~~SECRET//~~RESTRICTED DATA

U.S. DEPARTMENT OF ENERGY | NNSA National Nuclear Security Administration

(U) Research Program Plan for Plutonium and Pit Aging

DEPARTMENT OF ENERGY DECLASSIFICATION REVIEW	
1st REVIEW – DATE: 5/12/2023	DETERMINATION (Circle Number(s))
EHSS-60 REVIEWER: (b) (6)	1. CLASSIFICATION RETAINED
AUTHORITY: ☐DC ☒DD	2. CLASSIFICATION CHANGED TO:
	3. CONTAINS NO DOE CLASSIFIED INFO
Derived From:	4. COORDINATE WITH:
Declassify On:	5. DECLASSIFIED
	6. CLASSIFIED INFO BRACKETED
2nd REVIEW – DATE: 5/16/2023	7. OTHER (SPECIFY): w/ attch(s)/encl(s)
EHSS-60 REVIEWER: (b) (6)	
AUTHORITY: DD	

Report to Congress
September 2021

~~RESTRICTED DATA~~
~~This document contains Restricted Data as defined in the Atomic Energy Act of 1954. Unauthorized disclosure subject to Administrative and Criminal Sanctions.~~

~~CLASSIFIED BY: (b) (6)~~
~~Lawrence Livermore National Laboratory~~
~~DERIVED FROM: TCG-WS-1 DOE OC~~
~~Issued: 10/84, Last Change: 5/18~~

National Nuclear Security Administration
United States Department of Energy
Washington, DC 20585

~~SECRET//~~RESTRICTED DATA

Message from the Administrator

The radioactive decay of the plutonium contained within a U.S. nuclear weapon's primary has potential cumulative effects on nuclear weapon performance. This cumulative effect of plutonium's radioactive decay is referred to as plutonium aging or pit aging. To improve scientific understanding of this phenomenon, the Department of Energy's National Nuclear Security Administration (DOE/NNSA) established a National Strategy for Plutonium Aging in 2017. This National Strategy, which was updated in 2020, is focused on obtaining experimental data to improve and underpin DOE/NNSA's numerical simulation of nuclear weapons performance.

Pursued through the National Strategy and guided by the 10-year National Plutonium Aging Research Program Plan, the National Plutonium Aging Program will provide DOE/NNSA with improvements in understanding the potential impacts on weapon performance due to plutonium and pit aging. This data will support the assessment of enduring stockpile systems and certification of ongoing and future warhead acquisition programs.

Pursuant to legislative language, this report is being provided to the following Members of Congress:

- **The Honorable Patrick Leahy**
  Chairman, Senate Committee on Appropriations
- **The Honorable Richard Shelby**
  Vice Chairman, Senate Committee on Appropriations
- **The Honorable Dianne Feinstein**
  Chairman, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations
- **The Honorable John Kennedy**
  Ranking Member, Subcommittee on Energy and Water Development
  Senate Committee on Appropriations
- **The Honorable Rosa L. DeLauro**
  Chairwoman, House Committee on Appropriations
- **The Honorable Kay Granger**
  Ranking Member, House Committee on Appropriations
- **The Honorable Marcy Kaptur**
  Chairwoman, Subcommittee on Energy and Water Development
  House Committee on Appropriations
- **The Honorable Mike Simpson**
  Ranking Member, Subcommittee on Energy and Water Development
  House Committee on Appropriations

If you have any questions or need additional information, please contact me or Ms. Katie Donley, Deputy Director for External Coordination, Office of the Chief Financial Officer, at (202) 586-0176.

Sincerely,

Jill Hruby
Under Secretary for Nuclear Security
Administrator, NNSA

Executive Summary

Plutonium is a key constituent of the primary (the plutonium pit) in a U.S. stockpile two-stage nuclear weapon. The average age of plutonium in the U.S. stockpile has continued to increase following the post-Cold War cessation of weapons-grade plutonium production at reactors at the Hanford site in Richland, Washington and the Savannah River Site near Aiken, South Carolina, as well as the closure of the Rocky Flats Plant near Denver, Colorado. The accumulation of radiation damage due to the radioactive decay of plutonium in the pit over time continually changes the properties of the material composing the pit. These processes and associated property changes are collectively referred to as plutonium aging or pit aging.

