



**Report of the  
Plutonium Disposition Working Group:**

**Analysis of Surplus Weapon-Grade  
Plutonium Disposition Options**

**April 2014**

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## ACRONYMS

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ADR	Advanced Disposition Reactors
BCA	Blanket Commercial Agreement
BWRs	Boiling-Water Reactors
CCO	Criticality Control Overpack
DNFSB	Defense Nuclear Facilities Safety Board
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
FETF	Fast Flux Test Facility
FGE	Fissile Gram Equivalent
FY	Fiscal Year
HEU	Highly Enriched Uranium
HLW	High-Level Waste
HM	Heavy Metal
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
ISFSI	Independent Spent Fuel Storage Installation
KAFF	K-Area Fuel Fabrication Facility
KAMS	K-Area Material Storage
kg	Kilogram
LANL	Los Alamos National Laboratory
LEU	Low Enriched Uranium
LLNL	Lawrence Livermore National Laboratory
LWRs	Light Water Reactors
MFFF	Mixed Oxide Fuel Fabrication Facility
MOX	Mixed Oxide
MT	Metric Tons
NAS	National Academy of Sciences
NEPA	National Environmental Policy Act
NNSA	National Nuclear Security Administration
NPT	Nuclear Nonproliferation Treaty

NRC	Nuclear Regulatory Commission
PMDA	United States-Russia Plutonium Management and Disposition Agreement
PRISM	Power Reactor Innovative Small Module
Pt/Rh	Platinum/Rhodium
PWRs	Pressurized-Water Reactors
RD&D	Research, Development, and Demonstration
RFETS	Rocky Flats Environmental Technology Site
ROD	Record of Decision
SNM	Special Nuclear Material
SRS	Savannah River Site
TRU	Transuranic
WIPP	Waste Isolation Pilot Plant
WTP	Waste Treatment and Immobilization Plant Project

# *Analysis of Surplus Weapon-Grade Plutonium Disposition Options*

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## **1.0 INTRODUCTION**

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Speaking at the National War College in December 2012, President Obama reiterated that “nuclear terrorism remains one of the greatest threats to global security.” As stated in the 2010 U.S. Nuclear Posture Review, “by demonstrating that we take seriously our Nuclear Nonproliferation Treaty (NPT) obligation to pursue nuclear disarmament, we strengthen our ability to mobilize broad international support for the measures needed to reinforce the nonproliferation regime and secure nuclear materials worldwide.” The disposition of surplus fissile materials is an important element of our NPT commitments since it serves both the disarmament and nonproliferation pillars of the NPT by rendering Highly Enriched Uranium (HEU) and plutonium that have been declared excess as no longer suitable for weapons.

For HEU, this is done by downblending the material to Low Enriched Uranium (LEU). For plutonium, the Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation (Plutonium Management Disposition Agreement, or PMDA) calls for each nation to dispose of no less than 34 metric tons (MT) of surplus weapon-grade plutonium by irradiating it as mixed oxide (MOX) fuel in nuclear reactors or by any other method that may be agreed by the Parties in writing.

The Administration remains firmly committed to disposing of surplus plutonium. However, it has become evident that the MOX fuel approach for U.S. plutonium disposition will cost significantly more and take longer than initially anticipated. As a result, the President’s Fiscal Year (FY) 2014 budget request for the Department of Energy (DOE) stated that, due to cost increases associated with the MOX fuel approach, DOE would assess plutonium disposition strategies in FY 2013 and would identify options for FY 2014 and out-years. This options analysis documents DOE’s assessment of the disposition strategies and provides the foundation for further analysis and validation, including additional National Environmental Policy Act (NEPA) review if necessary, that will enable a decision on the disposition of surplus weapon-grade plutonium.

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## 2.0 BACKGROUND AND PREVIOUS CONSIDERATIONS

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The end of the Cold War left a legacy of surplus weapon-grade fissile materials, both in the United States and the former Soviet Union, with substantial quantities of plutonium no longer needed for defense purposes. Global stockpiles of weapon-grade fissile materials pose a danger to national and international security due to proliferation concerns and potential use by non-state actors for nuclear terrorism purposes, as well as the potential for environmental, safety, and health consequences if the materials are not properly secured and managed. In September 1993, in response to these concerns, President Clinton issued a Nonproliferation and Export Control Policy, which committed the United States to seek to eliminate, where possible, the accumulation of stockpiles of HEU and plutonium, and to ensure that where these materials already exist, they are subject to the highest standards of safety, security, and international accountability.

The United States has conducted numerous evaluations of plutonium disposition strategies beginning in the early 1990s, when a National Academy of Sciences (NAS) review contributed to the identification of viable options to address the “...clear and present danger...” posed by excess weapon-grade plutonium in the United States and Russia. The 1994 review recommended that disposition should meet the spent fuel standard, i.e., “...result in a form from which the plutonium would be as difficult to recover for weapons use as the larger and growing quantity of plutonium in commercial spent fuel.” [NAS 1994] The review indicated that the two most promising alternatives were immobilization of plutonium in combination with high-level waste (HLW), and irradiation of plutonium as MOX fuel in commercial reactors. These alternatives were preferred since they created physical, chemical, and radiological barriers to the retrieval of the material, and would meet the spent fuel standard, thus reducing the risk of recovery.

On March 1, 1995, the United States declared 38.2 MT of weapon-grade plutonium as surplus to defense needs. In addition, DOE announced that it had 14.3 MT of non-weapon-grade plutonium that was no longer needed. The following year, at the April 1996 Moscow Nuclear Safety and Security Summit, the leaders of the seven largest industrial countries and Russia issued a joint statement endorsing the need to make excess fissile materials in the United States and Russia unusable for nuclear weapons.

In January 1997, after examining 37 different plutonium disposition technology options and completing a Final Programmatic Environmental Impact Statement [DOE/EIS-0229], DOE decided to pursue a hybrid U.S. plutonium disposition strategy that allowed immobilization and irradiation of MOX fuel in existing Light Water Reactors (LWRs). [Record of Decision (ROD) 62 FR 3014] Following this decision, in September 1997, former Russian President Yeltsin declared up to 50 MT of Russian plutonium as surplus to defense needs.

In January 2000, after completing the Surplus Plutonium Environmental Impact Statement [DOE/EIS-0283], DOE decided to immobilize some of the plutonium using the can-in-canister approach (imbedding the plutonium in a ceramic matrix emplaced in cans, placing

the cans in canisters and surrounding each can with vitrified HLW to provide a radiological barrier and deter theft or diversion) and to fabricate some of the plutonium into MOX fuel, in facilities to be located at the Savannah River Site (SRS). [ROD 65 FR 1608]

In September 2000, the United States and Russian Federation signed the PMDA, which calls for each country to dispose of at least 34 MT of excess weapon-grade plutonium. According to the 2000 agreement, Russia would dispose of its material by irradiating it as MOX fuel in LWRs, and the United States would dispose of the majority of its material by irradiating it as MOX fuel in LWRs. In addition, some U.S. material would be disposed of through immobilization using the can-in-canister system (or other system agreed to by the Parties). [PMDA 2000]

In 2002, the Bush Administration directed a review of nonproliferation programs that included the plutonium disposition program. The DOE review considered more than forty (40) approaches for plutonium disposition, with twelve (12) distinct options selected for detailed analysis. Following this review, DOE cancelled immobilization due to budgetary constraints, and announced that DOE was conducting further reviews of a MOX-only approach and making no decision on the plutonium disposition program until those reviews were completed. [ROD 67 FR 19432] Cancellation of the immobilization approach was meant to save time and money over the previous hybrid strategy. At the time, the revised life cycle costs for the MOX-only approach were estimated to cost \$3.8 billion (in constant FY 2001 dollars) to be implemented over approximately 20 years. This estimate included the MOX Fuel Fabrication Facility (MFFF), pit disassembly and conversion facility, and other program costs. [NNSA 2002]

In addition to the progress regarding the 34 MT of plutonium under the PMDA, between 1998 and 2002 DOE announced a series of decisions to dispose of a variety of plutonium residues stored at Rocky Flats Environmental Technology Site (RFETS) as transuranic (TRU) waste at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico. These materials were originally part of a set of materials designated to be repackaged and sent to SRS in South Carolina for storage and subsequent disposition. This action paved the way for disposal of surplus plutonium at WIPP from other DOE Sites including the Hanford Site, SRS, Los Alamos National Laboratory (LANL), Idaho National Laboratory (INL), and Lawrence Livermore National Laboratory (LLNL).

Thereafter, DOE stated that it had completed its evaluation of changes entailed by a MOX-only disposition strategy, and decided to fabricate 34 metric tons of surplus plutonium into MOX fuel, including 6.5 metric tons originally planned for immobilization. [ROD 68 FR 20134]

In 2006, at the request of Congress, DOE again analyzed its strategy for disposing of surplus plutonium in a report entitled "*Disposition of U.S. Surplus Materials: Comparative Analysis of Alternative Approaches*". [DOE 2006] In addition, in 2007 DOE submitted to Congress a report entitled "*Business Case Analysis of the Current U.S. Mixed Oxide (MOX) Fuel Strategy for Dispositioning 34 Metric Tons of Surplus Weapon-Grade Plutonium*", which reconfirmed the MOX approach. [DOE 2007a]



In 2007, DOE announced its decision to consolidate the remaining surplus non-pit plutonium at SRS since the majority of the facilities supporting the plutonium disposition mission would be located there. [ROD 72 FR 51807] DOE consolidated surplus plutonium from the Hanford Site, LANL, and LLNL, saving millions of dollars by avoiding the cost of operating numerous secure facilities. In 2007, former Secretary of Energy Bodman declared an additional 9 MT of U.S. weapon-grade plutonium as surplus to defense needs. [DOE 2007b] Secretary Bodman stated the additional plutonium would be removed in the coming decades from retired, dismantled nuclear weapons, and planned to be eliminated by fabrication into MOX fuel that would be irradiated in commercial nuclear reactors to produce electricity.<sup>1</sup>

There have been many changes to the plutonium disposition program since the 2002 and 2003 decisions to pursue a MOX-only approach, one of which resulted from a Russian Government reassessment of technical options for disposing of its plutonium. As a result of its reassessment, Russia stated its preference to dispose of its material in fast reactors instead of LWRs, an approach that is more consistent with Russia's national energy strategy. This decision led to a renegotiation of key provisions of the PMDA. During the April 2010 Nuclear Security Summit in Washington, DC, former Secretary of State Hillary Clinton and Russian Foreign Minister Sergey Lavrov signed a protocol amending the PMDA to formalize the shift to fast reactors for Russian plutonium disposition.<sup>2</sup> The protocol also established a number of nonproliferation conditions under which Russia could operate its fast reactors for plutonium disposition that limit the ability to produce additional weapon-grade plutonium. In July 2011, after ratification by the Russian Duma and formal approval of both governments, the PMDA with its protocols entered into force.

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<sup>1</sup> DOE has determined that 1.9 MT from the 9 MT of pit plutonium in the 2007 declaration qualifies for inclusion within the 34 MT slated for disposition as MOX fuel.

<sup>2</sup> An additional Protocol to the PMDA was signed in 2010.

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### 3.0 STATUS OF THE MOX FUEL APPROACH

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In addition to the evolution of the Russian program, the U.S. program has also changed significantly. The current MOX fuel approach involves construction and operation of a MOX facility, construction and operation of a Waste Solidification Building to handle the wastes from the MOX facility, a capability to disassemble nuclear weapons pits and convert the resulting plutonium metal into plutonium oxide, MOX fuel qualification activities, reactor modifications for utilities willing to irradiate MOX fuel, and packaging and transportation activities.

In 2008, the cost and schedule baseline for the U.S. Mixed Oxide Fuel Fabrication Facility that would produce MOX fuel for irradiation in LWRs was established at \$4.8 billion for design, construction, and cold start-up activities with a hot operations start-up date of November 2016. In August 2012, the MOX facility contractor submitted a baseline change proposal for the facility that would increase its cost for design, construction, and cold start-up activities to \$7.7 billion, assuming an optimal funding profile, and extend the schedule by 3 years to November 2019. [BCP 12-121] After analysis of the proposal by DOE and independent experts, including the Army Corps of Engineers, DOE believes that the cost of the MOX facility will be substantially higher than the contractor's estimate due to several factors such as omission of several hundred million dollars of equipment procurements and underestimation of schedule impacts and the resulting cost impact if certain risks are realized.

In addition, the estimates to operate the MOX facility after construction have continued to rise, as well as the costs of other related activities, such as the Waste Solidification Building. According to a recent independent review of the MOX facility operating costs by the National Nuclear Security Administration (NNSA) Office of Defense Programs' Office of Analysis and Evaluation, the annual operating costs of more than \$500 million may be underestimated. The analysis indicated that the contractor likely underestimated the cost of maintenance and labor compared to the market values seen at other processing facilities in the NNSA and that issues arising during hot start-up could have costly schedule and production rate impacts during the operations phase. [NNSA 2013a]

In January 2012, DOE decided to pursue cancelling one of its planned plutonium disposition projects at SRS, a stand-alone facility to disassemble nuclear weapons pits, and convert the plutonium metal into an oxide to be used as feedstock for the MOX facility. [EXEC-2012-000647] Instead, DOE's preferred alternative is to use existing facilities to accomplish this part of the plutonium disposition mission. However, the potential savings resulting from the cancellation of a stand-alone pit disassembly and conversion facility are not enough to halt the overall rising costs of the program.

As a result of the cost increases, and the current budget environment, DOE announced in April 2013 that it would assess alternatives to the current plutonium disposition approach.

Beginning in third quarter FY 2013, the NNSA began to slow down activities associated with the plutonium disposition strategy, while assessing alternative strategies.

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## 4.0 PLUTONIUM DISPOSITION WORKING GROUP

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As part of DOE's efforts to determine ways to improve the efficiency of the plutonium disposition mission and conduct the assessment process discussed in the President's FY 2014 Budget Request, Secretary of Energy Ernest Moniz established a special working group in June 2013 to undertake a detailed analysis of options. The Plutonium Disposition Working Group is an internal DOE entity that is headed by a Senior Advisor to the Secretary and includes experts from the following offices: Office of the Secretary, Office of the NNSA Administrator, Office of Defense Nuclear Nonproliferation, Office of Nuclear Energy, NNSA Office of Acquisition and Project Management, NNSA Office of the General Counsel, and Office of the Assistant Secretary for Congressional and Intergovernmental Affairs.

The Plutonium Disposition Working Group has prepared analyses that take into account the status of the current disposition approach of disposing of surplus weapon-grade plutonium as MOX fuel in LWRs, fast reactor options to dispose of weapon-grade plutonium, and certain non-reactor based options. [See Appendix A, B, and C, respectively] In addition, the working group conducted a classified analysis of transferring U.S. weapon-grade plutonium overseas for fabrication into MOX fuel at a non-U.S. MOX facility. [NNSA 2013b]

As part of these analyses, the Plutonium Disposition Working Group examined the changing paradigm of nonproliferation, and its impacts on the definition of disposition. Since the MOX fuel approach was first selected for plutonium disposition, the United States has changed its strategic focus to address 21<sup>st</sup> century terrorism threats and opportunities, in addition to traditional arms control policies rooted in the Cold War era. As such, the working group evaluated whether, based on today's current non-state actor threats, the desired end state of weapon-grade plutonium had also changed over this timeframe.

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## 5.0 OPTIONS

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### 5.1 DESCRIPTION OF APPROACH

The purpose of this document is to provide a summary of the Plutonium Disposition Working Group's analysis of plutonium disposition options that could potentially provide a more cost effective approach to dispose of at least 34 MT of U.S. surplus weapon-grade plutonium to meet international commitments.

Since 1995, numerous options have been analyzed and dismissed. After careful consideration, the following five options were deemed the most reasonable to reassess at this time. The analysis focuses on the advantages and disadvantages of these five (5) primary options:

- Option 1: Irradiation of MOX Fuel in Light Water Reactors (LWRs);
- Option 2: Irradiation of Plutonium Fuel in Fast Reactors;
- Option 3: Immobilization (Ceramic or Glass Form) with High-Level Waste;
- Option 4: Downblending and Disposal; and,
- Option 5: Deep Borehole Disposal.

The following criteria were used to determine the advantages and disadvantages of the various options in this non-reactor-based analysis:

- Meeting international commitments;
- Cost;
- Duration to begin disposition and complete the U.S. 34 MT mission;
- Technical viability; and,
- Legal, regulatory, and other issues.

This analysis does not include evaluation of any long-term storage options since storage does not constitute disposition and therefore would not meet long-standing U.S. government policy objectives and international commitments. Rather, this analysis focuses on options that could either alone, or in combination with others, address at least 34 MT of U.S. surplus weapon-grade plutonium. There may be hybrid approaches that merit further study, that could combine different disposition options, possibly at different times, and still achieve the disposition of at least 34 MT of plutonium. For example, an optimal approach might be to pursue multiple options or begin disposition with one option and then transition to another. All of the non-MOX options may require further development and/or analysis (e.g., technology development, discussions with Russia, modification of federal legislation) during a standby period.

## 5.2 DESCRIPTION OF OPTIONS

This section provides a summary description of each option. All of the options maximized the use of existing facilities to the greatest extent possible. In addition, all options included nuclear weapons pit disassembly and conversion activities at both LANL and SRS. For further details on options analyzed, see Appendices A, B, and C.

### 5.2.1 OPTION 1: IRRADIATION OF MOX FUEL IN LIGHT WATER REACTORS<sup>3</sup>

This option is the United States Government's current approach for surplus plutonium disposition and involves irradiating plutonium as MOX fuel in nuclear power reactors. The MOX fuel will be irradiated in domestic commercial nuclear power reactors, including existing pressurized-water reactors (PWRs) and boiling-water reactors (BWRs). The resulting MOX spent fuel will be stored with the commercial utilities' spent uranium fuel.

To implement this strategy, the United States is currently constructing two facilities at SRS: the MOX facility and the Waste Solidification Building to handle certain waste generated by the MOX fabrication process. The MOX facility, which is subject to licensing and related regulatory authority of the Nuclear Regulatory Commission (NRC) and based on technology in use at AREVA's LaHague and Melox facilities in France, will fabricate plutonium oxide and depleted uranium oxide into MOX fuel. The MOX facility design includes the MFFF and support structures, such as the Secure Warehouse, the Receipt Warehouse, the Administration Building, and the Technical Support and Reagents Processing Buildings. The MFFF is designed to meet structural and safety standards for storing and processing special nuclear materials (SNM). The walls, floors, and building roof are built with reinforced concrete. Areas that will contain plutonium are designed to survive natural phenomenon hazards, such as earthquakes, extreme winds, floods, and tornadoes, as well as potential accidents. MFFF will have three major functional areas: 1) the Shipping and Receiving Area, which contains equipment and facilities to handle materials entering and exiting the facility; 2) the Aqueous Polishing Area which houses the processes to remove impurities from plutonium oxide feedstock; and, 3) the MOX Processing Area, which includes the blending and milling, pelletizing, sintering, grinding, fuel rod fabrication, fuel bundle assembly, laboratory, and storage areas.

### 5.2.2 OPTION 2: IRRADIATION OF PLUTONIUM FUEL IN FAST REACTORS<sup>4</sup>

This option would involve the use of plutonium fuel for irradiation in domestic fast-spectrum burner reactors, which would require the construction of an Advanced Disposition Reactor (ADR), which is similar to General Electric Hitachi's Power Reactor

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<sup>3</sup> Light water reactors are reactors that use water as its coolant and neutron moderator. The moderator slows down fast neutrons released from fissions, turning them into thermal neutrons capable of sustaining a nuclear chain reaction. PWRs and BWRs are varieties of light water reactors.

<sup>4</sup> Fast reactors are reactors that rely on fast neutrons alone to cause fission, and have no moderator.

Innovative Small Module (PRISM). Unique attributes of these reactors include: 1) the ability to use metal fuel; 2) impurity tolerance in the fuel; and, 3) higher plutonium loadings. In this analysis, the ADR is defined as an NRC-licensed advanced pool-type fast-spectrum liquid-metal cooled reactor using metal fuel. Metal fuel was chosen because of the operating experience in the U.S., passive safety characteristics, and compatibility with the plutonium feedstock.

For the proposed fast-spectrum burner reactor option, plutonium metal resulting from the disassembly of nuclear weapons pits along with other stocks of clean plutonium metal would be used to charge a casting furnace directly, in which the plutonium would be blended with uranium metal and zirconium metal. Because the metal fuel fabrication process and resulting fuel form allow for more of the typical impurities found in the pits and clean metal feed, aqueous purification or polishing would not be required. Fuel slugs would be cast directly from the fuel blend that is homogenized in the casting furnace.

The slugs would be trimmed to the required length and loaded into steel cladding tubes, along with a small amount of sodium metal ribbon. Casting and trimming waste would be recycled into each batch without additional purification or other processing. The bonded fuel pins would then be loaded into finished fuel assemblies. A typical ADR metal fuel assembly contains about 40 kilograms (kg) heavy metal (HM), of which about 8 kg is plutonium.

