid phases (allotropes), but plutonium stands out even among its peers, transitioning among six different structures under the influence of temperature alone (at constant pressure) before it melts (Figure 3.3).

FIGURE 3.3. Phase Changes in Plutonium



Left: Plutonium undergoes dramatic changes in crystal structure with large changes in volume as a function of temperature. The least-dense delta (δ) phase, normally only stable at high temperatures, can be stabilized to ambient conditions with the addition of gallium. Right: A pressure-temperature phase diagram shows the relatively small region of stability of the δ- phase and the many other solid phases that plutonium can assume as a function of its thermodynamic state. SOURCES: Söderlind et al. 2015; Young 1975.

Compared with aluminum, steel, or many other engineering materials, the phase transitions in plutonium present a much greater challenge. Many of plutonium's phases are relatively close in energy (hence relative thermodynamic stability) (Söderlind, Landa, and Sadigh 2019). Therefore, they require little persuasion to go from one to the other.

At room temperature, the alpha phase has a crystal structure that is more typical of a mineral than a metal (called monoclinic, with low internal symmetry), resulting in a brittle solid that is extremely dense (19.8 grams per cubic centimeter, compared with 11.33 grams per cubic centimeter for lead). As temperature rises, the material undergoes several abrupt and extremely large volume changes to lower-density phases before slightly shrinking again just before melting. Like water, liquid plutonium is denser than the solid, and plutonium has one of the lowest melting temperatures of any of the actinides, 650 degrees C (roughly half the temperature at which iron melts) (Smith and Kmetko 1983). Upon melting, the liquid also has the highest viscosity of any metal (Boring and Smith 2000). Each of these phases presents unique mechanical, electrical, and chemical properties.

The many possible crystal structures make manufacturing processes (e.g., casting, machining) difficult if not impossible for pure plutonium. As the material is heated or cooled, it may crack or develop stress with changing temperature as a result of its unusually large volume changes. This would severely complicate efforts to machine, cast, and otherwise use it in any kind of engineering application were it not for the ability to "tame" plutonium by mixing it with other metals into an alloy with more tractable characteristics.

Taming Plutonium for Weapons Use

Understanding how to stabilize plutonium's favorable phases (crystal structures) is key for weapons production. Specifically, it is ideal if the material does not undergo large volume changes or degrade due to local heating. Also, it must remain stable in the range of environments it will experience throughout its service life (on the order of decades for most warheads).

Alloying plutonium with other elements is one way to achieve this, and Manhattan Project metallurgists were quick to do so in developing the first atomic weapons. Gallium was found to stabilize the relatively simple (cubic-structured) δ-phase that, unlike the brittle monoclinic α-phase, is ductile (allowing it to be wrought) and easily machinable to precise dimensions. The δ-phase is normally stable only above 600 degrees K (Figure 3.3). However, with the addition of a few percent gallium, plutonium can remain in this phase at room temperature, making this the preferred phase for weapons.

Adding gallium brings other benefits as well. Unlike pure plutonium, in which the solid is less dense than the liquid at melting, the plutonium-gallium alloy is denser in the solid state. This is an advantage for casting. Plutonium-Gallium alloys can also be welded; this is critical for joining the hollow hemishells in many pits and for the boost-gas fill tubes, which must withstand pressure under operation. Also, when subject to alpha radiation from the natural decay of plutonium, gallium does not generate neutrons, which could contribute to an undesirable, premature nuclear chain reaction before the plutonium is fully compressed (Mitchell et al. 2004). Although the δ-phase has one of the lowest densities, during operation of the weapon, it will transition back to a denser state under compression such that the phase transition effectively accelerates the path to criticality. Finally, the δ-phase plutonium-gallium alloy is less susceptible to corrosion and experiences lower thermal expansion than pure plutonium, both of which are favorable characteristics for a longer shelf-life within the stockpile.

3.3 Aging Gracefully?

When the United States detonated the first atomic implosion devices at Trinity and over Nagasaki in 1945, Manhattan Project scientists has barely begun to master plutonium's complexities. With both devices detonated within weeks of the nation's amassing sufficient fissile material, no one seriously considered the longevity of nuclear weapons.

Throughout the Cold War, pits were manufactured in large numbers for evolving weapons designs as the US and Soviet stockpiles grew into the tens of thousands. The question of pit aging came into focus as materials science and metallurgical studies matured in the growing national laboratory complex. This was particularly the case when the United States ended full-scale nuclear testing and adopted the science-based Stockpile Stewardship Program in the 1990s.

In the post-Cold War era, focus has turned to maintaining and monitoring weapons components to determine appropriate intervals for refurbishing life-limited parts. While most non-nuclear components of a weapon can be tested using traditional laboratory techniques, the nuclear explosive package clearly cannot. Thus, a detailed scientific understanding of plutonium down to the atomic level is crucial for determining its long-term stability and ensuring the stockpile's reliability over time.

Plutonium Aging Mechanisms

Material Stability

Plutonium's complex electronic behavior and the resulting phase instability raise two primary questions. After plutonium is produced, how long is it stable in the δ-phase? And what perturbations would induce it to transform out of this structure?

Although alloying plutonium with gallium has its benefits, it is not without associated complexities. Depending on the amount of gallium added, a mixture of plutonium and gallium can form 11 different compounds (Peterson 1988; Ellinger et al. 1968). Early data-sharing between US and Soviet labs around the peaceful uses of atomic power revealed disagreement over whether δ-phase plutonium-gallium was thermodynamically stable. Los Alamos scientists believed that it was the equilibrium phase at ambient conditions, while Soviet results predicted that it would eventually decompose to a mixture of the (unfavorable, brittle) α-phase and Pu_3Ga (Hecker and Timofeeva 2000). It is now believed that the Soviet results are correct and that δ-plutonium-gallium actually slowly decomposes at ambient conditions (termed metastable). This would be problematic for the aging of weapons were it not for the fact that the rate of decomposition is so slow as to be negligible (requiring 10,000 years or more except at elevated temperatures) (Turchi et al. 2004).

Further, plutonium-gallium alloys are "self-healing." Work from scientists at Los Alamos, Lawrence Livermore, and the French Commissariat à l'Énergie Atomique has diminished concern that self-radiation could enhance the decomposition of the (desirable) δ-phase into the (undesirable) α-phase and Pu_3Ga. Their research has shown that radiation-enhanced diffusion of Ga can help form small pockets of Pu_3Ga, but, in a reversal of fortune, radiation-induced disordering breaks them up and moves the material back into its metastable state. The net effect of these competing processes is stabilizing, helping "heal" the undesirable transformation to a new phase (Wolfer, Oudot, and Baclet 2006).

To understand whether migration of gallium might affect the alloy, researchers can empirically examine its distribution as a function of concentration, temperature, and time using a variety of techniques. X-ray absorption spectroscopy, which is sensitive to nearest-neighbor configurations in the crystal structure of a material, can reveal the coexistence of different crystalline environments at the atomic scale (Conradson 1998; Conradson 2000).

These data show that crystallinity (or regularity of the atomic arrangement in the δ-phase structure) actually improves with time (Jeanloz 2000). Combined with electron backscattered diffraction (EBSD, which can map crystalline orientation, distribution, and microstructure) and electron microprobe analyses (which can map compositional variation), the uniformity and longevity of chosen alloys can be monitored, and appears to be stable and to exhibit long-range order in decades-old samples (Boehlert et al. 2003).

Radioactive Decay

While the δ-phase is known to be stable in today's nuclear stockpile, determining the maximum acceptable lifetime of a pit requires further understanding of radiation-related damage mechanisms as well. This is particularly true if they result in unfavorable changes to the pit's structure, volume, or chemical makeup.

The first thing associated with plutonium that comes to mind in the public psyche is its inherent radioactivity. Indeed, the natural radioactive decay of ^{239}Pu is one of the primary mechanisms leading to age-related damage and accumulated change in a plutonium pit.

Pits are produced from weapons-grade plutonium (at least 93 percent ^{239}Pu). The remainder includes ^{240}Pu (up to several percent) as well as ^{241}Pu (about 0.5 percent) (Condit 1993; Wolfer 2000). Each of these isotopes has a unique half-life and decay chain that act to change the pit chemically and physically over time.

The process of radioactive decay affects materials in two primary ways. Energy released from the decay (often in the form of kinetic energy of the daughter products) can tear up the crystalline lattice around the site of the parent nucleus. Within nanoseconds, much of that damage will disappear as the lattice naturally recovers. However, some damage will remain as defects within the material. Second, the accumulation of daughter products leads to the gradual buildup of impurities that often do not fit neatly within the crystal lattice. This can result in distortion and/or volumetric changes over time (through changes in what is called the lattice parameter or the periodic distance between atoms in the crystal structure). The gradual buildup of daughter products from radioactive decay results in a slight chemical change as the total amount of plutonium is reduced. Due to the random nature of radioactive decay, this occurs homogenously throughout the material.

^{239}Plutonium

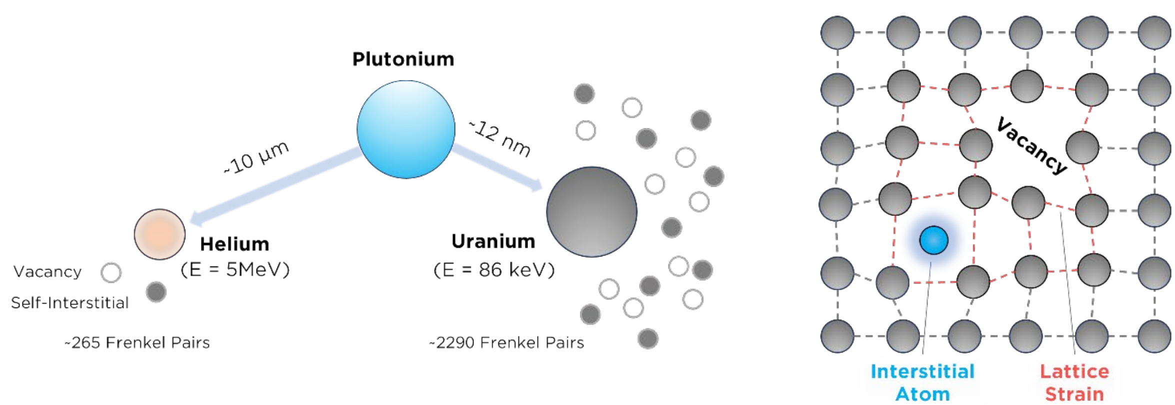
^{239}Pu is the predominant isotope in weapons-grade plutonium alloy, making its radioactive behavior of primary interest. It has a long half-life (24,390 years) and a relatively low spontaneous fission rate (about 10 fissions per second per kilogram). Thus, the probability is low that spontaneous fission will prematurely initiate a chain reaction during the pit's implosion.

^{239}Pu spontaneously undergoes alpha decay: it emits an alpha particle (a helium nucleus, composed of two protons and two neutrons) and is transformed to ^{235}Uranium. The decay releases energy, with the resulting uranium atom and helium nucleus flying through the crystal lattice, displacing neighboring plutonium atoms as they go.

$$^{239}_{94}Pu \xrightarrow[24390\text{ y}]{} {}^{235}_{92}U + {}^{4}_{2}He$$

Some of this energy is dispersed as heat, making a lump of plutonium metal warm to the touch under ambient conditions. The helium nucleus, being relatively light and small, can travel about 1,000 times further than the uranium, which, being relatively large and heavy, does significantly more damage over a shorter distance. Together, they displace about 2,500 atoms per decay event. Approximately 90 percent of these displaced atoms return to their original positions because it is thermodynamically favorable for them to snap back into their periodic arrangement. However, some remain lodged between neighboring plutonium atoms in the lattice in what are called interstitial configurations, leaving a corresponding vacancy elsewhere and forming what is known as a Frenkel pair, a combination of one interstitial atom and one lattice vacancy (Figure 3.4).

FIGURE 3.4. Radioactive Decay in ^{239}Pu

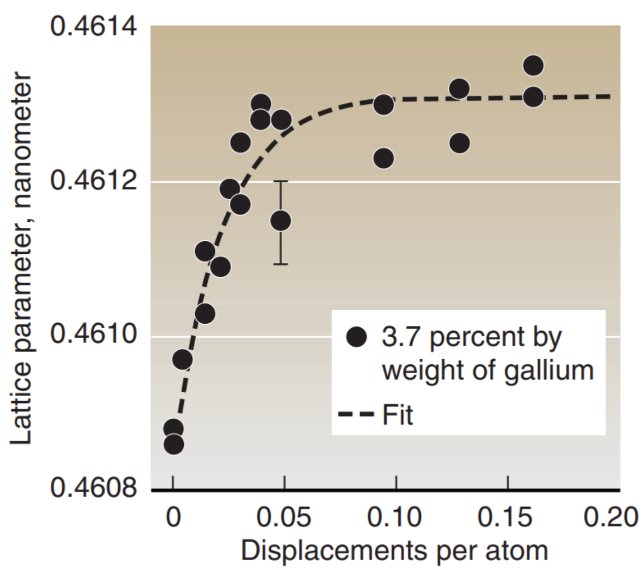


Left: Plutonium radioactively decays to 235-Uranium and 4-He. These daughter products move through the surrounding plutonium lattice, depositing kinetic energy and creating pairs of defects as they go in the form of interstitial atoms and vacancies in the crystal lattice. Being heavier and having greater energy, the uranium results in the most damage to the lattice. Right: An interstitial atom and vacancy are, together, referred to as a "Frenkel Pair". Roughly 2500 Frenkel pairs can result from the decay of a single plutonium nucleus but many of these irregularities in the crystal structure are self-repairing. SOURCE: UCS, after Wolfer 2000; material-properties.org.

Based on the decay rate of ^{239}Pu and the number of atoms displaced per decay event, it is likely that each atom in the lattice gets displaced approximately once per decade. This rate is measured in displacements per atom, or dpa, such that rate is about 0.1 dpa per year for plutonium (Chung 2005; Wolfer 2000; Jeanloz 2000). The associated energy imparted to the lattice during a decay event is enough to raise around a million plutonium atoms above the melting point (Maiorov et al. 2017). While this may seem dramatic, the duration is brief and spatially localized. Also, heat energy assists in reestablishing local equilibrium to the lattice, sometimes healing defects from preexisting damage by providing the requisite energy to nudge atoms back into a periodic arrangement. Indeed, X-ray absorption fine structure (XAFS) measurements from Los Alamos, which can document the near-neighbor arrangements of atoms around particular atomic species, demonstrate that displacement from radiation "damage" can actually result in an evolution toward a more ordered structure with age (Conradson 1998; Jeanloz 2000). Such annealing of fission-track damage in materials is a relatively well-understood phenomenon because of its utility in geologic studies of the thermochronology (or cooling history) of rocks (Reiners and Ehlers 2005).

The helium nucleus resulting from the decay of ^{239}Pu strips off the two electrons it needs to become a helium atom and end up as an impurity in the lattice, typically finding a spot in an unfilled vacancy. These helium-filled vacancies can eventually migrate and coalesce into bubbles of one to two nanometers. There has been significant concern that such bubbles could continue to grow, effectively swelling the pit. However, these fears have been largely allayed by laboratory studies of plutonium of different ages using positron annihilation spectroscopy (Martz and Schwartz 2003; Selim 2021). Also, transmission electron microscopy shows that the helium remains relatively uniformly distributed in small bubbles rather than clustering in excessively large bubbles (Figure 3.8) (Chung, and Heller, 2012). Exquisitely precise dilatometry experiments (sensitive to changes in length or dilation), coupled with careful measurements of bulk density, confirm that helium-bubble ingrowth does not result in catastrophic damage on timescales of less than a century.

FIGURE 3.5. Alpha-Decay Damage over Time



The effect of alpha-decay damage to the crystal lattice appears to stabilize with time (expressed here in terms of displacements per atom, where 0.1 corresponds to approximately 1 year and 1 dpa to approximately 1 decade), suggesting that the plutonium lattice experiences transient change in the spacing of plutonium atoms (lattice parameter) but that this effect slows significantly as a function of time. Source: Heller 2007; Wolfer, Oudot, and Baclet 2006.

The accumulation rate of helium is actually quite small given that only one helium nucleus results per decay. Therefore, the accumulation rate is about 400 helium atoms per million plutonium atoms per decade (or 0.04 atomic percent). Even after 60 years, resulting volume increases in plutonium are less than about 0.3 percent (Wolfer 2000; Wolfer, Oudot, and Baclet 2006). Follow-up studies by Lawrence Livermore National Laboratory have suggested that helium accumulation should not result in significant dimensional change or changes in strength for the plutonium pits even after 150 years (Heller 2012).

Uranium and helium will continue to accumulate as products of the decay of ^{239}Pu but with apparently non-deleterious effects on timescales of a century or more. In fact, Lawrence Livermore researchers have shown that, after about a decade (or about 1 dpa), the rate of damage from alpha decay is approximately matched by the rate of self-healing. Thus, changes in the lattice parameter (the distance between atoms in the crystal structure) are relatively rapid in the first decade, but they effectively plateau thereafter (Heller 2007).

^{240}Plutonium

When plutonium is produced in a reactor, a ^{239}Pu atom may absorb an extra neutron, creating ^{240}Pu. The longer the nuclear fuel remains in the reactor, the higher the proportion of ^{240}Pu relative to ^{239}Pu. ^{240}Pu has a higher rate of spontaneous fission than ^{239}Pu, which makes it undesirable for use in weapons in any large quantity; it would introduce an excess source of neutrons that could initiate a nuclear chain reaction prematurely (before maximum supercriticality). It is difficult to efficiently separate two isotopes that are so similar in mass and chemical behavior. Due to this, a small percentage of ^{240}Pu remains in weapons-grade plutonium used for pits but in a quantity that does not compromise performance.

^{240}Pu decays to ^{236}U via alpha decay, forming a helium atom. This has virtually the same effect on the pit as the decay of ^{239}Pu.

$$^{240}_{94}Pu \xrightarrow[\text{6560 y}]{\alpha} {}^{236}_{92}U + {}^{4}_{2}He$$

The contribution to helium ingrowth from ^{240}Pu in pits will be proportionally smaller the smaller the initial concentration.

^{241}Plutonium

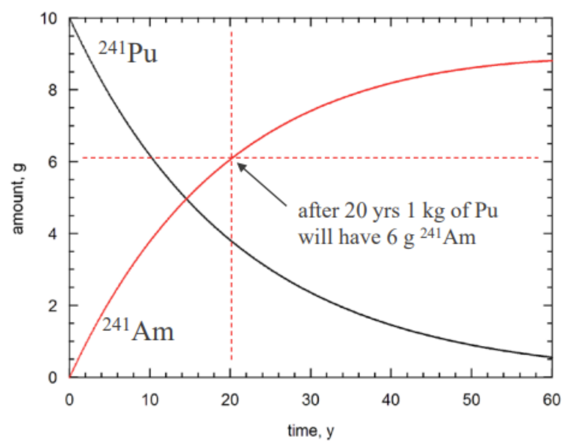
Americium, the element adjacent to plutonium on the periodic table, is another impurity that accumulates in pits in small quantities over time. It does so as a result of the radioactive (beta) decay of ^{241}Pu, present in weapons-grade plutonium at the level of about 0.5 percent. ^{241}Pu has a half-life of only 14 years, meaning that the amount of americium in the pit approaches a plateau on decadal timescales (e.g., while a pit likely still resides in the weapon) and will not proceed further once the parent ^{241}Pu is exhausted (Figure 3.6).

$$^{239}_{94}Pu \xrightarrow{2(n,\gamma)} {}^{241}_{94}Pu \xrightarrow[\text{14.35 y}]{\beta^-} {}^{241}_{95}Am \xrightarrow[\text{432 y}]{\alpha} {}^{237}_{93}Np + {}^{4}_{2}He$$

Americium may further decay to neptunium, although the small initial quantities and longer half-life of ^{241}Am mean that the total quantities of neptunium will be relatively insignificant compared with the uranium and helium buildup from ^{239}Pu and ^{240}Pu. Thus, ^{241}Pu contributes relatively little to aging effects, and it does so in a predictable way that stabilizes over time.

The accumulation of such impurities within the plutonium-gallium alloy are significant to the extent they irreversibly change the local inter-atomic distance within the crystal structure. This will have a negative effect on the integrity of the pit only if those changes are appreciable enough to affect the bulk properties of the alloy, leading to either mechanical failure or a change in the alloy's high-pressure properties as it is compressed during a weapon's operation. The extensive array of experimental and computational capabilities outlined below makes it possible to study such changes in detail and to compare differences in new and aged plutonium.

FIGURE 3.6. Americium Buildup from Radioactive Decay of ^{241}Plutonium over Time



The accumulation of americium reaches equilibrium as ^{241}Pu is depleted. This plot illustrates the decay of pure ^{241}Pu, and the vertical scale is only for the americium curve.
SOURCE: Gardner, Kimball, and Skidmore 2016.

Void Swelling

Void swelling is a phenomenon often discussed as a potentially catastrophic mechanism in the aging of metals subjected to radiation and as a possible secondary effect of radioactive decay in plutonium pits. Void swelling occurs when empty spots in the lattice coalesce, forming larger voids that are akin to the coalescence of helium bubbles. The distribution of accumulating vacancies dictates how and whether this process proceeds, including whether there is a critical incubation time before coalescence results in catastrophic physical change in the material.

Temperature plays a role. Void swelling is most often observed in a temperature range between about one-third and three-fifths of the melting temperature of the metal in which it occurs. For δ-phase plutonium-gallium (which melts near 650 degrees C), that is about 220 to

390 degrees C. This is significantly above the temperature that a pit should normally experience in storage or deployment.

The ease with which voids can coalesce also depends in part on the crystal structure. The preferred δ-phase plutonium-gallium alloy in pits has a "face-centered cubic" (*fcc*) crystal structure: the atoms are positioned at the corners of an imaginary cube, with one additional atom at the center of each face of the cube. In a perfect crystal, that structure would repeat itself throughout, with each cubic face shared with the adjoining one. Metals with the same structure (particularly austensitic stainless steel) are especially sensitive to void swelling in the nuclear reactor environments where they are exposed to radiation, leading to anxiety over whether the same effect would occur in plutonium after a long enough (but unknown) incubation period. Los Alamos scientists cited a possible onset time of anywhere from 10 to 100 years (Wolfer 2000). Also, it was initially thought the swelling could be as much as 1 percent in volume per decade (Martz and Schwartz, 2003; Wolfer 2000). However, this has not been observed in the oldest available plutonium samples, including those rapidly aged through the inclusion of faster-decaying plutonium isotopes (further discussed below).

Indeed, δ-phase plutonium-gallium alloy appears to behave quite differently from similarly structured metals, again setting itself apart as an unusual case in metallurgy. In the δ-phase alloy, the apparent absence of void swelling thus far is hypothesized to be due to the stabilizing presence of helium within the vacancies in which they reside. The accumulation of helium sets plutonium apart from analogous reactor materials, which are mostly irradiated and transmuted by neutrons from the surface. The abundance and distribution of helium may actually create preferential sinks for radiation-induced defects in a way that precludes their coalescence into larger voids (Allen and Wolfer 2015). This would act to prevent void swelling or at least significantly increase the incubation time that has not yet been empirically reported in the open literature.

The complete absence of void swelling has been reported several times by both Livermore and Los Alamos researchers, first in 2003 in 40-year-old samples, again in 2006 in samples containing a fraction of ^{238}Pu (Martz and Schwartz 2003; Chung et al. 2006). Livermore scientists reported similar, even more encouraging results in 2012, indicating that dimensional measurements of aged samples showed no signs of void swelling and that only a 0.25 percent expansion in volume could be expected over 100 years (Heller 2012). The 2006 independent JASON advisory group, reviewing laboratory results on plutonium aging, further suggested that plutonium's unusual material behavior likely means that void swelling will not occur *at all* because perturbations to the structure are more likely to drive it towards the α-phase ($PuGa_3$) rather than a more expanded structure (Hemley 2006). The metastability and relative precarity of the cubic δ-phase may therefore actually eliminate one of the most potentially catastrophic and life-limiting processes for pits in the stockpile.

Corrosion and Environmental Exposure

Chemical corrosion from environmental exposure could potentially shorten the lifespan of plutonium pits. However, this has historically been the easiest process to predict and control of all those that could affect the longevity of pits in the stockpile.

Within the warhead, pits are sealed within the nuclear explosive package (NEP), the nuclear subassembly containing the primary and secondary stages. The NEP is designed to maintain its contents in a safe, inert environment, with little opportunity for contamination as long as the pit resides within the weapon's radiation case. Although the NEP's contents are relatively immune to corrosion from external sources, outgassing from decomposing components within it may lead to some long-term chemical reactivity that must be monitored. Despite this, corrosion is not thought to be a major driver of degradation in the current stockpile.