A substantial amount of work to-date has been pursued to assess primary and pit lifetimes and assure the integrity of the current and future stockpile. [redacted] DOE b(3)

(b) (4) [redacted]

To account for complex plutonium aging processes, DOE/NNSA established a National Strategy for Plutonium Aging in 2017, which was updated in 2020. The National Strategy informed the National Plutonium Aging Plan for fiscal years (FY) 2021-2030, outlined in this report, which guides the activities of the National Plutonium Aging Program. The Program is not a line-item project but instead includes multiple activities across several different DOE/NNSA offices and national security laboratories.

National Plutonium Aging Program efforts are focused on obtaining experimental data to improve and underpin the numerical simulation of weapons performance. These data support assessments of enduring stockpile systems and certification of on-going and future warhead acquisition programs. (b) (4) [redacted]
(b) (4) [redacted]

The National Plutonium Aging 10-year Research Program Plan, or National Plutonium Aging Plan, outlined within this report, includes an extensive program of research designed to meet the strategic timelines in the near-, mid-, and long-term that support ongoing nuclear weapons stockpile sustainment. To meet the goals within this National Plutonium Aging Plan, the DOE/NNSA national security laboratories require a combination of curated material samples, advanced diagnostic capabilities and testing facilities to experimentally probe aging phenomena at focused (to the extent possible, experiments designed to explore isolated, specific physics issues) and integral (combining many physics issues at once) levels, as well as state-of-the-art modeling and simulation tools. By combining and building upon these efforts, executing the National Plutonium Aging Plan will improve DOE/NNSA understanding of the potential impacts on weapon performance due to plutonium and pit aging.

The National Plutonium Aging Plan, which covers activities through 2030, clearly defines the direction and scope required to address key knowledge gaps and develop the required next-generation models to improve assessments of future performance of the legacy stockpile warheads and ongoing and planned warhead acquisition programs.

National Nuclear Security Administration

(U) Research Program Plan for Plutonium and Pit Aging

Table of Contents

I. Legislative Language

This report responds to provisions contained in the Joint Explanatory Statement to Accompany the *Energy and Water Development and Related Agencies Appropriations Act, 2021* (P.L. 116-68), wherein it is stated:

> *There is concern with the apparent lack of focus on advancing knowledge regarding pit and plutonium aging since the JASONs conducted its first study in 2006. Given the future needs of the nation's nuclear deterrent, a robust program of research and experimentation is needed. Therefore, NNSA is directed to develop a comprehensive, integrated ten-year research program for pit and plutonium aging that represents a consensus program among the national laboratories and Federal sponsors. Such a plan shall include estimated cost of ongoing research, new or upgraded capability needs, and key near-, mid-, and long-range milestones. The plan shall be submitted to the Committees on Appropriations of both Houses of Congress no later than 180 days after enactment of this act.*

II. The National Plutonium Aging Plan

Introduction

This document outlines the National Plutonium Aging 10-year Research Program Plan, or National Plutonium Aging Plan, for executing experiments and assessments through 2030. To

(b) (4) [redacted]

Improving confidence (through reducing uncertainty) in weapon performance predictions of warheads with pits older than the current year must come from a better understanding of how plutonium aging phenomena affect primary performance, as well as actively developing mitigation strategies should a major concern be revealed.