The fuel would be fabricated in a potential K-Area Fuel Fabrication Facility (KAFF), a new metal fuel fabrication facility that would be constructed in the K-Reactor Building within the K-Area Complex at SRS. It was assumed that spent fuel would be stored in dry casks at an NRC-licensed Independent Spent Fuel Storage Installation (ISFSI) adjacent to the ADR throughout the life of the mission, and subsequently transferred to an on-site dry cask storage pad.

A new ADR single-module prototype would be constructed, preferably within SRS to avoid the necessity of transporting the fresh fuel on public roadways, and to minimize the size of the on-site fresh-fuel storage facility at the ADR.

Two potential variants of the fast reactor option were considered in this analysis:

1. Constructing a two-module ADR power block configuration at SRS for added disposition capacity.
2. Start-up and use of the currently deactivated Fast Flux Test Facility (FFTF) at the Hanford Site to supplement the single-module or two-module ADR approach.

Both of these variants would increase the disposition rate for this option. In a two-module ADR power block, a number of important systems and functions including the turbine would be shared between the two modules, lowering the per-module capital cost. The FFTF variant would allow disposition to start earlier based on an expected faster start-up when compared to the ADR. However, the FFTF's disposition rate is

small, and as a result, would serve as a supplement to either a single-module or two-module ADR.

### 5.2.3 OPTION 3: IMMOBILIZATION (CERAMIC OR GLASS FORM) WITH HIGH-LEVEL WASTE

This option would involve immobilizing plutonium oxide using a “can-in-canister” facility that would need to be constructed. The plutonium would be immobilized into either a ceramic or glass form, placed into a can, and then surrounded with HLW<sup>5</sup> glass in a glass waste canister, hence the term “can-in-canister”. The immobilization process would begin by milling plutonium oxide to reduce the size of the powder, and achieve faster and more uniform distribution of the plutonium for processing. Although some milling would be performed at LANL during oxide production, additional milling would be required to ensure the plutonium and the glass particles are both milled to similar particle sizes.

For a glass process, the milled plutonium oxide would be blended with borosilicate glass frit containing neutron absorbers (e.g., gadolinium, boron, and hafnium). The mixture would be melted in a platinum/rhodium (Pt/Rh) melter vessel, and drained into stainless steel cans. The cans would be sealed, leak-tested, assayed, and transferred out of the immobilization facility.

A ceramic process would produce a titanate-based ceramic that immobilizes the weapon-grade plutonium. The ceramic would be produced by mixing the plutonium feed stream with oxide precursor chemicals (e.g., pyrochlore and rutile in addition to neutron absorbers such as hafnium and gadolinium), forming the mixed powder into “pucks” and sintering the pucks in a resistively heated furnace. The ceramic pucks would be placed in stainless steel cans, sealed, leak-tested, assayed, and transferred out of the immobilization facility.

The cans filled with either the ceramic or vitrified plutonium would then be loaded into long stainless steel cylinders called magazines, and loaded into empty HLW canisters. The canisters containing the cans of immobilized plutonium would then be filled with HLW that has been melted into glass to complete the process and produce a waste form that would provide a radioactive barrier to the retrieval of the plutonium and would be suitable for repository disposal. The plutonium would be disposed of with the placement of the HLW canister containing the immobilized plutonium in a geologic repository.

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<sup>5</sup> High-level radioactive wastes are defined in the Nuclear Waste Policy Act of 1982, as amended, to mean: a) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and b) other highly radioactive material that the Nuclear Regulatory Commission, consistent with existing law, determines by rule requires permanent isolation.



There are only two U.S. DOE sites that have significant quantities of HLW, and that have, or will have, the capability to encapsulate HLW into glass logs for ultimate disposal: SRS and the Hanford Site. SRS has been operating its Defense Waste Processing Facility (DWPF) since 1996 to vitrify HLW into glass logs. However, since nearly half of SRS's HLW has already been remediated, there is not enough HLW remaining to dispose of 34 MT of surplus plutonium. In addition, DWPF is scheduled to complete operations by 2032, which would likely be before a new immobilization facility could be designed and constructed. [SRR-LWP-2009-00001]

An alternative of pursuing this immobilization option at the Hanford Site is not viable. To do so, would require a new secure plutonium storage facility or repurposing of an existing facility, as described above, a new plutonium immobilization facility, and modifications to the current Waste Treatment and Immobilization Plant (WTP), which is under construction to vitrify the 56 million gallons of HLW. Building a new immobilization facility at the WTP and modifying WTP for the plutonium disposition mission is not a viable option as the Department needs to maintain its focus and resources at Hanford on completing the WTP for the tank waste immobilization. It would introduce unacceptable technical, regulatory, and financial and other risks to the completion of WTP. These risks are discussed later in the report.

Two potential variants of the immobilization option that were considered during the early stages of this analysis were:

1. The use of H-Canyon at SRS to dissolve the plutonium and then transfer it to the HLW system for vitrification into glass through the DWPF.
2. Direct injection of plutonium into the DWPF or WTP melter process for HLW.

Regarding the first variant, there is not enough HLW at SRS to vitrify the full 34 MT of plutonium with the limitations of the H-Canyon dissolution process and the waste transfer capabilities. However, a limited amount of plutonium (approximately 6 MT) could be immobilized in this variant. The second variant, although technically feasible, would require significant research, development, and demonstration (RD&D) to determine the loading limits of each glass canister, determine the controls required to prevent criticality during the injection process, and develop the design modifications required for the injection process. [Vitreous Laboratory 2013]

#### **5.2.4 OPTION 4: DOWNBLENDING AND DISPOSAL**

This option would involve downblending plutonium oxide with inhibitor materials, packaging it into approved containers, and shipping the downblended plutonium to a repository for permanent disposal. A reference case analysis for the downblending option is based on utilizing information on technical feasibility, cost and schedule impacts, and regulatory considerations gained from the operating experience at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico.

The WIPP facility began receipt and disposal of Contact Handled TRU waste in March 1999 and Remote Handled TRU waste in January 2007. Currently, it is the only underground repository in the U.S. authorized to dispose of TRU waste generated by defense activities. Established over the course of a twenty year time period, the siting, construction, and authorization to operate WIPP required significant Congressional action, approval by the EPA, public input and consent from the State of New Mexico. In 1979, WIPP was authorized by Congress through annual authorization. [Public Law 96-164]

The Waste Isolation Pilot Plant Land Withdrawal Act of 1992 allowed DOE to withdraw the land around WIPP from general use and put it under exclusive use of DOE. The Act contained specific limitations on the quantity of transuranic waste that could be disposed of in WIPP and limitations on the overall capacity. It also provided that the facility comply with EPA regulations for disposal (Solid Waste Disposal Act).

While technically feasible, pursuing an option such as WIPP or an alternate location today for 34 MT of surplus plutonium would require significant engagement with federal, state, and local representatives. Disposal of these additional materials in WIPP would require amendment of the WIPP Land Withdrawal Act as well as federal and state regulatory actions. For an alternate site, a new TRU-waste repository would need to be established. The additional costs for such an option are not included in the downblending reference case analysis since they would be site specific and depend on the inventories of materials to be disposed.

To downblend the plutonium, material would be added to plutonium oxide to inhibit recovery. This downblending process would involve mixing the plutonium with inhibitor materials to reduce the plutonium content to less than 10 percent by weight. Downblending would be conducted at SRS. Two additional gloveboxes would be installed for this option. The containers of downblended plutonium would be characterized (non-destructive assay, digital radiography, and headspace gas sampling) to ensure that they meet waste acceptance criteria prior to shipment to a TRU-waste repository. Once shipped to a repository, the packages containing the plutonium would be emplaced in the salt bed. Over time, high pressure on the salt formation would cause the salt to creep, filling in the voids in the disposal rooms, and entombing the packages permanently. This disposal method has been proven and continues to be used to dispose of surplus plutonium from various DOE sites. Approximately 4.8 MT of plutonium that was downblended have been shipped to WIPP, mostly from six sites: RFETS, Hanford, INL, LLNL, LANL, and SRS.

For the downblending effort at SRS, this analysis assumes existing infrastructure and capabilities are used to the maximum extent possible, and addresses the enhancements that would be needed. For the disposal as TRU in a repository, it also takes advantage of a large body of actual cost data on operations, and estimates the additional resources that would be required to dispose of 34 MT. The analysis also identifies the additional staff required to accommodate increased throughput. As such, the costs are the

incremental costs and do not include the sunk costs associated with existing infrastructure. The cost of constructing WIPP was approximately \$700 million (1986). Two potential variants of the downblending option were considered in this analysis:

1. Downblending plutonium oxide at SRS and LANL with inhibitor material and packaging into approved containers, prior to shipment of downblended plutonium to a repository.
2. Downblending plutonium oxide at SRS with inhibitor material, increasing plutonium loading within each can and packaging into approved containers, prior to shipment of the downblended plutonium to a repository.

The first variant is comparable to Option 4 described above, but involves downblending plutonium at both SRS and LANL. The second variant could be used to enhance this option overall, and involves further increasing the plutonium loading within each can at SRS.

#### **5.2.5 OPTION 5: DEEP BOREHOLE DISPOSAL**

This option involves direct disposal of surplus plutonium in a deep geologic borehole. Direct disposal in a deep geologic borehole could involve the disposal of plutonium metal and/or oxide in suitable canisters. The concept consists of drilling boreholes into crystalline basement rock to approximately 5,000 meters deep. The canisters would be emplaced into the lower 2,000 meters of the borehole. The upper borehole would be sealed with compacted clay or cement. A liner casing would be in place for the emplacement of waste canisters. To emplace the waste canisters, one proposal is to establish a device that would rotate the shipping cask at the surface to a vertical position then lower it into the borehole remotely. Multiple “strings” of canisters would be lowered to the disposal zone, and each canister string would be separated from the overlying canister string using a series of plugs. After the waste canisters are emplaced, and the overlying plugs have been set, the guide casing would be removed and the borehole sealed. [SAND2011-6749] Based on the 1996 estimates used to support the Programmatic Plutonium Storage and Disposition Environmental Impact Statement, this analysis assumes that 3 deep boreholes would be required to emplace 34 MT of surplus plutonium. [DOE/EIS-0229] This concept would require further RD&D to resolve uncertainties and to allow for a more comprehensive evaluation.

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## 6.0 COMPARISON OF OPTIONS

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This section summarizes the results of the options analysis as assessed against the following criteria:

- Meeting international commitments;
- Cost;
- Duration to begin disposition and to complete the U.S. 34 MT mission;
- Technical viability; and,
- Legal, regulatory, and other issues.

### 6.1 MEETING INTERNATIONAL COMMITMENTS

Article VI of the NPT states that “...each of the Parties 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...”. As a nuclear weapons state signatory of the NPT, the United States demonstrates that it is meeting its obligations by dismantling nuclear warheads, disassembling nuclear weapons pits, and permanently disposing of surplus U.S. weapon-grade plutonium and HEU. Since long-term storage is not an option in this analysis, all of the options examined would dispose of plutonium, thereby demonstrating that the United States is meeting its NPT obligations.

The United States-Russia PMDA specifically calls for each nation to dispose of no less than 34 MT of surplus weapon-grade plutonium by “...irradiation of disposition plutonium as fuel in nuclear reactors...” or “...any other methods that may be agreed by the Parties in writing”. The PMDA also allows for amendment by written agreement of the Parties. As specified by the PMDA, the United States will use LWRs, and Russia will use fast reactors to meet the disposition rate of no less than 1.3 MT per year of dispositioned plutonium. Under the provision related to the irradiation method of disposition, the PMDA requires the plutonium in the spent fuel to no longer be weapon-grade (i.e., changing the isotopic composition<sup>6</sup> so that the ratio of the isotope 240 to isotope 239 is greater than 10 percent), and has other criteria to determine that the plutonium has been dispositioned (e.g., long-term radiation levels).

Option 1, irradiation of MOX fuel in LWRs, is the only option that corresponds to the U.S. disposition method specified in the PMDA, whereas the other options would require varying levels of supplementary agreement with Russia pursuant to existing PMDA provisions.

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<sup>6</sup> Isotopic composition is the percent of each plutonium isotope within a given quantity of plutonium. The PMDA defines weapon-grade plutonium as plutonium with an isotopic ratio of plutonium-240 to plutonium-239 of no more than 10 percent. The only options in the analysis that degrade the isotopic composition of weapon-grade plutonium are reactor-based options.

Option 2, irradiation of plutonium fuel in fast reactors, is not identified in the PMDA as a method to disposition U.S. plutonium; however, the PMDA specifies that Russia will use both the BN-600 and the BN-800 fast reactors for disposition of its plutonium. The BN-800 is to operate with a 100 percent MOX fuel core, and thus is more representative of the ADR; therefore, the disposition criteria for the BN-800 were used as the baseline disposition criteria for evaluating the ADR options. The single-module ADR meets the PMDA's burn up and radiation criteria for spent fuel; however, it achieves roughly 60 percent of the 1.3 MT/year disposition rate agreed to in the PMDA. The disposition rate could be achieved in a single-module ADR if the burn up criteria were modified. Modification of the PMDA would be necessary to enable U.S. blending of fuel-grade and reactor-grade plutonium, consistent with the allowances included for Russian blending. If the PMDA requirement for isotopic degradation (i.e., changing the isotopic composition so that the ratio of the isotope 240 to isotope 239 is greater than 10 percent) were removed, the disposition rate would be increased and the life cycle costs would be significantly decreased. The spent fuel would still provide physical, chemical, and radiological barriers to minimize accessibility of the plutonium. The two-module ADR variant satisfies all of the PMDA spent fuel disposition criteria and the 1.3 MT/year disposition rate required by the PMDA.

Options 3, 4, and 5, the non-reactor-based options, are not described in the PMDA. While none of the non-reactor options presented in this analysis change the isotopic composition of the weapon-grade plutonium, the 1994 NAS report on the *Management and Disposition of Excess Weapon Plutonium* discussed other ways to minimize accessibility of the plutonium by creating physical, chemical, or radiological barriers. Examples of the barriers include: physical -- burial significantly below the ground surface; chemical -- downblending the plutonium with other materials; and, radiological -- mixing it with HLW. [NAS 1994] Each of the non-reactor-based options would provide barriers to retrieval of the plutonium. The immobilization option (Option 3) rated the highest of the three options, with the least risk when judged against this criterion.

Option 3, immobilization (ceramic or glass form) with HLW, meets all three attributes (physical, chemical, and radiological barriers), and therefore would be the most difficult to retrieve. Option 4, downblending and disposal meets two of the attributes (chemical and physical barriers). Option 5, deep borehole disposal, contains, at a minimum, the physical barrier; if the plutonium were buried with spent fuel, it could also include a radiological barrier; if mixed with other constituents, it could also include a chemical barrier. For Option 5 to meet all three attributes; however, it would require significantly more RD&D to determine and to approve this waste form.

All of the options (with the exception of Option 1) would require varying levels of supplementary agreement with Russia pursuant to existing PMDA provisions. [PMDA 2000] Beginning in 2006, the United States undertook a major effort to update the 2000 agreement, primarily at Russia's request that it conduct its entire disposition in fast reactors to fit with its nuclear energy strategy. In contrast to the current U.S. review, this earlier effort to update Russian and U.S. program elements entailed a wide range of substantial changes to the PMDA (including new nonproliferation provisions). Still, this effort exemplified a willingness to accommodate each Party's national interests. The PMDA

requires both Parties to take all necessary steps to complete an appropriate verification agreement with the International Atomic Energy Agency (IAEA). This requirement would be applicable to all options.

The following summarizes the key points for meeting international commitments of each alternative:

**Option 1: Irradiation of MOX Fuel in Light Water Reactors**

- Demonstrates the United States commitment to meeting its NPT obligations.
- Conforms to the U.S. approach and criteria in the PMDA.
- Changes isotopic composition of the weapon-grade plutonium.
- Meets all three attributes for minimizing accessibility through physical, chemical, and radiological barriers.

**Option 2: Irradiation of Plutonium Fuel in Fast Reactors**

- Would demonstrate the United States commitment to meeting its NPT obligations.
- Would require reaching consensus in the PMDA's Joint Consultative Commission:
  - to enable the United States to dispose of plutonium in fast reactors instead of LWRs; and,
  - to change the PMDA required disposition rate, or the burn up criteria for a single-module ADR.
- Meets all three attributes for minimizing accessibility through physical, chemical, and radiological barriers.

**Option 3: Immobilization (Ceramic or Glass Form) with High Level Waste**

- Would demonstrate the U.S. commitment to meeting its NPT obligations.
- Would require supplemental U.S.-Russian agreement pursuant to Article III of the PMDA.
- Previous 2000 PMDA included immobilization as an element of United States plutonium disposition, but limited the quantity to 9 MT of plutonium material not from pits.
- No change in the isotopic composition, but would meet all three attributes for minimizing accessibility through physical, chemical, and radiological barriers.

**Option 4: Downblending and Disposal**

- Would demonstrate the United States commitment to meeting its NPT obligations.
- Would require supplemental U.S.-Russian agreement pursuant to Article III of the PMDA.
- No change in the isotopic composition, but would meet two of the attributes for minimizing accessibility through physical and chemical barriers.
- Although all three non-reactor based options include IAEA monitoring and inspection, the reference case WIPP is the only facility of the three currently on the list of potential DOE sites for future IAEA monitoring and inspection.

- Plutonium currently disposed of at WIPP meets DOE Order 474.2, which requires meeting certain conditions before nuclear materials are considered sufficiently unattractive for illicit purposes.

#### **Option 5: Deep Borehole Disposal**

- Would demonstrate the United States commitment to meeting its NPT obligations.
- Would require supplemental U.S.-Russian agreement pursuant to Article III of the PMDA.
- No change in the isotopic composition, but as a minimum would meet the physical barrier by itself; if buried and/or mixed with other materials, could also include a radiological barrier and chemical barrier but would require significant development and approval of this waste form.

### **6.2      *NORMALIZED COST ESTIMATES***

A comparative evaluation was performed to analyze the cost of the options. The lead program office each developed their option including the cost data (refer to Appendix A, B, and C for the individual analyses). With the exception of the MOX option, the capital estimates are preliminary and developed by parametric analysis or comparing to similar projects or activities, and as such have a very high level of uncertainty. The purpose of developing the cost data was to determine whether cost was a discriminator for any of the options, i.e., significantly higher or significantly lower when compared to one another. The life cycle cost data were normalized for consistency among options related to escalation rates and funding constraints. Due to the current budget environment, this analysis assumed a constraint of \$500 million annually in capital funding. This normalization was performed after the options had been developed, and the options as described in Appendix A, B, and C were not optimized with consideration of the annual funding constraint. This constraint had the effect of lengthening the construction schedule for large projects, shifting costs out in time that would be subjected to increasing escalation but held against a flat \$500 million constraint. If capital funding in excess of \$500 million annually were assumed, then the capital construction schedules would generally be accelerated and the escalated life cycle cost estimates would decrease. In addition, the assumption of performing design and construction of facilities in series instead of in parallel to meet new project management requirements further lengthened the schedule of completing large construction projects.

The life cycle estimates were based on the to-go costs and include capital/construction costs and operational costs for the disposition facilities, and other program costs, such as for feedstock preparation. The life cycle estimates do not include any potential offsets from the sale of fuel or electricity generation. Option 4, downblending and disposal was the least costly, with the least technical risk in this analysis, which used WIPP as a reference case. The costs for disposal would be higher for an alternate TRU-waste repository. Option 5, deep borehole disposal was also favorable, but not as attractive due to significant uncertainties.

Option 1, irradiation of MOX fuel in LWRs requires completion of the Waste Solidification Building and MOX project facilities, currently under construction at SRS, as well as reactor modifications to irradiate MOX fuel and other related activities. Due to many factors, the cost estimate to complete and start-up the MOX facility continues to increase. Also, the cost estimate to operate the facility has more than doubled over the past few years. The projected, normalized life cycle to-go cost is estimated at \$25.12 billion (more than \$31 billion when sunk costs are included), of which \$6.46 billion to go is in capital costs. Other to-go program costs, including the Waste Solidification Building cost, are estimated at \$8.40 billion.

Option 2, irradiation of plutonium fuel in fast reactors, requires construction of a multi-billion dollar reactor, preferably at SRS, significant modification to K-Area at SRS for fuel fabrication, and construction of a spent fuel storage facility. The total normalized life cycle to-go and MOX demobilization cost for a single-module ADR is estimated at \$50.45 billion (more than \$58 billion when sunk costs are included), of which \$9.42 billion is capital cost. It should be noted that the total normalized cost for the two-module ADR variant were lower than the single-module ADR reactor at \$38.01 billion normalized life cycle and MOX demobilization cost (more than \$45 billion when sunk costs are included) but the capital costs were higher at \$17.65 billion. The operational cost for the single-module ADR is estimated at \$33.41 billion and the two-module ADR variant is estimated at \$13.14 billion. The other program costs are estimated at \$7.62 billion for the single ADR and \$7.22 billion for the two-module ADR variant. There would likely be an approximately \$1-\$2 billion offset for feedstock preparation by producing metal in lieu of oxide, but this was not included in the total life cycle cost.