Bare plutonium in air presents many challenges. Plutonium oxidizes easily and can even burn in air, making shavings from machining pyrophoric. The oxide can form small particles that may be easily ingested or inhaled (Condit 1993). Also, surface oxidation may preferentially draw gallium out of the δ-phase alloy (Donald et al. 2022). Because gallium stabilizes the δ-phase, its depletion in the near-surface layer may encourage the transformation of plutonium back to the α-phase, accompanied by a rather significant volume change (Figure 3.3) (Hecker and Timofeeva 2000).

In the presence of hydrogen, plutonium can form a surface hydride layer that is mechanically unstable and therefore leads to pitting and physical degradation. This would be particularly detrimental to a weapon's performance: both the internal and external surfaces of the hollow pit must be pristine to avoid hydrodynamic instabilities upon compression during use. The susceptibility to hydride formation is likely why the hydrogen isotope tritium for boosted weapons cannot be built into the pit effectively; rather, it is introduced at the time of use (in addition to the likely utility for variable-yield weapons of metering boost gas into the pit).

Within a primary, the plutonium is typically clad on the outside by a thin layer of another metal to avoid exposure to the atmosphere, but handling and cleaning pits during warhead assembly and disassembly introduces further opportunities for unwanted contamination. This may have been a larger problem in the past, although it was reported in 2003 that "pits have remained remarkably pristine and free of corrosion, especially since the adoption of modern cleaning and sealing methods" (Martz and Schwartz 2003). Good laboratory hygiene and an awareness of compatible cleaning methods easily eliminate this risk. This is why all work on raw metal, oxides, and particulates takes place in sealed gloveboxes under either inert or very-low-oxygen environments. The infrastructure requirements to protect both plutonium workers and the material itself are one of the many reasons why a pit-production facility is so difficult to establish.

Storage conditions for plutonium metal and pits that are no longer in the active stockpile are also critical but have a checkered past. Indeed, lessons about catalyzed plutonium corrosion have been learned the hard way at Los Alamos. Nearly catastrophic worker exposure resulted when inadequate storage methods led to the rupture of packaging and the release of plutonium oxides, exposing workers (Haschke, Allen, and Morales 2000).

When weapons are retired, primaries containing plutonium are removed from the disassembled weapon at the Pantex Plant near Amarillo, Texas. The pits are packaged and stored in bunkers onsite, awaiting disposition or reuse. In the past, pits were stored in special containers designed by Dow Chemical in the 1960s (called AL-R8 containers). However, these provided insufficient sealing against the outside environment, requiring the use of extra temperature and humidity controls that are difficult or impossible to achieve in bunker storage in an environment with wide-ranging winter and summer temperatures (BREDL n.d.). Furthermore, Celotex, a packing material made from sugar cane, paper starch and wax, is a source of moisture and chlorides, both of which lead to corrosion and pitting (Defee, Landsberger, and Iskander 2001; Connery 2021). The packages also provided poor radiation shielding for workers and were structurally inadequate to protect the pits from serious physical damage.

Efforts to repackage pits in containers with sealed inserts that would protect against corrosion and increase safety for Pantex workers suffered many setbacks, including inadequate funding (Dwyer and Waugh 1999). In 2021, the Defense Nuclear Facilities Safety Board expressed concern that many pits at Pantex remained stored in unsealed containers, potentially causing accelerated degradation and likely leading to corrosion, which could negate any possible reuse (Connery 2021). Pits within assembled weapons, including thousands of reserve warheads and others awaiting disassembly, would not be expected to suffer environmental degradation and, in principle, could be reused.

3.4 Experimental Techniques to Monitor Plutonium Aging

When weapons in the stockpile were originally designed, full-scale nuclear explosive tests validated their performance. That the functionality could actually be demonstrated allowed increased engineering uncertainties relative to present standards. As weapons age, their functionality and safety must still be certified annually and must account for accumulated, age-induced uncertainties. To address this, the national laboratories have developed a broad array of scientific capabilities within the Stockpile Stewardship Program to gain a deeper fundamental understanding of materials, their dynamic response under compression, and their evolution with time. The program includes a variety of experimental methods to study and compare new plutonium not only with older pits but also with samples that have been artificially aged to accelerate specific radiation-induced effects. Together, these tools can provide a very good understanding of the reliability of plutonium pits in the stockpile and how long to expect them to remain reliable.

Tools available today allow access to high energy density (HED) regimes, meaning a regime in which a large thermodynamic energy is constrained within a given volume. Such states are encountered in both stars and thermonuclear weapons. Materials science in these regimes can differ dramatically from more familiar behavior under ambient conditions. Temperatures and pressures are high enough to drive new kinds of chemistry as compressive energies become comparable or even exceed electronic bonding energies. Experimental capabilities now offer unprecedented access to these conditions. Largely developed within the national labs, these advances make possible an elemental, microscopic understanding of materials within weapons that was previously only verified through the cumulative performance of the assembly (Park et al. 2021). Technology for detailed physical measurements in these regimes have kept pace; precise, detailed data at conditions comparable to those encountered during the operational cycle of a weapon can now be collected without requiring explosive testing.

To assess concerns over plutonium aging, the national laboratories have at their disposal a number of significant techniques, tools, and facilities to explore its physical, chemical, and metallurgical properties. The labs have put all of the following methods to active use over the past two decades, contributing significantly to the understanding of plutonium aging.

Accelerated Aging Studies

The technique of accelerated aging takes advantage of plutonium's diverse family of isotopes to artificially age plutonium-gallium alloy much faster than would occur naturally in weapons-grade material. In effect, scientists can speed up the clock by enhancing radiation-induced damage, enabling them to test predictions or verify critical thresholds for damage without having to wait for these effects to occur in the stockpile.

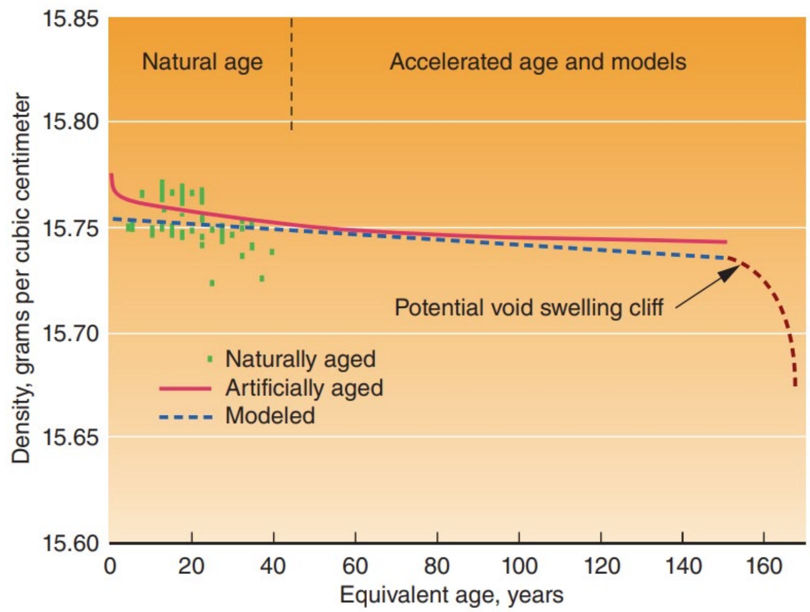
Whereas the half-life of ^{239}Pu is 24,390 years, that of ^{238}Pu is only 87 years. By introducing a few percent of ^{238}Pu into the alloy, the sample experiences much more frequent radioactive decay, accumulating radiation-induced damage some 14 to 16 times faster than a naturally aged sample. Any changes in material dimensions, density, strength, or other physical properties can be directly compared between naturally and artificially aged samples using techniques such as dilatometry, immersion density, and tensile tests (McCall et al. 2017; Chung et al. 2006; Chung, Lema, and Allen 2016).

In 1997, the laboratories began a long-term study of plutonium aging as part of the Enhanced Surveillance Campaign, a $100-million-dollar effort that was part of the newly formed Stockpile Stewardship Program. Initial results were reported publicly in 2006 based on samples that ranged from 15 to 44 years old (including plutonium from legacy pits), as well as samples artificially aged to an effective age of 65 years. Comparative tests on these samples indicated no significant degradation in strength and no change in density commensurate with helium-bubble formation or the onset of void swelling. These results led then-NNSA Director Linton Brooks to state, "It is now clear that although plutonium aging contributes, other factors control the overall life expectancy of nuclear weapons systems" (Pincus 2006).

Despite this confidence, measurements continued in a multilab effort. In 2012, Lawrence Livermore published follow-up results when the plutonium samples had aged to 50 years naturally and 150 years through accelerated aging. The labs again reported no signs of deleterious effects, stating that plutonium continues to "age gracefully" (Figure 3.7) (Heller 2012). Lawrence Livermore provided further confirmation in 2015 when the oldest artificially aged samples had reached 200 years of age and the naturally aged samples 53 years (about 13 years older than the oldest currently deployed pit in the stockpile as of 2023) (NNSA 2015). In fact, these most recent studies reported an apparent stabilization and slowing of apparent change in the samples, with no more than 0.25 percent cumulative change in volume and only a slight increase in material strength (Chung, Lema, and Allen 2016).

Despite the clever nature and apparent utility of accelerated-aging experiments, they come with caveats. Some radiation-induced effects in metals may depend on the dose rate; in that case, accelerated aging may not be directly analogous to natural aging for specific mechanisms. In the case of the possible incubation period for void swelling, the lower dose rate in naturally aged samples (e.g., in the stockpile) should work in favor of their useful shelf-life.

FIGURE 3.7. No Signs of Runaway Damage in Plutonium Aged 150 to 200 Years



As reported in 2012, density variations as a function of effective age in naturally aged (green points) and artificially aged plutonium samples (red curve; individual data not shown) showed no signs of a void-swelling cliff—the point at which catastrophic growth of voids would result in swelling and potential mechanical failure of the metal, as illustrated by past models of plutonium aging (dashed curve). Follow-up results from 2015, including samples with an effective age of 200 years (beyond the range of this graph), also showed no signs of such failure, further emphasizing the unreliability of the past models. SOURCE: Heller 2012.

As noted, while radioactive decay induces damage in plutonium, thermal effects serve to heal some of that damage. Therefore, thermal effects must also be accelerated appropriately to match the increased rate of damage. This can be done by maintaining samples at elevated temperatures, but different diffusion (healing) mechanisms require different activation temperatures. To be sure that accelerated aging experiments are not unintentionally misleading, samples have to be kept at a range of temperatures and compared (Chung et al. 2006).

Assuming that the same sample populations have continued to be monitored, as of 2025 the laboratories should have naturally aged samples at least 62 years old and artificially aged samples with effective ages of more than 300 years.

Microstructural Measurements: Monitoring Crystal Structure and Stability

Measuring physical dimensions and volume helps demonstrate material stability, but it does not give a microscopic understanding of how plutonium in pits may be evolving internally at the atomic level. Modern imaging and spectroscopic techniques do offer such detail and provide additional means of monitoring microstructural changes in plutonium.

Because of the large volume changes among the many phases of plutonium, it is important to understand how and whether microscopic changes could serve to nucleate phase changes and to understand how defects evolve in the crystalline lattice to characterize their lifetime and mobility. Pit alloys are polycrystalline (composed of many granular, crystalline regions rather than a single, perfect crystal), and the structure and chemistry of grain boundaries is particularly important to understand in these regions of greater disorder where unfavorable changes can potentially nucleate.

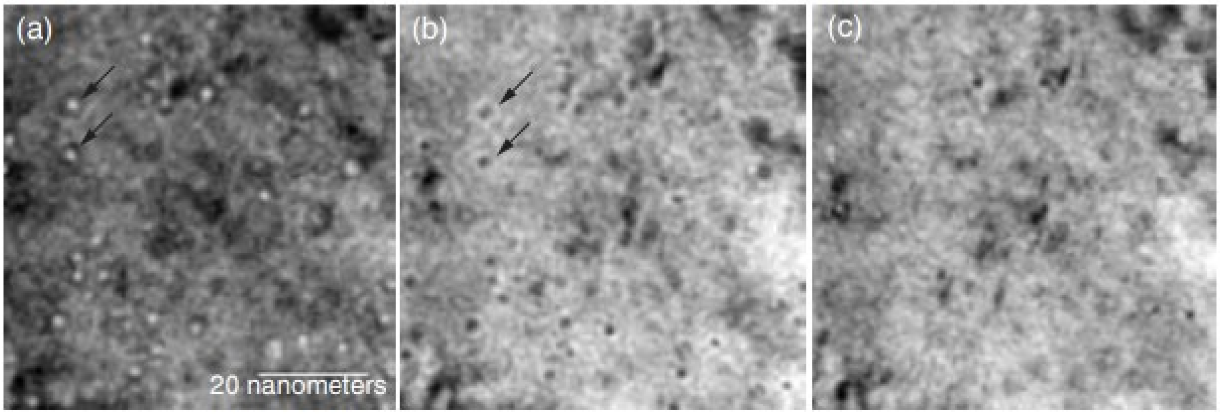
Microscopy, including scanning electron microscopy and transmission electron microscopy, permits imaging with approximately nanometer resolution and has been used to verify that the population density of helium bubbles indeed increases as a result of alpha decay. However, the bubbles do not grow beyond a few nanometers in size and do not coalesce into larger ones (Figure 3.8).

Short wavelength X-rays are useful for probing the crystal structure, including the distance between atoms in the crystal lattice, the regularity of the lattice, and other properties such as the density and phase of the metal as a function of the atomic arrangement. X-ray diffraction is most often used for determining crystal structure, while X-ray Absorption Fine Structure (XAFS) measurements can characterize the local atomic environment around a given atomic species—essentially the distance to the nearest neighbors around a given element and how they interact. Both techniques inform whether the regularity of the crystal structure is breaking down or is maintained with age. XAFS measurements have shown that δ-phase plutonium-gallium appears to evolve toward a *more* regular, ordered structure (Conradson 1998; Conradson 2000).

X-ray diffraction measurements conducted simultaneously on new, naturally aged, and artificially aged samples have shown no significant difference in the behavior of the samples as a function of pressure and temperature. This indicates that the samples remained functionally identical (Heller 2007).

Sound waves can also be used to probe plutonium, providing information on elastic properties ("stiffness" or resistance to various deformations). Ultrasonic excitation, including a technique called Resonant Ultrasound Spectroscopy, can provide such information. This is a sophisticated way of exciting vibrations in a small sample of metal in a way that makes it effectively ring like a bell. Frequency resonances can be observed with exquisite precision and used to derive elastic properties, including the shear and bulk moduli of the plutonium (Migliori, Baiardo, and Darling 2000). These quantities describe the material's resistance to deformation under stress. This technique has been used to observe minute changes over periods of roughly one month (Maiorov et al. 2017). However, the measurements are extraordinarily sensitive to experimental perturbation, and the observed changes are not consistent with multiple independent measurements on decades-aged samples; so far, they appear to lack comparison to controls with well-understood behavior. Thus, the results' relevance to understanding the long-term evolution of plutonium in the stockpile is unclear.

FIGURE 3.8. Scanning Electron Microscopy Allows Direct Observation of Helium Bubble Behavior in Plutonium



Scanning electron microscopy at various focal levels reveals the nanometer size of helium bubbles from alpha decay. Bubbles appear as light spots in (a) and dark spots in (b), but show no contrast in (c), according to focal depth. These images demonstrate the relatively uniform distribution of bubbles and absence of coalescence into larger volumes. SOURCE: Heller 2007.

Equation of State and Dynamic Properties

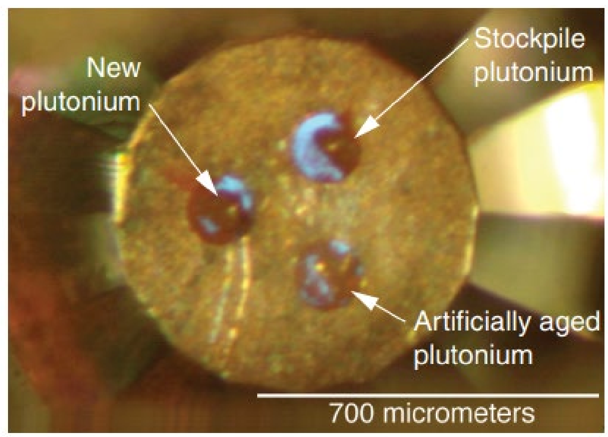
Potential aging effects are relevant not only at ambient conditions as nuclear weapons sit within delivery systems or in storage. Every material has a unique response to changes in pressure and temperature; for a weapon, its operation depends critically on plutonium's response to dynamic compression as the surrounding explosive drives it to a supercritical state. The relationship between pressure, volume, and temperature (or other thermodynamic variables) for a given material is described by what is known as its "equation of state." Such relationships are often mapped out as phase diagrams or as equation-of-state surfaces in three dimensions.

To map out equations of state, a number of experimental techniques, developed over the past century, have been applied to hundreds or even thousands of materials over various ranges of pressure and temperature. These techniques include various means of static and dynamic compression and an ever-evolving suite of measurement techniques that deliver increasingly precise materials-science data. Historically, the national labs have been leaders in developing such techniques, many of which require infrastructure that is only feasible in a large, federally funded setting. Nevertheless, such experiments now provide a more detailed, more precise understanding of materials than do full-scale nuclear tests—and in a manner that is highly tunable and gives access to the full range of conditions that plutonium experiences in the operation of a weapon.

Diamond Anvil Cells

A number of primary experimental platforms help the national labs understand plutonium aging and the high-pressure properties of plutonium alloys (Figure 3.9). One of these, the diamond anvil cell, is a remarkably simple yet versatile tool for squeezing small samples to extraordinarily high static pressures. Within a diamond cell, a sample is compressed between the opposing (flattened) tips of two diamonds. A metallic gasket prevents the material from squeezing out the sides of the assembly. Because diamond is the hardest natural material, it can be used to apply tremendous force; with that force applied over a very small area, the pressures achieved can reach several million atmospheres. Diamond also has the advantage of being transparent to a wide range of the electromagnetic spectrum, so the sample can be observed visually and also subjected to a wide range of spectroscopic techniques using lasers, X-rays, and other methods.

FIGURE 3.9. Diamond Anvil Cell Investigations of Plutonium



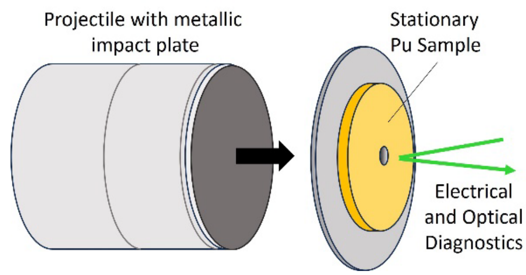
Left: Two diamonds contain a sample at high pressure within a metallic gasket. Adjusting the force on the diamonds controls the pressure. Right: Three different plutonium samples as seen through one of the diamonds. Blue regions are areas of transmitted light through the opposite diamond anvil. Spectroscopy, x-ray diffraction, and other measurements can be made through the diamond anvils, and samples can be held at high pressure for arbitrarily long periods. SOURCE: Left: Courtesy Sébastien Merkel, Université de Lille; Right: Heller 2007.

Diamond anvil cells have been used to study changes in phase and structure in plutonium (Faure and Genestier 2009; Dabos-Seignon et al. 1993) and plutonium alloys (Faure and Genestier 2010), including at high temperatures using in-situ resistive or laser heating (Heller 2007). Livermore scientists have studied both naturally and artificially aged plutonium—for example, compressing and directly comparing multiple plutonium samples simultaneously and using synchrotron X-ray diffraction, which reveals the crystal structure and volume. While results from the latter experiments do not appear to have been published in the open literature, Lawrence Livermore summarized them in 2007: "[The experiments] revealed no significant differences among the plutonium samples and no sudden or unexpected changes in properties" between newly produced samples, artificially aged samples, and 45-year-old samples extracted from the stockpile (Heller 2007).

The Joint Actinide Shock Physics Experimental Research Facility

The Joint Actinide Shock Physics Experimental Research (JASPER) facility at the Nevada Nuclear Security Site houses a two-stage, light-gas gun, a sophisticated cannon that uses compressed hydrogen to fire a small projectile toward a stationary sample at velocities of up to about seven to eight kilometers per second (Figure 3.10). The collision of the projectile with the target assembly results in a shock wave that compresses and heats the sample, enabling scientists to study the dynamic response to pressures of about 6 million atmospheres and several thousand degrees Kelvin. JASPER was built expressly to handle plutonium samples using a nested, double-containment vacuum chamber system to contain the material fragments.

FIGURE 3.10. The JASPER Facility at the Nevada National Security Site



The Joint Actinide Shock Physics Experimental Research (JASPER) facility is a two-stage light-gas gun. A projectile is driven at high velocity down a roughly 25-meter barrel before hitting a stationary target. The impact drives a shock wave through the target, compressing it and allowing measurements of its high-pressure responses, including changes in density, temperature, sound speed, and other properties. Measurements are made optically (with lasers and various forms of Doppler interferometry) and/or electromechanical sensors directly on the target. SOURCE: left, Hager 2017; right: UCS.

Light-gas guns have been a staple of materials science for decades. They allow a very tailored (and reasonably economical) means of subjecting a sample to high dynamic pressures. The JASPER facility carried out its first experiment in 2003 (Heller 2004). By 2012, it had completed 100 shots; many, although not all, were on plutonium. While the dynamic-compression results on plutonium remain classified, in 2007 the lab quoted JASPER's lead scientist as saying that comparisons showed "no statistically significant difference in the [equation of state] of the new and old plutonium" that had been tested up to that time (Heller 2007). This is significant because light-gas guns can measure differences in the compressive behavior of materials with high precision and relatively small uncertainty. Differences in bulk density or material strength can be observed in such experiments, but apparently they were not in these early datasets. Experiments have continued at JASPER, and the NNSA has reported the completion of a key data set on the dynamic equation of state of plutonium (NNSA 2015).

Another light-gas gun dedicated to plutonium has been used at Los Alamos's PF-4 plutonium facility and preceded JASPER in its investigations of shocked plutonium. This device is much smaller—contained entirely in a glovebox—and is capable of projectile speeds of about 2 kilometers per second and pressures of about 300,000 atmospheres. While data in these regimes compliment those provided by JASPER, the practicality of operating within a containment system likely complicates use of this platform while competing for space within the PF-4 facility.

National Ignition Facility

The National Ignition Facility (NIF) at Lawrence Livermore National Lab is a stadium-sized laser facility. Housing 192 laser beams that converge on a target, it is used for a variety of physics and materials-science experiments. The NIF garnered significant press attention for its December 2022 fusion experiment (Bishop 2022). However, stockpile research is its primary role. The NIF can compress materials to pressures of several terapascals (1 terapascal ≈ 10 million times atmospheric pressure) and temperatures of millions of degrees. The development of facilities like the NIF has become a signature of nations with advanced nuclear arsenals. Such facilities give controlled access to physical conditions otherwise only encountered in thermonuclear burn or inside stars.

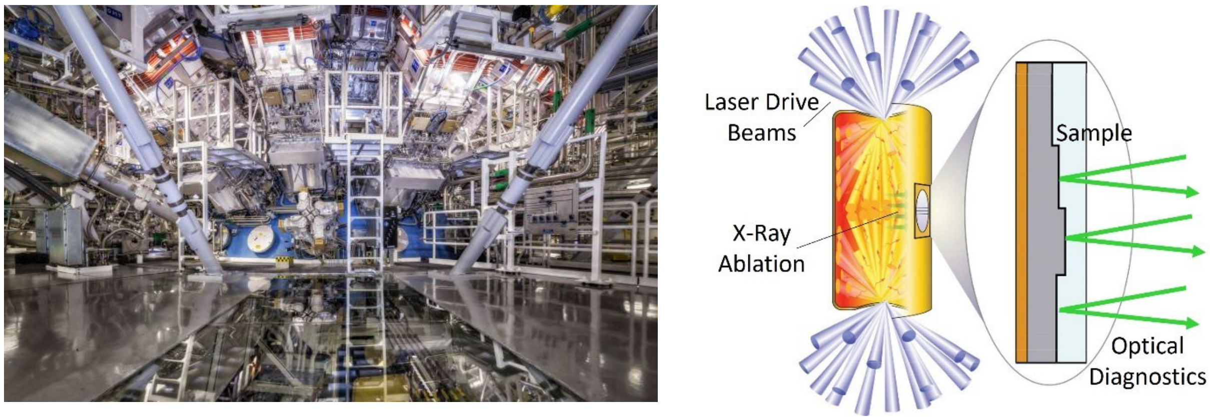
Plutonium work at the NIF, which began in 2015, has included a number of experiments to measure plutonium's strength and equation of state, as well as to gain information about crystal structure in the solid-state under compression. Many NIF experiments work by focusing the tremendous laser energy into a small gold or uranium capsule that acts like a small X-ray oven under the intense laser irradiation. The laser-generated X-rays irradiate the back surface of the sample package, driving a shock wave through the sample in a manner analogous to JASPER but at far more extreme conditions and at a much smaller scale (Figure 3.11). As with JASPER, most measurements are optical, using lasers, various forms of spectroscopy, and fast-imaging cameras with sub-nanosecond resolution.