(b) (4) [redacted]

(b) (4) [redacted]

Reducing uncertainties must come from (a) an improved understanding of aging mechanisms and trends using data from engineered aged (EA) and accelerated [redacted] (b) (4) well as NA plutonium to test aging models and extrapolations, and [redacted] (b) (4) [redacted]

DOE/NNSA's Los Alamos National Laboratory (LANL) in Los Alamos, New Mexico, and Lawrence Livermore National Laboratory (LLNL) in Livermore, California agree that (b) (4) [redacted] (b) (4) [redacted] (b) (4) [redacted] The National Plutonium Aging Plan, which covers activities through 2030, outlines a path to providing conclusions on aging by using physics-based considerations to reduce bounds on the physical property changes of aging plutonium.

Importance of Plutonium Aging to Nuclear Weapon Performance

A primary is composed of a thin shell of plutonium surrounded by high explosives (HE) and filled with deuterium and tritium (DT) gas. The detonation of the HE implodes the plutonium shell until it achieves criticality and begins to undergo rapid fission. [redacted]

DOE b(3)

(b) (4) [redacted]

[redacted]

DOE b(3)

Plutonium material properties are known to change with time, and these changes may affect the performance of the primary. As a result of its radioactive nature, the plutonium pit undergoes self-irradiated damage throughout its volume. This constant decay alters the composition of, and deposits energy into, the plutonium metal. The accumulation of radiation damage over time, the deposition of energy, and the inception of impurities in the plutonium (products due to radiological decay) result in an aged material that may have different material properties than at origination. (b) (4) [redacted]
(b) (4) [redacted]
(b) (4) [redacted] To that end, the National Plutonium Aging Strategy and National Plutonium Aging Plan have been developed to outline the requisite physics that must be addressed to sufficiently bound the effects of plutonium aging on primary performance. At the highest level, the goals associated with the National Plutonium Aging Program's 10-year Research Program Plan are to:

- Mid Term Goal: Provide experimental data and modeling capabilities sufficient to inform and bound certain plutonium aging effects that enable improved weapon performance assessment of warheads with older pits; evaluate the experimental results; and characterize the reduction in uncertainty obtained through the use of peer and outside expert reviews.
- Long Term Goal: Provide the necessary plutonium aging models and simulation infrastructure, validated by experiments in weapons regimes, which reduce the uncertainties in predicted performance of primaries with aged pits to the point where the program can confidently use the models developed to predict primary lifetimes for stockpile systems. Peer reviews and external expert review teams will again play an important role in judging progress.

[redacted]

DOE b(3)

Body of Work Since 2006 JASON Study

Since the 2006 JASON study on plutonium aging, the existing plutonium aging program has indicated aging-related changes in plutonium are more complex than previously assessed. Concerns about plutonium properties under dynamic conditions and the effect of changing properties on the integrity of the aging stockpile require study beyond that the aging program pursued after the 2006 JASON study.

As part of DOE/NNSA's National Plutonium Aging Strategy,[5] DOE/NNSA and the national security laboratories established a cross-program integration and support structure for implementation of the strategy and performed regular progress reviews. As a result, the national security laboratories have made significant advancements in several areas: improving data collection to inform and (b) (4) [redacted] planning future experiments to continue to improve understanding; and in developing and using platforms to interrogate the effects of plutonium aging. These advancements are described briefly in **Appendix 1**. Progress evaluations include studies by the DOE/NNSA Defense Program Advisory Committee (DPAC), a JASON letter study (2019)[6], and internal laboratory reviews.

The National Plutonium Aging Strategy was updated in 2020. The 2020 update recommended refocusing work based on knowledge garnered since 2017 (see **Appendix 2**) and targeted goals that are achievable with a consistent or modest increase in resources. The 10-year Research Program Plan contained in this report, in response to the legislative request, reflects the full extent of data and model development required to underpin advanced, age-aware primary performance assessments by 2030. This 10-Year Research Program Plan gives attention to the progress possible, as well as (b) (4) [redacted]
(b) (4) [redacted]

Enabling Pit Lifetime Assessments

Pit lifetime assessments are time-dependent studies assessing the accumulated effects of plutonium radioactive decay on the primary performance of a specific weapon type or design. Pit lifetime assessments require validated and accurate age-aware models in the codes that capture the property changes caused by plutonium aging. These assessments are crucial to quantifying the effects of aging on nuclear weapon performance and help inform decisions about whether changes to current stockpile management plans are warranted. As DOE/NNSA is attempting to predict the performance of primaries containing plutonium pits roughly 40 years into the future, the approach identified includes a series of gates or checkpoints to evaluate and assess progress.