Option 3, immobilization (ceramic or glass form) with HLW, requires construction and operation of a secure Hazard Category<sup>7</sup> 2 immobilization facility; construction or significant modification and operation of a secure Hazard Category 2 plutonium storage facility; security costs; potential modifications to WTP to complete the can-in-canister process; and a glass waste storage building for the additional HLW canisters produced. The total normalized life cycle to-go and MOX demobilization cost for this option is estimated at \$28.65 billion (more than \$36 billion when sunk costs are included) of which \$10.67 billion is capital cost, \$11.58 billion is operational cost, and \$6.39 billion is other program cost.

Option 4, downblending and disposal, requires adding two additional gloveboxes at SRS to increase downblending, packaging, certification. The analysis includes repository costs for the 34 MT based on current operating experience. For purposes of this analysis, using WIPP as a reference case, the total normalized life cycle to-go and MOX demobilization cost is estimated at \$8.78 billion (more than \$16 billion when sunk costs are included), of which \$290 million is capital enhancements needed, based on a 380 fissile gram equivalent (FGE) loading limit per can, \$3.00 billion is operational cost, and \$5.49 billion is other program

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<sup>7</sup> In accordance with DOE-STD 1027-92, each DOE nuclear facility is characterized by the level of hazard it presents to the public and workers from the amount and type of nuclear materials present at the facility. Hazard Category 2 is assigned when an on-site consequence is significant, i.e., facilities with the potential for a nuclear criticality event or with sufficient quantities of hazardous material and energy which would require on-site emergency planning activities.



cost. WIPP is an approved operation, and is currently a disposal method used by DOE sites for limited quantities of surplus plutonium. There is a potential for a significant offset due to converting the plutonium metal to oxide that does not need to meet stringent fuel specifications, but this offset was not included in the life cycle cost estimate.

Option 5, deep borehole disposal, has the potential for a long site selection and characterization process, as well as an uncertain regulatory process to operate the facility. In 2011, Sandia National Laboratory estimated the cost to drill each borehole at approximately \$40 million. [SAND2011-6749] However, the cost for site characterization, regulatory reviews, and qualification of the plutonium waste form is unknown at this time, and will be dependent on completion of the RD&D activities to help resolve key uncertainties. A 2012 Sandia National Laboratory report indicates that the preliminary estimates for the RD&D activities (without the use of radioactive waste or materials) would require approximately 5 years and \$75 million. The subsequent cost to deploy full-scale operational facility (ies) is yet to be defined. [SAND2012-8527P] While the cost for a deep borehole disposition option cannot be estimated to the same degree as the other options, based on the similarities between disposition of plutonium in a deep geologic repository and disposition of plutonium in a deep borehole, the costs for disposition in a deep borehole would likely be closer to Option 4, downblending and disposal. As a comparison, the 1986 cost to construct and start-up WIPP was approximately \$700 million, or \$1.47billion in 2013 (escalated). The cost of constructing and licensing a new repository today would cost substantially more than this due to today's design, construction, and operation standards.

**Table 6-1: Normalized Cost Comparison of Options \***

<b>Option</b>	<b>Capital Project Point Estimate</b>	<b>Operating Cost Estimate</b>	<b>Estimate of Other Program Costs</b>	<b>Total Life Cycle Cost To-Go Estimate**</b>
<b>Option 1: Irradiation of MOX fuel in LWRs</b>	\$6.46 billion to go	\$10.26 billion	\$8.40 billion	\$25.12 billion
<b>Option 2: Irradiation of Plutonium Fuel in Fast Reactors (Single-Module ADR)</b>	\$9.42 billion	\$33.41 billion	\$7.62 billion (\$1-2 billion offset from metal not included)	\$50.45 billion
<b>Option 3: Immobilization (Ceramic or Glass) with HLW</b>	\$10.67 billion	\$11.58 billion	\$6.39 billion	\$28.65 billion
<b>Option 4: Downblending and Disposal</b>	\$290 million	\$3.00 billion	\$5.49 billion	\$8.78 billion
<b>Option 5: Deep Borehole Disposal</b>	Not Estimated	Not Estimated	Not Estimated	Not Estimated

\* Based on \$500 million annual capital costs constraint and escalating capital and operating costs.

\*\* Based on Capital Point Estimate

The following summarizes the cost effectiveness key points of each alternative:

**Option 1: Irradiation of MOX Fuel in Light Water Reactors**

- Multi-billion dollar capital project for MOX facility, of which DOE already has invested approximately \$4 billion in capital cost.
- Total to-go cost of approximately \$25.12 billion (including \$6.46 billion to go in capital and \$10.26 billion operating).
- More than \$31 billion life cycle cost when sunk costs are included.

**Option 2: Irradiation of Plutonium Fuel in Fast Reactors**

- New multi-billion dollar capital project including new reactor, modifications in K-Area for fuel fabrication, and construction of a spent fuel storage facility.
- Total to-go and MOX demobilization cost of approximately \$50.45 billion (including \$9.42 billion for capital/enhancements, \$33.41 billion in operating costs).
- More than \$58 billion life cycle cost when sunk costs cost are included.

**Option 3: Immobilization (Ceramic or Glass Form) with HLW**

- New multi-billion dollar capital project for the immobilization facility, secure plutonium facility and modifications to WTP, most likely resulting in cost and schedule impacts to the WTP project and operations.
- Total to-go and MOX demobilization cost of approximately \$28.65 billion (including \$10.67 billion for capital/enhancements, \$11.58 billion in operating costs).
- More than \$36 billion life cycle cost when sunk costs are included.

**Option 4: Downblending and Disposal**

- Relatively cost effective under the reference case since it would utilize an existing operating infrastructure at SRS (based on experience of currently shipping surplus downblended plutonium to WIPP).
- Small incremental annual operational funding for increased downblending throughput and repository disposal, under the reference case, based on use of current WIPP operating data.
- Total to-go and MOX demobilization cost of approximately \$8.78 billion (including \$290 million for capital/enhancements, \$3.00 billion in operating costs).
- More than \$16 billion life cycle cost when sunk costs cost are included.

**Option 5: Deep Borehole Disposal**

- Cost for site characterization, development of regulatory criteria, and qualification of the plutonium waste form is unknown at this time, and would be dependent on completion of the RD&D to help resolve key uncertainties.

### **6.3 DURATION TO BEGIN DISPOSITION AND TO COMPLETE THE 34 MT MISSION**

A comparative evaluation was performed to analyze the duration to begin disposition and to complete the 34 MT mission. All of the durations estimated for the individual options were adjusted to reflect the effects of both the normalization for funding constraints and performing design and construction of facilities in series instead of in parallel. The durations are based on point estimates. The earliest the program could begin disposition would be under Option 4. The earliest the program could complete the 34 MT mission under any of the options would be in the 2040 – 2050 range, for Options 1 and 4. This long duration significantly impacts the total cost estimate for all alternatives when considering escalation/inflation.

Option 1, irradiation of MOX fuel in LWRs, has the MOX facility completing construction in 2027. Disposition would begin in 2028, with the MOX facility operating through 2043 based on the normalized data.

Option 2, irradiation of plutonium fuel in fast reactors, would require significant modifications to the K-Area complex at SRS to perform metal fuel fabrication, and construction of a new single module fast reactor. The duration to construct and begin operations is estimated to take 18 years, with disposition beginning in 2033. The estimate to complete the 34 MT mission is 2075. Even though the two-module ADR option is included as a variant, the constraints in the design and construction would lengthen the time to begin operations and begin disposition, therefore; the estimated date to begin disposition is 2053 and would complete the 34 MT mission in approximately 2065. The hybrid option of restarting and operating FFTF at the Hanford Site could expedite the duration to completion; however, the additional cost of starting FFTF would further strain the challenging capital costs of this option. Final design of a commercial fast reactor would require significant engineering and licensing and as such carries uncertainties in being able to complete within the assumed duration.

Option 3, immobilization (ceramic or glass form) with HLW, assumed the design and construction to be 20 years consistent with the MOX facility, then normalized so that construction completion and start-up was estimated to be in 2038. With disposition beginning in 2039, the completion of the 34 MT mission was estimated to be approximately 2060. This analysis assumes the Option 3 end date to be when all of the plutonium is immobilized and placed in an interim storage location. This option also carries a high risk due to the significant up-front capital requirements, and major risks in completing the capital asset projects in the assumed duration. In addition, given that this option depends on HLW as feed for the can-in-canister approach this option introduces potentially significant, and thus unacceptable, schedule risk to the Hanford tank waste immobilization mission, particularly if it were to impede or delay the tank waste immobilization. Hanford is not a viable option for the mission of disposing of 34 MT of weapon grade plutonium and will not be considered.

Option 4, downblending and disposal, under the WIPP reference case, is estimated to begin disposition in 2019 and take 28 years in duration, completing in 2046, assuming enhancements and increased staffing to support throughput requirements and minimize conflicts with other missions at SRS, and the availability of a repository. To implement such an option, DOE would propose to package the 34 MT of downblended plutonium into the recently certified criticality control overpack (CCO) packages, which have a maximum limit of 380 FGE per package. If the higher rate of 1,000 FGE per package were approved, then the duration for the 34 MT disposal mission would be 15 years. Under the reference case, the downblending option carries the least technical risk. An alternate TRU-waste repository would add cost and schedule delay to the reference case, since a new repository could not be operational by 2019.

Option 5, deep borehole disposal, has the highest uncertainty in duration for site selection, characterization process, regulatory review, construction and start-up. For comparative purposes, the timeline for the deep borehole option was assumed to be similar to the timeline for a geologic repository for spent fuel as outlined in the January 2013 *“Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste.”* The timeline assumes a repository sited by 2026, the site characterized and the repository designed and licensed by 2042, and the repository constructed and operational by 2048. [DOE 2013] Assuming one year to drill each borehole (3 would be needed), disposition would begin by 2048 and the 34 MT of surplus plutonium would be disposed of by 2051.

The following summarizes the duration to begin disposition and to complete the 34 MT mission key points of each alternative:

**Option 1: Irradiation of MOX Fuel in Light Water Reactors**

- Would begin disposition in 2028.
- Would complete irradiation of 34 MT of plutonium in 2043, but has significant risks due to construction and start-up of major capital project.

**Option 2: Irradiation of Plutonium Fuel in Fast Reactors**

- Would entail a lengthy process to construct new reactor facility, with disposition beginning in 2033.
- Estimated completion for 34 MT mission in 2075 for the single-module ADR and 2065 for 2-module ADR reactors, but has significant risks due to construction of major capital projects.

**Option 3: Immobilization (Ceramic or Glass Form) with HLW**

- Would begin disposition in 2039.
- Would complete immobilizing 34 MT of plutonium in 2060, but has significant risks due to construction of major capital projects.
- Potential for significant schedule risk to the tank waste immobilization mission.

**Option 4: Downblending and Disposal**

- Under the reference case, could begin disposition in 2019.

- Known and ongoing process with estimated completion of 2046 loaded at 380 FGE limit under the reference case.

#### **Option 5: Deep Borehole Disposal**

- Would begin disposition in 2048.
- Unknown and lengthy process expected for regulatory review, start-up, and qualification of the waste form, estimated to be completed by 2051.

### **6.4 TECHNICAL VIABILITY**

The primary considerations for the technical viability were process maturity (whether or not the process is proven), and the risk of successful implementation and execution. Option 4, downblending and disposal carries the lowest risk since WIPP currently receives plutonium as an approved TRU waste form for disposal.

Regarding Option 1, irradiation of MOX fuel in LWRs, construction of the MOX facility is more than 50 percent complete, but the project still faces technical challenges to complete construction and start-up the facility. The MOX facility design is largely based on the French LaHague and Melox facilities, operated by AREVA. These reference plants were constructed and operated in a different regulatory environment in France than exists with the NRC in the U.S., and the U.S. facility must be adapted accordingly. In the 1990's, the Melox facility underwent an expansion that resulted in significantly higher costs than planned due to difficulties in completing integrated testing of systems in a large, complex facility. To mitigate these risks for start-up of the MOX facility, personnel from the MOX will train at AREVA's facilities, and the U.S. contractor will have personnel from AREVA at SRS to work with U.S. operations staff during start-up. However, with differing regulatory requirements, the construction and operation still remains a significant risk.

Option 2, irradiation of plutonium fuel in fast reactors, faces two major technical challenges: the first involves the design, construction, start-up, and licensing of a multi-billion dollar prototype modular, pool-type advanced fast-spectrum burner reactor; and the second involves the design and construction of the metal fuel fabrication in an existing facility. As with any initial design and construction of a first-of-a-kind prototype, significant challenges are endemic to the endeavor, however DOE has thirty years of experience with metal fuel fabrication and irradiation. The metal fuel fabrication facility challenges include: scale-up of the metal fuel fabrication process that has been operated only at a pilot scale, and performing modifications to an existing, aging, secure facility (K-Area at SRS). Potential new problems also may arise during the engineering and procurement of the fuel fabrication process to meet NRC's stringent Quality Assurance requirements for Nuclear Power Plants and Fuel Reprocessing Plants, 10 CFR 50, Appendix B.

Option 3, immobilization (ceramic or glass form) with HLW, would require further development to qualify the can-in-canister technology and throughput. Essentially, all of the process steps have been previously demonstrated in a variety of applications; however,

validation testing would be needed to integrate the process steps for this application and demonstrate that a reasonable throughput can be achieved with the appropriate nuclear safety controls. Additional testing would also be necessary to demonstrate the variety of plutonium feeds can be effectively processed. However, the most significant challenges are the design, construction, and start-up of a new multi-billion dollar facility and modifications to WTP.

Option 3, immobilization (ceramic or glass form) with HLW, also requires qualification of the waste form for a potential geologic repository. For a waste form to be acceptable in a potential federal repository system, it is necessary to demonstrate that it will meet all the requirements, and provide evidence of acceptability during production. Although the technical requirements for the certified waste form are yet to be defined, previous efforts to qualify HLW glass for repository disposal could be leveraged for qualification of the can-in-canister waste form. To implement an immobilization option at the Hanford Site, modifications to the WTP would be required to support receipt of the immobilized plutonium cans. The specific modifications to WTP would not be known until the design is completed; however, based on the DWPF changes that were identified during the cancelled Plutonium Vitrification Project, it is expected that WTP would require receipt and handling capabilities for the canisters filled with immobilized plutonium.

For Option 4, downblending and disposal, as proven by WIPP, technology maturation is advanced; however, this option is not without technical risk, primarily due to facility enhancements to increase throughput capacity. This option assumes two additional gloveboxes would be installed in K-Area Material Storage (KAMS) at SRS. The additional gloveboxes would be required to handle the increased downblending and packaging operations. The technology and process steps are relatively uncomplicated and known; however, additional controls may be required to the facility safety basis that could limit operations and potentially impact other missions in K-Area at SRS. As with Option 2, challenges include performing modifications to an existing, aging, secure facility (K-Area at SRS). Also additional analysis would be required at WIPP to understand whether any design enhancements over the reference case would be needed.

Similar to Option 3, immobilization (ceramic or glass form) with HLW, the technical requirements for the certified waste form for Option 5, deep borehole disposal, are yet to be defined. Until such time that the RD&D for deep borehole disposal is authorized and nears completion, and DOE decides whether or not to proceed with this technology, the scope of this project (i.e., facilities, utilities, support systems and infrastructure) are yet to be defined. The RD&D would demonstrate the feasibility of deep borehole disposal and would be focused on completing conceptual design analysis, and demonstrating key components of borehole drilling, borehole construction, waste canisters, handling, emplacement, and borehole sealing operations. Planning for drilling a deep demonstration borehole would concentrate on using existing technology. The RD&D would also focus on the data gaps in the borehole geological, hydrological, chemical, and geophysical environment important to post-closure safety of the system, materials performance at the depths that the material would be emplaced, and construction of the disposal system. [SAND2012-8527P]

The following summarizes the technical viability key points of each alternative:

**Option 1: Irradiation of MOX Fuel in Light Water Reactors**

- MOX fuel fabrication process based on existing, operating technology in France.
- Facility must be adapted to U.S. standards for construction and operation of nuclear facilities.
- Significant risk associated with construction and start-up of major nuclear facility.

**Option 2: Irradiation of Plutonium Fuel in Fast Reactors**

- Design, construction, start-up and licensing of prototypical modular, pool-type advanced fast-spectrum burner reactor has significant technical risk.
- Design, construction, and start-up of a full scale metal fuel fabrication facility in an existing operating Category 1 facility faces significant technical challenges.
- Metal fuel fabrication process has only been operated at the pilot scale.

**Option 3: Immobilization (Ceramic or Glass Form) with HLW**

- Technical uncertainty of the can-in-canister technology and throughput.
- Technological uncertainty of the glass can-in-canister form for disposal in a geologic repository.
- Specific modifications and impacts to WTP are yet to be fully defined. WTP, itself, is still under construction. This is not a viable option for the Hanford Site.

**Option 4: Downblending and Disposal**

- Under the reference case, least risk.
- Two additional gloveboxes would be installed to increase throughput; however, the technical requirements are known and in use today.

**Option 5: Deep Borehole Disposal**

- Drilling the deep boreholes would be technically viable.
- Technical requirements for the certified waste form are yet to be defined.
- Concept is still under development.

**6.5 LEGAL, REGULATORY, AND OTHER ISSUES**

All options have legal and/or regulatory risks.

Option 1, irradiation of MOX fuel in LWRs, requires completion of the ongoing NRC licensing process for the MOX facility, the fuel design, and license modifications, if required, for the reactors that will use MOX fuel. The willingness of utilities to accept MOX fuel has not been demonstrated to date, however. DOE has been working with the Tennessee Valley Authority and nuclear fuel vendors to determine their interest in using or selling MOX fuel to their customers; however no agreements to purchase MOX fuel have been finalized. DOE has negotiated a Blanket Commercial Agreement (BCA) with Areva that would establish the terms and conditions as well as pricing for the purchase of MOX fuel assemblies fabricated



at the MOX facility by AREVA's utility customers; however, DOE has not signed the BCA due to the analysis of plutonium disposition options.

Option 2, irradiation of plutonium fuel in fast reactors, would require NRC licensing of the construction and operation of the ADR and spent fuel storage facility, and also a metal fuel fabrication facility. There would be an added complication to this licensing due to the facility being co-located in the K Area facility at SRS, which falls under the purview of DOE with independent technical oversight by the Defense Nuclear Facilities Safety Board (DNFSB).

Option 3, immobilization (ceramic or glass form) with HLW, would adversely impact the tank waste disposition mission at the Hanford Site, further slowing the completion of WTP and delaying treatment of the 56 million gallons of high level waste stored at Hanford, which would be unacceptable. For context, construction on the Pretreatment Facility has been suspended pending resolution of technical issues. This is the facility through which all the waste would be processed and fed to the respective low and high activity immobilization facilities. As a result, DOE has notified the State of Washington that it is at serious risk of missing the milestones associated with WTP that are contained in Consent Decree in *State of Washington v. United States Department of Energy*, No. 08-5085-FVS (E.D. Wash.). DOE's recently submitted proposal to the State of Washington to amend the Consent Decree does not contemplate modifications to WTP to accommodate the plutonium disposition mission. Further, over the last 5 years, DOE went through great efforts to consolidate storage of non-pit plutonium at SRS, and has de-inventoried the surplus plutonium from the Hanford Site to SRS. Furthermore, shipping the plutonium back to the Hanford Site would face strong State and public opposition.

Option 3 also would require significant involvement with the regulators on environmental permitting and with the DNFSB concerning nuclear facility safety, start-up, and operations for these high hazard nuclear facilities.

Option 4, downblending and disposal in a repository would raise legal and regulatory issues that would require resolution prior to any serious consideration of WIPP or another location. The Waste Isolation Pilot Plant Land Withdrawal Act of 1992 contained specific limitations on the quantity of transuranic waste that could be disposed of in WIPP and limitations on the overall capacity of the facility. Disposal of the entire 34 MT of material in WIPP would require amendment of the WIPP Land Withdrawal Act as well as federal and state regulatory actions. As with any location considered for this disposal mission, significant engagement with federal, state, and local representatives would be required. Implementing such an option would require Congressional action.

For Option 5, deep borehole disposal, establishing performance requirements, and developing a suitable waste form for disposal are steps that would require further development. The EPA and the NRC would need to develop a new safety standard and regulatory framework for plutonium disposition in deep boreholes informed by an RD&D effort. Further analysis of deep borehole disposal would be needed to address the technical, cost, and regulatory uncertainties.

An extensive NEPA process (2 years or more) would be required for all options other than the MOX fuel approach, and therefore was not a discriminator in this evaluation.