Many unique diagnostic tools have been developed specifically for the NIF, one of which is the capability of doing multi-exposure dynamic X-ray diffraction during the brief time the sample is under compression. Until recently, high-pressure diffraction was only possible on relatively long timescales at large synchrotron X-ray facilities, but the ability to generate laser-induced X-rays from metallic foils placed near the plutonium sample has allowed maturation of this technique. This is useful for investigating the crystal structure and kinetics of phase changes on nanosecond timescales and under extreme pressures and temperatures.

A typical NIF sample for an equation-of-state measurement would be on the order of about 0.5 millimeters square with a thickness of about 100 microns. The NIF does not conduct experiments on weapons grade ^{239}Pu, but it does on ^{242}Pu, which has a significantly longer half-life of 375,000 years and therefore proportionally lower radioactivity.

Compared with other sites across the nuclear weapons complex, Lawrence Livermore handles only very small quantities of plutonium. However, the lab maintains expertise in preparing samples for the NIF, including precision diamond-turning, as well as the ability to prepare and measure samples for aging experiments. Of all the platforms across the complex, the NIF is likely the most capable of delivering data in regimes directly comparable to data from legacy nuclear tests.

FIGURE 3.11. The National Ignition Facility (NIF) at Lawrence Livermore National Laboratory



Left: Laser-beam paths and diagnostic equipment surround the target chamber (in blue) at the heart of the National Ignition Facility (NIF) . Right: Lasers enter a small gold or uranium capsule from either end, irradiating the interior and generating intense X-rays. Those X-rays drive a shock through the sample via ablation of the interior surface. Data are collected optically from a variety of diagnostics. The total size of the target package is comparable to a #2 pencil eraser. SOURCES: left: Damien Jemison/Lawrence Livermore National Laboratory n.d.; right: modified from Heller 2019.

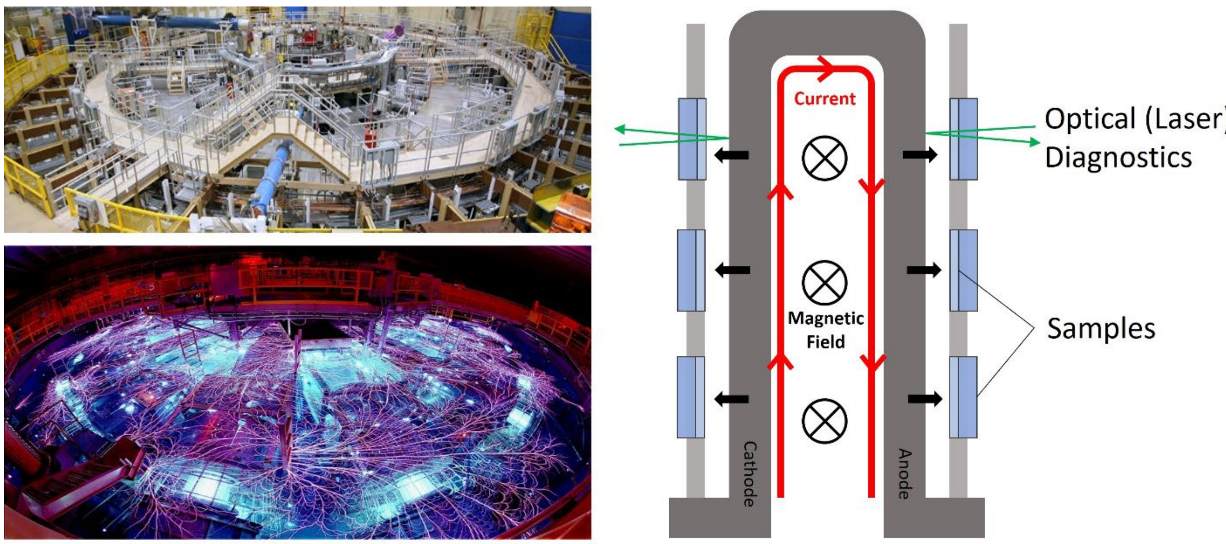
Sandia Z Pulsed Power Facility

Sandia National Laboratory's Z-accelerator (also known as the Z Machine) also conducts shock-compression experiments on plutonium (Figure 3.12). The facility, which explores many of the same science questions as the NIF, can subject materials to pressures of up to about 1 terapascal (≈10 million atmospheres). Z has been used for conducting plutonium experiments since about 2006, with reports of three or four experiments per year since 2010 in collaboration with Los Alamos National Lab (*ScienceDaily* 2016).

Shaped like a wheel 33 meters in diameter, Z functions by generating an extremely large pulse of electrical current (up to 26 million amps) that is compressed in space and time as it propagates toward the center of the machine along specially designed pulse-forming lines (the "spokes" of the wheel). The resulting electromagnetic energy can drive a number of types of experimental assembly, although most high-pressure, materials-science experiments use the interaction of extremely high current and magnetic field to accelerate a thin metallic impactor toward a sample. Velocities of up to about 40 kilometers per second can be reached over very short distances, with the acceleration tuned to generate either a ramped compression or a planar shock wave in multiple samples simultaneously. As with JASPER and the NIF, the end result is to use the resulting compressive wave to reach extreme pressures and temperatures in the material of interest.

The total number of plutonium experiments conducted on Z is unknown; however, at least 18 experiments had occurred by August 2015, and records indicate that, unlike the NIF, weapons-grade plutonium is used at Z (Moore 2016). Sample sizes are typically somewhat larger for Z than for the NIF (about 1 to 2 millimeters square or a few hundred milligrams of plutonium), and a specially designed double containment chamber used for plutonium avoids contaminating the primary vacuum chamber at the center of the machine.

FIGURE 3.12. The Z-Accelerator at Sandia National Laboratory



Left: Sandia National Lab; Z-Accelerator. Right: The interaction of high current density and magnetic field drive a thin, metallic plate outward toward stationary samples at velocities of up to about 40 kilometers per second. The acceleration and final velocity can be precisely tuned to tailor the pressure state achieved in the sample. Optical diagnostics return data on the physical properties of the sample throughout the experiment. SOURCES: Left: Sandia National Laboratory; Right: UCS

PULSE Subcritical Testing Facility

While all these facilities can deliver exquisitely detailed data on equations of state, physical properties (e.g., strength), and how plutonium evolves under dynamic compression, they are limited to relatively small sample sizes. Also, they cannot test assemblies or combinations of components representative of a weapon's actual design. The Pulse (Principal Underground Laboratory for Subcritical Experimentation) facility at the Nevada National Security Site has taken on that role as the sole US facility capable of conducting subcritical tests with weapons-relevant quantities of nuclear material and in geometries that reproduce or mimic a weapons design or engineered assembly but without resulting in a self-sustaining nuclear chain reaction (hence subcritical) (Figure 3.13).

Researchers use subcritical tests to study such things as the implosion of a plutonium shell into a gaseous medium to examine the boost process in modern thermonuclear weapons, or they may be used to qualify new formulations of conventional explosives to drive implosion of the primary (plutonium) stage. Subcritical tests are often considered controversial because they may be seen to approach the allowable limits of a nuclear test ban (in the absence of a nuclear yield), yet they are tremendously beneficial to a nuclear state that wishes to make technological advancements to its arsenal. Furthermore, subcritical tests are difficult to monitor and detect without international transparency. Conducted in heavy containment vessels deep underground, they do not result in the strong seismic signature that would be associated with a full-scale underground nuclear test.

PULSE is an underground facility composed of a network of tunnels that house experimental space, extensive diagnostics, and preparation and control-room areas, as well as tunnels dedicated to the permanent entombment of spent experimental vessels. The first subcritical tests there, in 1997, studied ejecta produced from coin-sized, explosively driven plutonium samples (Drell et al. 1997). Numerous other geometries have since been used, with a total of 34 subcritical tests carried out as of mid-2024 (Kimball 2024). Subcritical tests are orders of magnitude more expensive and time-consuming to carry out than the types of dynamic compression experiment described above. Typically, they are planned years in advance and involve large, multi-laboratory collaborations.

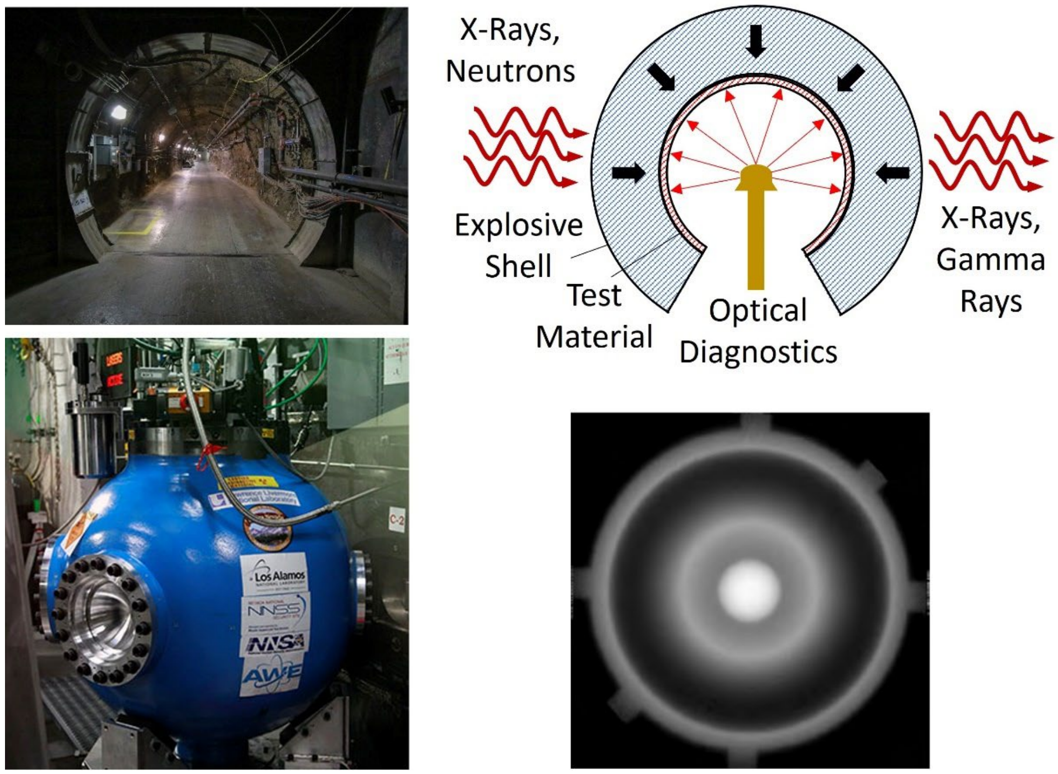
The current emphasis for such tests is on understanding the latter stages of plutonium implosion when the weapon's primary stage is explosively driven to near criticality. This is useful for validating and benchmarking codes used to simulate such processes. The mechanics of such experiments require X-rays to diagnose the evolution of material density as a function of time. PULSE includes Cygnus, a special X-ray generator called that can probe the early stages of implosion (producing two radiographs using 2.2 mega-electron volt X-rays), but it does not produce high enough energy X-rays to probe late-stage implosion when plutonium is near its fully compressed density—a state now seen as a potential knowledge gap in understanding stockpile behavior.

Consequently, the NNSA is building two new instruments at PULSE to characterize plutonium's late-stage implosion: a 125-meter-long, 22.4-mega-electron volt X-ray device known as Scorpius and a neutron source called Zeus. Scorpius may capture up to eight X-ray radiographs. Zeus will generate neutrons to induce fission in the plutonium assembly and thereby emission of fission-product de-excitation gamma rays; the gamma rays can be used to measure the rate of fission reactions and thereby the level of nuclear reactivity (while remaining subcritical). Collectively, the two devices represent an investment that will likely exceed $1 billion before completion (Kramer 2020).

Los Alamos operates an aboveground facility called the Dual Axis Radiographic Hydrodynamic Test Facility (DARHT) for a similar purpose. Despite being conceived to characterize implosion dynamics, DARHT has never done tests involving plutonium. It only performs experiments with other dense metallic surrogates such as lead, cerium, or depleted uranium.

The scientific value of subcritical experiments lies primarily in their ability to provide data using larger quantities of fissile material in the form of engineered assemblies and in a manner that can help validate design choices and combinations of explosives with fissile samples. This enables the NNSA to characterize modifications to weapons without resorting to full-scale explosive testing. Such experiments are not possible at other US facilities, which use only very small quantities of plutonium. Subcritical experiments can play a role in comparing aged plutonium with more recent samples; however, the relative cost and complexity of such experiments favors the other dynamic compression facilities for most measurements of material properties at extreme pressure and temperature.

FIGURE 3.13. Subcritical Experimental Facilities at the Nevada National Security Site



Subcritical Experimental Facilities at the NNSS allow testing of larger quantities of plutonium and validation of design characteristics without full-scale nuclear explosive tests. Subcritical tests may use weapons-relevant quantities and geometries of fissile material, including the implosion of plutonium shells using explosives, as occurs in a weapon. Such geometries can be observed using hundreds of channels of laser interferometry, X-ray radiography, and the detection of neutrons and gamma rays from fission reactions. Clockwise from top left: Tunnel at PULSE, Nevada National Security Site; notional schematic of a test assembly for an explosively driven experiment; simulated radiograph illustrating X-ray penetration of regions of variable density; a subcritical test containment vessel.
SOURCES: US Department of Energy; NNSS/Mission Support and Test Services (MSTS) ; UCS

Computational Capabilities

The nuclear complex's final, but possibly most versatile, tool to investigate plutonium and aging effects is the advanced computational infrastructure maintained by the national labs. Each lab's supercomputing facilities, such as Crossroads at Los Alamos and Sequoia at Lawrence Livermore, routinely rank among the top in the world in computing power. The facilities enable scientists to test theories and conduct simulations of complex behavior while tuning various physical parameters. Using computational tools, scientists can go where real-world experiments cannot, whether because of physical scale, risk, or cost or because experimental techniques do not yet exist to address certain problems.

Codes maintained by the labs can examine everything from chemical processes at the atomic level (e.g., ab-initio molecular dynamics) to shock propagation in large-scale, 2-D or 3-D assemblies using hydrodynamic codes (Iftimie, Minary, and Tuckerman 2005; Crawford 2008). Computational models directly complement experimental work in that an iterative process often exists between the two: real-world data (e.g., legacy nuclear test data or laboratory experiments) can inform the creation of codes, which can then be used in a predictive manner and continually benchmarked against physical results. Discrepancies between the two typically indicate a learning opportunity in which either an experiment has overlooked a physical mechanism or an approximation in a computational model reveals itself to be insufficient to match the real-world observation.

Nuclear weapons codes have been calibrated based on data collected from more than 1,000 nuclear explosive tests prior to 1992. Today, these codes are continually revised and improved using what is learned from experimental platforms across the complex. Reliable codes require reliable data on material response, and the equation-of-state data across a wide range of pressure and temperature are a critical input for hydrodynamic modelling that simulates the operation of a weapon.

In the case of plutonium aging, simulations can take advantage of the whole suite of physical measurements described here, and they can use those data both to test design sensitivities to any perturbations in material properties and to determine acceptable margins of uncertainty (Box 3.1). This may include artificially testing changes to design parameters that cannot be easily tested experimentally. Future changes in pit performance can also be forecast to some degree using data from careful surveillance of the present stockpile and models that propagate observed rates of change under various circumstances. Current advances in machine learning and quantum computing for predicting materials behavior, crystal structures, and electronic band structures should also enhance computational capabilities in materials science, including the understanding of how plutonium behaves over time (Mobarak et al. 2023; Jeong et al. 2024).

3.5 The Path Forward for Studies of Plutonium Aging

In 2006, the JASON group conducted the first major external review of plutonium-aging data from the national laboratories (Hemley 2006). This was before many of the major experimental capabilities described here had been thoroughly developed and when accelerated aging data were limited in scope. In its unclassified summary, the JASON group concluded, “Most primary types have credible minimum lifetimes in excess of 100 years as regards aging of plutonium; those with assessed minimum lifetimes of 100 years or less have clear mitigation paths that are proposed and/or being implemented.”

Those conclusions were often cited over the next decade as many of the experimental platforms reached maturity and began producing new datasets reflecting previously inaccessible conditions. Despite this apparent progress, a 2019 follow-up evaluation found that the laboratories’ “studies on Pu aging and its impacts on the performance of nuclear-weapon primaries have not been sufficiently prioritized over the past decade” (JASON 2019). The more recent JASON assessment followed with several recommendations for further aging studies, including:

- Investigation of the properties of naturally and artificially aged plutonium that are relevant to primary yield, which include compressibility, strength, and entropy at weapons-relevant pressures and densities;
- Completion of aging studies for the full set of plutonium materials used in the stockpile;
- Extending the range of accelerated aging to identify the types, modes, timescales, and uncertainties in changes of plutonium behavior that would affect primary performance; and
- Exploring the utility of integrated subcritical experiments with new and aged plutonium pits, covering for example, the temperature and pressure conditions encountered during primary implosion to provide information about consequences of plutonium aging.

Many of these recommendations bear on topics that the labs have been studying—including compressibility, strength, and entropy (extra energy locked up inside the crystal)—and that are the purview of the labs' many large dynamic-compression facilities.

Extending the range of aging studies to include broader isotopic and alloy variations has not been limited by technical capability. To the degree that data are lacking in these areas, it would appear to be from lack of concern. Presumably, accelerated aging studies have continued, so the labs should now have access to samples with effective ages of roughly three centuries—far longer than any plausible pit lifetime. Finally, developments underway on the Scorpius and Zeus detectors at PULSE will address compression characteristics at very high density—research that was proposed and underway as early as 2014.

Thus, it is unclear precisely what the 2019 JASON evaluation thought to be lacking that the labs have not already been capable of exploring. In the absence of any more comprehensive review of existing data, the report nonetheless recommended that the NNSA reestablish pit-production capabilities "as expeditiously as possible." That conclusion drew significant attention from Congress and the Senate Appropriations Committee, which echoed "concern with the apparent lack of focus on advancing knowledge regarding pit and plutonium aging since the JASONs conducted their first study in 2006" (US Congress 2021).

In response to these concerns, the Senate required the NNSA to develop a "ten-year research program for pit and plutonium aging that represents a consensus program among the national laboratories and federal sponsors" (US Congress 2021). Such a plan may have been produced in 2021, but, if so, it does not appear to be publicly available. Assuming it incorporates the JASON's recommendations, the apparent lack of cross-lab consensus prior to major appropriations for pit-production facilities suggests a disconnect of pit-aging concerns and the present motivations for pit production. Further external review of the purported ten-year plan is not required before 2030, by which time investment in the new production facilities will likely be substantially complete.

Although pit aging is often cited as the primary motivation for new pit production, a critical look at the history, currently available unclassified data, and the national laboratories' present capabilities suggests otherwise. While the national laboratories have indeed developed and exercised an experimental program across multiple platforms to collect data on both new and aged plutonium, the program has not been pursued with enough effort or coordination to yield a clear consensus among the labs on aging—despite the policy implications and costs associated with reviving pit production. The apparent lack of a cross-lab consensus report on plutonium aging—despite technical capability and clear productivity at many facilities—again suggests a lack of concern rather than the more unlikely scenario in which an unexpected technical issue is driving current pit-production efforts.

While gaps likely remain in our understanding of plutonium aging and the evolution of pit performance, any remaining gaps should be resolvable with existing or planned capabilities within the nuclear complex.

Some weapons in the US nuclear stockpile may have lifespans shorter than 85 to 100 years. However, given what is known about plutonium aging, the plutonium itself is unlikely to be the life-limiting component as stated by former NNSA administrator, Linton Brooks in 2006 (Pincus 2006). In that case, refurbishment strategies other than repurifying and recasting pits should be considered. They could be carried out with less infrastructure and at a slower pace than the current program demands.

Indeed, it appears that plutonium aging will not affect the currently deployed stockpile for decades to come. Instead, it appears that the NNSA's present motivations are driven by plans for new weapons and a desire to reestablish production capacity well before approaching the margins of uncertainty for existing weapons. This realistically requires decades of forethought, but, according to the laboratories' own statements on plutonium aging, the current production is still early-to-need if we choose to maintain the stockpile we have rather than expand or modify it.

If aging is the primary concern, the NNSA has time to take a more measured, more cost-effective approach to the resumption of pit production rather than proceed with a crash program that lacks proper planning, justification, and management.

Findings and Recommendations

Plutonium aging is not a credible motivation for renewing pit production at this time. No new technical evidence suggests that the lifetime of plutonium in pits is any shorter than the previously determined 85 to 100 years. If anything, accelerated aging studies have shown that the onset of deleterious effects is slower than expected and that plutonium's unusual metallurgical behavior may slow or counteract many processes thought to contribute to aging.

Publicly reported conclusions regarding both static and dynamic equation-of-state data suggest that the performance of plutonium in US weapons is not measurably different at four to five decades of age.

Signs of void swelling and helium-bubble accumulation, often cited as a potentially catastrophic mechanisms that could result in an unacceptable reduction in performance margin, have not been seen to be significant in samples aged at an accelerated rate to 200 years of age.

The acceptable service life of the primary stage in nuclear weapons may be determined by components other than plutonium. The service life of a nuclear weapon's primary stage may be shorter than 85 to 100 years, but such effects could, in principle, be handled without remanufacturing the plutonium pit itself.

Since the 2006 JASON assessment, the national laboratories have demonstrably improved their understanding and experimental capability with regard to plutonium's material properties.

The national laboratories should continue exercising their existing scientific capabilities to monitor plutonium aging and produce a comprehensive report summarizing all available results.

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Chapter 4
The Human and Environmental Impacts of Pit Production

"We're still cleaning up the legacy mess that we made by working the way we did." — Robert Webster, Los Alamos Deputy Director for Weapons (Hennigan 2023)

"We cannot wait for science to validate the harm we know is happening. We must be counted as experts that can help heal this place we are a part of." — Beata Tsosie-Peña, Santa Clara Pueblo, Tewa mother, and birth worker (Tsosie-Peña 2017)

Introduction

The renewal of plutonium-pit production and the manufacture of new warheads have implications far beyond the fences of the national labs and production sites. Undertakings of such magnitude reverberate in myriad ways, often as invisible costs borne by workers and communities in the form of environmental, economic, and health impacts that may outlast the programs associated with them.

While practices for handling plutonium have changed, the harmful aftermath of past activities with plutonium haunts nearly every site that has been involved in such work, and the present-day risks remain poorly understood or overlooked outside the national laboratories. Today, the labs apply improved practices to minimize human risk, but humans ultimately remain fallible. Where there are severe hazards, there is the potential for severe risks.

Calling attention to the human context surrounding renewed pit production highlights the critical role of protective measures, adequate and inclusive environmental analyses, and sound engineering and work practices for protecting people. The historical context of the production sites at Los Alamos and Savannah River carries relevance that cannot be overlooked, given that frontline communities have historically suffered from the inadequacy of such measures. The legacy of contamination and health effects is still felt deeply today.

To understand the potential risks requires understanding the populations facing the highest danger, the health effects and mobility of plutonium, and the methods of mitigation, as well as the broader social and economic impacts that surrounding communities can expect from today's proposed activities.