In fiscal year (FY) 2023, a lifetime assessment using the updated and advanced age-aware physics models developed within the National Plutonium Aging Plan will be conducted. The

---

(b) (4) [redacted]

[6] (U) *Pit Aging Letter Report*, JASON, JSR-19-2A, November 2019 (delivered to Congress in April 2020).

assessment will focus on applying the advanced, newly developed, age-aware model sets to a limited subset of weapons systems. After successfully demonstrating these new capabilities, a full system pit lifetime assessment is scheduled for FY 2025 (mid-term). A pit lifetime assessment will be performed in FY 2030 (long-term) that incorporates models with advancements in understanding and validation by large scale experiments.

III. Enabling Capabilities

The National Plutonium Aging Plan relies heavily on realizing key enabling capabilities that are supported broadly by DOE/NNSA's Office of Defense Programs and used by plutonium aging efforts.

Experimental Samples

Well-pedigreed samples and shape assemblies are required to underpin aging property measurements and the models validated by these data. These include stockpile return, NA materials, EA samples, AA alloys, and baseline materials and subcritical assemblies. Since the oldest existing NA material is less than 60 years old, a central aspect of the National Plutonium Aging Plan is to develop AA and EA plutonium alloys to investigate changes in plutonium physical properties at ages exceeding 100 years in order to bound aging effects.

(b) (4) [redacted]

(b) (4) [redacted]

(b) (4) [redacted] nter-program agreements govern the exchange of samples and data [redacted] s, and it is assumed that these agreements will remain in place to support the National Plutonium Aging Plan. Key midterm goal timelines associated with the development

(b) (4) [redacted]

Experimental Facilities and Diagnostics

The National Plutonium Aging Plan requires access and availability of a variety of national plutonium experimental platforms, including LANL's Plutonium Facility-4 (PF-4) within Technical Area 55 (TA-55), both the U1a and Joint Actinide Shock Physics Experimental Research (JASPER) facilities at the Nevada National Security Site (NNSS) near Mercury, Nevada, the National Ignition Facility (NIF) and Superblock facility at LLNL, the Z Machine at Sandia National Laboratories (SNL), in Albuquerque, New Mexico, (b) (4) [redacted] (b) (4) [redacted] (b) (4) [redacted] For example, the Enhanced Capabilities for Sub-critical Experiments (ECSE) Project, including associated construction at NNSS's U1a, will allow for the first integral assessments of primary reactivity with age to occur in the mid to late 2020s.

At the focused science level, this plan requires continued expansion of the diagnostic capabilities and the range of thermodynamic states achievable on platforms such as LANL's Proton Radiography (pRad) and TA-55 capabilities, NIF, Z, and JASPER. A brief description of the national facilities supporting plutonium aging is given in **Appendix 1.**

IV. Program Elements of the National Plutonium Aging Plan

The program elements, or "thrust" areas, supporting the National Plutonium Aging Plan are presented graphically in **Figure 2**, and explained in greater detail in the following sub-sections. Each thrust area reflects a distinct and complementary body of work building upon: (1) fundamental experimental data at the focused and integral scales; (2) the development and validation of theoretical and computational models; and, (3) the application of these advancements to assess the impact on primary performance.