The following are the legal, regulatory, and other issues key points for each alternative:

**Option 1: Irradiation of MOX Fuel in Light Water Reactors**

- NRC licensing process; several steps completed for the MOX facility.
- Fuel qualification by the NRC.
- Willingness of utilities to use MOX fuel in their reactors.

**Option 2: Irradiation of Plutonium Fuel in Fast Reactors**

- Lengthy NRC licensing process.
- Fuel qualification by the NRC.
- Compliance with NRC requirements.

**Option 3: Immobilization (Ceramic or Glass Form) with HLW**

- Option is not contemplated under current agreements with Washington State, and potential implications associated with changes to WTP scope and schedule.
- Would require qualification and permitting of this waste form in a geologic repository.
- Strong opposition likely from the State of Washington.
- Opposition by State regulators; significant involvement with the DNFSB.
- This is not a viable option for the Hanford Site.

**Option 4: Downblending and Disposal**

- Would require significant engagement with federal, state, and local representatives before any decision to go forward with this option.
- Implementation would require Congressional action, including amendment to existing legislation or enactment of new legislation.

**Option 5: Deep Borehole Disposal**

- Significant regulatory challenges and establishing the requirements for the qualified waste form.

**6.6 KEY POINT SUMMARY**

Table 6-2 provides a summary of the key points identified in the analysis for each option and criteria.

**Table 6-2: Key Point Summary**

Options	International Commitments	To Go Cost (in \$)	Completion Timelines	Technical Viability	Other Factors
<b>1) MOX Fuel Irradiation in Light Water Reactors</b>	<ul style="list-style-type: none"> <li>Conforms to the U.S. approach and criteria in the PMDA</li> <li>3 barriers to retrieval (physical, chemical, radiological)</li> </ul>	25.1 B	2043 with significant risks	<ul style="list-style-type: none"> <li>Low process risk due to proven operations of reference plants, but significant risk remains due to challenges associated with construction and start up of a highly complex nuclear facility</li> </ul>	<ul style="list-style-type: none"> <li>NRC licensing process; several steps completed for MOX facility</li> <li>Fuel qualification by the NRC</li> <li>Willingness of utilities to use MOX fuel in their reactors</li> </ul>
<b>2) Plutonium Fuel Irradiation in Fast Reactors</b>	<ul style="list-style-type: none"> <li>Would require reaching consensus in the PMDA's Joint Consultative Commission</li> <li>3 barriers to retrieval (physical, chemical, radiological)</li> </ul>	50.5 B	2075 with significant risks (could be accelerated with 2-module ADR or FFTF variant)	<ul style="list-style-type: none"> <li>Issues with designing and building a fast reactor (as well as restarting FFTF if it were used)</li> <li>Uncertainty with design and building a metal fuel facility in an existing, aging Category I facility</li> </ul>	<ul style="list-style-type: none"> <li>Licensing of the ADR by the NRC</li> <li>Fuel qualification by the NRC</li> </ul>
<b>3) Immobilization</b>	<ul style="list-style-type: none"> <li>Would require supplemental U.S.-Russian agreement pursuant to Article III of the PMDA</li> <li>3 barriers to retrieval (physical, chemical, radiological)</li> </ul>	28.7 B Total	2060 with significant risks	<ul style="list-style-type: none"> <li>Technological uncertainty with can-in-canister technology, throughput, and form for disposal in geologic repository</li> <li>Specific modifications and impacts to WTP are yet to be fully defined – WTP is still under construction</li> </ul>	<ul style="list-style-type: none"> <li>Not contemplated under current agreements with the State of Washington and WTP implications</li> <li>Would require qualification/permitting of waste form</li> <li>Strong opposition likely from the State of Washington</li> </ul>
<b>4) Down-blending &amp; Disposal</b>	<ul style="list-style-type: none"> <li>Would require supplemental U.S.-Russian agreement pursuant to Article III of the PMDA</li> <li>2 barriers to retrieval (physical, chemical)</li> </ul>	8.8 B Total	2046 with least risk	<ul style="list-style-type: none"> <li>Under the reference case, low risk due to current operations</li> <li>Additional gloveboxes are needed but technical requirements are known</li> </ul>	<ul style="list-style-type: none"> <li>Would require amendments to the WIPP Land Withdrawal Act to expand capacity at WIPP and scope of mission at WIPP</li> </ul>
<b>5) Deep Borehole Disposal</b>	<ul style="list-style-type: none"> <li>Would require supplemental U.S.-Russian agreement pursuant to Article III of the PMDA</li> <li>1-3 barriers to retrieval (physical, potentially chemical and radiological)</li> </ul>	Cost range not estimated but likely closer to the WIPP option	Uncertain but assumed 2051 based on SNF repository	<ul style="list-style-type: none"> <li>Drilling boreholes technically viable</li> <li>Technical requirements for certified waste form TBD</li> <li>Further RD&amp;D needed</li> </ul>	<ul style="list-style-type: none"> <li>Regulatory challenges with establishing requirements for qualified waste form</li> </ul>

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## **Appendix A**

# **Disposition of Surplus Weapon-Grade Plutonium As MOX Fuel in LWR Reactors**





**Disposition of  
Surplus Weapon-Grade Plutonium  
as Mixed Oxide (MOX) Fuel  
in Light Water Reactors**

**Prepared by the  
National Nuclear Security Administration's  
Office of Acquisition and Project Management**

**April 2014**

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## 1.0 BACKGROUND

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The United States Government's current approach for surplus plutonium disposition involves irradiating plutonium as mixed oxide (MOX) fuel in nuclear power reactors. The MOX fuel will be irradiated in domestic commercial nuclear power reactors, including existing pressurized-water reactors (PWRs) and boiling-water reactors (BWRs). The resulting MOX spent fuel will be stored with the commercial utilities' spent uranium fuel.

This approach, which is being implemented by the Department of Energy's National Nuclear Security Administration (NNSA), involves construction and operation of a MOX Fuel Fabrication Facility (MFFF), construction and operation of a Waste Solidification Building to handle certain wastes from the MOX facility, a capability to disassemble nuclear weapons pits and convert the resulting plutonium metal into plutonium oxide, MOX fuel qualification activities, reactor modifications for utilities willing to irradiate MOX fuel, and packaging and transportation activities.

The MOX facility is subject to licensing and related regulatory authority by the Nuclear Regulatory Commission (NRC) and based on technology in use at AREVA's R4 and Melox facilities in France. The MOX facility design includes the MOX Fuel Fabrication Facility and support structures, such as the Secure Warehouse, the Receipt Warehouse, the Administration Building, and the Technical Support and Reagents Processing Buildings. The MOX Fuel Fabrication Facility is designed to meet structural and safety standards for storing and processing special nuclear material. The walls, floors, and building roof are built with reinforced concrete. Areas that will contain plutonium are designed to survive natural phenomenon hazards, such as earthquakes, extreme winds, floods, and tornadoes, as well as potential accidents. The MOX Fuel Fabrication Facility will have three major functional areas: 1) the Shipping and Receiving Area, which will contain equipment and facilities to handle materials entering and exiting the facility; 2) the Aqueous Polishing Area, which will house the processes to remove impurities from plutonium oxide feedstock; and, 3) the MOX Processing Area, which will include the blending and milling, pelletizing, sintering, grinding, fuel rod fabrication, fuel bundle assembly, laboratory, and storage areas.

In 2008, the cost and schedule baseline for the MOX facility was established at \$4.8B for design, construction, and cold start-up activities, with a hot operations start-up date of October 2016. In September 2012, the MOX facility contractor submitted a baseline change proposal for the facility that would increase its cost to \$7.7B, and extend the schedule by 3 years to November 2019. After analysis of the proposal by DOE and independent experts, including the U.S. Army Corps of Engineers, DOE believes that the cost of the MOX facility will be substantially higher than the contractor's estimate due to several factors discussed in detail in the following sections.

In addition, the estimates to operate the MOX facility after construction have continued to rise, as well as the cost of other related activities, such as the Waste Solidification Building. According to a recent independent review of the MOX facility operating costs by NNSA's

Office of Defense Programs' Office of Analysis and Evaluation, the annual operating cost of more than \$500M may be underestimated. The analysis indicated that the contractor likely underestimated the cost of maintenance and labor compared to the market values seen at other processing facilities in the NNSA and that issues arising during hot start up could have costly schedule and production rate impacts during the operations phase.

In January 2012, DOE decided to pursue cancelling one of its planned plutonium disposition projects at the Savannah River Site (SRS), a stand-alone facility to disassemble nuclear weapons pits, and convert the plutonium metal into an oxide to be used as feedstock for the MOX facility. Instead, due to changes in the operating plans for other facilities in the DOE complex, DOE's preferred alternative is to use existing facilities to accomplish this part of the plutonium disposition mission. However, the potential savings resulting from cancellation of a stand-alone pit disassembly and conversion facility are not enough to halt the overall rising costs of the program.

As a result of the cost increases, and the current budget environment, DOE announced in April 2013 that it would assess alternatives to the current plutonium disposition approach. Beginning in third quarter FY 2013, NNSA began to slow down activities associated with the plutonium disposition strategy, while assessing alternative strategies.

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## 2.0 ESTIMATE METHODOLOGY AND ROUGH ORDER OF MAGNITUDE ESTIMATE FOR THE MOX FUEL FABRICATION FACILITY

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DOE commissioned and received two sets of estimates: 1) one from MOX Services<sup>1</sup>, the contractor designing and constructing the MOX facility, and 2) the other from the U.S. Army Corps of Engineers (USACE). The purpose of these estimates was to develop an understanding of the total project cost (TPC) and estimate to complete (ETC) the MOX facility given various out-year funding limitations. The two sets of estimates at three different funding constraints of \$350M/year, \$400M/year, and \$500M/year and their respective assumptions and methodologies were investigated by NNSA's Office of Acquisition and Project Management (NA-APM).

### 2.1 MOX SERVICES ESTIMATES

On June 30 2013, MOX Services provided a letter to DOE analyzing the impacts of various funding scenarios and the respective cost and schedule for completion of the MOX facility project.

Table 1 refers to the funding profiles associated with the baseline change proposal (BCP)<sup>2</sup> submitted to NNSA in 2012. All cases contain the scope to complete the MOX project through cold start-up including the contractor fee and the technology transfer cost, but not the cost of the scope for the direct metal oxidation (DMO) capability<sup>3</sup>, hot start-up, operations, and decommissioning.

MOX Services specified that all funding profile scenarios were derived from the baseline change proposal.<sup>4</sup> MOX Services further stated that "as the funding scenarios are based on the 85 percent confident estimate from 2012, the funding scenario results are no better than 85 percent confident and likely less confident as the model appears to understate the impacts from schedule extension due to escalation, supplier disruption, and work-force disruption." The analysis conducted by NA-APM concluded that the estimates based on

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<sup>1</sup> MOX Services represents a LLC, Shaw AREVA MOX Services.

<sup>2</sup> As cited by the FY14 Congressional Budget Request (FY14 CBR),

*"The MFFF project continues to have cost and schedule pressures due to several factors. As a result, NNSA tasked its contractor, Shaw AREVA MOX Services (MOX Services), to conduct a bottoms-up review and update cost and schedule estimates to provide an 85% confidence level. In late FY 2012, MOX Services submitted a Baseline Change Proposal (BCP) with the resulting project cost and schedule estimates to NNSA... The contractor-submitted BCP increases the current TPC from \$4.8B to \$7.7B and extends the schedule from October 2016 to November 2019, which includes one year of schedule contingency."*

<sup>3</sup> DOE decided to pursue cancellation of its plans to construct a stand-alone Pit Disassembly and Conversion Facility and is examining options to perform some plutonium metal to plutonium oxide conversion in the MOX facility. This would require adding a direct metal oxidation capability to the scope of the MOX project.

<sup>4</sup> The Baseline Change Proposal is also referred to as BCP-12-121 Rev. 1, dated September 28, 2012 and is the second Baseline Change Proposal that the MOX project has had at the threshold required for the Secretarial Acquisition Executive approval.

estimating methodology were a Class 3 Estimate, which are within a -10 percent to + 30 percent expected accuracy range.<sup>5</sup>

**Table 1, Summary of Funding Profile Impacts (Shaw AREVA MOX Services LLC, 2013)**

<b>Summary of Funding Profile Impacts</b>				
<b>Case</b>	<b>Out-year Funding Limit \$M/Yr</b>	<b>Total Project Cost (\$B)</b> <i>(amount in parenthesis represents costs with DMO scope<sup>6</sup>)</i>	<b>Estimate to Complete (\$B)</b> <i>(amount in parenthesis represents costs with DMO scope)</i>	<b>Project Complete (with Contingency)</b> <i>(schedule durations do not include completion of DMO scope)</i>
<b>Base</b>	630	<b>7.7</b> <i>(includes DMO Scope)</i>	<b>\$ 3.9</b> <i>(includes DMO Scope)</i>	<b>Nov-19</b> <i>(June -23 with DMO Scope)</i>
<b>1</b>	<i>Best</i>	<b>7.9 (8.1)</b>	<b>\$ 4.1 (\$4.3)</b>	<b>Mar-21</b> <i>(completion date with DMO TBD)</i>
<b>2</b>	500	<b>8.2 (8.4)</b>	<b>\$ 4.3 (\$4.6)</b>	<b>Aug-23</b> <i>(completion date with DMO TBD)</i>
<b>3</b>	400	<b>8.5 (8.7)</b>	<b>\$ 4.7 (\$5.0)</b>	<b>Sep-26</b> <i>(completion date with DMO TBD)</i>
<b>4</b>	350	<b>9.4 (9.7)</b>	<b>\$ 5.6 (\$5.8)</b>	<b>Mar-32</b> <i>(completion date with DMO TBD)</i>

## 2.2 U.S. ARMY CORPS OF ENGINEERS FUNDING CONSTRAINED ESTIMATES

In addition to receiving funding scenario data from MOX Services, the USACE conducted funding profile analyses in 2013 for three different funding profiles: a constrained funding profile of \$350M/year, \$400M/year, and \$500M/year. The USACE had previously conducted an independent cost estimate (ICE)<sup>7</sup> of the TPC, commissioned by DOE’s Office of Acquisition and Project Management (DOE-APM), fulfilling the requirements for the DOE capital acquisition process as outlined in DOE Order 413.3B. Based on that bottom-up ICE, the USACE adjusted the schedule (a schedule constructed from the MOX Services schedule and adjusted per USACE judgment for the purpose of the ICE). Through multiple iterations of further schedule adjustments for the funding scenario exercise, a schedule, and thus cost that corresponded with ± 10 percent of the fiscal resources of the three constrained spend plans, were determined. The results are contained in Table 2.

<sup>5</sup> Based on Cost Estimate Classification Matrix for Process Industry, Advancement of Cost Engineering International (ACEI) Recommended Practices, No. 17R-97, Cost Estimate Classification System, and No. 18R-97, Cost Estimate Classification System – As Applied in Engineering, Procurement and Construction for the Process Industries, dated January 15, 2011.

<sup>6</sup> Costs that reflect Direct Metal Oxide (DMO) Scope were not included in June 30 2013. The cost of DMO Scope was extracted from BCP-12-121 Rev. 1 at \$261,120,690 Estimate to Complete and \$262,341,721 Estimate at Complete.

<sup>7</sup> Revision 0 of the DOE-APM ICE (completed by USACE) published in February 2013.

**Table 2, Summary of Funding Profile Impacts (USACE)**

<b>Summary of Funding Profile Impacts</b>				
<b>Case</b>	<b>Out-Year Funding Limit \$M/Yr</b>	<b>Total Project Cost (\$B)</b>	<b>Estimate to Complete (\$B)</b>	<b>Project Complete (with Contingency)</b>
<b>Base</b> <sup>8</sup>	<i>Constrained funding varies, peak at \$631M</i>	<b>9.4</b>	6.3	<i>Sept-28 (with DMO included)</i>
<b>1</b>	350	<b>11.7</b>	8.6	<i>FY 2040</i>
<b>2</b>	400	<b>10.6</b>	7.6	<i>FY 2035</i>
<b>3</b>	500	<b>10.0</b>	6.9	<i>FY 2027</i>

All cases contain the scope to complete the MOX project. However, in contrast to the MOX Services estimate, the scope of the DMO capability was included, but not the cost of the Contractor Fee and the Technology Transfer. Also, the contingency<sup>9</sup> for the USACE ICE had been estimated at a 95 percent confidence level. The USACE ICE applied the contingency with a linear relationship to project percent complete. However, for the purpose of the constrained funding scenarios, the USACE did not reevaluate the contingency magnitude, and only redistributed the ICE contingency amount based on the revised schedule and the linear relationship to total percent complete. For the approximated schedule adjustments and the minimal revaluation of the contingency, based on an extended schedule, the analysis by NA-APM concluded that the funding estimates were a Class 3 Estimate, which are typically within a -10 percent to + 30 percent expected accuracy range.

### **2.3 ISSUES RELATED TO FACILITY START-UP**

The MOX facility’s design is largely based on two facilities operated by AREVA in France: the Melox fuel fabrication facility and the R4 spent fuel reprocessing facility at the LaHague Plant. Project documentation refers to these as the “reference plants.” The reference plants are 2 – 2.5 times the capacity of the U.S. MOX facility and were started in a different regulatory environment in France than exists with the NRC in the United States.

The most recent applicable experience with the reference plants was a project to expand the Melox facility in the 1990s. The cost and schedule to start-up the Melox expansion was significantly higher than planned due to difficulty in completing integrated testing of the systems in such a large, complex facility. To mitigate these risks the MOX project is training U.S. MOX facility personnel in France at the reference plants and is having personnel from AREVA at SRS to work with the operations staff during start-up of the U.S. MOX facility.

Regarding the regulatory issues involved in start-up, the NRC will oversee the conduct of an Operational Readiness Review (ORR) before it issues a license to operate the MOX facility. Obtaining this license is a Key Performance Parameter (KPP) for the completion of the project and is, per DOE Order 413.3B, a prerequisite to obtaining Critical Decision 4 (CD-4),

<sup>8</sup> Total Project Cost, Independent Cost Estimate Revision 0, Volume 1, May 2013 from USACE.

<sup>9</sup> Government and Contractor Contingency, also known as DOE Contingency and Management Reserve, respectively.



*Approve Start of Operations or Project Completion.* Until CD-4 is attained the project cannot be considered complete and cost charges to the project continue. Radioactive material cannot be introduced to the facility until this license is issued.

The conduct of the ORR will occur during the start-up phase of the project. An ORR typically consists of putting in place the personnel that will operate the facility and having them operate the control panels and other stations in a form of dress rehearsal. Actual procedures developed for the plant are then used to determine the effectiveness of personnel and procedures in keeping the plant operating as designed (i.e., within its approved safety limits under a range of conditions). Several risks to start-up exist which make estimating the cost and duration of this project phase difficult: availability of necessary skill and experience within the NRC to oversee start-up of this type of facility; the time that can occur between when the ORR occurs on-site (demonstrating that the operations personnel have necessary procedures developed and mature conduct of operations in place to ensure safe operations) and when the final approval to operate is granted by the NRC; and NNSA unfamiliarity with the conduct of an NRC ORR and any features of it that are different from those run by DOE personnel.

## **2.4 OPERATIONS COSTS**

The nominal design life of the MOX facility is 40 years, however, it will take approximately 15 years to complete the 34 MT mission. The current annual estimate to operate the MOX facility after cold start-up is approximately \$543M/year.

This estimate has been determined by averaging the escalated costs over the 15 years of operations (inclusive of hot start-up, steady state operations and de-inventory/flushing). The escalated life cycle cost estimate includes the following assumptions: (a) the MOX facility CD-4 date is November 2019; (b) the MOX facility de-inventory/flushing is complete in March 2034; (c) includes all MFFF operating costs, including operations costs prior to CD-4; and (d) the annual operating cost out-year projections are extrapolated based on the proposal for the scope to complete the first 8 fuel assemblies. The estimate includes labor during operations and other direct costs (ODC) including spare parts, sub-contracts such as maintenance, drums/boxes/containers information technology maintenance, chemicals/gases, etc. Also included are NRC pass-through costs for the regulatory oversight of MOX facility, costs for mission reactor personnel to support qualification of MOX fuel produced in the MOX facility, and contractor fee. Additionally, the projection includes costs for Management and Operating (M&O) support such as utility costs, environmental permits and monitoring, emergency response, etc. Six months of operating costs were included for de-inventory activities and flushing.

In December 2012, NNSA's Office of Fissile Materials Disposition authorized an ICE for the operating costs for the MOX facility using NNSA's Office of Defense Programs' Office of Analysis and Evaluation. NNSA finalized the independent report in April 2013. The findings included: annual operating cost estimates by year by work breakdown structure (WBS); comparisons across like-facilities including shift analysis; and a discussion of risk and cost drivers. In summary, the report indicated that the \$543M/year average may be

low due to underestimating equipment maintenance costs and the risk that hot start-up activities may take longer than anticipated.