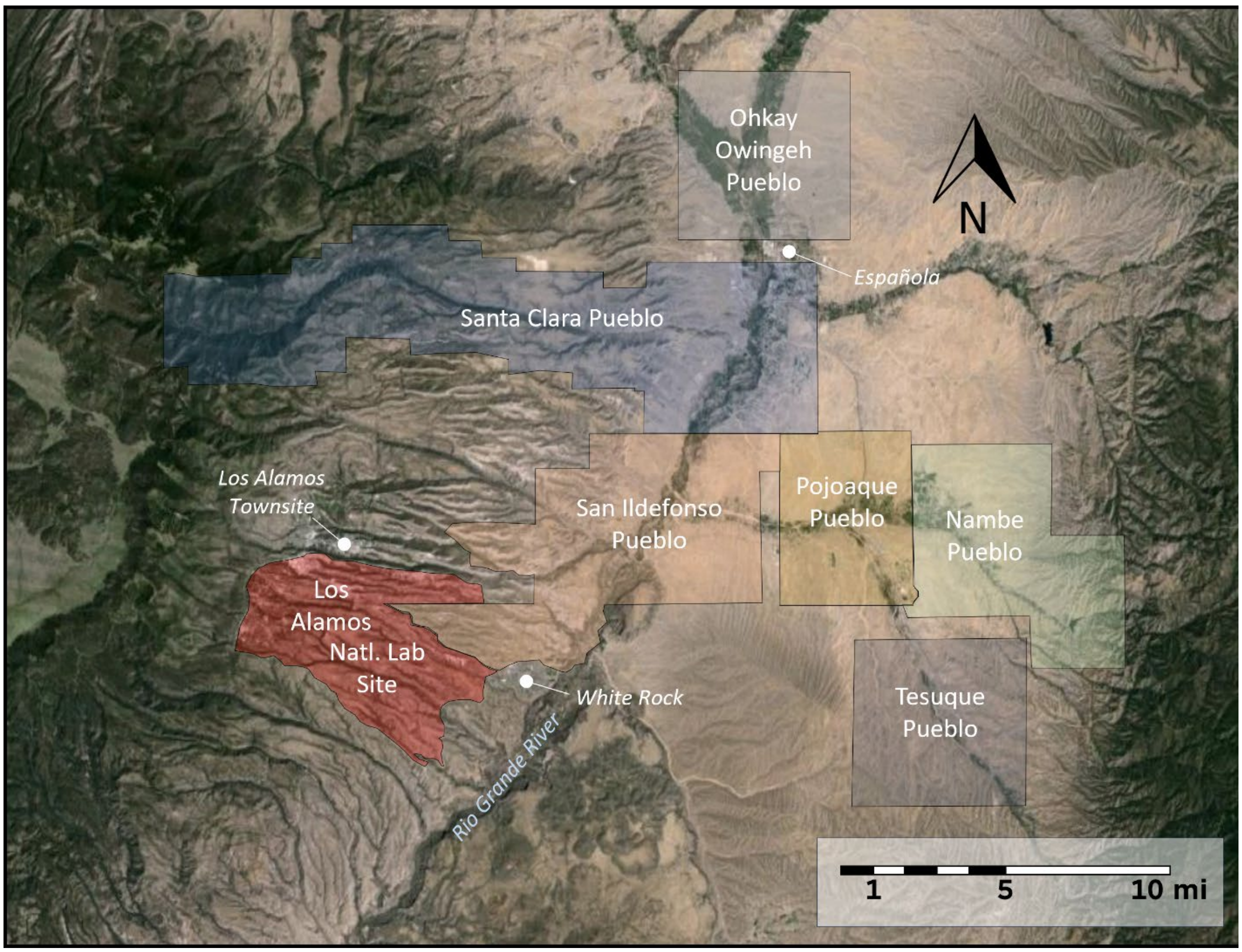
4.1 The Legacy of Cold War Plutonium: Environmental and Human Costs

The two proposed sites for resuming pit production differ vastly from one another—geographically, culturally, and demographically. As a result, the impacts on neighboring communities, infrastructure, and workforce are site-specific yet wide-ranging in both cases.

Los Alamos, New Mexico

Los Alamos National Laboratory (LANL) is located in north-central New Mexico, about 25 miles northwest of Sante Fe. Its 900 individual facilities span roughly 40 square miles and include numerous "technical areas" (LANL 2024). Perched on the side of the Valles caldera, the lab sits atop the volcanic Pajarito Plateau, cut by deep canyons containing seasonal streams that drain to the Rio Grande River (Figure 4.1).

FIGURE 4.1. The Geographic Context for Los Alamos National Laboratory



Los Alamos National Laboratory (highlighted in red) is surrounded by the federally recognized sovereign nations of Po-Woh-Geh-Owingeh (San Ildefonso) and Kha'p'oo Owingeh (Santa Clara). Many lab employees live in the community of White Rock (pop. 5,800) and Espanola (pop. 10,500). SOURCE: UCS, modified from Google Earth, 2024.

The laboratory and town of Los Alamos comprise their own county (incorporated in 1949) consisting predominantly of federally owned land. Perched on mesa tops, its unique geography limits municipal expansion, and only about 35 percent of the lab's current workforce lives in Los Alamos County. Some 990,000 people live within 60 miles of the lab, and about 65 percent of the workforce commutes from surrounding communities in Rio Arriba, Sante Fe, and Sandoval counties (Connery, Roscetti, and Summers 2023).

Demographically and culturally, Los Alamos County is exceptional compared with its surroundings. It is the most affluent county in New Mexico, with a median income more than twice that of its neighbors (Clark 2023; Lerner 2017). In stark contrast, neighboring Rio Arriba County remains one of the poorest, with a poverty level twice the national average (US Census Bureau 2022). The median household incomes in Los Alamos and neighboring Rio Arriba counties are $135,801 and $52,031, respectively (US Census Bureau 2024a). Unlike most of the communities in and around the northern Rio Grande Valley, Los Alamos is comprised mainly of non-Hispanic whites, while Hispanic and Native American populations represent a cumulative majority statewide (US Census Bureau 2021).

Ostensibly chosen during World War II for its remote nature, the Los Alamos National Laboratory is in fact built upon land continuously inhabited by the Tewa tribes, *Po-Woh-Geh-Owingeh* (San Ildefonso) and *Kha'p'oo Owinge* (Santa Clara), for more than 1,000 years before Spanish colonization of New Mexico. These Pueblo communities are among the longest continuously inhabited communities in the United States. Today, Los Alamos shares its eastern boundary with the pueblo of *Po-Woh-Geh-Owingeh* and the community of White Rock; the remaining perimeter abuts national forest or national monument land.

The Environmental Legacy of Historical Activity at Los Alamos

Historically, LANL's research activities have left a heavy environmental and health burden on the region. The initial rush to complete the Manhattan Project (1942 to 1945), coupled with relative ignorance of some of the health and safety risks associated with newly produced fissile materials, resulted in work practices considered exceedingly reckless by today's standards. In the postwar years and into the 1950s, technology to monitor human and environmental exposure was relatively undeveloped and used only sporadically even when available. And even as the risks of radioactivity and the associated health effects became better understood, the lab's work practices exposed many staff to radionuclides and other noxious chemicals, either through direct handling or accidental overexposure.

Direct releases of hazardous materials to the environment were common practice before the enactment of environmental regulations (e.g., the Clean Air Act in 1963; the Clean Water Act in 1972). Throughout the 1940s and 1950s, LANL often disposed of radioactive waste in canyons surrounding the research sites (Figure 4.2). Airborne and waterborne releases were largely uncontrolled, resulting in direct environmental contamination and the spread of contaminants to neighboring communities.

The degree to which LANL released hazardous substances, including radioactive materials, is not fully known, either because of the lack of monitoring or the absence of early recordkeeping, particularly during the Manhattan Project and the immediate postwar years. An extensive study conducted on behalf of the Centers for Disease Control (CDC) sought to gather historical records from LANL and document or reconstruct past releases of radionuclides and chemicals from the lab's inception through the 1990s. Referred to as the Los Alamos Historical Document Retrieval and Assessment (LAHDRA) project, the report provided revised estimates of laboratory effluents (Widner 2010).

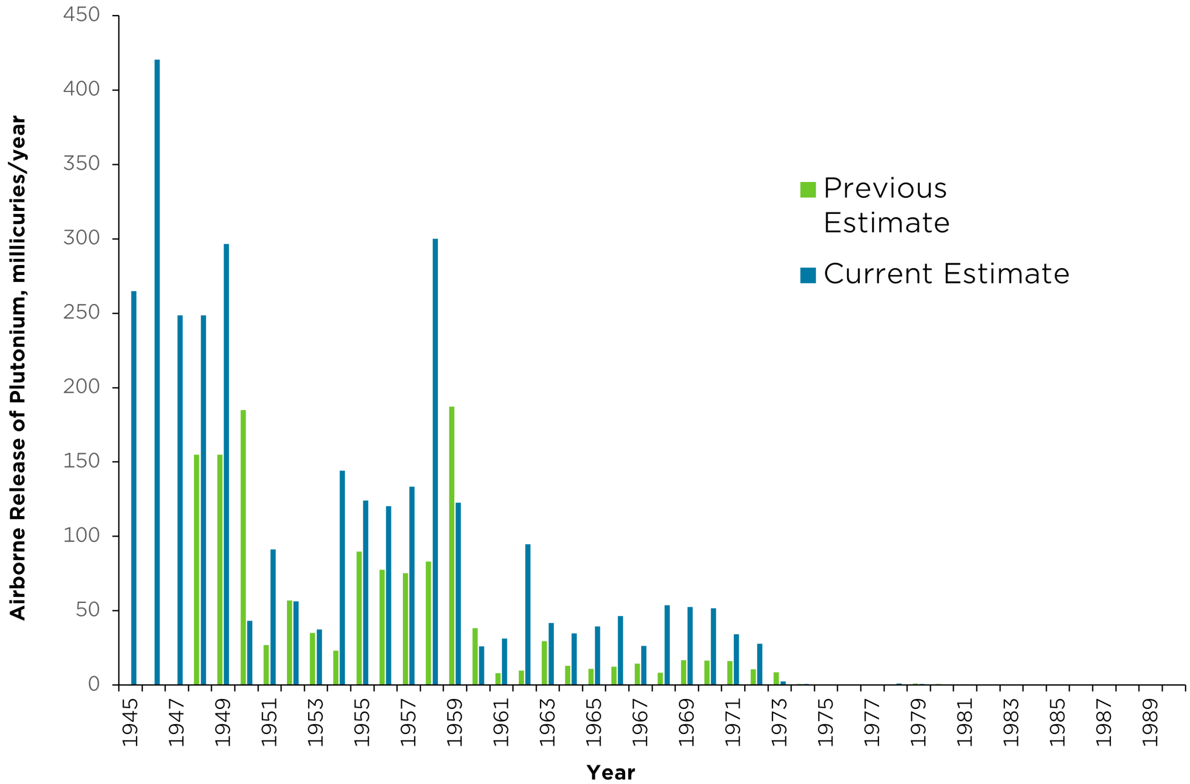
FIGURE 4.2. Past LANL Practices Included Waste Discharge Directly into the Environment

LANL discharged liquid radioactive waste into Acid Canyon in the late 1940s (left) and liquid waste into DP Canyon, c. 1973 (right). SOURCE: Widner 2010.

The LAHDRA study concluded that plutonium releases were of greater concern over most of the lab's history than releases of other materials such as uranium or tritium. It also said that airborne releases of plutonium were significantly higher than officially reported before 1970, and that soil samples surrounding LANL may contain as much as 100 times more plutonium than previously estimated (Widner 2010). A 2018 study conducted by the independent Boston Chemical Data Corporation surveyed 80 off-site locations in or near Los Alamos National Laboratory. It found concerning levels of radioactivity in indoor dust in homes and offices—high enough to result in more than four times the permitted off-site annual dose of radiation. Strontium-90 was discovered in locations over 42 miles away (Kaltofen 2018).

D-building at TA-1, where the first plutonium work was done, vented directly to the air and even maintained positive pressure internally, which would serve to expel radioactive contamination rather than contain it. From 1945 until 1978, plutonium work occurred at the DP site (about 1.5 miles to the east of the original site at TA-1); despite the use of filtering there, the estimated airborne releases just from 1948 to 1955 were over 10 times the total reported by LANL for operations before 1973 (Figure 4.3) (Widner 2010). While the DP site was largely decommissioned by 1981, buried tanks contain aqueous plutonium residues, contaminated soil, and waste disposal wells within a quarter mile of residential and commercial property in Los Alamos (DOE 2020a). The western-most edge of the site has been developed recently for residential housing.

FIGURE 4.3. Airborne Releases of Plutonium from LANL, 1945–1990



Airborne releases of plutonium were extraordinarily high throughout the early history of the Los Alamos National Laboratory. Laboratory estimates have been shown to be systematically lower than those reconstructed from historical data. Data beyond 1973 are vanishingly small but not zero. SOURCE: reproduced with data from Franke et al. 2003.

Research and development on plutonium was of the highest priority at LANL—not just in the leadup to the first plutonium implosion device over Nagasaki, but also in the postwar years as the United States forged ahead with developing a nuclear arsenal. As a result of the varied activity, plutonium was present in numerous facilities across the lab (contrary to today's practice of strictly isolating plutonium work to dedicated facilities). This resulted in measurable contamination, particularly in LANL's older areas that are now part of the townsite outside the present-day laboratory's boundaries.

Other sources of significant radioactive contamination include outdoor explosive tests that used radioactive lanthanum, referred to as "RaLa" experiments. LANL conducted 254 RaLa tests between 1944 and 1962 in Bayo Canyon to study implosion designs for weapons. Lanthanum, a strong gamma-radiation emitter, was used to help diagnose density changes occurring during implosion of test devices that employed surrogate metals in place of plutonium. These tests, which involved large quantities of high explosives, spread fallout regionally, with radioactive releases varying in magnitude from 25 curies to 4,200 curies (Dummer, Taschner, and Courtright 1996; Widner 2010; Advisory Committee Staff 1995).

Initially, these tests were only permitted when the wind was blowing away from Los Alamos toward “uninhabited land” to the north and northeast—in fact, directly toward the inhabited San Ildefonso and Santa Clara pueblos. Later tests were carried out with the intent of tracking and studying fallout using equipment flown on B-17 aircraft. At least one flight tracked radiation as far as 70 miles away, past Sante Fe and beyond the Sangre de Cristo Mountains to the east (Markey 1986).

Today, residential developments are less than half a mile from the former RaLa test site, which is also directly adjacent to the sovereign nation of *Po-Woh-Geh-Owingeh* (San Ildefonso Pueblo Trust land). While the Department of Energy considers the site remediated and suitable for recreational use, it also notes that Strontium-90 will remain elevated through the year 2142 (DOE 2003a). The site includes markers to indicate the presence of buried radioactive waste and discourage excavation, but it is open for public recreational use. Despite this, remaining contamination means that the site is no longer available for the type of sustenance or sustainability practices considered sacred by neighboring tribal nations and to whom these locations bear significant cultural and historical importance.

Human Impacts from Historical Activity at Los Alamos

The degree to which past activities have harmed workers and the public is only partially documented owing to incomplete records and monitoring. Significantly, little attention has been paid to neighboring communities and pueblos beyond Los Alamos County. Population studies are difficult in part because of the relatively small statistical sample compared with average incidence rates for various health outcomes and population mobility. Contributing to the difficulty is that the county is demographically unrepresentative of the state’s racial, ethnic, and economic diversity as a whole. In addition, possible intergenerational consequences of radiation exposure are only beginning to be understood (Amrenova et al. 2024).

Some evidence suggests that the cumulative exposures from LANL operations have resulted in elevated cancer rates for Los Alamos County residents (Richards 2003; DOE 2003b). The county’s cancer-incidence rates are elevated relative to cases from the statewide New Mexico Tumor Registry for 1970 to 1996 for seven types of cancer: breast, melanoma, non-Hodgkin’s lymphoma, ovary, prostate, testis (significant at the 90 percent confidence interval), and thyroid. With the possible exceptions of melanoma and testicular cancer, all of these can potentially be radiogenically induced, and all are potentially eligible diagnoses under the Energy Employees Occupational Illness Compensation Act (DOE 2023).

Some contributions to these rates, such as for thyroid cancer, remain poorly explained (DOE 2003b; Athas 1996). Also, Catherine Richards, author of the report, acknowledges several limitations. These include complications establishing cause and effect, population mobility, and the disparate socioeconomic status and ethnicity between Los Alamos County and the rest of the state. Perhaps most significant, however, is that the “uncertainties and discriminatory nature associated with the existing LANL occupational health studies prevents full analyses of exposures” (Richards 2003).

Even within the laboratory, accurate analysis of historical occupational health is challenged by the fact that LANL was long divided between the technical staff (predominantly white, Anglo, and male) who were employees of the University of California (which ran LANL independently until 2006) and contract workers (called "Zia" workers) who provided maintenance, construction, and support services. Zia workers included a larger number of Hispanics and Native Americans, many of whom performed cleanup activities and other hazardous work. One LANL occupational health study found that records were available for 97 percent of University of California employees but only 20 percent of Zia workers, creating a huge disparity in understanding long-term outcomes (Wing and Richardson 2003).

It is now established that LANL's past releases of plutonium affected the general population, both in Los Alamos County and beyond. Autopsy results collected as part of the Los Alamos Human Tissue Program (1959–1994) surveyed plutonium distribution in the bodies of more than 1,000 employees known to have had occupational exposure, as well as many non-occupationally exposed members of the public (McInroy 1995; Widner 2010; Gaffney et al. 2013). The latter were intended as both a control group and to assess expected biological background levels from atmospheric fallout as a result of nuclear testing. The control population initially included members of the public who died at the Los Alamos Medical Center; later, it included members of the public from 27 states, including residents autopsied at medical centers near Rocky Flats and Savannah River. (Controversy surrounds whether the subjects or next of kin consented to sampling for the study (McInroy 1995; Guzmán 2023a; Hughes et al. 1996).)

Significantly, the Human Tissue Program documented the presence of plutonium in non-lab workers at elevated levels, particularly people living near the lab before 1955 (Gaffney et al. 2013). In at least one case, a woman living over 30 miles from LANL but whose husband worked as a janitor had 60 times the average level of plutonium in her body compared with the statewide reference (Guzmán 2023a; Widner 2010).

The studies described here paint a worrying picture, even though they are manifestly incomplete, unrepresentative of the total population, and challenged by a number of issues important for complete epidemiological understanding. From relatively scant available data, the magnitude and extent of harm remains undefined, but its presence has been documented. Because of this, a great deal of public concern and fear remains over the potential for additional health impacts from resuming large-scale plutonium activities at LANL, despite the lab's assurances of improved procedures and safety culture.

Cumulative Regional Impacts of Renewed Pit Production

While historical impacts linger in Los Alamos and surrounding communities, the current effort to produce pits is already making itself felt in the region in ways that go beyond human health. Pit production, one of the largest efforts undertaken in the lab's history, is creating palpable ripples for the region's economy, infrastructure, and transportation. Although risk analyses for siting potentially hazardous projects typically consider factors such as proximity to population centers, sensitive environmental areas, and prevailing wind directions, the NNSA acknowledged that these were "moot" for LANL because it was the only site capable of handling pit production when alternatives were studied. Thus, it was "grandfathered in" with regard to such considerations (NNSA 2017).

Pit production has created a record demand for new staff, with 2,500 new workers hired in 2023 (Wyland 2024a). Most new employees are under the age of 35. They encounter a saturated housing market that is largely unable to expand due to Los Alamos's geography.

Many homes are priced at more than twice the state average. (LANL 2023a; Nakhleh 2023). As a result, many employees commute, sometimes from more than 50 miles away. This has a noticeable impact on rental markets as well as on traffic on the few roads leading to the lab; an increasing number of fatal accidents have occurred.

While LANL offers salaries well above the state average, the result for non-employees who do not receive such salaries is detrimental. What is perceived as a sort of “technical gentrification” exacerbates preexisting economic inequality.

Los Alamos contributes substantially to the state economy through employee expenditures, creating demand in the regional service industry, and from the use of in-state vendors. This indirectly supports more than 20,000 jobs outside the laboratory and contributes roughly $3 billion annually to the state economy. However, as the University of New Mexico’s Bureau of Business and Economic Research has pointed out, these numbers do not tell the complete story. In the seven-county region surrounding Los Alamos, more money is spent on basic services to support LANL employees living there than the counties collect from taxes paid by those employees. The result is a net loss for the bedroom communities where many LANL workers live (Associated Press 2020; Montgomery 2020; Mitchell, Betak, and Baca 2019). These basic services include such things as roads, parks, police, and firefighting.

This mixed economic picture must also be considered in the context of socioeconomic challenges that have long plagued New Mexico. The Annie E. Casey Foundation has ranked New Mexico 49th or 50th for child well-being every year since 2012. In 2024, it ranked the state in last place for child well-being and 48th in economic well-being, 50th in education, 44th in health, and 49th in family and community (AECF 2024). These trends have persisted despite decades of defense spending’s contributions to the state economy, leaving many skeptical of LANL’s claims of net economic benefit to New Mexico—benefits that are neither palpable to most residents nor evident in the state’s standings in national rankings of measures of well-being.

Other impacts include required changes in infrastructure to support activities at the lab. LANL expects to reach capacity on existing power lines leading to the site as soon as 2026, and it proposes to install a 14-mile-long, 115-kilovolt power line across protected wilderness outside of Sante Fe, known as the Caja del Rio (ExchangeMonitor 2024). Residents and members of nearby pueblos are questioning whether the cultural and environmental impacts have been carefully studied and properly addressed (Dix 2024). Previous proposals for a road and bridge through the region (intended to alleviate regional traffic) met with vehement local opposition (New Mexico Wild n.d.; CLF n.d.). The planned power line appears poised to move forward, despite the more than 23,000 comments submitted in opposition by members of the public and the Sante Fe City Council (CLF 2024).

BOX 4.1. A Voice from the Community: Kathy Wan Povi Sanchez, San Ildefonso Pueblo

"For members of the Pueblo and Hispano communities in the immediate vicinity of LANL's boundaries, life, family, and culture were forever altered by the beginning of production on the Pajarito Plateau. Tewa peoples, including San Ildefonso Pueblo and Santa Clara Pueblo, are rooted in this landscape by the threads of thousands of human and non-human ancestors, and the generational responsibility to love, caretake, and steward this place, and one another, in alignment with cultural and spiritual values.

"The cultural values of Tewa people emphasize and celebrate humility, generosity, discretion, hospitality, and acceptance—all values that were readily manipulated and exploited, just as the people's bodies and homelands were, and continue to be. While hundreds of Pueblo communities were lost to the phases of colonization by the Spanish, Mexican, and American governments, a new colonizing power—nuclear colonialism—shook this foundation in its own way. At the time that the Atomic Energy Commission was searching for a suitable site for the Manhattan Project, the Pajarito Plateau and its surrounding communities were seen as more favorable due to its 'exploitable local workforce.'"

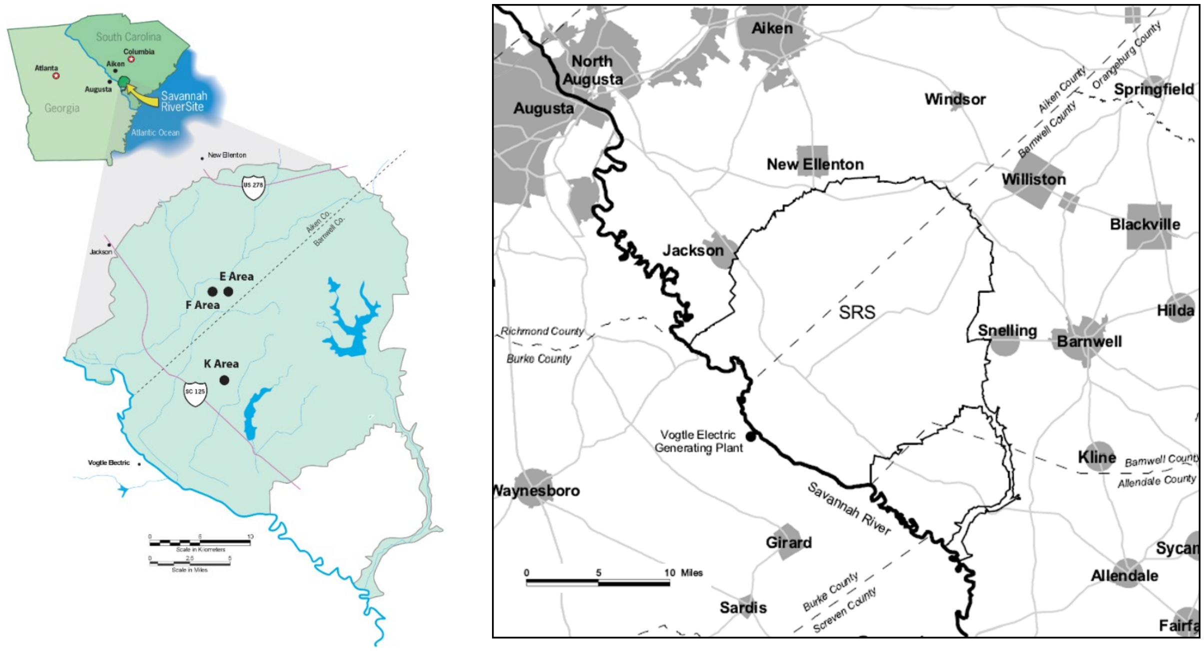
Kathy Wan Povi Sanchez is an elder, community activist, and traditional black-ware potter from San Ildefonso Pueblo, which neighbors Los Alamos National Laboratory. She is a previous Environmental Health and Justice Program Manager at Tewa Women United, a nonprofit organization that centers indigenous women in its work on environmental justice, reproductive health, and healing.