[redacted]

DOE
b(3)

(b) (4)

(b) (4) [redacted]

(b) (4) [redacted]

(b) (4) [redacted]

[redacted]

DOE b(3)

(b) (4) [redacted]

(b) (4) [redacted]

[redacted]

DOE b(3)

[redacted]

DOE b(3)

(b) (4)

[redacted]

[redacted]

DOE b(3)

[redacted]

DOE b(3)

[redacted]

DOE b(3)

(b) (4)

[redacted]

DOE b(3)

(b) (4)

[redacted]

DOE b(3)

(b) (7)(F)

[redacted]

(b) (7)(F)

[redacted]

DOE b(3)

(b) (4)

[redacted]

(b) (4)

[redacted]

(b) (4)

[redacted]

DOE
b(3)

(b) (4)

[redacted]

V. Budget Summary

The estimated budget requirements to execute the National Plutonium Aging Plan are given in **Table 1**, and represent the total estimates across the national security enterprise, inclusive of LANL, LLNL, SNL, and NNSS.

DOE/NNSA will review the requirements to the current program of record and adjust to support this coordinated inter-program plan across the nuclear security enterprise. Forecasted budgets in Table 1 are requirements-based estimates for FY 2022 – FY 2030 and are subject to change due to reprioritization, risk realization, and experimental results.

Fiscal Year (FY)	Office of Experimental Sciences	Office of Advanced Simulation and Computing	Office of Engineering and Technology Maturation	Office of Research Development, Test, and Evaluation Total
FY 2021	52.0	7.9	3.0	**62.9**
FY 2022	56.9	9.8	6.1	**72.8**
FY 2023	61.6	9.6	7.2	**78.4**
FY 2024	74.9	9.7	7.3	**91.9**
FY 2025	142.7	9.2	7.4	**159.3**
FY 2026	139.9	8.9	8.2	**157**
FY 2027	75.1	8.5	8.3	**91.9**
FY 2028	64.7	8.3	8.4	**81.4**
FY 2029	65.1	8.2	7.6	**80.9**
FY 2030	59.2	8.1	7.7	**75**
Total	**792.1**	**88.2**	**71.2**	**951.5**

Table 1. High-level Office of Research, Development, Test, and Evaluation budget requirements to execute the National Plutonium Aging Plan (amounts are given in $M)

Assumptions and Risks

The National Plutonium Aging Plan carries a set of common assumptions and risks:

Assumptions:

(a) The funding levels captured in **Table 1** only represent scope that is specifically focused on plutonium aging. It is assumed that baseline funding of the supporting facilities (outlined in **Appendix 1**) will be available.

(b) (4) [redacted]

Risks:

(a) Operational and responsive plutonium sample fabrication, characterization, and waste facilities are crucial to execution of the scope of the National Plutonium Aging Program. The importance of well-characterized sample streams cannot be overstated – from stockpile returns, baseline samples, shape parts for integral experiments, and an ability to fabricate AA and EA samples. Pathways to sufficient sample streams and supporting characterization have not yet been fully realized.

(b) The experiments in the National Plutonium Aging Plan are designed to operate within facilities' currently established and authorized safety bases. However, changes to authorization bases could occur that would require the modification, insertion, or deletion of specific experimental efforts.

VI. Stockpile Benefits

The advancements in plutonium aging science provided by the National Plutonium Aging Plan are required to support both legacy stockpile assessments and certification of ongoing and planned warhead acquisition programs. While the data collected and models developed will continue to evolve over the coming years, there are three distinct points at which pit lifetime assessments will be updated and progress assessed in the near-term (FY 2023), mid-term (FY 2025), and long-term (FY 2030). At these points in time, the weapons design laboratories will provide DOE/NNSA their best assessment of stockpile primary lifetimes, using the full extent of updated age-aware plutonium physics models available.

(b) (4)

[redacted]

VII. Conclusions

Following the post-Cold War cessation of weapons-grade plutonium production at reactors at the Hanford site in Richland, Washington and the Savannah River Site near Aiken, South Carolina, as well as the closure of the Rocky Flats Plant near Denver, Colorado, the average age of plutonium in the U.S. stockpile has continued to increase. At the same time, the weapons design laboratories must continue to certify this aging U.S. stockpile and maintain the nuclear deterrent. DOE/NNSA recognizes the importance of evaluating changes in material properties for aging plutonium that could affect weapon performance.