### 3.0 DISCUSSION OF ANALOGOUS DOE FACILITIES

The MOX facility main process building is hardened concrete construction housing process equipment contained in approximately 340 gloveboxes built to prevent the release of radioactive material, much of which is in the form of a very fine powder. The glovebox equipment in particular is very specialized (much of it had to be procured from vendors in Europe). In addition, because of the dose rates associated with plutonium materials, the MOX facility is designed to be largely automated. As currently envisioned, within the hardened space of the main process building, the only significant plutonium handling functions not automated are those for opening cans of plutonium oxide sealed at certain sites, and the DMO equipment being considered for converting plutonium metal into oxide. The following list is the portfolio of DOE's recent experience in construction of large nuclear projects. These projects have begun construction within the last ten years, have total project costs greater than \$500M, and were required to adhere to nuclear quality assurance standards (NQA-1).

**Table 3, Consolidation of Historic DOE Project Baseline Change Information<sup>10</sup>**

<i>Project</i>	<i>Square Footage</i>	<i>TPC at CD-2</i>	<i>TPC (current)</i>	<i>No. of BCPs Approved</i>	<i>% Complete at each BCP (date)<sup>11</sup></i>
<i>Sodium Bearing Waste Facility (SBWF)</i>	<i>73,000<sup>12</sup></i>	<i>\$462M</i>	<i>\$571M (actual)</i>	<i>2</i>	<i>1: 50% (Jan. 2009) 2: 90% (Feb. 2011)</i>
<i>Depleted Uranium Hexafluoride 6 Conversion (DUF6)</i>	<i>80,000<sup>13</sup></i>	<i>\$345.5M</i>	<i>\$580M (actual)</i>	<i>2</i>	<i>1: 50% (Oct. 2007) 2: 80% (Dec. 2008)</i>
<i>Salt Waste Processing Facility (SWPF)</i>	<i>140,000<sup>14</sup></i>	<i>\$900M</i>	<i>\$1,950M (TBD, const. only, no start up)</i>	<i>2 (Interim)</i>	<i>1: 10% (Jan. 2009) 2: 70% (Sep. 2013)</i>
<i>Mixed Oxide Fuel Fabrication Facility (MOX)</i>	<i>500,000</i>	<i>\$4,814M</i>	<i>TBD (BCP submitted \$7,675M)</i>	<i>2<sup>15</sup> (Interim)</i>	<i>1: 20% (Dec. 2008) 2: 50% (Sep. 2012)</i>

<sup>10</sup> Data compiled as of October 2013

<sup>11</sup> Calculated from the Department's Project Assessment and Reporting System earned value data at time of each BCP. Percentages are approximate and rounded to the nearest ten percent.

<sup>12</sup> Data from the Commissioning Working Group.

<sup>13</sup> Source: Portsmouth and Paducah DUF<sub>6</sub> Conversion Final Environmental Impact Statement (EIS) Summaries, Conversion Process Description sections.

<sup>14</sup> SWPF fact slide provided by SWPF project personnel Oct. 23, 2013.

<sup>15</sup> Directed Change (annual funding below approved baseline) increased the TPC by \$43M.

The MOX project can be considered to be analogous to DUF6, Sodium Bearing Waste Treatment Facility (SBWF), and Salt Waste Processing Facility (SWPF) based on the following factors:

- First-of-a-kind facility
- Applicability of the nuclear-grade quality assurance standard (ASME NQA-1)
- Applicability of nuclear safety requirements, either by the NRC or the Defense Nuclear Facilities Safety Board (DNFSB)

Each of these facilities is built to protect workers and the external environment. Quantities of commodities like concrete and steel are affected by the need to provide this protection. Additionally, each of these facilities offers insights into the challenges of starting up a complex nuclear facility. In the SWPF and SBWF, the purpose is to treat waste generated from processing products from the nuclear reactor fission process, meaning that the structure must be able to provide shielding from intense radiation. In the case of the MOX facility, the material is also radioactive, but there are smaller amounts batch handled in glovebox equipment (with the desired throughput achieved through the use of multiple, parallel lines). DUF6 processes depleted uranium material where the radiological hazards can be seen as matched by the chemical toxicity hazards; protection from radiation is important, but it is to a lesser degree than it is in a facility like the SWPF.

The MOX facility is unique (i.e., factors that make it difficult to identify strong analogs) because of the amount of special facility equipment in gloveboxes controlled by automation. DOE has not built and operated a stand-alone plutonium processing facility since the Los Alamos Plutonium Facility 4 (PF-4) in 1978, so identifying an ideal technical analog in the United States is difficult. Furthermore, facilities built in the era of PF-4 did not have automated plutonium handling.

In project terms, the SWPF, DUF6, and SBWF projects are the best analogs available among DOE projects to compare to the MOX facility. Due to the quality, security, and safety requirements, completing design before establishing performance baseline costs and schedule estimates is critical to success.

### **3.1 DEPLETED URANIUM HEXAFLUORIDE FACILITIES**

The Depleted Uranium Hexafluoride (DUF6) facilities are located in Paducah, Kentucky and Portsmouth, Ohio; the two facilities combined size is approximately 183,000-square feet, or 40 percent of the size of the MFFF for a total project cost at CD-4 of \$592M. The purpose of the DUF6 facilities is to process the DOE inventory of DUF6 to a more stable chemical form suitable for beneficial reuse or disposal, utilizing technology of a proprietary fluidized bed. At the start of construction, there was no lab scale, pilot scale, or full scale testing of the technology. The facilities were constructed as capital asset line item projects under the DOE acquisition process as outlined in DOE O 413.3A<sup>16</sup>, and at the onset of the project a legacy amount of approximately 700,000 metric tons of DUF6 were to be processed at

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<sup>16</sup> DUF6 was executed under DOE O 413.3A, rather than DOE O 413.3B which was released November 2010.

Paducah, Portsmouth and other East Tennessee Technology Park (ETTP) sites during the operations run. The project achieved Construction Complete in May and December 2008 (Portsmouth and Paducah, respectively) and CD-4 in October 2010. The project also had two baseline changes requiring Secretarial Acquisition Executive approval<sup>17</sup>, the first with a total project cost increase of \$84M and a one-year schedule delay with the construction estimated at 70 percent complete<sup>18</sup>; the second only 14 months later for an additional increase of \$162M and a 25-month schedule delay.

For DUF6, the CD-4 definition included achievement of beneficial occupancy, the ORR complete, pre-operational performance tested and design requirements demonstrated. However, the DUF6 facilities did not have simulants available for a “cold” functional test and thus transitioned to additional hazards such as H<sup>2</sup> and higher temperature limits post completion of ORR, authorized in May 2010. The hot functional test, introduction of hazards aforementioned, was not part of the CD-4 requirements. The first introduction of DUF6 began in July 2010 at the Portsmouth facility in a series of six tests that investigated different functionalities of the process. Test 1 began on July 14, 2010, with the completion of the first 5 tests in October 6, 2010. However, on September 15, 2010, (one month prior to CD-4), Test 6 began experiencing equipment performance issues that created cross-contamination of the process lines. Although full operations were intended to commence in the fall of 2010<sup>19</sup>, based on an early estimate of the operations baseline that was published three months prior to construction completion, events continued to prolong the start-up of the DUF6 facility far beyond what was originally estimated. As a project progresses past CD-4, issues discovered during operations that have root causes attributable to the design and construction transfer entirely to DOE, becoming an owner’s risk. In FY 2014, DOE requested funding for the Paducah and Portsmouth facilities to continue steady state operations with emphasis on finally achieving nominal conversion capacity.

### **3.2 SODIUM BEARING WASTE FACILITY**

The Sodium Bearing Waste Facility (SBWF), also referred to as the Integrated Waste Treatment Unit, is a 53,000-square foot facility that is designed to treat 900,000 gallons of radioactive liquid waste stored in underground tanks located in Idaho. The SBWF uses a steam-reforming technology to heat up the liquid waste, essentially drying it, consolidating the solid, granular material, packaging it in stainless steel canisters, and storing the containers in above-ground concrete vaults at the site. Ultimately, the treated material will be transported to a national geologic repository for permanent disposal. DOE negotiated a consent order with the State of Idaho for removal of the waste by a specific timeline, with fiscal consequences to DOE if the terms of the agreement were not met. Like DUF6, the

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<sup>17</sup> Per DOE O 413.3A, a Baseline Change Proposals requiring Secretarial Acquisition Executive approval are required for approval if the performance baseline changes includes an increase in excess of the lesser of \$25M or 25% (cumulative) of the original CD-2 cost baseline, a delay of six-months or greater (cumulative) from the original project completion date, or a change in scope that affects the ability to satisfy the mission need, an inability to meet a Key Performance Parameter, or non-conformance with the current approved Project Execution Plan, which must be reflected in the Project Data Sheet.

<sup>18</sup> Source is the Memorandum dated 10/1/2007 of the Approval of BCP of DUF 6 through Under Secretary of Energy to the Department of Energy Deputy Secretary.

<sup>19</sup> Based on the Operations Baseline, Revision 1, UDS-OPS-BASE, March 2008.

project was constructed in accordance with DOE O 413.3A and achieved CD-0, CD-1, and CD-2/3<sup>20</sup> baseline in January 2005, August 2005, and December 2007 respectively. The baseline cost for the project was \$462M.

The first baseline change proposal from the CD-2 baseline was approved in January 2009 to increase the project cost from \$462M to \$571M and extend the project schedule by 11 months for an anticipated completion date of August 2011. Post the first BCP, and unlike DUF6, SBWF was executed during the timeframe in which DOE's revised system for assessing capital project performance (PARS II) was implemented for enhanced transparency of cost and schedule performance. The cost and schedule data produced by the Earned Value Management System (EVMS) allowed DOE to independently assess project performance and complete advanced schedule analysis that subsequently led to downgrading the project status because of schedule performance degradation starting in October 2011<sup>21</sup>. In February 2011, a second baseline change proposal was processed that included a schedule extension of four months to December 2011 and that specified that the project now would have a contract modification for a cost cap of \$571M.<sup>22</sup> Included in the second baseline change proposal was the removal of scope, specifically the Comprehensive Performance Testing required for operation. The project achieved CD-4 in April 2012, four months post the second baseline's projected completion date. In May 2012 the cost not billed to DOE due to a contract modification exceeded \$90M, of which the majority of those costs were directly attributable to the start-up of the facility. As with DUF6, SBWF experienced events that elongated the proposed time to full operation, of which the realized risk is held entirely by DOE as the project has completed CD-4. As of January 2014, SBWF has still not become fully operational.

### **3.3 SALT WASTE PROCESSING FACILITY**

The Salt Waste Processing Facility (SWPF) is a 140,000-square foot facility (~28 percent the size of the MOX facility) now under construction at SRS. At this time, the estimated cost at completion for the facility is approximately \$1.95B, although the cost to perform commissioning and start-up activities post-construction are being renegotiated with the contractor. The purpose of the SWPF is to separate and concentrate high-activity salt wastes from the high-level waste tanks at SRS to prepare them for processing at the site's Defense Waste Processing Facility (DWPF) and prepare a lower activity waste stream for disposal at the SRS Saltstone Facility. This separation allows DOE to send only the most intensely radioactive salt waste (there are an estimated 33 million gallons of salt waste at SRS) to the DWPF and supports the site's commitment to close its high level waste tanks by the year 2028.

The project baseline was established (CD-2), per the requirements of DOE Order 413.3A, in 2007 with a TPC of \$900M and a CD-4 date of November 2013. Construction was

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<sup>20</sup> Critical Decision 2 and Critical Decision 3 are sometimes a combined decision by the Acquisition Executive in the DOE O 413.3A and DOE O 413.3B process.

<sup>21</sup> A monthly report published for DOE senior management by the DOE Office of Acquisition and Project Management (DOE-APM), formally the Office of Engineering and Construction Management.

<sup>22</sup> Contract Modification 167.

authorized at CD-3 in 2009 at which time a baseline change was approved increasing the TPC to \$1.34B and extending the CD-4 date to October 2015.

A prototypical testing facility, at much lower throughput, is demonstrating the same technical processes under construction at the SWPF, including the separations technologies to be used to separate the high activity components of the waste. This has allowed the project to validate the technical parameters that it will have to meet (i.e., the Key Performance Parameters that define the state of the completed project). These include throughput, successful completion of cold commissioning, and producing waste streams that meet the acceptance requirements of DWPF and the Saltstone Facility. Use of this testing facility minimized the largest remaining cost risks that the project faced<sup>23</sup>. However, other lower-probability, lower-impact risks on the project were underestimated and the contingency freed up by operation of the testing facility was insufficient to cover them. As of August 2013, based on funds spent to date (~\$1.3B) and estimate at completion (~\$1.95B) the facility was approximately 70 percent complete<sup>24</sup>. Additionally, the ~\$1.95B does not include start-up activities and as a result the project will be more expensive than originally planned.

One driver of the project delays – with associated cost impacts – was the difficulty of the project to acquire, on schedule, the 10 large process tanks for the plant. This issue was identified in 2010, and while the project attempted to re-sequence work to mitigate the impact, it nevertheless led to subcontractor vendor termination for default and an approximate 3-year impact to project completion. Like the MOX facility, the project has now procured almost all of its required process equipment, with bulk commodity installation (pipe, insulation, ductwork, etc.) being the primary driver of performance now.

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<sup>23</sup> CD-3 BCP approval memo references continuing to obtain data from the prototype systems as part of the Project Execution and Risk Management for the project

<sup>24</sup> This may be adjusted once the new baseline, including renegotiated commissioning, is established.

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## 4.0 ACTIVITIES TO ESTABLISH A NEW BASELINE FOR THE MOX FACILITY

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Should the Secretary decide to proceed with completion of the MOX project, the following would need to be accomplished:

- NNSA would request a new baseline change proposal and associated contract cost proposal from the contractor. Over a year has elapsed since the first BCP was submitted and, in addition to a new funding profile, the spend rate and progress to date are different. The contract cost proposal submitted in October 2012 is also no longer valid.
- MOX Services would submit the requested BCP and cost proposal. Previous experience is that this required six to eight months; however, because the project did a revised bottom-up estimate in 2012 and built an integrated resource-loaded schedule in 2013, it is expected to require less time.
- DOE-APM would commission an external independent review (EIR) and ICE of the BCP per DOE Order 413.3B. Just like the preparation time for the BCP and cost proposals, the time to review them should be shorter due to the use of many of the same personnel already familiar with the project. However, the ICE would likely include development of an independent schedule prior to the beginning of the development of the ICE.
- DOE and the Defense Contract Audit Agency (DCAA) would audit the cost proposal to ensure the costs are appropriate, allowable, and meet all the applicable requirements of the Federal Acquisition Regulations (part 15). There is a team of federal price analysts already familiar with the previous cost proposal; it is expected that many of the same personnel would be used to review the new cost proposal submitted to the project.
- DOE-APM and MOX Services would conduct a bilateral reconciliation between the MOX Services estimate in the BCP and the ICE to identify and reconcile the differences between the estimates for submittal to the Acquisition Executive as a proposed new TPC.
- The Deputy Secretary of Energy as the Secretarial Acquisition Executive would approve a new TPC and schedule based on input from the above process and advice from the Energy Systems Acquisition Advisory Board (ESAAB).



## **Appendix B**

### **The Advanced Disposition Reactor Study:**

### **A Comprehensive Analysis of Plutonium Disposition Options Using Advanced Fast Reactors**



The Advanced Disposition Reactor Study:  
A Comprehensive Analysis of Plutonium Disposition Options  
Using Advanced Fast Reactors

Prepared by the Office of Nuclear Energy  
April 2014

## Executive Summary

Disposition of separated plutonium is an important and urgent element of global nuclear threat reduction.<sup>1</sup> Currently, more than 240 metric tons (MT) of separated civil plutonium and approximately 80 MT of weapons plutonium that has been declared excess to weapons needs exist globally.<sup>2,3</sup>

The U.S. and Russian Federation are leading efforts to dispose of excess weapons material through the Plutonium Management and Disposition Agreement (PMDA), which commits each country to dispose of at least 34 metric tons of weapon-grade plutonium withdrawn from their respective nuclear weapon programs.<sup>4</sup> However, the reference U.S. PMDA implementation approach, using MOX in light water reactors, has experienced significant delays and cost increases. Recognizing the impact of plutonium disposition on global nuclear threat reduction, the scope of the challenge, and the unique characteristics of fast-spectrum burner reactors applicable to plutonium disposition, this Advanced Disposition Reactor (ADR) Study was chartered as part of the effort to explore alternatives to the reference PMDA implementation approach.<sup>5</sup>

Fast-spectrum burner reactor attributes include: 1) the ability to use metal fuel, 2) impurity tolerance in the fuel, and 3) higher plutonium loadings. These characteristics have generated broad international interest in the use of these reactors for plutonium disposition. Three plutonium disposition options using advanced fast-spectrum burner reactors were analyzed to determine the technical viability, cost, and schedule for plutonium disposition in a once-through open cycle to support PMDA implementation:

- Option I: Single-Module<sup>6</sup> ADR Prototype
- Option II: Two-Module ADR Prototype
- Option III: Fast Flux Test Facility (FFTF) Restart

For the purpose of this study, the ADR was defined as a Nuclear Regulatory Commission licensed advanced pool-type fast-spectrum liquid-metal cooled reactor using metal fuel. Metal fuel was chosen because of the successful operating experience with the more than 14,000 fuel pins irradiated in the U.S., passive safety characteristics, and compatibility with the feed form. The study considered the processing of feed materials, fuel fabrication, transport of nuclear materials, and storage of the spent nuclear fuel. Optimized use of existing facilities was included to the greatest extent possible.

This study indicates that advanced fast-spectrum burner reactors are technically viable options for use in plutonium disposition, consistent with the approach selected by the Russian government for disposition of their surplus plutonium. Advanced fast-spectrum burner reactors can meet all of the current PMDA spent

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<sup>1</sup> "Remarks by President Obama at Opening Plenary Session of the Nuclear Security Summit," The White House, March 27, 2012. Accessed August 14, 2013. <http://www.whitehouse.gov/photos-and-video/video/2012/03/27/president-obama-speaks-nuclear-security-summit#transcript>.

<sup>2</sup> "Plutonium," World Nuclear Association, Last updated March 2012. Accessed August 12, 2013. <http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Fuel-Recycling/Plutonium/#.UgueyG3pwUJ>.

<sup>3</sup> "Military Fissile Material Stockpile (Metric Tons)," NTI: Nuclear Threat Initiative. Accessed August 12, 2013. [http://www.nti.org/media/pdfs/military\\_fissile\\_material\\_stockpile\\_1.pdf](http://www.nti.org/media/pdfs/military_fissile_material_stockpile_1.pdf) (October 2012).

<sup>4</sup> *Agreement between the Government of United States of America and Government of Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation.*

<http://www.state.gov/documents/organization/18557.pdf>. The April 2010 Protocol to the 2000 PMDA is available at [http://dtirp.dtra.mil/pdfs/pmda\\_protocol\\_text.pdf](http://dtirp.dtra.mil/pdfs/pmda_protocol_text.pdf).

<sup>5</sup> The National Nuclear Security Administration is separately reviewing the reference MOX approach, as well as other possible alternatives.

<sup>6</sup> The ADR can be configured with a single reactor module or with two reactor modules sharing infrastructure as a "power block."

fuel disposition requirements. The costs of these options could be reduced if the PMDA burnup criteria were to be eliminated, leaving as the primary disposition criterion only the self-protection requirement.<sup>7</sup> A key benefit identified through this study was significant estimated savings (\$1-2B) attributable to use of metal feed (thus avoiding oxidation and aqueous polishing steps). Additional benefits include: 1. surplus inventory reduction at Pantex would be accelerated through dual-path pit processing at LANL and SRS, enabling avoidance of construction of the Material Staging Facility at Pantex, 2. production challenges at Los Alamos National Laboratory (LANL) arising from deferral of the CMRR-NF project and projected increased pit-production demands would be reduced through transfer of some pit-disassembly work to the Savannah River Site (SRS) K-Area Complex, 3. demands on Office of Secure Transport (OST) resources would be reduced, and 4. demands on the SRS H-canyon would be reduced. The key results for Options I and II are shown in Figure ES-1 below.

Specific outcomes for Option I and Option II include:

- Capital cost for fuel production facility (K-Area Fuel Fabrication Facility) – \$1.9B (\$1.1B less than for a green-field fuel fabrication facility)
  - Use of the MOX Fuel Fabrication Facility at SRS was considered but K-Area complex was more cost effective
- ADR can be operational in 14-15 years (aligned with the operational readiness of the K-Area Fuel Fabrication Facility)
  - Option I (\$4B), a single-module ADR, fulfills the 1.3 MT/yr throughput criteria only if the disposition criteria are reduced to the requirement for self-protection; the throughput is reduced to 0.8 MT/yr if the current PMDA burnup criteria are used
  - Option II (\$6B), a two-module ADR, fulfills all current PMDA criteria at 1.6 MT/yr throughput; throughput increases to 2.6 MT/yr if only the requirement for self-protection is used
- Cost for independent spent fuel storage installation – \$50M capital, plus \$10M/yr
- For Option II, net estimated annual operating costs are less than \$100M/yr over 30 years.