Savannah River Site, South Carolina

The Savannah River Site (SRS) is the second proposed site for producing plutonium pits. Located along the Georgia-South Carolina border, about 20 miles southeast of Augusta, it covers more than 300 square miles (SRS n.d.). The town nearest the proposed site is Jackson, South Carolina, 6.5 miles to the west-northwest, although some isolated residences are closer; 690,000 people live within 50 miles of the site (Connery, Roscetti, and Summers 2023). The demographics of Aiken and Barnwell counties, which SRS spans, are predominantly white and African American, with median household incomes of $63,212 and $42,470, respectively (2022 dollars) (US Census Bureau 2024b).

Activity at the site postdates the Manhattan Project. Construction began in 1951, and from 1953 until 1988, the site (in parallel with the Hanford plant in Washington state) produced plutonium for the growing US nuclear arsenal. Five SRS reactors were operational throughout the Cold War, producing plutonium for pits manufactured at Rocky Flats as well as tritium, an isotope of hydrogen used to boost the yield of nuclear weapons. The shutdown of Rocky Flats in 1989, along with the end of the Cold War, led SRS to cease plutonium production by 1992. Tritium processing continues there today at extraction facilities that treat irradiated fuel rods from the Tennessee Valley Authority's Watts Barr Nuclear Plant. Because tritium has a short half-life—12.3 years—the nuclear complex must maintain consistent production and handling capability for preserving the existing stockpile.

FIGURE 4.4. Geographic Context for the Savannah River Site, South Carolina



Left: The region surrounding the Savannah River Site. The site's boundaries include Lower Three Runs Creek that leads to the Savannah River, wrapping around an area that includes private farmland and some residences. Right: The map shows the proximity of communities surrounding the SRS site. SOURCES: DOE 2020b; Mamatey 2009.

More recently, SRS was to be the site of a mixed oxide (MOX) fuel reprocessing facility. In something of a reversal of the original processes undertaken at Savannah River, the MOX facility would have transformed excess weapons-grade plutonium into reactor fuel for producing commercial energy. Construction began in 2007 but was terminated in 2018 after the projected construction cost had nearly doubled to $8 billion dollars, with an estimated $50 billion projected for future operation (Sonne and Mufson 2018; Lyman 2014). This is the same facility that the NNSA is now retrofitting to produce plutonium pits.

The Environmental Legacy of Historical Activity at Savannah River

Historically, SRS was involved in separating isotopes (heavy water production), fabricating fuel and targets (involving highly enriched uranium and lithium), reactor operations, and chemical separations to produce plutonium and tritium. Plutonium operations occurred primarily at two major facilities, known as F-Canyon and H-Canyon. These facilities used remotely operated chemical processing lines to separate plutonium and uranium from irradiated reactor fuel using a process known as Plutonium Uranium Reduction Extraction (PUREX). SRS and Hanford were the first sites to carry this out at industrial scale.

PUREX involves the dissolution of the reactor material, separation of fissile materials and subsequent reconstitution into purified metallic form (called "buttons"). These could then be shipped to Rocky Flats for pit production (Reed et al. 2013). This process is inherently "dirty," producing high-level radioactive waste at several stages. The dissolution involves tributyl phosphate (TBP), nitric acid, kerosene, and hydrazine (which is also a rocket fuel). The combination of TBP and nitric acid can react explosively at temperatures above 130 degrees C and has resulted in severe accidents at Savannah River (in 1953 and 1975) (Conway 2003). Similar accidents occurred at Hanford (1953) and an analogous Russian facility, Tomsk-7, in 1993 (IAEA 1998).

The waste from plutonium separation is a lasting environmental concern at SRS because it contains radioactive byproducts. As at Los Alamos, little thought was given to waste treatment or disposal in the early rush to assemble the US nuclear arsenal. Low-level waste (including TBP byproducts from PUREX) was buried directly in the ground in some cases (Condit 1993), while high-level waste (including large volumes of radioactive liquid waste) went into subterranean steel tanks, awaiting a more permanent solution that never materialized. By the time the last SRS reactor was shut down in 1988, "tank farms" had proliferated, containing more than 35 million gallons of mixed liquid and solid waste (Reed et al. 2013). Attempts to vitrify waste (convert it to glass) proved relatively ineffective. Cementitious grout has been used to immobilize roughly 35 million gallons of liquid waste; this waste remains onsite as a designated permanent landfill (NRC n.d.).

Although SRS has about half of Hanford's volume of waste, the SRS waste is some 1.5 times more radioactive. This makes it more challenging to remediate (DOE 1997). Stewardship of this legacy waste has been a primary part of the SRS mission since the end of the Cold War. The Department of Energy's Office of Environmental Management has had responsibility for the site since 1989, but the NNSA will assume management in 2025, largely due to the proposed pit-production mission.

Human Impacts from Historical Activity at Savannah River

Documentation of impacts to communities surrounding the Savannah River Site is sparse compared with that for Los Alamos. Because of the site's size, an appreciable buffer zone of wooded land separates the perimeter from the nearest communities. In contrast to Los Alamos, SRS was never a residential site, although its creation displaced some 6,000 people from the former communities of Ellenton, Dunbarton, and others (DOE 2019). With a mission focused on production rather than experimentation, SRS did not conduct outdoor tests such as those conducted at LANL, but contamination still entered water, soil, and air.

Information on historical impacts to the public appear to be sparse, but impacts on workers are better documented. A survey of SRS occupational health records shows a disproportionate burden on Black employees. They had higher odds of detectable radiation doses than did non-Black workers, and from the late 1970s until the mid-1980s, male and female Black workers received higher average annual doses than did non-Black workers (Angelon-Gaetz, Richardson, and Wing 2010). Positive associations between mortality from leukemia and radiation dose have been demonstrated for past SRS workers (Richardson and Wing 2007). Cancer rates in past SRS workers have been so high that a special exposure cohort was created to monitor and address these cases. While affected workers are entitled to seek compensation, only 34 percent of applications were approved, according to a 2023 report (Anderson and Cox

2023). Black workers sought recognition in a class-action lawsuit against the DOE contractor in the early 2000s. It failed, leaving each worker to press their own case and requiring resources that many did not have (*Lott v. Westinghouse Savannah River Co., Inc.*).

Today, SRS is acknowledged to be among the most contaminated sites in the US nuclear complex due to the high-level waste remaining onsite. Studies have cited significant concerns for contamination of the regional Tuscaloosa aquifer as well as the Savannah River itself as a result of the local geology and hydrology (Makhijani and Boyd 2004). Tritium contamination is expected to easily infiltrate groundwater, as well as become mobile in the atmosphere as it evaporates from contaminated bodies of water onsite; this means the contamination could subsequently rain out on surrounding regions (Makhijani 2022). Further studies of the impacts of groundwater contamination are needed, particularly for people downstream along the Savannah River and who depend on it for drinking water, fishing, and agriculture.

Of course, Los Alamos and Savannah River are not the only sites that bear the environmental legacy of US weapons development. Plutonium is also present and unremediated (in fact, in much larger quantities) at other production and test sites. The Hanford site is estimated to contain up to 16,700 curies of plutonium. The soil at Rocky Flats was reported to contain about eight to ten curies prior to remediation in 1990 (Burley 1990). This is likely erroneously low, given evidence that individual events may have released up to 21 curies into the air (Voillequé 1999). Meanwhile, residual plutonium may be present where testing occurred: at the Nevada Test Site (155 to 160 curies) and the South Pacific islands and atolls (roughly 10,000 curies) (Hu, Makhijani, and Yih 1992; Makhijani 2024). Some testing areas in the Pacific remain uninhabitable; others have been resettled, although not without obvious risk and potential ongoing consequences for human health.

4.2 The Mobility of Plutonium in the Environment

The risk to the general public from plutonium operations, past and present, depends on the material's concentration and mobility in the environment. A synthetic element first produced in 1940, plutonium is virtually omnipresent in the environment today due to the global testing of nuclear weapons. The highest concentrations are found as contamination around sites of weapons production, but small concentrations are measurable around the world as a result of fallout from more than 500 aboveground (or atmospheric) tests conducted by the United States, Russia, the United Kingdom, France, and China.

For communities near former production facilities, including Los Alamos and Savannah River, the mobility of localized contamination is still of concern. In the event of potential future accidents at these facilities, environmental mobility determines who may be at risk and over what timescales and distances. Around both sites, understanding how plutonium (and other actinides) can move through air, water, and soil (in other words, through the food chain and drinking water) is paramount for protecting human health and the security of frontline communities. Many of these communities still bear the burden of past practices at Los Alamos and Savannah River, practices that included directly burying radioactive waste and discharging contaminated effluents directly into the environment. These practices resulted in long-lived sources of pollution for which complete remediation is nearly impossible.

Finally, because of the long half-lives and toxicity of plutonium and other radionuclides, knowledge of environmental mobility is key to the responsible stewardship of nuclear waste in geologic repositories. This problem will only grow as the United States and other nations continue developing their nuclear arsenals, and it is also one that exceeds human lifespans by orders of magnitude.

BOX 4.2. Understanding Quantities: What Is a Picocurie?
Levels of plutonium in the environment are often cited in units of curies or picocuries per gram in soil. These units make it difficult to appreciate how much material is actually being discussed. One curie is an amount of radioactive material that undergoes 37 billion (3.7×10^{10}) disintegrations per second. Because different radionuclides decay at different rates, the mass of material corresponding to one curie depends on the isotope and its particular half-life. 37 billion disintegrations per second is *very* big number—so big, in fact, that one trillionth of a curie (a picocurie or 0.037 disintegrations per second) is a much more practical and tractable unit for measuring plutonium in the environment, where most quantities are vanishingly small. Nonetheless, if lodged in lung tissue, there is no safe amount of plutonium. ^{239}Pu, the principal isotope in weapons-grade material, has a half-life of 24,390 years. One curie of plutonium is equivalent to 15 grams. 1 picocurie is therefore 0.000000000015 grams of ^{239}Pu. For ^{238}Pu (which has a half-life of only 88 days and is used in spacecraft batteries), one curie is only 54 milligrams and 1 picocurie is 0.000000000000054 grams of ^{238}Pu. Therefore, average background levels of plutonium from atmospheric fallout in the United States (about 0.01 to 0.1 picocuries per gram) correspond to trillionths of a gram of plutonium per gram of soil. In 1990, the total quantity of plutonium in soil was given as one to two curies at Los Alamos, three to five curies for Savannah River, eight to ten curies for Rocky Flats, and 16,700 curies for the Hanford Site (Burley 1990)

Mobility In Air

The atmospheric transport of plutonium has primarily been resulted from aboveground tests of nuclear weapons, which cumulatively distributed around 10,000 kilograms of plutonium to the environment (Peterson et al. 2007). Plutonium that is lofted into the atmosphere tends to adsorb (or stick) to particulates and is then deposited by rain or dry deposition. Before the Partial Nuclear Test Ban of 1963, such particulates were spread globally as nuclear fallout, including strontium-90, cesium-137, americium-241, and iodine-131. Recent reconstructions of fallout using historic weather patterns and atmospheric modeling have demonstrated that fallout from the 1945 Trinity test in New Mexico and aboveground tests in Nevada reached all the lower 48 US states (Phillipe et al. 2023). Larger radioactive particles are deposited downwind of test sites, with much higher local concentrations. This local fallout may represent up to 50 percent of the total, which can account for elevated cancer incidence and mortality in “downwinder” populations.

Across the United States, plutonium levels from atmospheric fallout can be measured in soil within a range of approximately 0.01 to 0.1 picocuries per gram (Rodriguez 2014). Around Los Alamos, expected plutonium fallout levels have been reported as 0.001 to 0.055 picocuries per gram, with a mean level of 0.015 picocuries per gram (Ryti et al. 1998). These fallout levels generally represent a very low risk to the public compared with other environmental exposures. The effects of radionuclides other than plutonium that are present in fallout carry their own health consequences that are beyond the scope of this work.

Mobility In Water and Soil

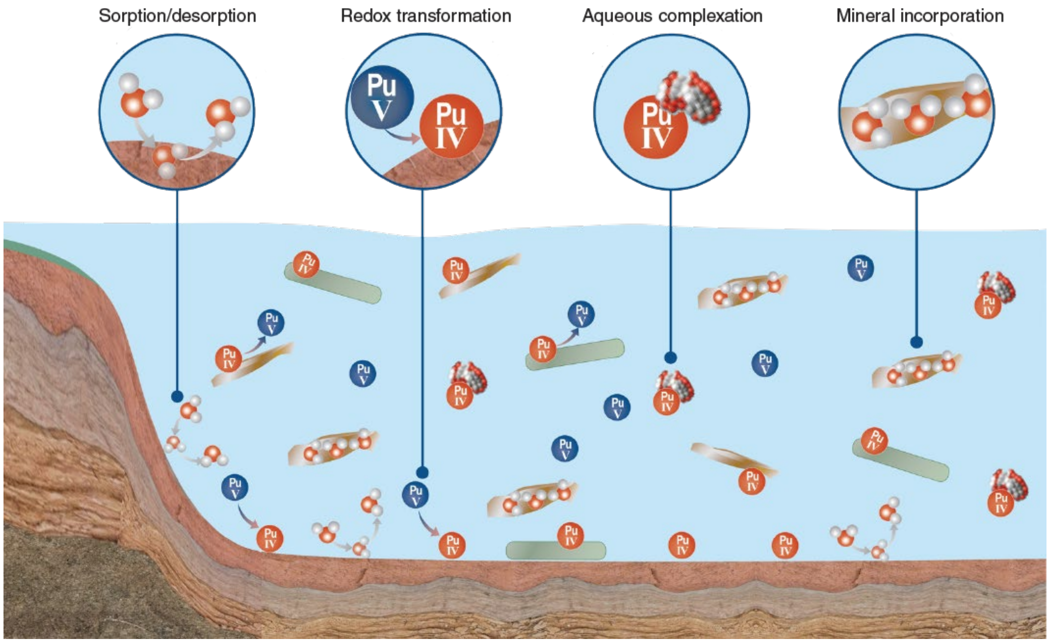
The mobility of plutonium in water and soil relies on its unusual and complex chemistry. Because of its precarious electronic properties, plutonium can easily be persuaded into different chemical bonding configurations (or "redox states"). In an aqueous solution, plutonium may be present in up to five different redox states simultaneously (a unique trait for any element) according to the local pH, allowing it to hitch a ride on a number of different chemical substrates in the environment (Clark 2000). Variations in environmental pH and the degree to which electrons are available from the environment play important roles in determining plutonium's chemical state. These various states have varying solubility and reactivity, meaning that they can be mobilized in different ways in nature (Figure 4.5).

Although water is an important driver for moving plutonium in the environment, plutonium tends to form insoluble compounds, so it does not tend to move in a dissolved form (Runde 2000; Katz, Morss, and Seaborg 1986). Instead, it has a strong proclivity to adsorb (or chemically stick) to surfaces, particularly mineral surfaces like clays. Therefore, its mobility in water is defined by what it attaches to, and its deposition may be relatively heterogeneous based on the hydrological deposition of contaminated sediments when it is present in surface water (Graf 1994).

These traits—insolubility and a tendency to stick to surfaces—may seem to act as barriers to transport, but, once again, plutonium's strange behavior challenges intuition. Colloidal transport in groundwater has been recognized as a rapid way of mobilizing plutonium underground. Colloids are small, naturally occurring particles that can be mineral, biological, or chemical in nature and that exist as a dispersed phase in another medium (e.g., inorganic precipitates in groundwater). They are typically small enough—less than 1/1000 millimeter in size—to be mobile within porous geologic media or the smallest of fractures.

As early as 1988, it was recognized that colloids played a role in transport of radionuclides at the Nevada Test Site (Buddemeier and Hunt 1988). But it was a 1999 Lawrence Livermore study that highlighted the surprising efficiency of this process, identifying plutonium isotopes from a distinct test more than 1.3 kilometers from the test site and suggesting a migration rate of at least 40 meters per year underground via colloidal transport (Kersting et al. 1999). Laboratory experiments have supported the idea that colloids enhance plutonium transport (Xie et al. 2013). These help explain its unexpectedly rapid dispersion from the test site. Plutonium's rapid mobility is concerning in regions where contamination could intersect with groundwater that local populations rely on.

FIGURE 4.5. Chemistry Determines Plutonium's Mobility in Water

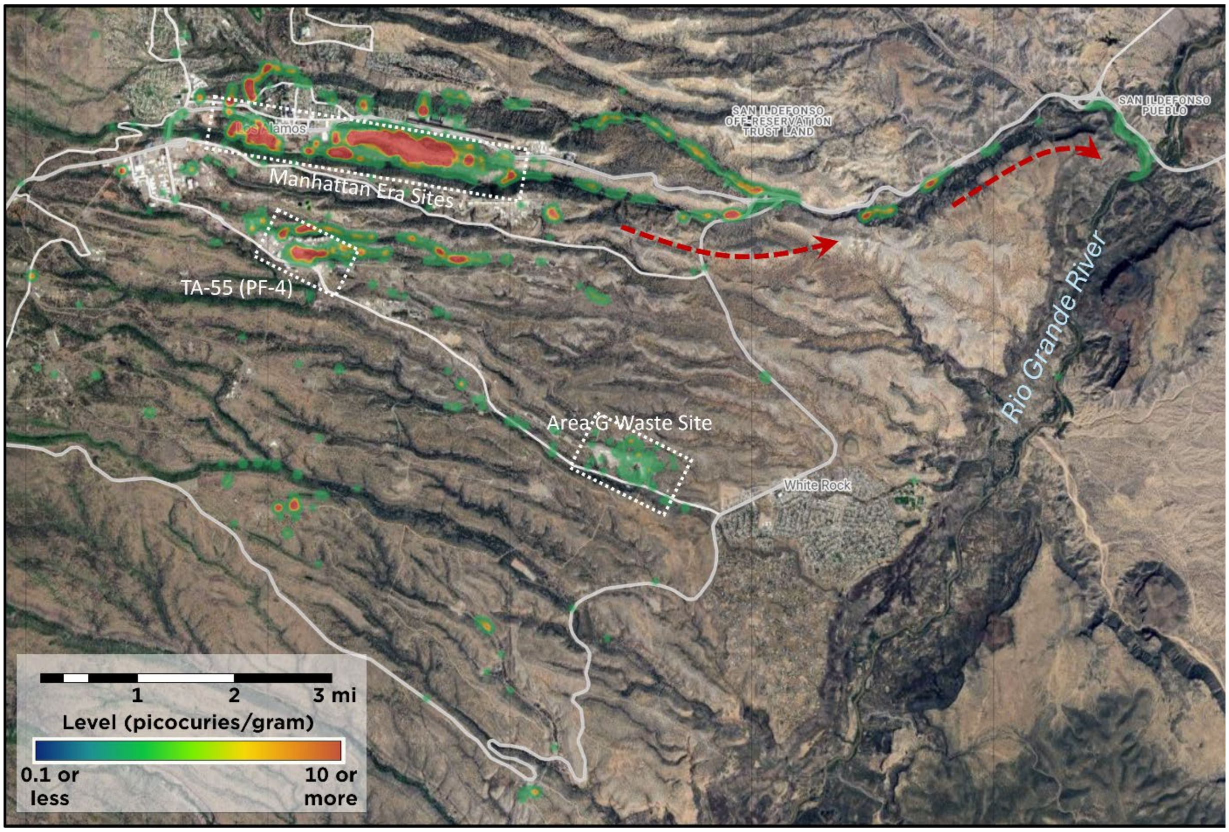


Plutonium can be mobilized in various ways in water and soil depending on its electronic charge, which determines how it bonds to other substrates and molecules. Roman numerals IV and V refer to electronic charge states, including the one assumed by plutonium in its common PuO_2 form in the environment. SOURCE: Chen and Zavarin 2021.

Similar mobility has been noted at Los Alamos, where liquid waste was formerly disposed in canyons and subsequently detected in test wells nearly 3.5 kilometers from the source (Penrose et al. 1990). Los Alamos, in annual environmental surveillance reports, has acknowledged the migration of plutonium (e.g., LANL 2004; LANL 2005). Publicly available data from the Los Alamos Intellus Environmental Monitoring database confirm that plutonium is mobile in the watershed below the laboratory (Figure 4.6) (Intellus New Mexico n.d.). Indeed, detections above the expected background level from fallout have been found as far away as Cochiti Reservoir, 19 miles downstream on the Rio Grande River.

Around Los Alamos, plutonium is present at levels well above 0.1 picocuries per gram, the upper limit of what could be expected from atmospheric fallout (Figure 4.6). The database lists nearly 5,000 regional measurements exceeding one picocurie per gram (at least 10 times fallout), 1,600 measurements over 10 picocuries per gram, 415 measurements over 100 picocuries per gram, and nearly 100 measurements exceeding 1,000 picocuries per gram (or 10,000 times what could be expected from fallout). A 1980 paper estimated that roughly 2 curies (about the equivalent of 30 grams) had been disposed of at Los Alamos in canyon waste-disposal sites (Harley 1980). The present-day distribution demonstrates clear patterns emanating from sites known to be associated with past and present plutonium activity, including canyon disposal sites, the former DP site, Technical Area 55, and the waste disposal

FIGURE 4.6. Plutonium Contamination and Migration in the Vicinity of Los Alamos



The map indicates measured plutonium concentrations in the environment across the LANL site. Data are filtered to show only measurements ranging from 0.1 (green) to 10 picocuries per gram (red). This excludes levels that could plausibly result from atmospheric fallout and includes measurements of up to 1,000 times that level. Many measurements in the dataset greatly exceed these thresholds in localized hotspots and are not plotted here. Much of the worst contamination is in or near the current townsite where Manhattan Project work took place, but mobility is also evident in and around the PF-4 plutonium facility at Technical Area 55 and the waste staging zone known as Area G. SOURCES: Map created from Intellus n.d., replotted with image courtesy of Google Earth and Intellus data compilation, after Coghlan, Stroud, and Kovac 2024.

and staging Area G at Technical Area 54. In addition, migration toward *Po-Woh-Geh-Owingeh* (San Ildefonso) Pueblo and the Rio Grande river via Los Alamos Canyon is evident.

Plutonium migration has been observed to accelerate following seasonal runoff, particularly after major wildfires around Los Alamos that decreased the vegetative capacity to retain soil and prevent rapid erosion. Following the 2000 Cerro Grande Fire, $^{239, 240}$Pu in storm runoff increased to levels 55 times what they were in the five years before the fire (LANL 2005). This may illustrate how future events induced by climate change (e.g., major wildfires, floods) could mobilize existing contamination and accelerate its spread.

The paucity of data pertaining to plutonium mobility at SRS is worrying, given that tritium and other hazardous radionuclides have been documented in groundwater (Flach, Hamm, and Harris 1996; Gardiner 2016; Savannah River Nuclear Solutions 2015) and vegetation (Pettitt, Duff, and VerMeulen 2022) and due to the site's relationship to the Savannah River watershed.

Biological Pathways

Pathways for environmental mobility that depend on the biological uptake of plutonium from the soil are less well understood but are gaining attention. Microbial uptake, either through surface adhesion or actual metabolic processes, may help or hinder mobility of actinides. On the one hand, microbes can act like self-propelled colloids, potentially enhancing mobility (Runde 2000). On the other hand, the ability to uptake plutonium could act as a means of remediation, using specific microbial communities to convert plutonium into less soluble, less-mobile chemical states, effectively locking them away.

The range of possible biochemical interactions turns out to be difficult to assess. Different bacteria have been observed to handle Pu(IV) in different ways (Kauri et al. 1991). Also, plutonium uptake can depend on whether bacteria promote reducing conditions (e.g., enhance chemical reactions that can provide electrons to plutonium, changing its charge state) (Mahara and Kudo 2001). Seasonal evolution of microbial communities can also affect uptake as the population cycles, as has been observed in a contaminated pond at Savannah River (Merino et al. 2023).

Plant uptake of plutonium is also of potential concern to communities in regions affected by contamination, given that this represents a possible route through potential human ingestion of crops (along with groundwater). The ability of plants to take up plutonium from soil underscores the importance of monitoring how it spreads, particularly where traditional agriculture is practiced (e.g., the pueblos neighboring Los Alamos) and where plutonium will continue to migrate underground well into the future in the absence of concerted remediation.

Plants can uptake plutonium from soil through their roots. This may be due to the release of compounds like citric acid that act as chelating substances (meaning they can effectively bind the plutonium) at the root surface (Brown 1979). Plants take up iron in a similar manner, and it has been suggested that plutonium can mimic iron and follow similar pathways for uptake from the soil in a competitive process in plants, including corn (Hoelbling 2016). Certain isotopes may be more readily taken up by plants than others (Brown and McFarlane 1977). However, all can end up in in leaves and fruiting portions of the plant. To further complicate the issue, different plants appear to have different affinities for plutonium, with differing uptake among species that grow in the same environment (Caldwell et al. 2011).