The 2018 DPAC report, *Assessment of the State of Understanding of Pu Primary Aging,* and the 2019 JASON summer study, *Pit Aging,* recommended that DOE/NNSA continue to pursue a sustained program to improve understanding of plutonium aging on pits with the goal to identify specific mechanisms for changes in plutonium properties that would degrade primary performance. The recommended program must also determine the timescales over which the performance margin of stockpile weapons would be sufficiently degraded to elicit concern. At the same time, these independent studies and reports emphasized a robust scientific and engineering program to enable the quick resumption of quality pit manufacturing. Both independent studies and reports noted that a speedy production capability would mitigate risks from unknown aging effects, while enhanced understanding of plutonium aging would mitigate risks caused by production delays. Vigorous scientific efforts in evaluating aging effects and accelerating production capabilities are equally important and crucial for the Nation's nuclear stockpile.

A substantial amount of work to-date has been pursued to assess primary and pit lifetimes and assure the integrity of the current and future stockpile. [redacted] DOE b(3)

(b) (4) [redacted]

(b) (4) [redacted]

(b) (4) [redacted] The National Plutonium Aging Plan clearly defines the direction and scope required to address key knowledge gaps and develop the required next-generation models to improve assessments of future performance of the legacy stockpile warheads and ongoing and planned warhead acquisition programs.

VIII. Appendices

Appendix 1: National Facilities Supporting the National Plutonium Aging Plan

Plutonium Facility-4 (PF-4), Technical Area 55 (TA-55)

TA-55 at the Los Alamos National Laboratory (LANL) provides a broad range of capabilities for plutonium materials synthesis, part fabrication, and test and evaluation. These capabilities include several static-to-dynamic experimental platforms, casting and machining operations for small-scale and integral parts, and various characterization techniques to probe the properties of plutonium at high shock pressures, temperatures, and strain rates. More specifically, these (b) (4) [redacted]

Joint Actinide Shock Physics Experimental Research (JASPER) Facility

JASPER is the premier facility for testing the response of actinides over a wide range of pressures and is the sole gas-gun facility able to measure the shock response of actinides above 30 GigaPascal, or GPa, a unit of pressure. The facility is a two-stage gun located at the Nevada National Security Site (NNSS) that conducts measurements of radioactive elements at high shock pressures, temperatures, and strain rates. JASPER has already delivered shock compression measurements on newly cast, naturally aged (NA), and accelerated aged (AA) plutonium, generating crucial data that have improved understanding and informed models of the dynamic response of plutonium as it ages. (b) (4) [redacted] (b) (4) [redacted]

U1a Complex

The underground infrastructure at the U1a complex at the NNSS supports the U.S. capability for dynamic plutonium experiments for both focused and integral experiments for the SCE program. U1a currently provides the capability for two independent, moderate-penetrating, radiographic images (Cygnus) along with the capability to field simultaneously a variety of other implosion related diagnostics, such as the Multiplexed Photonic Doppler Velocimetry (MPDV) system. In the future, the U1a complex will house Enhanced Capabilities for Sub-critical Experiments (ECSE), including multi-pulse, single axis, penetrating radiography (similar to the capability that the Dual-Axis Radiographic Hydrodynamic Testing Facility [DARHT] provides for surrogate materials at LANL) coupled with the Neutron Diagnosed Subcritical Experiments (NDSE) diagnostic. In fiscal year (FY) 2016, the U1a facility transitioned from a Hazard Category 3 nuclear facility to a Hazard Category 2 nuclear facility, thereby enabling a wider and more relevant variety of experiments. The construction of a second entrance to the U1a.05 Drift Zero

Room also allows the use of larger diameter confinement vessels for experiments and provide space for the entombment of future experiments. Together, these changes will allow continued operation of the U1a Complex to meet mission needs.