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<sup>7</sup> The PMDA includes three explicit and one implicit disposition criteria: minimum fuel assembly burnup, minimum batch-average burnup, minimum one-meter dose rate after thirty years cooling, and isotopic degradation such that the spent fuel no longer contains weapons plutonium as defined in the PMDA. The burnup criteria are limiting; the dose-rate criterion is met at much lower burnup than is specified as the minimum burnup. However, the implicit isotopic degradation requirement is more limiting than the dose-rate criterion for the ADR; thus, blending of fuel- or reactor-grade plutonium for isotopic degradation would also be required in conjunction with the dose-rate criterion. The minimum dose-equivalent rate codified in the PMDA, which was adapted from the IAEA and NRC requirements for self-protection, is 1 Sv/hr one meter from the centerline thirty years after irradiation.

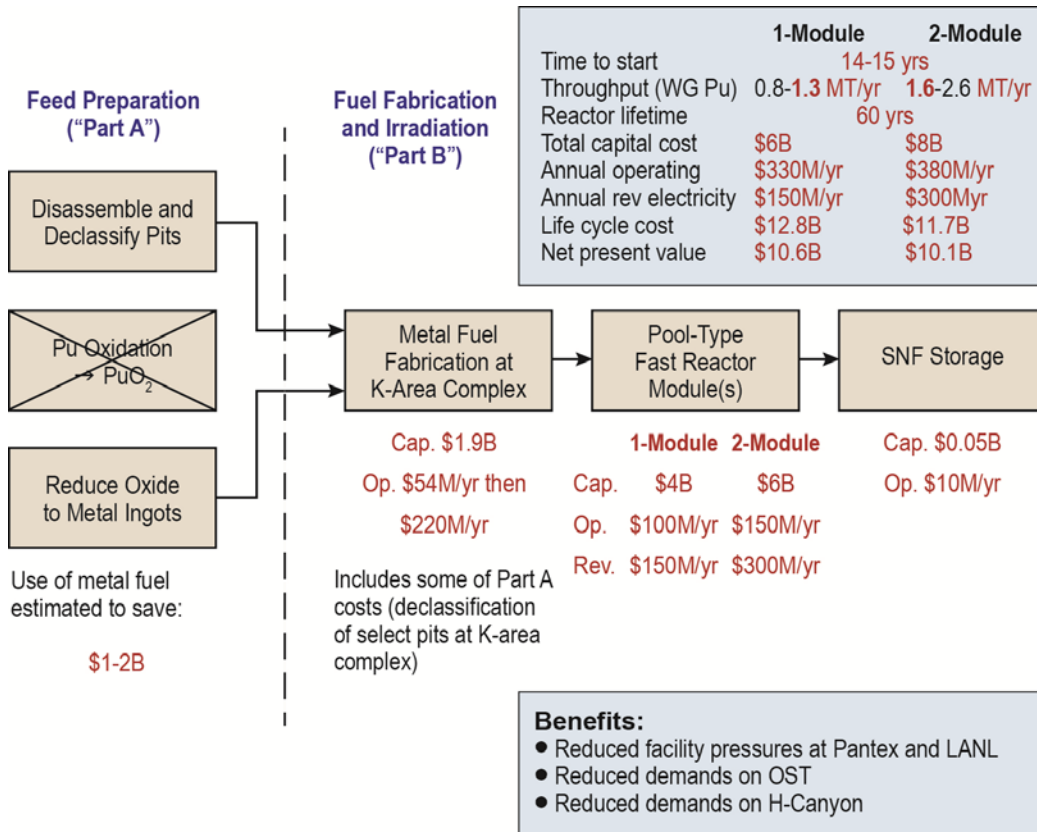


Figure ES-1. Results of Assessment for Options I and II

Restarting the FFTF, a fast-spectrum test reactor closed in 1994, enables initiation of PMDA disposition in five years with a throughput of 330 kg/yr. The key results for this Option III are shown in Figure ES-2 below. In addition, FFTF restart reduces technical risks for implementation of Options I and II.

Specific outcomes for Option III include:

- Near-term disposition capability
  - Initiates disposition in 5 years using restarted FFTF (\$1.4B to restart)
  - Fulfills all of the current PMDA criteria for 0.3 MT/yr throughput; throughput increases to 0.6 MT/yr if only the requirement for self-protection is used
- Low upfront cost, \$1.4B for FFTF restart and \$0.1B for restart of the Idaho National Laboratory (INL) Fuel Manufacturing Facility (0.3 MT/yr throughput)
- Net estimated annual operating costs are less than \$200M/yr
- Option for electricity generation (additional \$300M capital), for on-site government use.

Combining Options I or II with Option III provides decreased technical risk for Option I or II implementation, leverages use of existing DOE assets (Fuel Manufacturing Facility, FFTF, and K-Area Complex), and maximizes plutonium throughput (for Option I/III with only the requirement for self-protection = 2 MT/yr, for Option II/III with current PMDA criteria = 1.9 MT/yr), thereby shortening the mission duration.

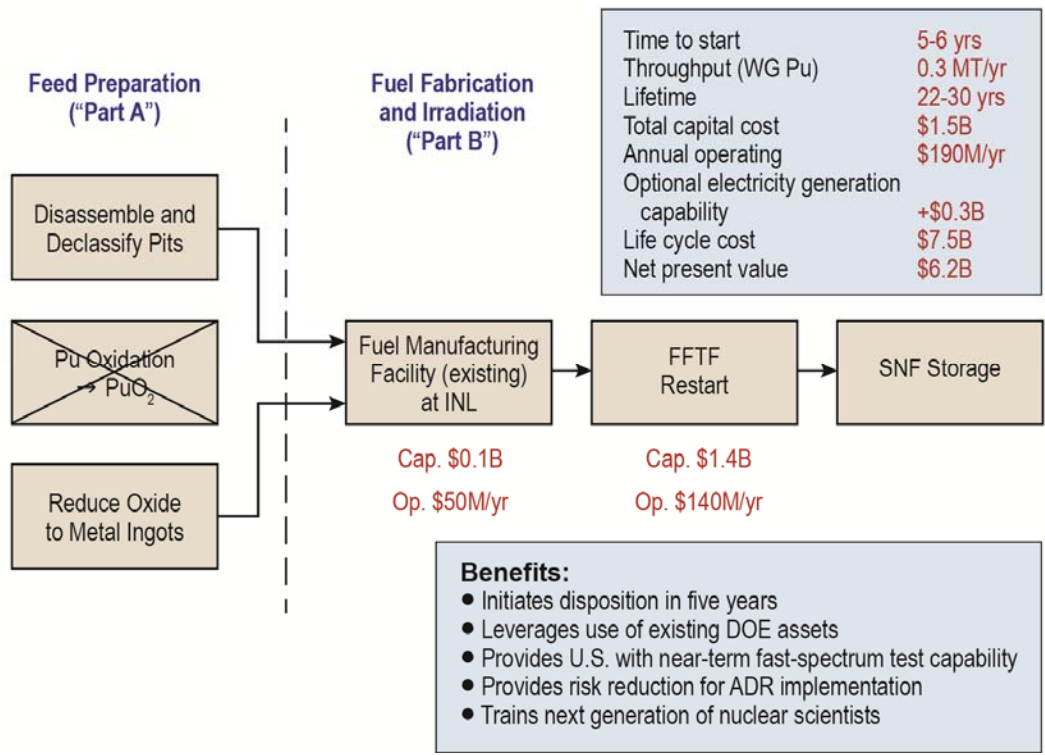


Figure ES-2. Results of Assessment for Option III

These preliminary technical results justify a more in-depth analysis of once-through fast-spectrum burner reactor options for plutonium disposition. Priority next-steps in further defining the technical role of ADRs in plutonium disposition include:

- Perform detailed analysis of the mission requirements for the K-Area Fuel Fabrication Facility
- Engage industry in defining required attributes of a fast-spectrum burner reactor
- Refine construction and operating cost estimates for the ADR approach in the context of current safety, security, and licensing requirements
- Revisit cost and schedule estimates for the FFTF restart in the context of the plutonium disposition mission.

These technical results could help to inform broader policy analyses on the possible roles of fast-spectrum burner reactor options for plutonium disposition.

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## Acronyms

ADR	Advanced Disposition Reactor
ALMR	Advanced Liquid-Metal Reactor
AP	Aqueous Polishing
BOT	Build-Operate-Transfer
BN-800	Russian acronym designating the “fast neutron, 800 MWe” reactor
CBCG	Columbia Basin Consulting Group
CISAC	Committee on International Security and Arms Control
DMO	Direct Metal Oxidation
DOR	Direct Oxide Reduction
DP	Office of Defense Programs (NA-10)
CSB	Canister Storage Building
EBR-II	Experimental Breeder Reactor II
FFTF	Fast Flux Test Facility
FMF	Fuel Manufacturing Facility
FOAK	First-of-a-kind
FSAR	Final Safety Analysis Report
GOCO	Government-Owned, Contractor-Operated
HDH	Hydride/De-Hydride
INL	Idaho National Laboratory
IRT	Independent Review Team
ISFSI	Independent Spent Fuel Storage Installation
KAMS	K-Area Material Storage
KAFF	K-Area Fuel Fabrication
KIS	K-Area Interim Surveillance
LANL	Los Alamos National Laboratory
LCC	Life Cycle Cost
LER	Lithium Electrochemical Reduction
LWR	Light Water Reactor
MCDOR	Multi-Cycle Direct Oxide Reduction
MFFF	MOX Fuel Fabrication Facility
NAS	National Academy of Sciences
NEPA	National Environmental Policy Act
NPV	Net Present Value
NRC	Nuclear Regulatory Commission
OFMD	Office of Fissile Materials Disposition
PDC	Pit Disassembly and Conversion
PDCF	Pit Disassembly and Conversion Facility
PDP	Plutonium Disposition Program

PMDA	Plutonium Management and Disposition Agreement
SFS	Spent-Fuel Standard
SRS	Savannah River Site
TPC	Total Project Cost
WIPP	Waste Isolation Pilot Plant

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## Introduction

Disposition of separated plutonium is an important and urgent element of global nuclear threat reduction (President Obama 2013). Currently, more than 240 metric tons (MT) of separated civil plutonium (World Nuclear Association 2012) and approximately 80 MT of weapons plutonium that have been declared excess to weapons needs exist globally (Nuclear Threat Initiative 2013). Additionally, more than 1000 MT of civil plutonium has accumulated in spent power reactor fuel worldwide.

The U.S. and Russian Federation are leading efforts to dispose of excess weapons material through the *Plutonium Management and Disposition Agreement* (PMDA), which commits each country to dispose of at least 34 MT of weapons plutonium withdrawn from their respective nuclear weapon programs (U.S. and Russian Federation 2000) (U.S. and Russian Federation 2010). However, the reference U.S. PMDA implementation approach, irradiating plutonium as mixed-oxide (MOX) fuel in light water reactors (LWRs), has experienced significant delays and cost increases. Recognizing the impact of plutonium disposition on global nuclear threat reduction, the scope of the challenge, and the unique characteristics of fast-spectrum burner reactors applicable to plutonium disposition, this Advanced Disposition Reactor (ADR) study was chartered as part of an effort to explore alternatives to the reference PMDA implementation approach.<sup>1</sup> To provide international perspective, representatives from the United Kingdom Nuclear Decommissioning Authority participated in this ADR Study.

## Purpose

Fast-spectrum burner reactor attributes include: 1) the ability to use metal fuel, 2) high fissile content in the fuel, which means that a relatively large amount of plutonium can be contained in the fuel and in the core overall, compared to LWRs, and 3) a higher tolerance for impurities in the fuel. Furthermore, fast-spectrum burner reactors are typically designed for plutonium-bearing fuels. Plutonium-bearing fuels have been successfully demonstrated through the fast reactor programs of the U.S., Russia, France, Germany, the UK, and Japan. These characteristics have generated international interest in the use of these reactors for plutonium disposition.

This ADR Study analyzes the technical viability, cost, and schedule for plutonium disposition using advanced fast-spectrum burner reactors in a once-through open cycle to support PMDA implementation. Three options were analyzed:

- Option I: Single-Module<sup>2</sup> ADR Prototype
- Option II: Two-Module ADR Prototype
- Option III: Fast Flux Test Facility (FFTF) Restart

For the purpose of this study, the ADR was defined as a Nuclear Regulatory Commission (NRC) licensed advanced pool-type fast-spectrum liquid-metal cooled burner reactor using metal fuel. Metal fuel was chosen because: 1) it is supported with an extensive U.S. experimental database, 2) operational experience with it has been successful, 3) it has positive passive safety characteristics, and 4) it is compatible with a metal feed form. The reference ternary U-Pu-10Zr metal alloy fuel form developed by the U.S. Advanced Liquid-Metal Reactor (ALMR) program was successfully demonstrated in the Experimental Breeder Reactor II (EBR-II) and the FFTF.

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<sup>1</sup> The National Nuclear Security Administration is separately reviewing the reference MOX approach, as well as other possible alternatives.

<sup>2</sup> The ADR can be configured with a single reactor module or with two reactor modules sharing infrastructure as a “power block.”

The study considered the processing of feed materials, fuel fabrication, transport of nuclear materials, and storage of the spent nuclear fuel. Green-field facilities were considered, as was optimized use of existing facilities to the greatest extent possible. However, the options have not been optimized.

## Background

During the early stages of the Plutonium Disposition Program (PDP) from 1992-1994, disposition of the excess weapons plutonium was perceived to be an urgent need. During that period, the PDP considered a variety of reactor options – existing and partially complete LWRs, advanced LWRs, Canadian Deuterium Uranium (CANDU) reactors, advanced liquid metal fast reactors, and gas-cooled thermal reactors. The initial Plutonium Disposition Study called for disposition of 100 MT of plutonium over a 25-year time period; thus, options that achieved disposition at a faster rate were preferred. This 25-year constraint led to a sharp focus on disposition using existing reactors, and all domestic work on advanced reactor options ceased in 1995. To quote the touchstone National Academy of Sciences (NAS) report, “Advanced reactors should not be specifically developed or deployed for transforming weapons plutonium into spent fuel, because that aim can be achieved more rapidly, less expensively, and more surely by using existing or evolutionary reactor types” (Committee on International Security and Arms Control, National Academy of Sciences 1995).

Since the PDP’s inception, the worldwide stockpiles of both weapons and separated civil plutonium have continued to grow such that the relevant problem is no longer limited to the 68 MT of excess weapons plutonium (34 MT each for the U.S. and Russia) committed for disposition in the PMDA. With the evolution of threat considerations including possible use of improvised nuclear devices, large stocks of separated plutonium are now considered more of a liability than an asset. Thus, this study analyzes technology options that could support disposal of plutonium stocks beyond 34 MT of excess U.S. weapons plutonium associated with the PMDA, including more than 14 MT of fuel-grade and reactor-grade U.S. plutonium that does not meet the criteria (including isotopic limits) defined for feed materials in the PMDA and approximately 7 MT of additional U.S. excess pit-origin plutonium declared excess to defense needs in 2007.

## Constraints Derived from the Plutonium Management and Disposition Agreement

The PDP, which is managed by the Office of Fissile Materials Disposition (OFMD) within the National Nuclear Security Administration (NNSA), is being implemented in accordance with the PMDA, which was signed in 2000 and amended in 2010. The PMDA commits the U.S. and Russia each to dispose of 34 MT of weapons plutonium at a minimum rate of 1.3 MT/yr. The agreement specifies that this disposition be accomplished in the U.S. by irradiating the material as MOX fuel in existing commercial LWRs and in Russia by irradiating the material as MOX fuel in the BN-600 and BN-800 fast reactors. Neither the ADR nor any other advanced fast reactor is defined in the PMDA for use as a U.S. disposition reactor. However, both the BN-600 and the BN-800 are fast reactors, and the BN-800 is more representative of the ADR. *Therefore, the disposition criteria for the BN-800 were used as the baseline disposition criteria for evaluating the ADR options as a part of this study. The impacts of relaxed disposition criteria resulting from elimination of the minimum burnup requirements were also considered.*

## **Report Organization**

The remainder of this report contains: a description of the key elements of the ADR approach; a description of the options assembled from these key elements; the results of the analysis; a discussion of the results; and conclusions and recommended next steps. Additional detailed information is contained in the Appendices.



## Key Elements of the Advanced Disposition Reactor Approach

The 34 MT of U.S. plutonium feed materials identified for disposition in accordance with the PMDA exist in two physical forms, metal and oxide. The metal is in the form of pits, clean metal, and metal ingots, and much of it remains classified in terms of one or more physical attributes.<sup>3</sup> The activities required to disposition surplus pits (from Pantex) and surplus oxide and metal [from the K-Area Material Storage (KAMS) facility at the Savannah River Site (SRS)] include multiple operations at several facilities and sites. These activities are divided into four key elements, described in the following subsections: front-end feed preparation activities, metal fuel fabrication activities, reactor irradiation, and spent fuel storage. These are shown as a simple flow diagram in Figure 1 below.

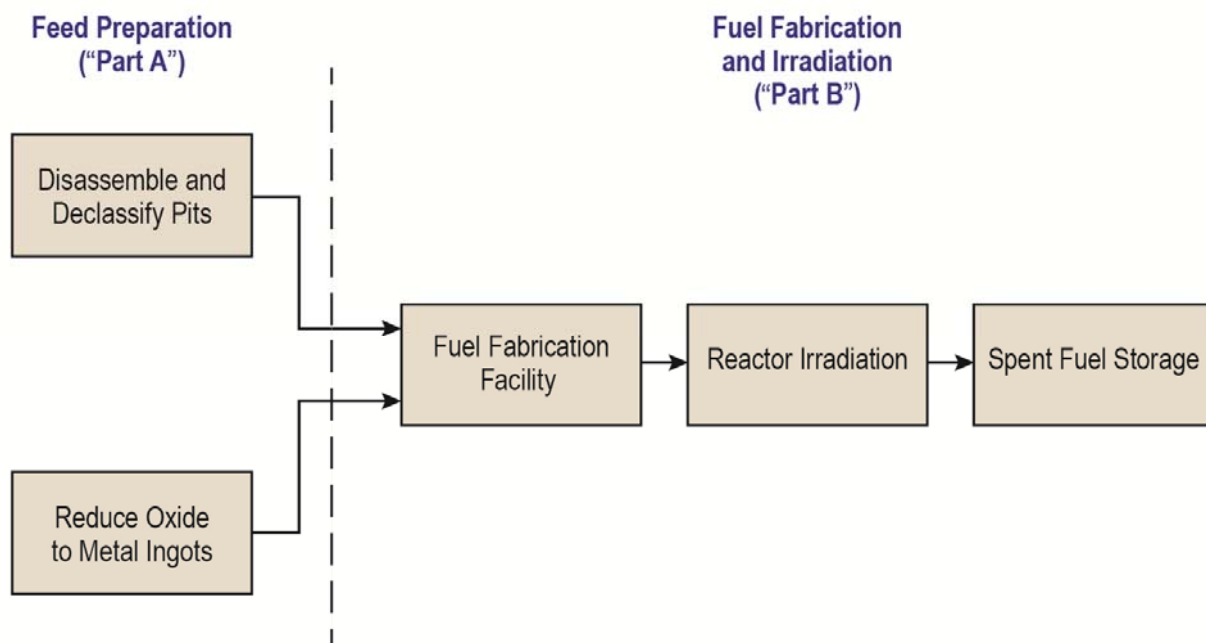


Figure 1. Key Elements of Plutonium Disposition

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<sup>3</sup> Under the current MOX option, the 34 MT target for the PMDA feed would include approximately 7.8 MT of non-pit plutonium, stored or to-be-received at SRS, that the OFMD has identified to DOE-EM as being suitable as feed for MFFF. The balance (34 - 7.8 = 26.2 MT) would be derived from pits. SRS and other DOE sites also hold excess plutonium that is not identified as likely feed for the MFFF, including more than 14 MT of fuel-grade and reactor-grade plutonium. The fuel-grade and reactor-grade plutonium does not meet the isotopic limits defined for feed materials in the PMDA and thus cannot be used towards the 34 MT U.S. plutonium disposition commitment. Approximately 7 MT of additional U.S. pit-origin plutonium was declared excess in 2007; this material is not included in the MFFF baseline of PMDA feed.