Given the anticipated heterogeneity in plutonium distribution around contaminated sites and the apparent complexity of its biochemical interactions in the soil and in plants, it is difficult to make conclusive risk assessments for particular locations without focused efforts to measure and monitor its presence locally in a comprehensive manner.

4.3 Human Uptake of Plutonium and Radiation Exposure

Unfortunately, epidemiological data on humans are sparse due to the relatively small sample size of exposed workers and verified public exposures, as well as due to the frequent lack of adequate monitoring throughout the period when the volume of plutonium processing was highest. Nevertheless, we do know that the consequences of exposure are significant. Depending on the specific route of ingestion, plutonium can reside in the body for decades, migrate within the body based on solubility, and lead to various forms of cancer. The size and chemical form can also determine the long-term health effects. Plutonium can enter the body through inhalation (to the lungs), ingestion (via the stomach and gastrointestinal system), or cuts or wounds (directly into tissue or the bloodstream).

Inhalation of small plutonium particles is one of the most consequential ways that humans can be exposed because small particles can lodge in lung tissue and remain there for decades (Gaffney et al. 2013). The smaller the particle, the more mobile (and therefore respirable) the material. Inhalation could result from exposure to powdered forms of plutonium (which are present at various stages of pit production and plutonium disposition), as well as from plutonium that is airborne in smoke or re-suspended in air from contaminated soil. In studies on dogs, inhaling even a minute amount (as small as tens of micrograms of ^{239}Pu) generated lung cancers (Bair and Thompson 1974). An estimated extrapolation to humans predicted that 80 micrograms of weapons-grade plutonium could present a high risk of lung cancer (Fetter and Von Hippel 1990; Hu, Makhijani, and Yih 1992).

Orally ingested plutonium typically poses the least risk compared with other routes of intake. It is not easily absorbed by the stomach or gastrointestinal system, so the body passes nearly all of the ingested plutonium relatively quickly in urine and feces (Bair 1974). This means that intake resulting from contaminated food or water is potentially less harmful than breathing small particulates unless local concentrations are extremely elevated. Communities growing food near plutonium sources should have access to reliable measurements of soil contamination to ensure that these are below acceptable levels.

In specific cases, plutonium could enter a worker's body directly through cuts, wounds, or other abrasions as a result of accidents or tool use during pit production. Such accidents have occurred at Los Alamos as a result of glove punctures, pinches, and cuts during operations carried out in glovebox enclosures. If this occurs, plutonium could directly enter tissue or the bloodstream. Plutonium compounds in the pit-production process have been found in workers' urine up to 20 to 30 years after exposure via wounds, again demonstrating its longevity in the body (Keith 2010; Woodhouse and Shaw 1998).

Regardless of the intake mechanism, plutonium within the body can and does migrate based on its solubility and chemical form. Once inhaled, plutonium can move from the lungs to the rest of the body. Some of it may be excreted through transport to the gastrointestinal tract, but it can also further mobilize to the lymph nodes and other tissue (Rodriguez 2014; Keith 2010).

Insoluble forms (such as ^{239}Pu) mostly concentrate in the lungs and lymph nodes, whereas more soluble forms (^{238}Pu) can enter the skeleton, liver, and kidney (Keith 2010; Wing and Richardson 2003). In some cases, uncertainties in solubility may not be accurately known, which affects the estimated dose to the individual. Estimation of the dose to an affected individual relies on quantitative conversion factors that have been updated with gradually improvements in the understanding of biokinetics—how plutonium moves through the body (Clement and Hamada 2015; Kaltofen and Plato 2024).

Improved understanding of biokinetics has come from autopsies on exposed workers (McInroy 1995) and animal studies that appear to show similar distribution paths and proportions in the body. Plutonium absorbed following inhalation distributes roughly equally between the liver and the skeleton (about 45 percent to each), with a much smaller amount distributed to other organs (Widner 2010; Keith 2010). Skeletal accumulation may slowly increase over long periods. Transfer of plutonium to the placenta and fetus of a mother who suffered exposure through occupational inhalation has also been documented (Russell, Sikov, and Kathren 2003).

Plutonium can be difficult to detect in the body. This is because it primarily decays via alpha emission, which can only penetrate about 50 microns in human tissue. Thus, radioactive decay is often not measurable externally (e.g., by *in vivo* counting) except in some cases where gamma emissions from other radionuclides (e.g., americium) may also be present. Counting of alpha particles can be done on urine, feces, tissue samples, or nasal swabs according to the routes of ingestion described above and the time since exposure. Nasal swabs have been a primary means of rapid assay for Los Alamos employees who have known or suspected inhalation risks. Chelation treatment is often used as an emergency medical countermeasure for exposed individuals whose dose exceeds critical levels. Chelation involves injecting zinc- or calcium-based compounds that help bind and accelerate the excretion of plutonium. It is far from 100 percent effective and is only a means of reducing the potential damage.

Ultimately, plutonium's residence in the body can lead to various forms of cancer as it undergoes radioactive decay. Because the alpha particles emitted cannot travel far, they deposit their energy over a short distance in a concentrated manner. This significantly damages cells in the immediate vicinity. The localized nature of the deposited energy affects methodologies for calculating dosages to internal organs (Kaltofen and Plato 2024; NRC 2006).

Increased cancer incidences have been observed in exposed populations, particularly workers at Russia's Mayak facility (the Russian equivalent of Rocky Flats). Workers there were exposed to plutonium at levels up to 10 times those estimated for Los Alamos workers over similar periods (Stram et al. 2021; Gilbert et al. 2004). At Los Alamos, plutonium intakes have been linked to an increase of bone cancer in workers (Boice et al. 2021). Other cancer rates exhibit increased incidence in both workers and county residents (DOE 2003b; Richards 2003).

Setting Standards for Human Radiation Exposure

Given the hazards associated with radiation exposure, it's important to understand the possible pathways for potential public exposure and how to best measure those exposures. Decisions over how much radiation exposure is acceptable have been largely left to institutional and expert judgement. Resulting regulations dictate how much radiation is allowable for occupational workers and members of the public. However, the regulations are typically based on a fictitious "Reference Individual" or an averaged population. Although the common mantra for radiation exposure is to keep it as low as reasonably achievable, quantitative regulatory standards exist for occupational workers as well as members of the public. These are set by federal and state agencies, including the Department of Energy, which manages the national laboratories and sets its own occupational limits.

The US Environmental Protection Agency (EPA) sets limits for the public, including maximum allowable amounts in air and water. The EPA has tightened these limits as links between radiation exposure and cancer have become better understood and quantified. As a result, the standard for maximum public exposure is 50 times lower today than in the 1950s (Makhijani, Smith, and Thorne 2006). Furthermore, the understanding of the possible long-term effects of low-dose ionizing radiation (in contrast to acute exposure) remains poor. Further studies are urgently needed and have been recently proposed by the National Academies of Science Engineering and Medicine (NASEM 2022).

BOX 4.3. Understanding Quantities: Radiation Dosage

Just as curies and picocuries are measures of the radioactivity of a substance, *rem* and *sieverts* are measures of the amount of energy that a radioactive source deposits in living tissue.

Units for dose equivalent:

Roentgen Equivalent Man (rem) = a unit of dose equivalent that takes into account the absorbed dose (how much radiation an individual absorbs) and a multiplier (called a quality factor) that depends on the type of radiation and its biological impact

For practical reasons of scale, millirem (mrem, or $1/1000^{th}$ of a rem) is used more often.

The international scientific unit (SI unit) for dose equivalent is the sievert (Sv). One Sv equals 100 rem.

Common sources of radiation exposure and the associated dose equivalent:

One coast-to-coast airline flight: ~1 mrem or 0.01 millisieverts (mSv)

One dental x-ray: ~ 1.5 mrem or 0.015 mSv

One head CT scan: ~200 mrem or 2 mSv

Cosmic ray exposure from one year living in Denver, Colorado: ~80 mrem or 0.8 mSv

One year of average exposure to remnant fallout from nuclear testing: ~0.5 mrem or 0.005 mSv

Acute dose equivalents:

Onset of radiation sickness: ~100,000 mrem, 100 rem, or 1,000 mSv

50 percent lethality: ~400,000 mrem, 400 rem, or 4,000 mSv

100 percent lethality: ~1,000,000 mrem, 1,000 rem, or 10,000 mSv

SOURCES: EPA 2015; CDC 2024a

How radiation exposure limits are set has come under increasing scrutiny. Typically based on a theoretical, idealized "reference man," such standards have been criticized for not adequately representing the most vulnerable members of the general population.

Who is "Reference Man?"

After World War II, American, British, and Canadian doctors devised the earliest guidelines for radiation exposure based on a standardized individual and with workers in mind (Lochbaum 2021). Given the average "worker" at the time, their description of a fictitious "reference man" is perhaps not surprising: He is "between 20-30 years of age, weighing 70 kg (154 pounds), is 170 cm (5 feet 7 inches) in height, and lives in a climate with an average temperature of from 10° to 20° C. He is a Caucasian and is a Western European or North American in habitat and custom" (Snyder et al. 1975). The Los Alamos Human Tissue Program used this model for analysis of human exposure to plutonium (McInroy 1995). That program helped define occupational and public exposure more widely and has since been used internationally in many contexts (Widner 2010).

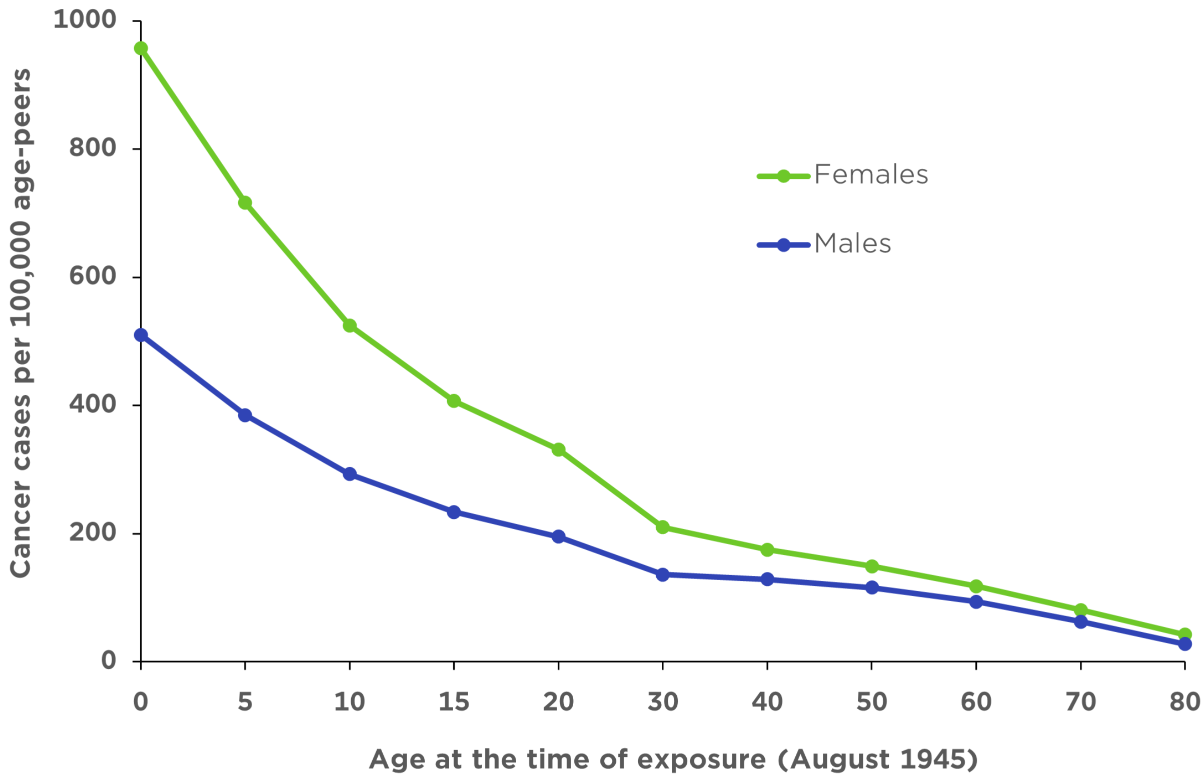
While reference man may have been a relatively close approximation of the "average" worker in the late 1940s, it is clearly not representative of the general population and almost undoubtedly results in underestimation of potential harm.

The effects of radiation on the body depend on whether a given dose is chronic (over a long period) or acute (e.g., a single incidence) and also on gender and age. Children may suffer worse consequences from radiation exposure because rapidly replicating cells are more sensitive to radiation (Keith 2010). Similarly, two influential studies from the EPA and the National Research Council have shown that, for a given dose of radiation, women are 52 to 58 percent more likely than men to develop cancer (Eckerman et al. 1999; NRC 2006; Makhijani, Smith, and Thorne 2006). This is due partly to the increased radiosensitivity of breast and thyroid tissue in women, but the complete mechanism is not totally understood. In addition, women can suffer harm to reproductive health as a result of the finite population of follicles in the ovaries.

These disproportionate effects of gender and age on health outcomes appear to be borne out by long-term studies on survivors of the atomic bombings in Hiroshima and Nagasaki—a grim case study in acute exposure of an entire population (Figure 4.7) (NRC 2006; Olson 2019).

The findings underscore the importance of understanding disparate responses to radiation exposure. They make it possible to develop critical radiation protection standards that assess risks to different populations. Reliable and equitable risk assessment requires standards that apply to the entire population, including its most vulnerable members, and not just an average "worker." As such, more comprehensive alternatives to "reference man" are required.

FIGURE 4.7. Increased Cancer Risk by Age (per 100,000) at Exposure to 20 mSv Radiation from the Use of Atomic Bombs in Japan



Data from atomic-bomb victims suggest that males and females experience disparate health outcomes following an equivalent exposure to radiation. In particular, young girls experience the highest rates of cancer incidence, but they are not adequately represented by a model such as "Reference Man," which is based on an adult, Caucasian male. SOURCES: NRC 2006; Data courtesy Olson 2019 and Makhijani, Smith, and Thorne 2006.

Alternatives to Reference Man

Gradually, new models have sought to capture different physiological risks as a function of gender and age. The International Commission on Radiological Protection introduced a "reference person" in 2007, based on an average of a reference female and reference male (Valentin 2007). However, such an assumption may not by physiologically representative of either.

Newer proposals go further, with the goal of considering the most vulnerable members of the population in terms of both human and ecological health. One example is the *Nava To'I Jiya* (Land Worker Mother) model, proposed by the Tewa Indigenous community neighboring Los Alamos. This model, which considers cumulative risk to the female body, assumes traditional agricultural practices that encompass chronic environmental exposure from land, water, and air. This is similar in spirit to other models—for example, "reference girl" based on the apparently increased risk for younger girls (Figure 4.7) and a more futuristic construction called "Jane," imagined as a case study in the context of remediation at Hanford (Olson 2019; Cram 2015). As of 2024, public limits for exposure have yet to be based on models as inclusive as these.

Limits for the Public for *All* Sources of Radiation

Regulatory limits constrain acceptable work practices and releases of material to the environment for facilities that handle radioactive materials like plutonium. Department of Energy regulations require limiting potential public exposure from onsite activities to 100 millirems per year from all pathways, including air and water (DOE 1990). If the release of material to the environment is required, it must be demonstrated that it does not exceed this limit.

For releases to the air and water, the Clean Air Act restricts airborne emissions of radionuclides (including but not limited to plutonium) to 10 millirems per year for an offsite member of the public (DOE 2020c; Rodriguez 2014) and 4 mrem per year in water for beta and gamma emitters (40 CFR Part 141—National Primary Drinking Water Regulations n.d.).

To understand these limits and their magnitudes, it is helpful to understand the levels of radiation that the population is exposed to via other sources. Everyone is exposed to *some* radiation from both natural and anthropogenic sources regardless of a person's professions, location, or proximity to nuclear facilities.

Radon from the natural radioactive decay of elements in soil is one common source of ubiquitous exposure (about 100 to 200 millirems per year), as is potassium-40 and carbon-14 that we ingest in food (about 30 millirems per year). Cosmic rays deliver a small amount of radiation (about 30 to 50 millirems per year); this increases with altitude. Artificial sources, including medical x-rays, CT scans, and consumer products, represent other common sources of public exposure (about 60 to 300 millirems per year). Cumulatively, these internal and external sources result in an average annual dose of about 300 to 600 millirems for most people (UNSCEAR 2008). Exposure resulting from residual global fallout from nuclear tests is typically only about 0.5 millirems per year in most regions (Box 4.3) (UNSCEAR 2008). This means that the national labs must limit the dose to the public to about one-third to one-sixth of the average annual dose that would be received otherwise. Such exposure, if it occurs, is in addition to all the others.

Besides setting guidelines for public exposure, regulatory limits inform remediation efforts where contamination is already present beyond laboratory boundaries. Consequently, the national labs and the public need to be aware of the evolution of environmental contaminants to ensure strict adherence and public safety. Continued or prolonged deemphasis on cleanup efforts in favor of scaling up production risks compounding existing problems, particularly for legacy contamination in the environment and waste.

Limits for Plutonium in the Environment

Specific limits for allowed quantities of plutonium-239 have been cited as 0.00002 picocuries per liter in air and up to 15 picocuries per liter in water, including any other alpha emitters that may be present. Recall that picocuries measure quantity, not dose (Box 4.2). Also note that the limits for air and water differ by a factor of 750,000 because humans take in more air than water each day, and because of the increased hazard posed by inhalation compared with ingestion (Hu, Makhijani, and Yih 1992). More recent analyses, based on improved understanding of physiology and biokinetics, have argued that the limit for water should be 100 times lower than it is (Makhijani 2005). Indeed, in Colorado, where plutonium contamination exists from Rocky Flats, the statewide standard has been set as 0.15 picocuries per liter (WQCC 2016). The admissible limit in New Mexico, set by the state's Water Quality Control Commission, is 10 times that level (1.5 picocuries per liter) (NMWQC 2000).

Limits for Workers

The permissible annual doses of radiation for occupational workers are much higher than those for the public, and this additional factor must be well understood as a condition of employment. Although the principle of maintaining exposure levels "as low as reasonably achievable" still applies, DOE workers are permitted to receive up to 5,000 millirems per year through occupational exposure (50 times the public limit). For workers, limits are published for each organ based on models (Sowby 1979; Widner 2010). Dosimetric measurements are used to monitor individuals often, with the frequency varying according to their perceived risk. In 1991, the International Commission on Radiological Protection recommended reducing the allowable dose for workers to 2,000 millirems per year, but the Department of Energy did not adopt that recommendation (Makhijani, Smith, and Thorne 2006).

4.4 How the National Laboratories Assess and Report Risk

Putting our knowledge of plutonium mobility, biological hazard, and admissible limits into the context of plutonium-pit production requires examining how the national laboratories assess and report risk from their proposed work. Environmental Impact Statements (EIS) issued by the national laboratories offer perhaps the best public-facing analyses of whether proposed actions comply with expected standards for protecting public safety and the environment, including probabilities for specific scenarios and associated risks of exposures. Commentary on new EIS documents is also one of the primary venues for public self-advocacy.

Environmental Impact Statements

Although many of the processes required for resuming plutonium-pit production are the same today as during the Cold War, the potential impacts and risks are not. Today's improved awareness of potential harms makes possible better administrative and engineering controls to improve safety. Stronger environmental regulation since the 1970s also helps reduce the potential for public exposure and environmental damage. Nonetheless, plutonium remains just as hazardous today and workers remain fallible, despite the best controls. Where there is hazard, there is always a risk of accidents, leading to harmful human and environmental exposure. Environmental impact statements are the means by which the national laboratories document, predict, and address such hazards.

It is important to understand how the risks inherent in the current plans of the National Nuclear Security Administration (NNSA) compare with risks in the past. The National Environmental Policy Act (NEPA) of 1970 (42 U.S.C. § 4321) requires Environmental Impact Statements, and these have become a primary mechanism for analyzing and communicating such impacts to the public. An EIS typically considers cumulative impacts to surrounding regions, including infrastructural, environmental, and economic repercussions, as well as analyses of possible accident scenarios and likelihoods.

Los Alamos's PF-4 facility, where pit production will take place, has indeed had numerous recent accidents, even without the level of activity required for pit production. One such incident was severe enough to shut down the facility for three years (Center for Public Integrity and Malone 2017). Many incidents have exposed workers to plutonium (DNFSB 2022a; Guzmán 2023b).

In the past, LANL has considered various levels of pit production, including scenarios in which up to 450 pits per year would be produced at a single facility onsite (DOE 2003b). Later iterations of this proposal varied in size and scope, including various facility options, but none ultimately materialized (see Chapter 1). Each of these proposals was typically accompanied by supplemental analyses to the laboratory's existing EIS, but, critically, none of them explicitly considered the two-site solution that the NNSA is currently pursuing.

Instead, the most recent scoping and draft EIS from LANL considers the new pit-production mission under what is known as a "no action alternative" (DOE 2022; DOE 2025). This means that any and all hazards are considered to be within the scope of existing analyses, and that the NNSA considers no new analysis to be required. Instead, it is relying on a complex "tiered" approach; addenda and supplements to previous analyses are used to compensate for evolving circumstances and decision making (in this case, a supplement to the 2008 EIS (DOE 2008; DOE 2020d).

While it is true that the NNSA and LANL had in the past considered scenarios for pit production that included PF-4, previous documents did not explicitly or holistically consider the specific plan being pursued. EIS analyses can be "site-specific" if impacts are limited to a specific location or "programmatic" if proposed actions are "connected," "cumulative," or "similar" across multiple sites or facilities (Hart and Tsang 2021; *American Bird v. Fed. Communications* 2008).

Given the magnitude of the pit-production mission and the fact that it involves numerous DOE sites—including LANL, SRS, the Pantex Plant, the Waste Isolation Pilot Plant (WIPP), and the Lawrence Livermore National Laboratory—listed to carry out work that is apparently "connected, cumulative and similar," it seems appropriate that a programmatic EIS be conducted, one that would holistically consider the national implications. While the NNSA's approach may technically comply with NEPA requirements, it arguably abuses the tiered decision making process for site-specific NEPA analyses and simultaneously downplays the magnitude of expanded operations across the complex.

This tactic has been used, even in the wake of accidents severe enough to result in a three-year closure of the WIPP due to an unanticipated radioactive contamination event (Klaus 2019). At that time, the NNSA concluded that an updated environmental analysis for the site was not required (DOE 2020d).

Indeed, in September 2024, a US District Court Judge in South Carolina ruled that the NNSA had violated NEPA by not explicitly considering the two-site approach or appropriately considering alternatives. Negotiations in the case will require the NNSA to prepare a Programmatic EIS over a 2.5-year period following negotiations with the plaintiffs who brought the case (Geiger 2024).

Planning for Alternatives

A new Environmental Impact Statement should consider the impacts of simultaneous pit production across multiple sites as well as for scenarios that require surge production (beyond currently projected capacity) at one or both sites.

The NNSA's history of embarking on multi-billion-dollar projects only to have them cancelled when budgets or schedules become untenable should also encourage exploration of scenarios in which a single production site dictates circumstances (Hunter et al. 2019). In this case, revisions to infrastructure, transportation, and waste management should be explicitly examined, along with justification and feasibility for expanded operations at one site or the other. The competing missions within the PF-4 facility will obviously be affected whether present goals are achieved or not. Extenuating circumstances affecting pit production may therefore have significant ripple effects on additional important programs, and these should also be considered in terms of their potential cumulative impacts and needs for associated risk management. The Government Accountability Office has raised such concerns regarding competing missions, but they remain, to our knowledge, unaddressed (GAO 2019).

Paths for Environmental Release

Accidental releases through fire, a failure of building systems (e.g., air handling), or a natural disaster are worst-case scenarios that could release relatively large quantities of radioactive material. More likely, and potentially more frequent, occurrences would involve very small amounts of material leaving the facility through contamination of worker's clothing or skin or deposition on surfaces removed from the building, particularly through the waste stream. Because pit production involves considerable waste, the handling, packaging, and transport of that waste likely represents one of the largest ongoing risks for accidental exposures outside the facilities.

In all cases, administrative controls (e.g., best practices for workflow or standard operating procedures) and engineering controls (use of built systems and safety and monitoring equipment) can help greatly reducing potential risks. They can also help contain accidental release in the event of human error or partial system failure.

Active vs. Passive Confinement

The most fundamental engineering control to minimize potential plutonium releases involves the construction of the facility itself. The DOE's preferred standard for nuclear facilities that could release radiological materials includes what is known as "active confinement ventilation" (DOE 2012; Guha 2013). This means constructing facilities in ways that actively contain potential radiological material. Such designs use fans, filters, and designed airflows such that the building's interior maintains negative pressure relative to its exterior, inhibiting particulates and vapors from escaping even under abnormal conditions (e.g., following an accident).