Z Pulsed Power Facility

Sandia National Laboratories' (SNL) Z is the world's most powerful pulsed power facility and X-ray generator. Z compresses energy in time and space to achieve extreme powers and intensities. Pulsed power is a technology that concentrates electrical energy and turns it into short pulses of enormous power to generate X-rays and gamma rays. Produced in the laboratory, this controlled radiation creates conditions similar to those caused by the detonation of nuclear weapons. The large currents generate strong magnetic fields that also create high pressures for dynamic materials properties experiments. This capability enables precise evaluation of material (b) (4) [redacted] at extreme conditions for a variety of materials, including plutonium, other metals, gases, and explosives.

(b) (4) [redacted]

National Ignition Facility (NIF)

NIF at the Lawrence Livermore National Laboratory (LLNL) is the most energetic laser in the world, and the first mega joule-class laser ever built. Each of its 192 beams can be focused to a spot approximately the diameter of a human hair, creating conditions hotter and denser than at the center of the Sun. NIF is able to create conditions of extreme temperature, pressure, and density that are crucial to understanding nuclear weapons performance. NIF's near-term efforts are divided into two major technical areas focused on resolving physics issues associated with nuclear weapon components. (b) (4) [redacted]

(b) (4) [redacted]

Superblock

Superblock is LLNL's Special Nuclear Materials facility, where the laboratory manipulates the chemistry of, and does experimentation on, plutonium isotopes. One of just two defense plutonium research and development facilities in the United States, the Superblock facility supports a wide variety of activities supporting the U.S. nuclear deterrent, including non-nuclear testing of components of weapons that are in the current U.S. stockpile as well as investigating technologies for remanufacture of plutonium parts in nuclear components. Superblock houses modern equipment for research and engineering testing of plutonium. The directors of the national security laboratories submit annual assessment reports each year that provide the technical basis for certification of the stockpile and confirm that the nuclear components for which they are responsible are safe and reliable. Ongoing research in Superblock contributes to this process and is ultimately submitted to the President through the annual Report on Stockpile Assessments.

Proton Radiography

LANL's Proton Radiography (pRad) facility uses the 800 mega electron-volt, or MeV, protons from the Los Alamos Neutron Science Center (LANSCE) to image the properties and behavior of materials driven by high explosives (HE). The energy of the proton beam provides sufficient penetrating power to image fine, internal details in objects with a wide variety of densities such as lead, plutonium, uranium, or HE. Since the beam consists of discrete bunches of protons, pRad can also produce images of the test object at multiple times during the experiment. The frames of the event under study may be spaced from one second to 0.1 microseconds apart. pRad provides quantitative measurements of material densities under extreme conditions.

Los Alamos Neutron Science Center (LANSCE)

LANSCE is a complex of facilities at LANL that provides experimental capabilities serving stockpile stewardship needs. The centerpiece of LANSCE is an 800-MeV proton linear accelerator that provides proton beams for dynamic plutonium pRad capability (Pu@pRad) and neutron beams for material studies and weapons nuclear physics research. The neutron beams at LANSCE are created from the 800-MeV proton beam by directing the proton beam into a heavy metal target (*e.g.*, tungsten). When protons collide with atoms of the target, the process of nuclear spallation results in the release of neutrons with a wide range of energies. The neutrons travel down multiple beam lines for various experimental applications. LANSCE has two major neutron spallation targets. The target at LANSCE's Weapons Neutron Research (WNR) facility is unmoderated, producing relatively high-energy neutrons for nuclear physics studies such as cross section measurements. On the other hand, the target at LANSCE's Manuel Lujan, Jr. Neutron Scattering Center is moderated, producing lower-energy beams that are useful as probes of material properties and in specific studies of low-energy nuclear cross sections.

Appendix 2: National Plutonium Aging Research Accomplishments

To provide additional context for the work in the 10-year National Plutonium Aging Research Program Plan, this appendix outlines accomplishments since the development of the National Plutonium Aging Strategy in 2017.