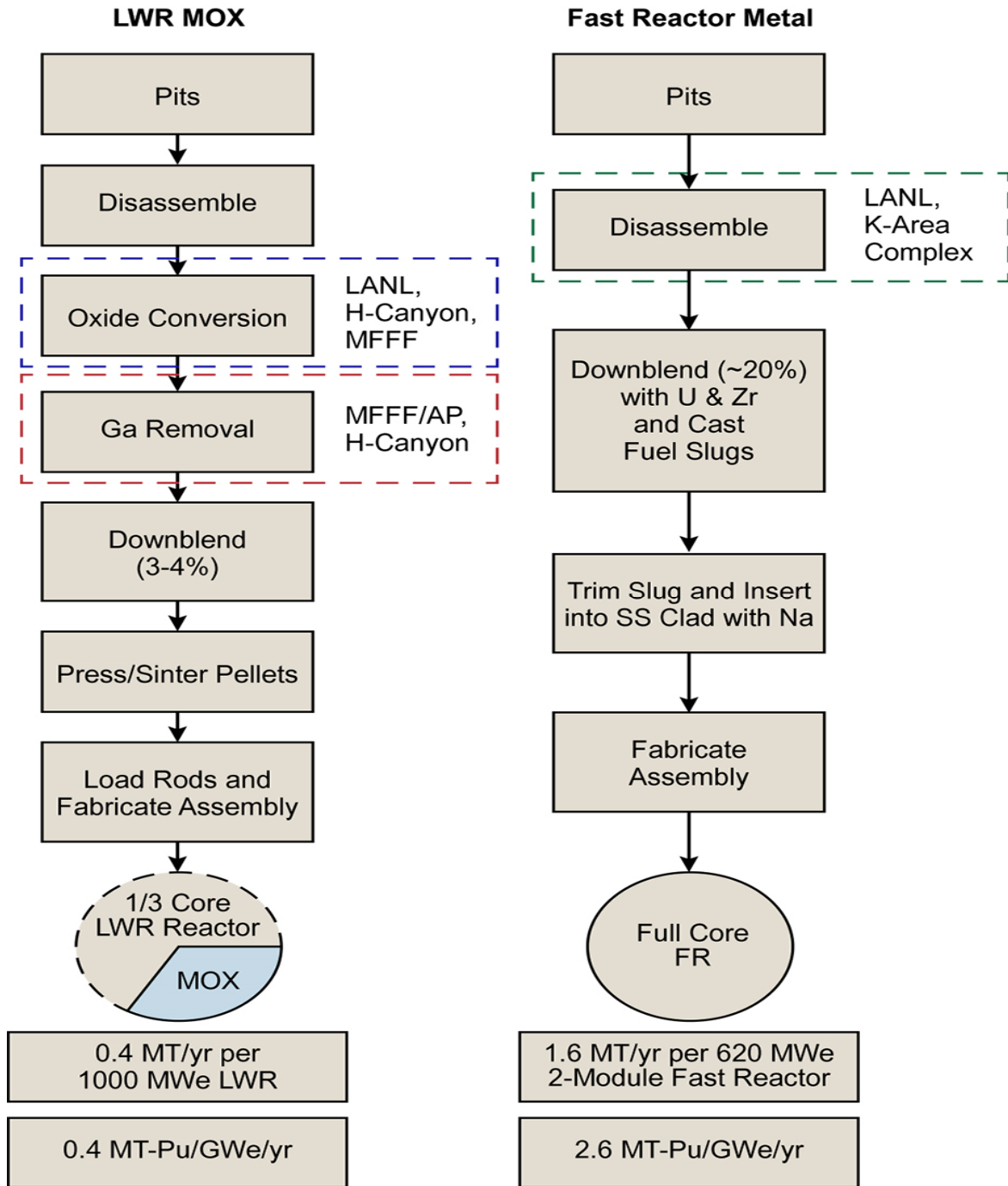


Figure 2. Comparison of the LWR MOX and ADR Disposition Processes Showing the Simplifications Achieved Using the ADR Approach

Use of metal fuel enables elimination of two steps in the disposition process as compared to the reference MOX option, the aqueous-purification (polishing) and conversion-to-oxide steps, as shown in Figure 2.

Under the reference MOX option for disposition of the 34 MT PMDA commitment, surplus pits are to be disassembled, typically through bisection. The resulting metal, along with other streams of clean metal, is to be either oxidized and subsequently dissolved for aqueous purification, or directly dissolved. The plutonium is then to be subjected to aqueous purification or polishing to remove trace elements, including gallium, which is of specific concern because of its potential to harm the performance of the Zircaloy cladding used in LWR fuel. Excess plutonium oxide stocks are also to be similarly processed through aqueous purification to ensure chemical purity and to obtain the required oxide powder morphology for the MOX ceramic pellet fabrication process. The plutonium powder is then to be mechanically downblended with uranium dioxide to approximately 4 wt.% plutonium and converted into fuel pellets through a standard cold-press/sinter ceramic fabrication process (adopted from commercial uranium oxide fuel manufacture). After centerless grinding to a uniform diameter, the pellets are to be loaded into Zircaloy rods. The rods in turn are to be loaded into finished fuel assemblies. A typical pressurized-water reactor MOX fuel assembly contains nearly 500 kg heavy metal (HM), of which about 20 kg is plutonium.

For the proposed once-through fast-spectrum burner reactor option, pits would be disassembled through bisection as in the reference LWR MOX option. The resulting metal along with other stocks of clean plutonium metal would be used to charge a casting furnace directly, in which the plutonium would be downblended directly with uranium metal and zirconium metal. Casting and trimming waste would be recycled directly into each batch without additional purification or other processing.

Because the metal fuel fabrication process and resulting fuel form are more forgiving of the typical impurities found in the pits and clean metal feed to be dispositioned, aqueous purification or polishing would not be required. Fuel slugs would be cast directly from the fuel blend that is homogenized in the casting furnace. The slugs would be trimmed to the required length and loaded into steel cladding tubes along with a small amount of sodium metal ribbon. The bonded fuel pins would then be loaded into finished fuel assemblies. A typical ADR metal fuel assembly contains about 40 kg HM, of which about 8 kg is plutonium. Compared to the LWR MOX fuel fabrication process, fabrication of the U-Pu-10Zr metal alloy fuel is simpler and requires fewer steps.

### **Feed Preparation (“Part A”) Activities**

The 34 MT of metal and oxide plutonium-bearing feed materials associated with the PMDA must be converted to a chemical and physical form suitable for feed to fuel fabrication. These front-end feed preparation activities are significant and impact numerous operating facilities and programs. However, detailed consideration of the full spectrum of front-end feed preparation activities was not included in this ADR Study, primarily because the necessary data on the required operations at Pantex, the PF-4 facility at Los Alamos National Laboratory (LANL), and at SRS were not available. It is recognized that the ADR option benefits from simplified front-end feed preparation, and some of these front-end feed preparation activities were incorporated into the scope of the metal fuel fabrication facility described in the next section. Thus, some of the “Part A” costs are included in the ADR option cost estimates. *Therefore, in comparing results developed for the ADR options to results for the reference MOX option, one must be careful to ensure a like-for-like comparison with respect to treatment of the front-end feed preparation activities.*

The MOX Fuel Fabrication Facility (MFFF) Project (99-D-143) does not include the front-end feed preparation activities required to prepare material for introduction into the MFFF process. These front-end activities were previously part of the Pit Disassembly and Conversion Facility (PDCF) and the subsequent Pit Disassembly and Conversion (PDC) projects, which have now been cancelled and replaced with an approach utilizing the PF-4 facility at LANL, the K-Area Complex, H-Canyon, and the MFFF at SRS to prepare feed. Under the reference MOX project, all of the excess pits at Pantex would be transported to PF-4 at LANL for processing, and subsequently transported to the KAMS facility at SRS for storage pending processing in H-Canyon/HB-line and in the MFFF, as shown in Figure 3.

Under the ADR option, the plutonium mass flow would be simplified as shown in Figure 4. A quarter to a third of the excess inventory would be shipped directly to the KAMS facility at SRS from Pantex, thereby accelerating inventory reduction at Pantex and reducing the burden on operations in PF-4 at LANL. The operations in PF-4 at LANL would be further simplified because purification and conversion to oxide would be eliminated from their scope such that only size-reduced metal and metal ingots would be produced. The Pantex inventory shipped directly to the KAMS facility would be select pits that could be readily processed in the proposed K-Area Fuel Fabrication (KAFF) facility into size-reduced metal and/or metal ingots.

The ADR option would utilize and repurpose multiple existing facilities through a series of modifications to optimize the disposition of the 34 MT of U.S. plutonium-bearing feed materials associated with the PMDA, as shown in Figure 5. The front-end feed processing portions of the new KAFF would be used to receive pits from Pantex and clean metal from the KAMS facility, provide interim storage capacity, disassemble the pits, and convert them into size-reduced metal and/or metal ingots suitable for production of metal U-Pu-10Zr fuel directly. This same facility would be used to reduce the oxide feed materials using either calcium metal [e.g., bomb reduction, the Direct Oxide Reduction (DOR) process, or

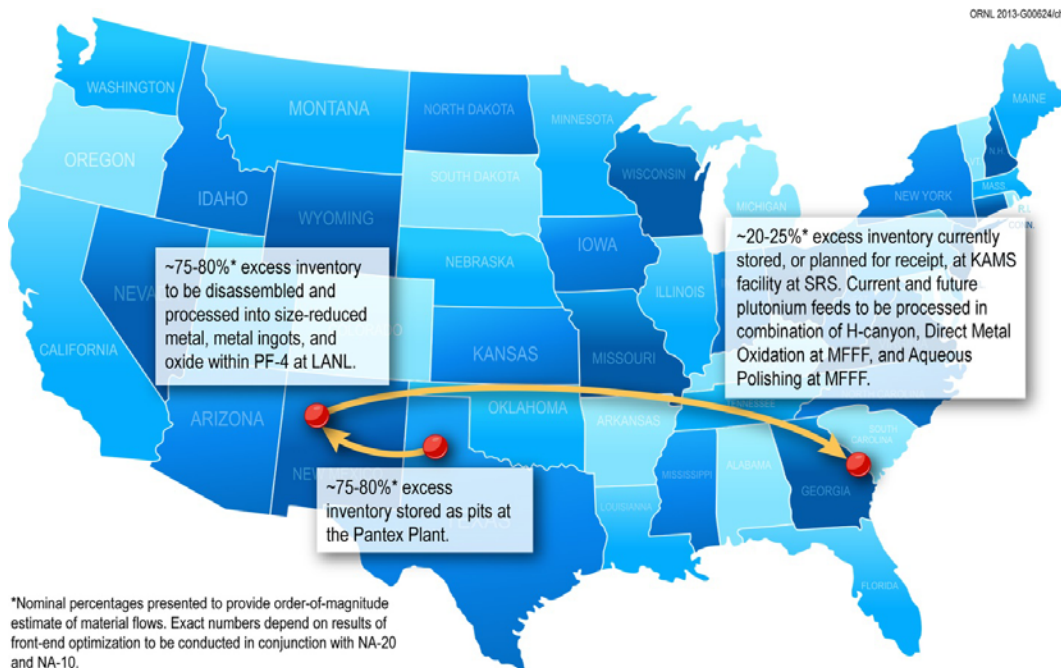
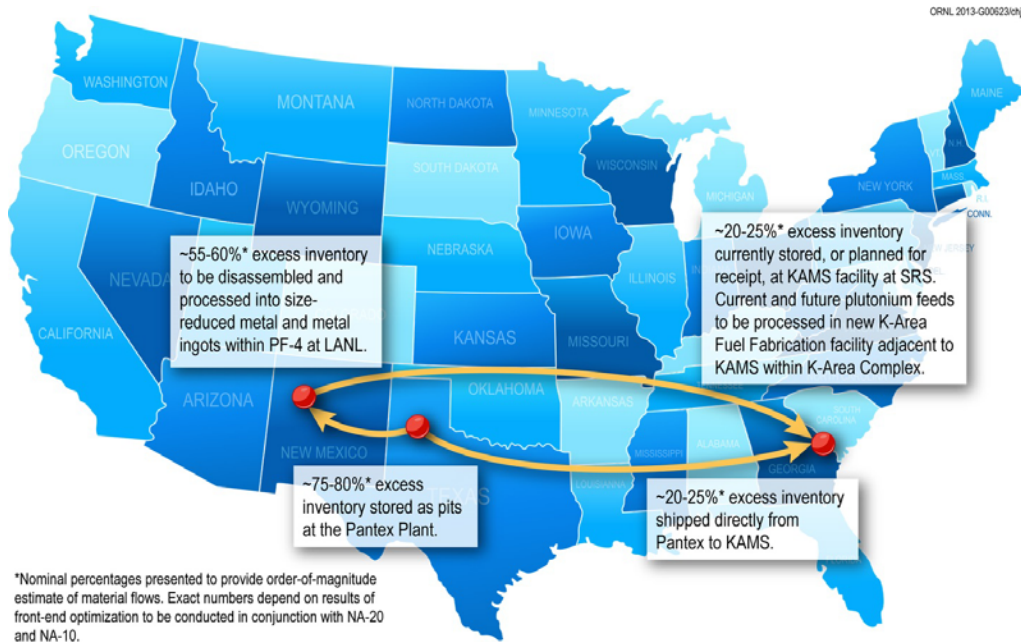


Figure 3. Plutonium Material Flow under the Reference MOX Option



**Figure 4. Plutonium Material Flow under the Advanced Disposition Reactor Option**

the Multi-Cycle Direct Oxide Reduction (MCDOR) process], or the Lithium Electrochemical Reduction (LER) process to produce plutonium metal ingots for fuel fabrication. Neither the pit disassembly nor the oxide reduction processes remove americium, gallium, or other impurities from the feed materials appreciably. Based on the feed metal purity specification and the limited experience irradiating pins derived from excess weapons plutonium in the EBR-II, the impurity content of the feed material would not affect fuel performance. Some limited purification capability, however, would be provided through incorporation of electrorefiners and molten-salt extraction equipment in the facility; these would be used only for a small fraction of the feed material, specifically some of the oxide feeds that are known to contain significant quantities of impurities.

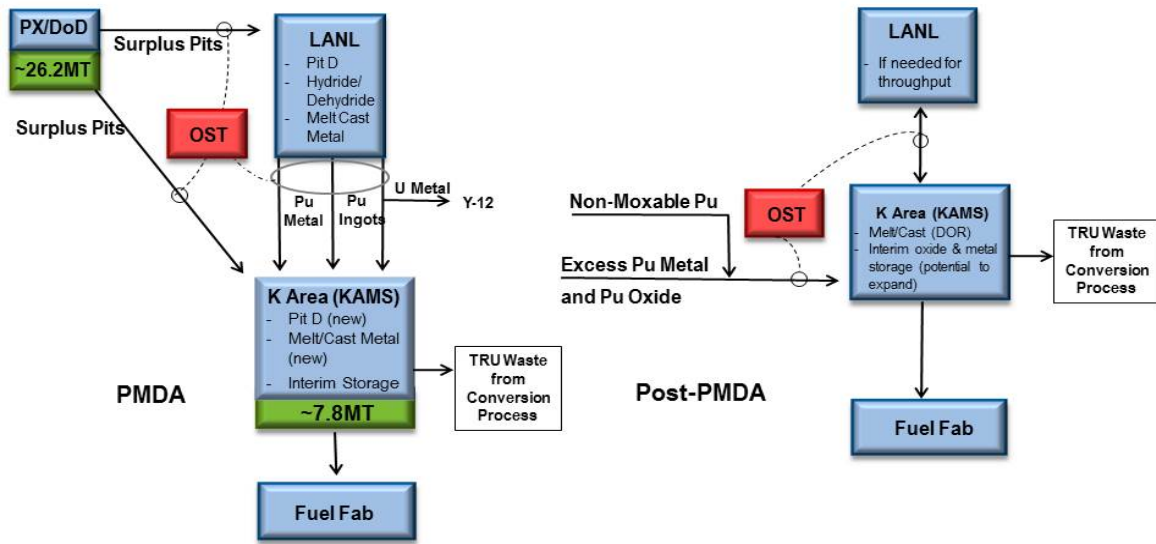
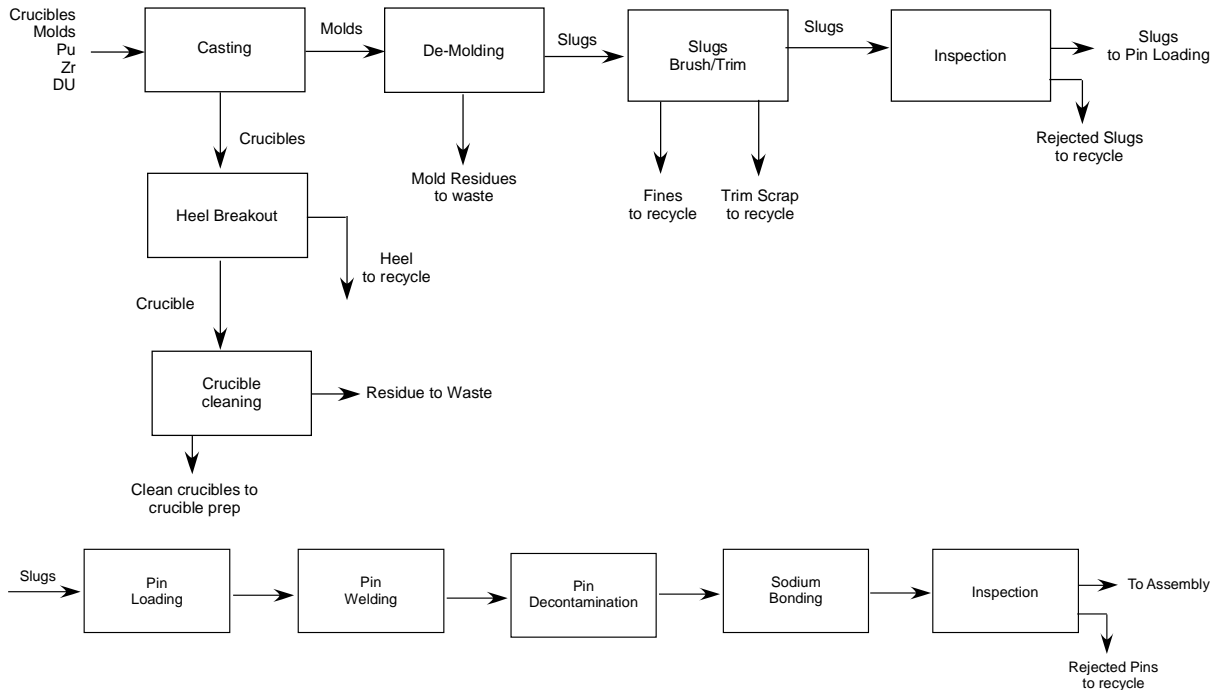


Figure 5. Optimized Use of Existing Facilities for PMDA and Post-PMDA Operations

### Metal Fuel Fabrication

Metal fuel has been used in fast reactors since the first fast-spectrum reactor, the Experimental Breeder Reactor I (EBR-I) operated, and metal fuel was used in the EBR-II throughout its operating history. The Fermi reactor used metal fuel, and a limited amount of metal fuel was also irradiated in the FFTF. One key benefit of metal fuel is its relatively simple fabrication process (Burkes 2009).

Figure 6 summarizes the principal metal fuel fabrication steps. The fuel fabrication process begins with injection casting of a 20% Pu-70%U-10%Zr alloy into quartz molds. Following cooling and breakout, the resultant slugs are trimmed to the appropriate size for loading into pins. Casting crucible heels, scrap from the trimming of the slugs, and metal fines from slug production are recycled directly to the casting furnace. Spent crucibles and mold residue are packaged as TRU waste. The loaded pins are combined with sodium metal, backfilled with helium, and fitted with a closure weld. The pins are decontaminated and transferred to a furnace to complete sodium bonding of the fuel slugs with the cladding. When bonding is complete, the pins are loaded into assemblies for final cleaning and inspection prior to storage and shipment.



**Figure 6. Process Flow Diagram for Metal Fuel Fabrication**

Metal fuel has been manually fabricated using glovebox facilities and remotely in hot-cell facilities. Currently, the only DOE facility with the capability to fabricate metal fuel is the Fuel Manufacturing Facility (FMF) at the Idaho National Laboratory (INL). Because this research and development facility is not sufficiently large to fuel an ADR as defined in this study (see ADR description below), implementation and use of a new fuel fabrication facility was analyzed. The FMF’s role would be limited to supplying fuel to the restarted FFTF, possibly supplying start-up fuel for the initial ADR module, and development and demonstration of fuel fabrication equipment for use in the KAFF facility. Although the fabrication process has been demonstrated through operation of FMF, some specific research, development, and demonstration is recommended to modernize and optimize a few key pieces of process equipment.

### **Fuel Manufacturing Facility at Idaho National Laboratory**

The FMF at INL was constructed in 1986 as a glove-box fabrication facility to supply fuel for the EBR-II reactor. The facility is located on the same site as the EBR-II, and includes a collocated special nuclear material storage vault. The FMF operated successfully through 1994, when fuel fabrication ceased in conjunction with the shutdown of the EBR-II. Since that time, options for use of FMF to fabricate plutonium-bearing metal fuel for FFTF and other fast reactors have been examined. Using the existing facility upgraded with new fabrication equipment, it is estimated that the FMF could produce 26 FFTF fuel assemblies annually, containing a total of about 330 kg of plutonium. Because the facility employs glove-boxes rather than hot cells, it is capable of handling only relatively clean plutonium.