To be qualified as a "safety class" system for protecting the general public, such systems must be engineered to moderate releases to less than 25 rem total effective dose. That is the approximate dose that most Americans receive over a lifetime from background sources (Box 4.3). Under DOE guidelines, this limit is a "planning and evaluation tool for accident prevention and mitigation assessment," rather than considered an acceptable or unacceptable dose from an accident (DOE 2014).

LANL's PF-4 facility has a version of active-confinement ventilation. However, it is not officially considered a safety-class system (capable of mitigating release in the event of an accident according to DOE standards) due to the potential seismic vulnerability of specific components (Randby et al. 2019). The Defense Nuclear Facilities Safety Board, which monitors public health and safety at DOE facilities, has long suggested improvements to PF-4's ventilation system. The NNSA had committed to upgrading its confinement system to meet safety-class requirements, including the required seismic criteria, as recently as 2020. However, the agency reversed course in 2022, informing the DNFSB that those modifications would prove too costly (Connery 2022a). The NNSA claimed to be undertaking improvements that would result in a robust, *albeit non-safety-class* confinement system as of 2022. The DNFSB notes that LANL's PF-4 facility is unique in the nuclear complex in not pursuing a safety-class, active-confinement strategy despite the inherent risks in the event of plutonium release (Randby et al. 2019).

Instead, LANL has chosen the alternative, which is considered "passive confinement": the building itself is credited with containing radiological release in the event of an accident. This strategy requires justifying that the potential offsite dose will fall below the federal regulatory limit for safety-class systems of 25 rem, doing so through estimating the fraction of material that could exit the facility under various scenarios using what is known as a Leak Path Factor (LPF) analysis.

Risk to offsite personnel and members of the public is quantified using specific assumptions to arrive at a "mitigated" dose level. LANL concludes that this is 24.2 rem—just below the 25 rem federal guideline.

Leak Path Factor Analysis

To arrive at an estimated release of 24.2 rem, LANL relies on a Leak Path Factor (LPF) analysis. The LPF represents the fraction of radioactive material (in this case, airborne plutonium) that escapes the facility during a bounding accident scenario. Quantifying the LPF depends on specific accident conditions (e.g., where and how an accident occurs), as well as on weather conditions that would determine how rapidly and far released radiological material could spread.

NNSA's methodology defines the amount of material that could be released as:

$$Mobile\ Quantity = MAR\ x\ ARF\ x\ RF\ x\ DR\ x\ LPF$$

MAR is the amount of “material at risk” in the facility (the total amount stored and/or in use). ARF is the fraction that becomes airborne. RF is the respirable fraction (the amount small enough to be inhaled). DR is the damage ratio, the amount of material damaged in the accident and therefore available for release to the environment. LPF is the fraction of the respirable material likely to have a physical pathway outside the building structure (DOE 2003b).

Clearly, such a calculation requires many assumptions because the only easily predictable factor is the material at risk, which corresponds to the facility’s inventory of plutonium. LANL relies on a number of computer codes to assess the LPF, including detailed modeling of aerosolized transport within the facility. LANL credits the LPF analysis in the oft-cited worst-case scenario of a post-seismic fire with reducing the off-site effective dose from 218.6 rem to the value of 24.2 rem noted above that, it notes, complies with the 25 rem off-site regulatory limit.

The DNFSB has criticized LANL’s methodology, citing concerns about both the codes and the critical assumptions that mathematically reduce the potential for public exposure: “The LPF calculations do not provide very high assurance of the confinement of radioactive materials, as required by DOE directives” (Randby et al. 2019; Connery 2022a). Most glaringly, arriving at a value below the 25-rem federal guideline requires that the exterior doors to the facility be open for no more than five minutes. This includes the time for all personnel to evacuate the facility, as well as the time the doors must be open for emergency response. Even before pit production has begun at full capacity, it has been reported that up to 1,000 people work at the facility on a given day, a number that would be expected to grow significantly as the lab approached its 30-pit-year milestone (Hennigan 2023). The DNFSB and others have called into question whether five minutes is long enough for lab staff to place lab systems (e.g., foundry processes) in a safe configuration, evacuate, and allow emergency response.

Potential measures to mitigate the amount of material that could be released in a worst-case, post-seismic fire include fully upgrading the active-confinement system to meet DOE safety-class standards (which would serve to reduce the LPF), reducing the amount of plutonium present at a given time (MAR, with implications for facility productivity), and additional facility modifications to reduce the fraction of material that could be damaged (DR). The choice to pursue a passive-confinement strategy increases the relative importance of other safety systems to keep the mobile quantity (hence, public risk) below the regulatory limit.

“Exigent Circumstances”

Inadequacies and delays to improving safety systems at PF-4 have been highlighted recently by the NNSA’s reliance on so-called “exigent circumstances” to justify potential public radiation exposure far beyond the 25 rem federal guideline. Under exigent circumstances, specific processes present a risk of exceeding the 25 rem guideline for offsite exposure, and existing safety systems do not or cannot provide adequate mitigation of risk. In effect, the NNSA may invoke this exception to the rule for atypical operations that it considers mission critical.

In 2022, the NNSA cited exigent circumstances to justify potential offsite exposure levels from 490 to 3,175 rem in the event of a serious accident during handling of ^{238}Pu for a repackaging effort. This is up to 127 times the federal guideline under DOE Standard 3009-2014, and it exceeds what is typically a lethal dose *under the most favorable assumptions* (Box 4.3).

The NNSA's invocation of exigent circumstances underscores the inadequacy of PF-4's safety systems for operations deemed necessary under LANL's competing missions (including pit production, heat-source plutonium-238, and excess plutonium disposition). DNFSB resident inspectors noted the LANL facility managers' determination that this exceptional operation required "no readiness activities, including a management self-assessment or subject matter expert checklist reviews" despite the associated and accepted risk (Boussouf, Gutowski, and Plaue 2022).

Such judgements on behalf of the laboratory call into question the authority of the standards for public protection, the development of adequate safety protocols, and when and how often exigent circumstances could be used in the future--for instance, if pit-production levels beyond 30 pits per year were deemed necessary to meet national security requirements, commensurately increasing the material at risk within the facility. When asked in a 2022 public hearing about whether increased pit production could lead to further invocation of exigent circumstances, NNSA administrator James McConnell replied, "I would like to say, but I can't, that this will be the last time that we use exigent conditions" (DNFSB 2022b).

Monitoring Airborne Effluents

Los Alamos and its surroundings are equipped with an air monitoring system intended to detect airborne radionuclides at some 40 locations at or near the lab's perimeter. Called AIRNET, this system is intended to monitor compliance with the lab's statutory requirement to keep public exposure from airborne sources below 10 millirems per year (from all sources). The system monitors for plutonium, uranium, tritium, and other possible radionuclides of interest, and stations are located both at potential source locations (e.g., emission stacks), as well as more distant regional locations expected to be representative of public exposure (Fuehne 2016).

Measurements from AIRNET have typically recorded emissions at levels below 1 millirem. While levels have generally improved since the 1990s, there have been measurements as high as 8 millirems (in 1993), 6 millirems (in 2005, due to a control-system malfunction at one facility), and about 3.5 millirems (in 2011, due to specific cleanup activities) (Fuehne and Allen 2015). Although these fall below the 10-millirem annual limit for public exposure, short-term emissions from point sources could be underreported given the geographic distribution of sensors. Also, measurements may not adequately capture diffuse sources like waste sites (Franke et al. 2003).

Unfortunately, both whistleblower testimony and critical shutdowns have cast doubt on the utility of AIRNET to provide a measure of public protection when and where it is most needed. In 1996, a former lab safety officer revealed "a pattern and practice of deception" at Los Alamos: employees would intentionally release airborne effluents, including radioactive tritium and contaminated water, away from stacks and monitoring locations to avoid setting them off, apparently in fear that the facility would be shut down if actual emissions were monitored (Guzmán 2024; Bartlein 1996). Additionally, the system was shut down during the peak of the 2000 Cerro Grande Wildfire, which could have mobilized radionuclides in smoke (Alvarez and Arends 2000). LANL published studies following the 2000 fire, as well as after the Las Conchas fire in 2011, showing that impacts from both events were minimal and that only naturally occurring radionuclides were detected in excess of normal background levels (Michelotti et al. 2013; LANL 2001).

The AIRNET system was updated recently, but it still does not provide real-time public alerts. Monitoring data are available to the public after the fact and in annual laboratory publications.

4.5 Risks to Workers from Pit Production

Workers in pit-production facilities face significantly greater risks that does the general public. Because they are in close contact with hazardous materials, these workers will be the first to suffer consequences during accidents. Although safety systems are inherently built into workflows (including both physical and administrative protections), humans are inherently fallible, and the PF-4 facility has a troubling history of accidents that have exposed workers to plutonium. As the NNSA rushes forward to achieve production capacity, recently hired and newly trained personnel are carrying out new procedures on both new and old equipment. All the while, mission-critical work, demolition and decontamination, and new construction and installation are happening concurrently on a 24/7 schedule. These circumstances, combined with an ambitious deadline and simultaneous, competing processes within the facility, significantly raise the risk of accidents.

Pit production involves a number of complex processes to recycle existing legacy pits, purify the plutonium, and remanufacture new pits from that material (see Chapter 1). Production involves both wet and dry chemical processes, using acids to dissolve chemicals, nitrate and chloride chemistry to recover specific products, and high-temperature chemistry (pyrochemistry/molten salt chemistry) to strip impurities and decay products from the metal. Molten plutonium is recast using processes akin to traditional foundries but adapted to take place within the necessary confines of gloveboxes under controlled atmospheres. The subsequent machining is delicate, precise, and produces pyrophoric (flammable) shavings and radioactive dust that pose risks of accidental fires—which have occurred on multiple occasions at Los Alamos and, catastrophically, at Rocky Flats.

As a result, workers are subject to many hazards, including the chemical, radiological, and mechanical risks that come with handling plutonium in metallic, powdered, and molten form, all while working without the usual dexterity that would normally be desirable for such processes.

Additional processes unrelated to pit production occur elsewhere in the Los Alamos plutonium facility (PF-4). These involve the preparation of ^{238}Pu “heat source” thermal batteries used in space missions and a process referred to as ARIES (Advanced Recovery and Integrated Extraction System), which converts excess plutonium to a diluted oxide powder for disposal. These processes use dedicated space within PF-4, but they also somewhat complicate administrative and radiological controls because they involve different isotopes and chemical forms of plutonium. Because of its higher radioactivity, ^{238}Pu is significantly more hazardous than the weapons-grade ^{239}Pu involved in pit production. However, the heat-source work cannot be paused while the rest of the facility is retrofit for the lab’s newly assigned pit-production mission because it is the only US facility that carries out such work. This creates a unique combination of hazards in a relatively constrained space—one that was neither originally designed as a production facility nor intended to support competing missions.

Worker Exposure to Plutonium

Plutonium poses the same health risks for workers as for the general public—with the obvious caveat that workers are much more likely to be exposed to larger quantities and more frequently. Exposure to fine particles is one of the most common documented occurrences, presenting the risk of inhalation. Because many processes at PF-4 either involve or produce small particles, and because some equipment remains contaminated from past work, the potential exposure to plutonium particulates is quite high.

Modern plutonium work takes place within glovebox enclosures, and, when possible, an enclosed production line moves material between gloveboxes along a trolley system (Figure 4.8). This physically separates workers from the material. The gloveboxes can often be purged with inert gas (e.g., argon, nitrogen) to avoid oxidation of the workpieces and scraps, and they are designed (in most cases) to maintain a slight pressure differential with the room to discourage outflow in the event of a glove rupture or other breach of the enclosure. Documented glove ruptures, one of the most common accidents, have occurred with surprising regularity. Usually, the consequences are controlled and remediated quickly, but they have been severe enough for the affected workers to require chelation treatment after confirmed uptakes of plutonium.

Over the history of plutonium work at Los Alamos, three worker have died from acute radiation poisoning. In each case, modern work practices would have prevented the incidents. A single plutonium pit (later termed ”the demon core”) caused two deaths during very early criticality studies in 1945 and 1946. Another death was caused when plutonium in a tank achieved a critical configuration in 1958, killing the chemist involved within 35 hours (McInroy 1995; Guzmán 2023a). The circumstances that led to these accidents would not be allowed today, given administrative limits and procedures. However, disregard for such limits and procedures, either deliberately or by accident, has been a recurring problem.

Possible Long-Term Occupational Health Effects from Plutonium

To predict the possible long-term health consequences for exposed workers, there are, unfortunately, only limited occupational health studies to inform us. This is simply because the number of plutonium workers with adequate monitoring and longitudinal health tracking is small compared with the general population.

That the long-term health consequences for plutonium workers are not always clear is also due, in part, to insufficient monitoring of those who may have been occupationally exposed, as well as a common epidemiological tendency known as the “healthy worker bias.” That bias describes the fact that those who suffer the most severe health consequences may leave the workforce and therefore not be sampled as part of the occupational population. Workers may also have access to better healthcare than the general population, and, because of occupational monitoring, they may be more likely to receive screening and treatment for health risks; this can sometimes skew epidemiological surveys when sample sizes are small.

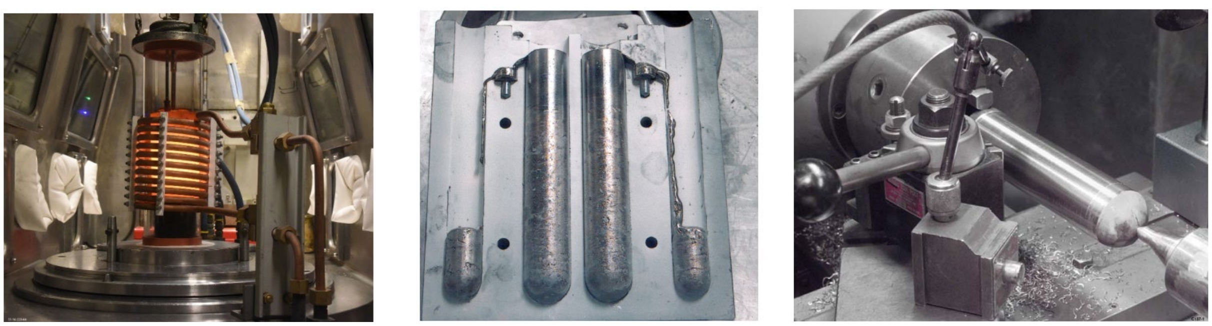
Historically, occupational health studies of LANL workers favored white, male, Anglo employees of the University of California but underrepresented women and contract workers, who were more likely to be of Hispanic or Native American descent (Wing and Richardson 2003). A cohort mortality study of these workers found that deaths from all cancers (among

1,196 individuals who could be tracked) were actually low compared with the US population. However leukemia, stomach, liver, pancreas, and bone cancers showed excess deaths, meaning they occurred at higher rates than would be expected for the general population. About half of the study population lacked bioassay data (Galke, Johnson, and Tietjen 1992; Wing and Richardson 2003). When compared with other lab workers, an increased risk of lung cancer was noted; however, this was based on only eight deaths.

Worker Exposure to Beryllium and Americium

Pit production also involves beryllium and americium, and both pose their own hazards for workers. Many pit designs are widely believed to contain beryllium, which reflects neutrons back into the imploding pit during the chain reaction and produces additional neutrons from alpha decay in the plutonium. Beryllium is a highly toxic metal that is also extremely dangerous to inhale. Inhaling it can lead to berylliosis, a chronic lung disease that can take years to appear (DHHS n.d.). Americium will be present in smaller amounts as a decay product of ^{241}Pu, but it poses an even greater inhalation risk than plutonium, including to the thyroid.

FIGURE 4.8. Foundry and Machining Processes Involved in Plutonium Pit Production



Left: An induction furnace within a glovebox melts plutonium "buttons" for casting into various shapes. Center: Plutonium rods, as cast. Right: A dry machining process on a lathe brings castings to the final desired dimensions. SOURCES: Kautz 2003; Los Alamos National Laboratory/US Department of Energy n.d.

Worker Protection Measures

Workers who handle plutonium and other nuclear materials are protected through a combination of on-the-job training, administrative controls (prescribed procedures and work flows), engineering controls that provide physical separation from hazards, and personal protective equipment. Where human error is more likely, the other safety elements gain increased significance. This tiered approach to safety is required because any one component of the system is likely to be insufficient to avoid potential exposure to radiation—a hazard that cannot be seen, smelled, or otherwise felt with human senses.

Alpha monitors are one of the primary engineering controls that must be used when workers withdraw their hands from gloveboxes within radiologically controlled areas or radiological buffer areas. In the event of a glove tear or breach, this is meant to ensure the immediate detection of the contamination so it can be contained and remediated. When entering and exiting controlled areas, hand and foot monitors survey workers' personal protective equipment for radiation. Full-body monitors at entries and exits of controlled areas are used to avoid contamination when workers leave the facility. For larger spaces, continuous air monitoring detects airborne contamination in work areas by pumping room air through a detector and providing an audiovisual alarm if radiation is detected (Cournoyer 2018). Positive detections typically require the evacuation of personnel, but in the past monitors have been accidentally tripped or ignored during maintenance activities in PF-4.

A variety of activities take place in PF-4 in addition to pit production. These entail different hazardous products and isotopes with varying radioactivity, potentially presenting a challenge for monitoring. Not all detectors are universally sensitive; they must be appropriately chosen for specific hazards and used according to protocol to avoid false negative readings that could (and have) allowed workers to leave controlled areas with contamination on their clothing or personal protective equipment (PPE).

Because worker fallibility is inevitable, particularly as new facilities undertake new and unfamiliar procedures, proper design and certification of engineering controls are critical. In 2023, the Defense Nuclear Facilities Safety Board criticized the DOE's assertion that additional safety controls were not required for designing and developing the pit-production facility at Savannah River. According to the DNFSB, project personnel asserted that "workers can use their senses to detect accidents such as a glovebox spill or fire and exit the area before receiving significant radiological exposure," thereby avoiding designation of certain systems as safety-significant controls (Connery 2023). This stance ignores the imperceptible risk of radiation and the well-documented history of accidents and worker exposure at both Los Alamos and Savannah River—a history that clearly demonstrates the ways in which both administrative and engineering controls have failed to protect workers.

Accidents

Even relatively sophisticated measures, procedures, and equipment to protect workers have not prevented a checkered safety history in LANL's plutonium facility. A number of relatively serious accidents have occurred over the past 15 years, involving violations of criticality safety rules, plutonium intake by workers, floods, glovebox fires, and failures of equipment that have led to contamination outside of gloveboxes.

In recent years, Los Alamos has experienced several instances of what the lab terms "overmass conditions" at PF-4 (perhaps deliberately avoiding the term "criticality" hazard). A well-publicized incident in 2011 ultimately triggered a multiyear shutdown of the facility in 2013 (Center for Public Integrity and Malone 2017; Center for Public Integrity, Smith, and Malone 2017). "Overmass" does not always imply that a criticality accident is imminent. Rather, it suggests that workers have exceeded what are considered safe administrative limits for material within a given space or geometry, often by accident, or an accounting fault occurred as the material moved through the facility or storage vaults.

The 2011 event was neither accidental nor attributable to faulty accounting. Workers staged eight plutonium rods within inches of each other to make a photograph (Figure 4.9). This was an egregious violation of basic criticality safety: putting fissile materials in close physical proximity can lead to a nuclear chain reaction, particularly in the presence of a means of slowing or reflecting neutrons back into the material. Water can have this effect but so can a worker's hand, making it potentially dangerous to physically intervene to increase separation. To make matters worse, the response to this event was mishandled when workers in the room were allowed to return to their tasks. The incident led to the resignation of several criticality-safety officers, allegedly out of frustration over lax attention to rules. Two years later, NNSA management ordered a complete facility shutdown while safety measures were reevaluated. When work resumed in 2017, the shortage of qualified criticality-safety engineers was cited as an ongoing concern (Malone and Smith 2017). Reestablishing a workforce of skilled nuclear criticality engineers is critical for pit production.

A 2003 risk assessment for the Modern Pit Facility (an earlier proposed pit-production facility) estimated the potential frequency of a criticality accident at about one in a hundred per year—higher than other risks, including fire and radioactive material spills (DOE 2003b). While criticality accidents are extremely dangerous and can expose anyone in close proximity to lethal acute doses of radiation, they do not result in a nuclear explosion because of the material configuration. Thus, criticality accidents do not pose a significant risk to the public, but they could be lethal for workers and result in significant contamination. PF-4 has continued to routinely log criticality incidents, including the flooding of a vault containing fissile material in 2021 and as recently as April 2024 as work accelerates to produce the first weapon-ready pit (Roscetti 2021; Gutowski 2024a).

Glovebox operations are another frequent source of accidents at PF-4. Gloveboxes are intended to protect workers from contact with hazardous materials. Compromised gloves have torn away from the glovebox when workers inserted their hands, and small tears or breaches of the gloves occur routinely as a result of chafing, tool use, pinches, or other mechanical or chemical insults. Many glove breaches are relatively benign if detected rapidly because plutonium is primarily an alpha-emitter, and personal protective clothing and skin can block alpha radiation. Any contamination can be localized if breaches are detected using routine hand scans when workers withdraw from the gloveboxes. Despite this, not all glove breaches are benign.

Some glovebox accidents have had serious consequences. In 2020, several incidents were attributed to a "bad batch" of gloves. In one case, a worker's personal protective clothing registered extremely high ^{238}Pu activity: 300,000 disintegrations per minute, or roughly a tenth of the annual occupational exposure limit per minute of exposure (Roscetti 2020). Just a few months later, another glove breach exposed 15 workers simultaneously to ^{238}Pu. Six of them were determined to have had internal uptake, and at least one underwent chelation treatment (Connery 2024; Wyland 2020). A 2022 incident exposed six workers, three of whom had suspected intake that could exceed two or more times the annual occupational limit (Roscetti 2022). One underwent chelation treatment (Connery 2024). These are just the most serious instances out of many cases that required biological monitoring of affected individuals.

FIGURE 4.9. Incidents and Accidents

Left: In this 2011 photograph, several kilograms of cast plutonium rods are in close proximity, violating criticality safety rules. This incident led to a multiyear facility shutdown, but other "overmass" incidents have since occurred. Right: Workers practice procedures in a glovebox training facility like this. The overhead trolley is similar to that used in PF-4 to move material between boxes. SOURCES: Left: Los Alamos National Laboratory/US Department of Energy; Right: Michael Pierce, Los Alamos National Laboratory.

Glove breaches occurred as often as three times in a single week and roughly 2.5 times per month before 2021, when 19 instances were noted. A series of 10 incidents in late 2022/early 2023 spurred further review and criticism of the lab's glovebox safety program as work accelerated at the facility (Connery 2024). The regularity of these events suggests the potential for routine mobility of plutonium throughout the facility—a possibility that appears to be borne out from reports of contamination on workers' skin in areas thought to be previously decontaminated and another recent case when contamination was detected on a worker who was near but had not used a glovebox that suffered a breach (Wyland 2024b; Dwyer 2024a).

Other glovebox incidents have included fires (three in 2023 alone due to the pyrophoric nature of plutonium and calcium in material being repackaged), a glovebox tipping over without releasing radioactive material (2016), and a glovebox window being shattered when a worker lost control of a container, causing it to slip. According to the DNFSB, failed seals, improper valve closure, and other engineering deficiencies have also led to dangerous conditions that compromised the integrity of gloveboxes meant to protect workers, and others have been exposed while decontaminating and removing older boxes from the facility.

Triad National Security LLC, the contractor operating LANL on behalf of the Department of Energy, was reprimanded by the NNSA in 2021 over safety lapses at PF-4. The NNSA noted five "series II violations" related to four separate incidents between February and July 2021. These involved a criticality safety violation, radioactive skin contamination of three employees, the aforementioned flooding of a fissile material vault, and separate flooding of gloveboxes containing fissile material through the glovebox ventilation system. According to the Department of Energy, “Series II” violations “represent a significant lack of attention or carelessness towards responsibilities of contractors for the protection of public or worker safety” (O’Neill 2023). This cluster of events resulted in a notice of violation from the NNSA and penalties totaling $1.4 million (Prokop 2023). This represents only 3 percent of Triad’s annual fee, and the NNSA’s FY2021 performance evaluation nonetheless gave Triad “excellent” or “very good” ratings in all categories (NNSA 2021a).

The most recent performance evaluation for Triad’s management of LANL, issued in December 2023, states, “Triad increased its production facility construction, maintenance, and program activity levels in pursuit of pit production milestones and identified several processes that needed improvement to provide for the safety of personnel. However, despite identifying needed improvements, Triad did not pursue safety related process improvements.” NNSA again issued “very good” or “excellent” scores on all performance categories despite the noted lack of improvements to protect workers (LANL 2023b).