(b) (4) [redacted]

(b) (4) [redacted] DOE b(3)

- [redacted] DOE b(3)

(b) (4) [redacted]

- [redacted] DOE b(3)
- [redacted] DOE b(3)

[redacted] DOE b(3)

(b) (4)

[redacted]

Appendix 3: References and Additional Reading

(b) (4) [redacted]

(b) (6) [redacted] *Pit Aging: LLNL Systems Lifetime Final Report (U)*. COPJ-2006-0857.

(b) (6) [redacted] (2005). (b) (4) [redacted]

(b) (4) [redacted]

(b) (6) [redacted] *Plutonium strength aging experiments at LANL*. LACP-12-00636.

(b) (6) [redacted] (b) (4) [redacted]

(b) (4) [redacted]

Chung, B. W., Thompson, S. E., Lema, K. E., Hiramoto, D., & Ebbinghaus, B. B. (2009). Evolving density and static mechanical properties in plutonium from self-irradiation. *Journal of Nuclear Materials, 385*, 91-94.

(b) (6) [redacted] (b) (4) [redacted]

(b) (4) [redacted]

Department of Defense. (2010). Nuclear Posture Review Report.

Dieter, G. E. (1986). *Mechanical Metallurgy.* Boston, MA: McGraw-Hill.

(b) (4) [redacted]

JASON. (U) *Pit Aging Letter Report*, JSR-19-2A. November 2019 (delivered to Congress in April 2020).

Jeffries, J. R., Wall, M. A., Moore, K. T., & Schwartz, A. J. (2011). He bubble coarsening by migration and coalescence in annealed Pu-Ga alloys. *Journal of Nuclear Materials, 410*, 84-88.

Mclean, W. (2014). *Systems MTE: Pit gas chemistry.* CODT-2014-0077.

Mitchell, J. N., Freibert, F. J., Schwartz, D. S., & Bange, M. E. (2009). Unconventional delta-phase stabilization in Pu-Ga alloys. *Journal of Nuclear Materials, 385*, 95-98.

Schwartz, A. J., Cynn, H., Blobaum, K. J., Wall, M. A., Moore, K. T., Evans, W. J., . . . Massalski, T. B. (2009). Atomic structure and phase transformation in Pu alloys. *Progress in Materials Science*, 909.

Schwartz, A. J., Wall, M. A., Zocco, T. G., & Wolfer, W. G. (2005). Characterization and modeling of He bubbles in self-irradiated plutonium alloys. *Philosophical Magazine, 85*, 479-488.

List of Acronyms

(b) (4) [redacted]

ASC – Advanced Simulation and Computing program (NA-114)

(b) (4) [redacted]

DMP – Dynamic Materials Properties (C2) subprogram of OES

DSW – Directed Stockpile Work

EA – engineered aged, (b) (4) [redacted] (b) (4) [redacted]

ECSE – Enhanced capabilities for subcritical experiments

(b) (4) [redacted]

JASPER – Joint Actinide Shock Physics Experimental Research, two stage gun located at NNSS and operated by LLNL and MSTS

LANL – Los Alamos National Laboratory

LANSCE – Los Alamos Neutron Science Center

LLNL – Lawrence Livermore National Laboratory

LEP – life extension program

NA – naturally aged, (b) (4) [redacted]

NDSE – Neutron diagnosed subcritical experiments

NIF – National Ignition Facility

NNSA – National Nuclear Security Administration

NNSS – Nevada National Security Site

OES – Office of Experimental Sciences (NA-113)

PF-4 – Plutonium Facility – 4 at LANL, building in which plutonium production and characterization is housed

pRad – proton radiography beamline at Area C, LANSCE

SNL – Sandia National Laboratories

TA-55 – LANL site of plutonium facility

U1a – facility at NNSS used for performing subcritical experiments

Z – Sandia's Z-pinch machine