The apparent contradiction between administering minor penalties for safety violations while citing “very good” and “excellent” achievement of performance metrics points to a mission-driven culture and an overreliance on human infallibility to ensure the safety of extremely hazardous processes. The 2021 notice of violation cited Triad’s failure “to identify and correct quality problems in a manner that effectively prevented recurrence” and an overemphasis on corrective actions “that focus on preventing employees from making mistakes rather than on making more effective and longer-lasting changes to engineered controls” that could serve to avoid the cause in the first place (NNSA 2023).

As with safety-class active ventilation, the cost of effective engineered controls is typically higher than the cost of employee training, but this choice results in less-reliable accident prevention. Moreover, it is contrary to widely accepted best practices in occupational health and safety that prioritize engineered controls as a first line of protective defense (CDC 2024b). An overreliance on worker training may be especially perilous during the ramp-up to full-scale pit production, when a large number of workers are new, temporary trade workers are on site, and new procedures and work flows are being developed.

> *“This is not a one-off. This is a pattern. This suggests the lab does not have sufficient controls to undertake the extraordinarily hazardous, new operations of pit production. They are having repeated contamination events, which shouldn’t be occurring.” — Dan Hirsch, retired director of environment and nuclear policy programs at the University of California, Santa Cruz, quoted in the* Sante Fe New Mexican*, January 9, 2024*

Adequacy of Worker Training

Many of the accidents at PF-4 over the past several years appear to have resulted from incomplete or inadequate preparation of workers to evaluate and manage the facility’s complex and interconnected risks.

Pit production has created a demand for thousands of new employees: 2,077 at Los Alamos in FY22 with a similar number anticipated in FY23 (LANL 2023a). Many of these new hires will lack significant experience in the setting of a high-security lab with its unique combination of hazards. As a result of difficulty in recruiting for certain positions, LANL is investing in its own training pipelines at nearby community colleges. It offers full-tuition scholarships for students on tracks that cater to the lab's staffing needs. These programs train would-be staff for such positions as radiological control technicians, the electrical and mechanical trades, waste management, and numerous other support roles. According to an LANL technical director, positions at PF-4 come with a $20,000 "environmental" bonus in order to recruit people to work in what are termed the "more challenging facilities" (Guzmán 2023c).

The cultural and socioeconomic differences between Los Alamos and the surrounding region create a stark contrast between most regional employment opportunities and those at the national lab. LANL's specialized training programs, which result in associate's degrees or specialized certificates, come with the allure of above-average salaries. However, it is not clear that the programs adequately prepare future employees for the on-the-job risks they will likely encounter.

LANL's 2023 performance evaluation noted that Triad had increased the number of craft workers and radiological control technicians, but it blamed schedule slippage and "substantial cost overruns" on inadequate training and a lack of "qualified and experienced resources" (LANL 2023b). This has resulted in numerous incidents, including unintended radiation exposures, damage to new equipment due to inexperienced installers, severe physical injuries, and electrical accidents that were blamed on employees performing "out of scope" work or not complying with procedures.

Recent events continue to call worker training into question. In March 2024, workers placed heavy equipment on a plate for a pressure-activated decontamination shower, apparently unaware of its purpose. Water flowed until it seeped through walls and floors, reaching the basement and requiring several areas to be decontaminated. This was the facility's sixth major flooding event since 2018. As a result, senior managers instituted a safety pause at PF-4 during which the lab "engaged the workforce in discussions about work tempo" and "balancing safety and production" (Dwyer 2024b; 2024c). Just a week later, night-shift employees largely ignored evacuation protocols in response to a glovebox fire alarm, having been told that it was actuated inadvertently.

Of greatest concern is whether all PF-4 employees receive adequate training for the potential radiological risk. Because of the classified nature of the work, a cleared individual must escort the many trade workers who perform temporary work and lack security clearances. In December 2023, the Defense Nuclear Facilities Safety Board noted, "Facility specific contamination monitoring training is not being assigned until personnel meet all security requirements for unescorted access to the facility." This implied that escorted personnel would not have received training to monitor themselves.

While radiological control technicians (RCTs) would normally ensure that protocols are followed, at least one newly trained RCT from the training pipeline performed work for several weeks in 2023, including entry into radiologically controlled areas, without having been assigned a personal radiation dosimeter (Dwyer 2023). Personal dosimeters represent one of the most fundamental components of radiological safety. This event calls into question the rigor and adequacy of the training provided in the new employee pipelines as well as how well employees appreciate the risk they could be exposed to. Such incidents are especially troubling because RCTs are responsible for ensuring the safety of others.

Ambitious Scheduling Increases Risk

The NNSA has a congressionally mandated deadline to produce 30 pits per year by 2026 at Los Alamos and 80 pits per year by 2030 using both Los Alamos and the Savannah River Site (50 U.S. Code § 2538a n.d.). Despite congressional proposals to remove the 80-pit requirement, the House version of the 2025 National Defense Authorization Act preserved it (Garamendi 2024).

It is widely acknowledged, including by NNSA administrators, that this goal is unattainable, particularly at the Savannah River Site, which faces severe delays and complications. The deadline was arbitrary to begin with, and it is increasingly out of sync with the delays facing the warhead and missile programs that it is intended to support. In rushing to meet the 2026 and 2030 production goals, the NNSA unnecessarily heightens the risk to workers, nearby communities, and its own ambitions should a severe accident occur.

In 2022, PF-4 began round-the-clock operations in an effort to maximize productivity and simultaneously remove and decontaminate old equipment even while installing and bringing online new equipment for pit production—all while the facility continued its other work. Not by coincidence, the number of reported safety incidents rose 33 percent in 2022 over the previous year. In 2023, the NNSA noted that Triad had struggled to gain timely approval for the Documented Safety Analysis and Technical Safety Requirements to meet DOE standards for the plutonium facility, often requiring multiple resubmissions to gain approval—yet another demonstration that inattention to safety is counterproductive rather than expedient (LANL 2023b).

In another sign that ambitious deadlines are leading to increased tolerance for risk, in January 2024 LANL requested permission to increase the types of activities allowed under what is called "limited operations mode"—a condition usually induced by the incomplete functioning of safety systems in the facility, whether planned or unplanned (Gutowski 2024b). Limited operations mode is sometimes invoked to allow construction activities or temporary shutdowns of critical systems during equipment changeovers, or in the wake of accidents requiring remediation or investigation. The request to increase the allowed scope of work under such conditions suggests that LANL's operating contractor finds that the associated safety requirements or lost time are too cumbersome for it to meet deadlines—and that they are willing to accept a higher risk threshold in the name of convenience.

Alleviating the mandate for arbitrary production deadlines could significantly improve worker safety, reduce overall project risk, reduce costs, and allow a more careful approach to what are arguably some of the most hazardous processes undertaken by the weapons complex. Rushing to achieve production with newly trained workers, new equipment, and new procedures, even while seeking opportunities to shortcut safety, endangers workers, communities, and the program.

4.6 Looking Forward: Handling a Growing Waste Stream

Long-Term Solution or Short-Sighted Plan?

A future risk—one that has yet to fully materialize—centers on the waste that results from pit production. How will it be handled in addition to existing waste streams and the legacy waste remaining onsite and awaiting remediation and disposal? Because LANL has limited capacity

FIGURE 4.10. Routes and Vehicles Used for Shipping Transuranic Waste to WIPP

Transuranic waste reaches the Waste Isolation Pilot Plant (WIPP) via interstate highways using specially designed trucks laden with "TRUPACT" waste-shipment containers. Each container can hold 14 55-gallon drums of waste. The containers are designed to be bulletproof and crash- and fire-resistant. Locations across the country ship waste to New Mexico.
SOURCES: WIPP/US Department of Energy, Office of Environmental Management; Los Alamos National Laboratory.

to accumulate nuclear waste onsite (and very little at the technical area where pit production takes place), continuous and efficient waste removal will be required to ensure productivity at projected levels. This risks overburdening an already challenged waste-management stream.

Pit production generates both liquid and solid wastes. These include acids, contaminated consumables (e.g., gloves, rags, other single-use items), metals, tools, and radioactive liquid waste, chemicals and salts—along with entire gloveboxes retired from service. This waste must be transferred to the laboratory's transuranic waste management site, where it is packaged and prepared for shipment to the Waste Isolation Pilot Plant, near Carlsbad, New Mexico. LANL estimates that it will generate in excess of 2,000 containers of transuranic waste per year once it is producing 30 pits per year (McConnell 2020). If the waste stream is proportional to production levels, Savannah River can be expected to contribute some 3,300 to 3,500 containers annually.

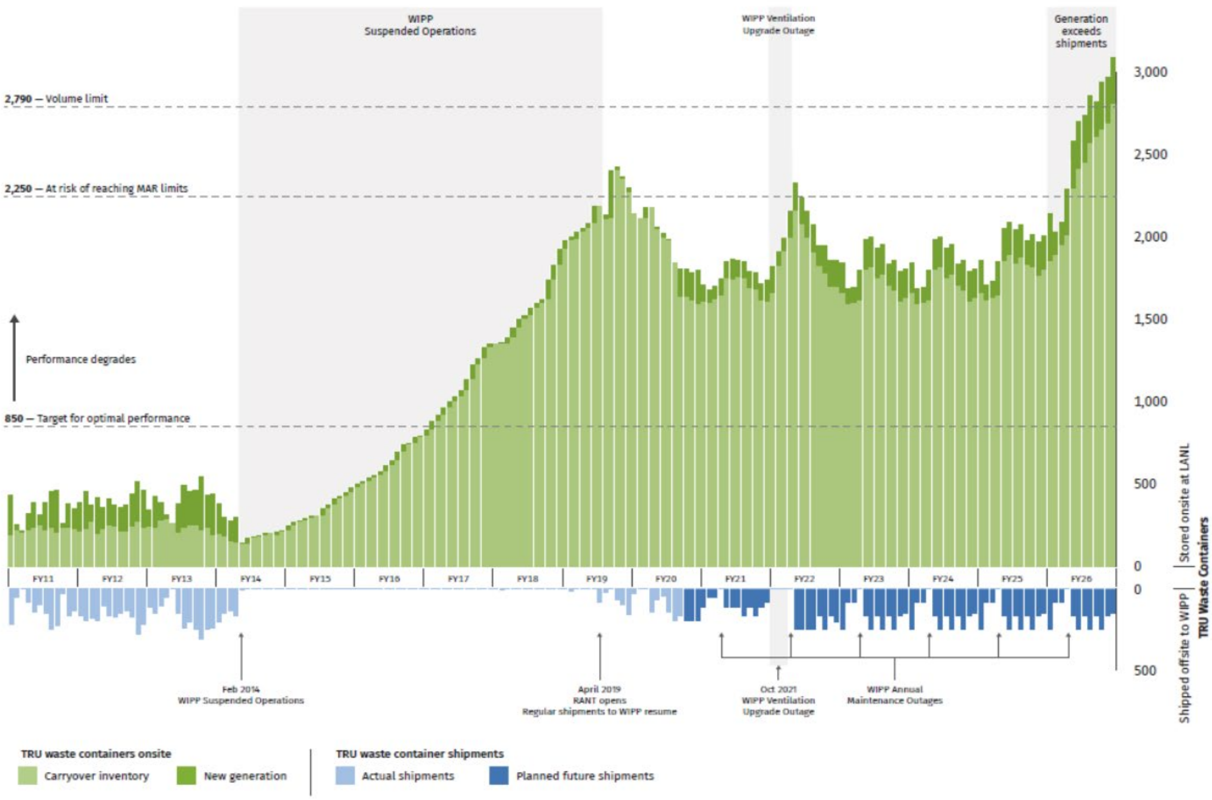
WIPP remains the sole US repository for nuclear waste (DOE n.d.). When it began receiving shipments in 1999, it was slated to house up to 175,000 cubic meters of nuclear waste in an underground geologic setting that would be secure for 10,000 years (^{239}Pu has a half-life of 24,300 years). As "Pilot Plant" in its name suggests, WIPP was originally expected to close in or around 2024. The lack of any feasible alternative disposal site has led to the inevitable extension of its operation. In 2023, the New Mexico Environmental Department renewed the permit for 10 years, but the DOE contends that it may need to rely on the facility into the 2080s (Hedden 2023). WIPP's projected capacity remains contentious, as does the question of how to prioritize legacy waste vs. newly produced waste, illustrating the multifaceted uncertainties in the US strategy for managing nuclear waste over the long term.

The DOE claimed that WIPP was nearing 43 percent of its licensed capacity as of 2024 but that it nonetheless required additional physical space going forward, resulting in additional excavation (Forinash and Hobbes 2024). A 2020 National Academies of Science study concluded that the facility's capacity may be too little to absorb pit waste in addition to other transuranic waste and surplus plutonium from across the complex under its originally specified quota (NASEM 2020).

One condition of the New Mexico Environmental Department's permit renewal is that it reserved the right to close the site should Congress approve increased capacity in the future, ostensibly prohibiting any future expansion. The recent defeat of a separately proposed interim storage facility for nuclear fuel, which would have been situated nearby, appears to demonstrate that long-time vocal opposition from New Mexico residents resonates with the state government and licensing agencies whose appetite for hosting nuclear waste may be diminishing (Luján 2023).

An accident could also jeopardize WIPP's future operation and capacity for pit waste. In 2014, two closely spaced accidents resulted in a three-year closure of the underground repository. A mining truck caught fire underground and a barrel of improperly packaged Los Alamos radioactive waste exploded, severely contaminating a portion of the facility and sending plutonium to the surface and as far as 20 miles away (Klaus 2019). Although the NNSA argues for the benefits of redundancy in having a two sites able to produce pits, another accident such as those in 2014 would likely cause both sites to cease operations; after all, the capacity for onsite waste accrual at Los Alamos and Savannah River is finite. In a rather cynical admission that such events could recur, LANL is now proposing up to four additional on-site waste staging areas “to minimize the potential for a long-term WIPP shutdown to affect pit production activities” (DOE 2025).

FIGURE 4.11. Waste Inventory Is Exceeding Optimal Capacity



LANL’s waste inventory has exceeded the target optimal storage level of 850 drums since around 2017—before any pit-production activity had begun. This inventory largely resulted from WIPP’s prolonged shutdown following two serious accidents in 2014. The effects of scheduled pauses and maintenance outages is evident, demonstrating the vulnerability of pit production should WIPP become unavailable for any reason in the future. Post-2021 levels are based on forecasts at the time. Source: NNSA 2021b.

The Perils of Yesterday’s Waste

Reliable, safe, long-term storage is an Achilles heel for plutonium-pit production as well as for the associated expansion of the US nuclear arsenal. Even in the absence of new waste from pit production, both Los Alamos and Savannah River still play host to decades-old waste that awaits proper disposal and remediation. That problem will only be compounded as pit production accelerates.

At LANL, most of this work occurs at the lab’s transuranic waste treatment facility at Technical Area 54, including a site known as Area G. This is where waste from pit production would be packaged and staged before being shipped to WIPP (Figure 4.10). Area G, originally opened in 1957 as a waste dump, contains “32 pits, 194 shafts, and four trenches with depths ranging from 10 to 65 feet below the original ground surface” (LANL 2019). The waste-burial sites are believed to be unlined and contain a mixture of legacy radioactive wastes (Abbott 2011). Aboveground, the site hosts around 2,200 transuranic waste drums, only about 170 of which met criteria for disposal at WIPP as of 2022. More than 1,550 drums are thought to require some type of remediation (Thatcher 2022), repackaging, or separation of incompatible waste in order to avoid a repeat of the WIPP’s 2014 drum explosion. Thirty to forty shipments of about 17 drums each are expected to be made annually, at a cost of around $100,000 per drum (Summerscales 2023).

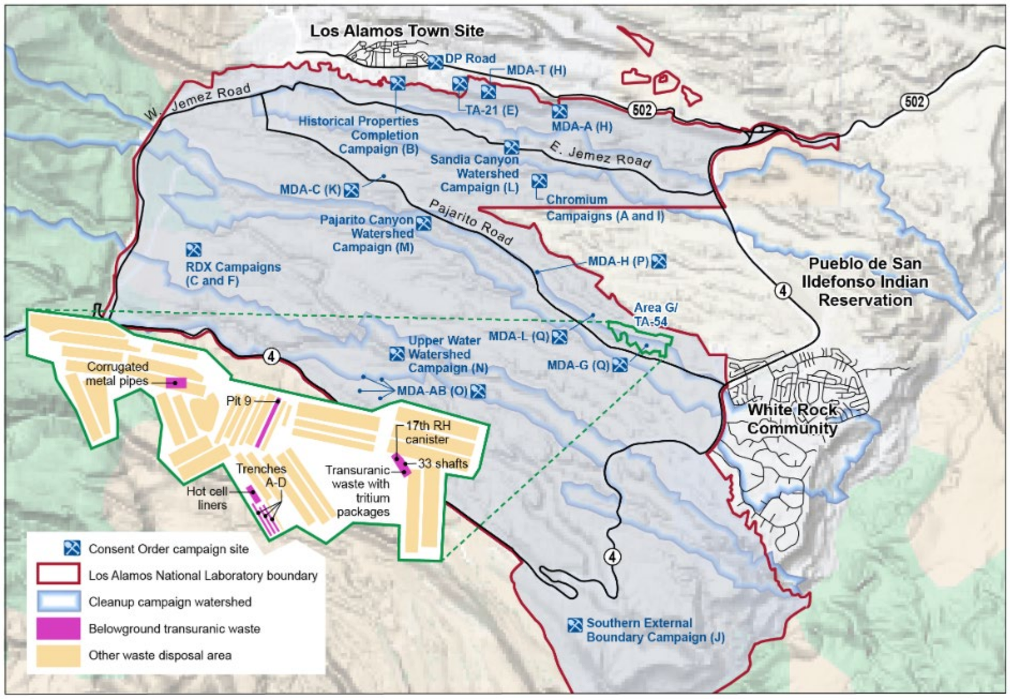
In addition to the hazards already present at Area G, the site may be one of the most vulnerable at Los Alamos. Temporary dome structures housing aboveground waste lack most of the structural and engineering controls (e.g., advanced fire suppression, HEPA air filtration) that would help prevent accidental material releases in more permanent structures. The domes are classified as Category 2 nuclear facilities, meaning that there is “the potential for significant onsite consequences,” according to DOE standards (DOE 1992). However, the site is less than one mile from new residential housing in White Rock, New Mexico (Figure 4.12), and wildfires have threatened it in recent years. Arguably, this raises the risk of significant off-site consequences as well, particularly from fire, the airborne dispersal of contamination, and the accidental rupture of waste containers, all of which could result in relatively high offsite doses of radiation (Connery 2022b; Dunlevy et al. 2020).

As with PF-4, increasing the demand and pace of work at Area G is likely to elevate risk for workers and nearby communities. These should be considered as part of the cumulative risk associated with pit production.

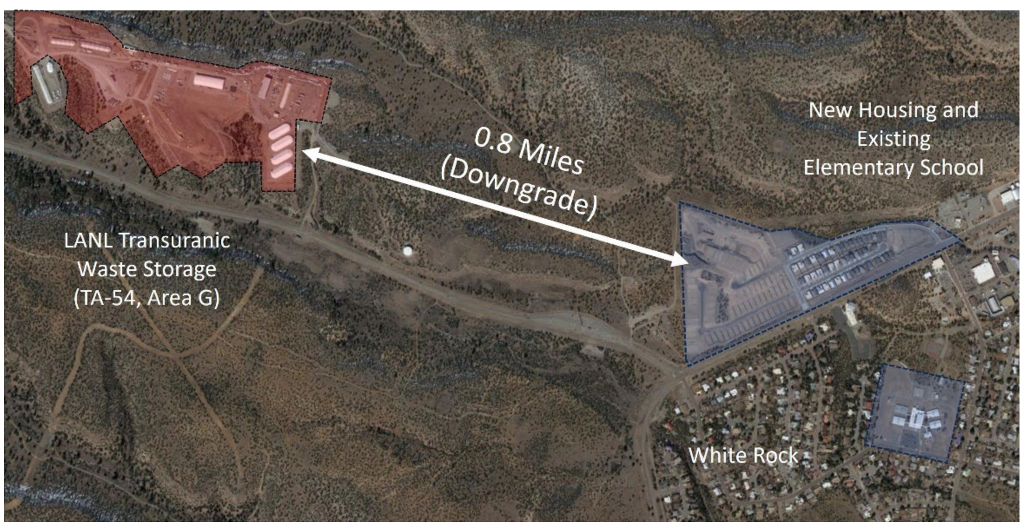
Ultimately, the problem of waste management and remediation of past waste is a question of priorities. The federal budget requests in FY25 for environmental management were 15.3 percent and 10.6 percent *below* FY23 levels at Los Alamos and Savannah River, respectively, while the NNSA saw a 16 percent *increase* in its weapons activities budget over the same period. Legacy-waste cleanup at Los Alamos represents roughly 5 percent of the lab’s FY25 funding; pit production will consume roughly 40 percent of a record $5 billion annual budget (DOE 2024).

The true environmental cost of nuclear weapons production is virtually insurmountable, given the long-lived nature of what is left behind and the near impossibility of achieving complete environmental restoration. As *The New York Times* reported in an analysis of what may be a $528-billion-dollar cleanup effort at Hanford, Washington, “At site after site, the solution has come down to a choice between an expensive, decades-long cleanup or quicker action that leaves a large amount of waste in place” (Vartabedian 2023). For the most part, current US plans prioritize the latter in favor of efforts that exacerbate the problem going forward as new weapons development is undertaken. As University of Washington associate professor Shannon Cram has written, “The challenge of remediation, then, is to measure and manage the conditions of carcinogenic encounter—titrating environmental contamination with human activity to achieve the appropriate balance of permissible dose” (Cram 2015).

FIGURE 4.12. Proximity of LANL's Primary Transuranic Waste Site to the Public



Sources: Department of Energy (map); ©2023 Google (terrain). | GAO-23-105665



Top: This map shows LANL cleanup locations, with the inset showing detail of TA-54 (Area G). The area contains numerous trenches and shafts containing buried waste, as well as aboveground transuranic waste, some of which is deemed unsuitable or unsafe to be shipped to WIPP. Bottom: The aerial image shows the proximity of the Area G transuranic waste storage area to new housing being built in White Rock, a community adjacent to Los Alamos. Many laboratory employees reside there. SOURCES: Top: Anderson 2023; Bottom: Modified by UCS from Google Earth, 2024.

The requirements for pit production outlined here recall a similar tension: between perceived national security requirements and the human and environmental costs that are deemed permissible and borne domestically to deliver that security.

Findings and Recommendations

Past activities at the Los Alamos National Laboratory and the Savannah River Site have left a legacy of environmental and human damage, with particularly acute consequences for the Native American and minority populations who were displaced at both sites and who continue to bear the brunt of environmental consequences. Although the present effort to produce pits will benefit from lessons learned from the past, the resumption of production at scale still poses significant risks to workers, the public, and the environment.

Rushing the pit-production program introduces unnecessary risks of accidents and radiation exposure, particularly to workers and potentially to the general public. The regularity of accidents at the PF-4 facility raises serious concern about the safety of work practices as pit production accelerates to meet an unnecessary production goal.

The NNSA and its national laboratories must provide complete, accessible, quantitative risk assessments that provide the information needed to support meaningful public input on new activities that could result in public risk. Such analyses and subsequent decisions should involve all stakeholders, particularly tribal entities and communities affected by past contamination. As the National Environmental Policy Act (NEPA) requires, these analyses should be undertaken *before* the United States, the Department of Energy, and the national laboratories make decisions on a course of action.

The National Nuclear Security Administration must prepare a new, Programmatic Environmental Impact Statement that explicitly considers alternatives to the two-site strategy for pit production. The EIS should include the potential for reusing pits, the consequences should either PF-4 or Savannah River become unavailable for production, and the cumulative impacts on the hazardous-waste stream that will result across the nuclear complex.

The Department of Energy must consider standards for radiation exposure that include the most vulnerable members of the population. Too little research has been conducted to determine the potential health consequences to the public from exposure to low-dose radioactivity. Further studies are urgently needed and should be commissioned, such as those in the research agenda laid out by the National Academies of Science, Engineering, and Medicine in 2022 (NASEM 2022).

Should LANL ever be required to implement “surge” pit-production capacity, the lab must neither cut corners nor invoke “exigent circumstances” to bypass federal regulations meant to protect the public. Pit-production requirements must not be used to justify exemptions, nor should the labs consider such exemptions as an alternative to implementing necessary safety-system improvements. The labs should prioritize investing in safety-class engineering measures, including active-confinement ventilation, improved air monitoring, and the control of airborne emissions.

Decades-old radioactive and other toxic waste from past activities at Los Alamos and the Savannah River Site have yet to be disposed of properly. Many areas remain insufficiently remediated, and they may continue to present a risk to surrounding communities. To protect the public and neighboring communities, the national laboratories should do all possible to conduct remediation to the highest achievable standards.

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