The FMF, as currently configured, also provides storage capacity for feedstock materials and fabricated fuel. Preliminary assessments indicate that the storage of a core load of FFTF fuel and the annual plutonium feed requirements can be accommodated in the existing vault space. Based on an initial assessment of the proposed use of FMF to support the ADR approach for plutonium disposition, it is believed that no action under the National Environmental Policy Act (NEPA) would be required prior to restarting fuel fabrication in FMF because fuel fabrication was the original mission for the facility. Additionally, it is believed that the DOE process for the acquisition of capital assets (DOE O 413.3b) may not apply because the asset already exists and will only be modified to return it to its original mission. However, modifications to the air permit for the facility may be required.

### **Metal Fuel Fabrication Facility**

The original concept for supplying fuel to the ADR was to construct a green-field government-owned, contractor-operated (GOCO) facility operating on the basis of DOE authorization. However, in considering possible use of existing facilities including the MFFF, the existence and possible use of portions of the K-Area Complex were identified. Once the possibilities for use of the K-Area Complex were understood by the study team, the team's efforts in defining fuel-supply options focused almost exclusively on repurposing portions of the K-Area Complex. Many of the capabilities that currently exist within the K-Area Complex, including KAMS, the K-Area Interim Surveillance (KIS) process, and the expansive footprint of the -40 foot level and Final Storage areas, which are directly applicable to the fuel fabrication facility needed to support the ADR. Additionally, the KAMS baseline mission includes storage of Category-I quantities of plutonium into the early 2030s. The K-Area Complex is a hardened, design-basis threat compliant facility, and only minimal security upgrades would be needed to increase the vault footprint or to create a collocated KAFF facility. The KAFF facility could be constructed within a part of the K-reactor building in far less time than a comparable green-field project could be completed.

A conceptual arrangement for the KAFF facility, including both front-end feed preparation and fuel fabrication processes, was developed. This conceptual arrangement uses repurposed areas of the K-Area Complex, including KAMS and the KIS process, as well as other parts of the K-reactor building. Approximately 50,000 ft<sup>2</sup> of process area, with up to an additional 100,000 ft<sup>2</sup> of support area, could be made available within the perimeter area, leveraging the significant previous investment in security infrastructure to meet requirements for protection of Category-I quantities of materials.

In addition to the reference-size KAFF facility, consideration was also given to a larger facility capable of processing up to 3 MT-Pu/yr, and a smaller facility capable of processing up to 1 MT-Pu/yr. The results for these alternative sizes were used to support parametric variations on the baseline options. A similar conceptual arrangement for installing the same front-end feed preparation and fuel fabrication processes into the MFFF building was also developed. In addition to analyzing the use of either the K-Area Complex or the MFFF for front-end feed processing and fuel fabrication, these conceptual arrangements were used to develop estimates for the total areal requirements of a green-field facility, including both hardened process space and support space.

### **Reactor Irradiation Options**

Another key element of the ADR approach is the reactors which could be employed; an overview of the reactors and key assumptions used in this ADR Study are provided below.



### Advanced Disposition Reactor

The ADR is defined as a modular, pool-type advanced fast-spectrum burner reactor optimized for plutonium disposition. Because this reactor design has not yet been completed, the ALMR Mod B design developed under the DOE ALMR program in the 1990s was used as a surrogate for this study. The ALMR Mod B is a modular, pool-type advanced fast-spectrum burner reactor that utilizes metal alloy fuel and employs passive safety and a digital instrumentation and control system. The ALMR Mod B has a rated thermal power of 840 MW and an electrical output of 311 MW. Being a pool-type reactor, intermediate sodium loops are used to exchange heat between the primary sodium coolant in the vessel with water in a sodium-water steam generator located outside the vessel. The steam from the sodium-water steam generator is used to generate electricity in a conventional steam turbine/generator. A diagram of the ALMR Mod B nuclear steam supply system (NSSS) is provided in Figure 7.

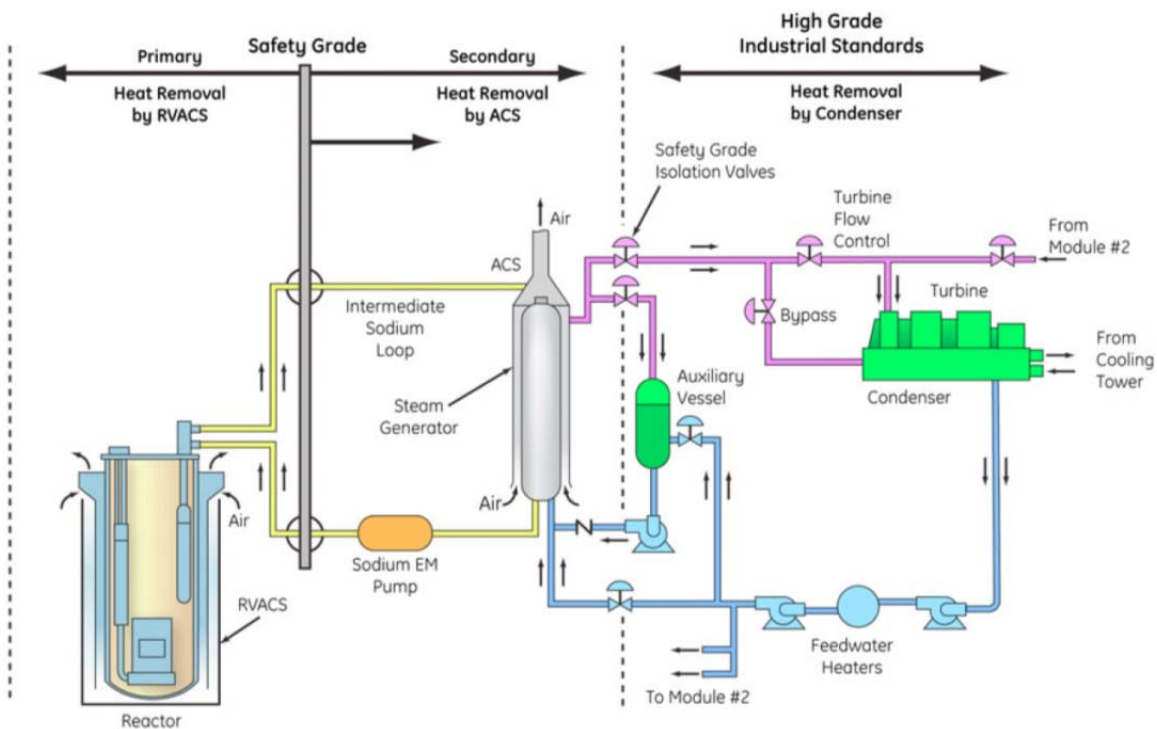


Figure 7. Nuclear Steam Supply System for the ALMR Mod B

Because the ALMR Mod B is a small modular reactor, the reactor modules are designed to form a two-module power block in which the steam from both modules drives a single turbine/generator. This multi-module arrangement allows sharing of equipment to take advantage of economy of scale, while maintaining the advantages of the small modular reactor for the NSSS. Each reactor module consists of the reactor vessel, the reactor closure, the containment vessel, the internal structures, the internal components, the reactor module supports, and the reactor core itself. The power level of the ALMR Mod B is primarily limited by the shutdown heat removal capabilities of the passive safety systems.

ALMR Mod B uses ternary U-Pu-10Zr metal alloy fuel to take advantage of this alloy's compatibility with the coolant, desirable thermomechanical properties, and ease of fabrication. In the baseline ALMR

Mod B design, the fuel is irradiated to high burnup levels (~10% average) to improve fuel cycle costs. Operating in this baseline mode, the fuel irradiation time is ~4.5 years, broken into four 16-month refueling intervals where ¼ of the core is replaced; no shuffling of the fuel is required.

The ALMR Mod B was evaluated for a variety of denaturing, spiking, and destruction options in the early stages of the PDP and the 1995 NAS study. However, this ADR Study reevaluated the ALMR Mod B performance in light of advancements in the understanding of burner reactor core designs, the specific spent fuel disposition criteria defined in the PMDA, and the urgency associated with the stocks of separated plutonium.

### Fast Flux Test Facility

An option for plutonium disposition using the FFTF, shown in cutaway in Figure 8, was included in this study because of the recognition that the FFTF could enable an early start of U.S. plutonium disposition using an advanced fast-spectrum burner reactor. Additionally, the FFTF could accelerate fuels testing and provide fast-spectrum burner reactor operational experience in support of an ADR option.

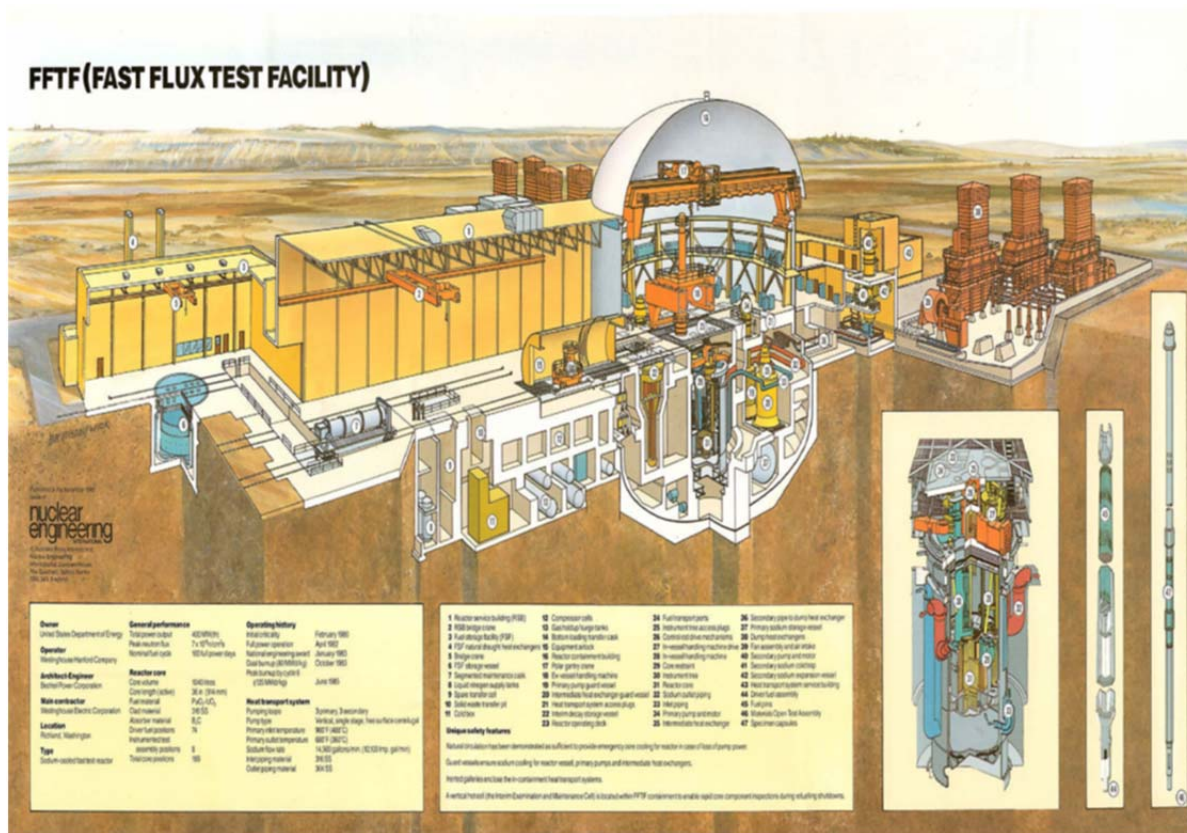


Figure 8. Cutaway View of the Fast Flux Test Reactor (Cruikshank 1985)

The FFTF was designed specifically for irradiation testing of nuclear reactor fuels and materials for advanced fast reactors (Cabell 1980). The FFTF is located on the DOE Hanford site near Richland, Washington. Construction of the FFTF started in June 1970 with startup in February 1980, and it operated until 1993. Since that time, the reactor has been in cold shutdown with an extended decommissioning

schedule. The ability to reconfigure the reactor for restart is described in a 2007 proposal (Columbia Basin Consulting Group 2007). Although the reactor operated with a MOX fuel core, the same ternary U-Pu-10Zr fuel proposed for use in the ADR has already been irradiated in the FFTF. The process for transitioning from a MOX core to a U-Pu-10Zr metal alloy core was underway when the FFTF was shutdown.

### **Spent Fuel Storage and Disposal**

The ALMR Mod B was designed for a long-life core with the goal of optimizing economic fuel utilization; therefore, application of the ALMR Mod B to the ADR disposition approach would require some design changes to accommodate the fuel handling requirements associated with high plutonium disposition rates. For example, the heat generation rate in a fuel assembly immediately upon discharge is quite high, and the ALMR Mod B is designed to store discharged fuel in the reactor vessel until it has cooled sufficiently for fuel handling purposes. However, the pool inside the ALMR Mod B reactor vessel does not contain a sufficient number of storage locations to handle the high loading rates envisioned for the plutonium disposition mission (the spent fuel discharge rate for the ADR approach is higher than that of the reference ALMR Mod B fuel cycle by a factor of approximately 2-4). Thus, this study evaluated several options for increasing the spent fuel storage capacity based on proven engineering solutions. The ADR Study also considered the PMDA requirement that irradiated disposition fuel be stored for the life of the agreement as a part of the ADR's once-through fuel-cycle approach.

It was determined not to address final fuel stabilization within the scope of this ADR Study. The reference U-Pu-10Zr metal alloy fuel includes sodium bonding between the fuel slugs and the cladding tube. As a result, the fuel's suitability for direct geologic disposal would need to be evaluated. With the termination of the Yucca Mountain repository project, options developed for the ultimate spent fuel disposition path would be based on highly uncertain assumptions. It was therefore assumed that the spent fuel would be stored on-site at an Independent Spent Fuel Storage Installation (ISFSI) for the duration of the PMDA.

## **Options Studied**

Within the schedule and resource constraints of this ADR Study, it was not possible to analyze all permutations of implementation possibilities, nor to optimize to a single implementation option in detail. However, parameters which most influence the study results were identified by initial consideration and analysis of a range of representative options. For example, green-field options for all of the proposed ADR facilities were considered, but it was quickly determined that a few existing facilities within the DOE complex offered significant cost and schedule advantages for implementation of the ADR option.

For the ADR reactor, it was not clear at the outset of the study which combination of fuel loading, core configuration, fuel cycle length, and number of batches in the core would be capable of meeting the PMDA criteria for throughput, burnup, and isotopic degradation. Scoping calculations were performed to help narrow the possibilities. The preliminary results from these scoping calculations were sufficient to eliminate many of the representative options from further consideration. Thus, the range of ADR options studied ultimately converged on two options— an option relying on a single ADR prototype module (Option I) and an option relying on a two-module ADR prototype power block (Option II). It was also determined that for both options, fuel would be fabricated in the proposed KAFF facility (a new metal fuel fabrication facility constructed in the K-reactor building adjacent to the KAMS facility within the K-Area Complex at the SRS). It was assumed that spent fuel would be stored in dry casks at an ISFSI adjacent to the ADR for the duration of the PMDA mission.

### **Option I: Single-Module Advanced Disposition Reactor Prototype**

As described in the *Key Elements of the Advanced Disposition Reactor Approach* section, for this option existing pits at Pantex would be directed in parallel to the KAFF facility at SRS and to PF-4 at LANL, based on required disassembly and processing capabilities. More challenging materials would be processed at LANL, and the resulting metal ingots and size reduced metal would be shipped to the KAMS facility for interim storage and ultimate use in the KAFF facility. The pits transported directly from Pantex to the KAMS facility would be disassembled using new equipment located within the KAFF facility and converted into metal ingots for interim storage prior to use in the fuel fabrication process. Plutonium oxide currently stored at KAMS would be reduced to metal, purified through electrorefining and/or molten-salt extraction, as necessary, using new equipment located within the KAFF facility, and then converted into metal ingots for interim storage pending their ultimate use in fuel fabrication. To produce fuel slugs, the plutonium ingots would be batched with metal scrap from casting and trimming and with commercially sourced uranium and zirconium metal ingots. Up to 10 wt.% fuel-grade or reactor-grade plutonium, some of which is already stored at KAMS, would be added to the casting furnace to ensure that the isotopic degradation achieved through blending and irradiation is sufficient to meet the PMDA requirements. Further processing would produce finished fuel subassemblies ready for transport to the new ADR. A new ADR single-module prototype would be constructed, preferably within the SRS to avoid the necessity of transporting the fresh fuel on public roadways and also to minimize the size of the on-site fresh-fuel storage facility at the ADR. The fuel would then be irradiated to the point that it would meet the self-protection requirement. The spent fuel would be stored in dry casks within a new ISFSI adjacent to the ADR throughout the life of the PMDA.

The key attributes of Option I include:

- Construction of a single-module, dedicated plutonium burning ADR that generates electricity and is licensed by the NRC as a commercial power reactor;
- Fuel fabrication in the KAFF facility;
- Modification of the PMDA to enable U.S. blending of fuel-grade and reactor-grade plutonium (consistent with the allowances included for Russian blending) and to codify the self-protection standard as the disposition criteria for ADR spent fuel<sup>4</sup>;
- Expansion of the base PMDA-mission from 34 MT to nearly 38 MT<sup>5</sup> to include blendstocks that are needed for isotopic degradation;
- Irradiation of the ADR fuel to the self-protection standard (a dose rate greater than one Sv/hr, one meter from the accessible surface after 30 years cooling); and
- Spent fuel transfer from the ADR to an adjacent ISFSI that uses dry-cask storage.

## **Option II: Two-Module Advanced Disposition Reactor Prototype Power Block**

The attributes of Option II are similar to those of Option I. However, an additional ADR module is included, and the two modules are constructed as a single prototype power block. The two modules share a number of important systems and functions including the turbine. This two-module power block arrangement was proposed and analyzed extensively under the ALMR program and had better economic indicators relative to single-module arrangements. With the added disposition capacity offered by a second module, all of the PMDA BN-800 spent fuel disposition criteria can be achieved, including assembly and batch-average minimum burnups. With this increased irradiation exposure, isotopic degradation is obtained through fission and transmutation without initial blending of up to 12% of fuel-grade or reactor-grade plutonium, as is required for Option I. It should be noted that even though two ADR modules are included in Option II, the fuel fabrication facility throughput is essentially unchanged because the fuel for Option II would contain on average more plutonium per fuel assembly than the fuel for Option I and would spend roughly twice the residence time in the core.

The key attributes of Option II include:

- Construction of a two-module, dedicated plutonium burning ADR power block that generates electricity and is licensed by the NRC as a commercial power reactor;
- Fuel fabrication in the KAFF facility;
- Modification of the PMDA to codify the use of the agreed BN-800 disposition criteria for ADR spent fuel;
- Irradiation of the ADR fuel to the PMDA BN-800 disposition criteria (to 4.5% minimum subassembly average and 6.0% minimum on a batch-average basis); and
- Spent fuel transfer from the ADR to an adjacent ISFSI that uses dry-cask storage.

A variant of Option II, denoted Option II-SP, was assessed to understand the cost impacts of reducing the disposition criteria to the self-protection standard.

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<sup>4</sup> The PMDA allows both parties to add blendstock plutonium, at up to the 12% level, but the blendstock plutonium does not count against the 34-MT target. However, the PMDA separately limits the total mass of Pu-238 and Pu-240 that can be contained in the final plutonium blend. The U.S. limits were set much lower than the Russian limits (8 kg Pu-238 vs. 50 kg Pu-238) on the assumption that the U.S. would not blend. Adoption of the Russian limits for the U.S. would enable blending with sufficient fuel-grade and reactor-grade plutonium to ensure isotopic degradation after irradiation.

<sup>5</sup> Based on the isotopics analyzed, 10% blendstock was assumed.

### Option III: Restart of the Fast Flux Test Facility and the Fuel Manufacturing Facility

Due to its relatively small size, the FFTF alone is not capable of meeting the current PMDA-specified disposition rate of 1.3 MT weapons plutonium per year. For this reason, Option III is considered to be complementary to the other options – it could be implemented as a complement to the reference LWR MOX option or as a complementary step in the implementation of Option I or II. In either case, it could enable early disposition. It could also be considered as a possible stand-alone option if a lower disposition rate were to be renegotiated for the PMDA.

Declassified metal ingots and size reduced metal for FFTF fuel would be produced in PF-4 at LANL, and subsequently shipped to the FMF at INL for fabrication into fuel.<sup>6</sup> Clean metal would also be shipped from KAMS to the FMF at INL, as required. The plutonium feed would be batched with commercially sourced uranium and zirconium metal ingots in the casting furnace (scraps from casting and trimming would be recycled into the process). The fuel would be further processed into finished fuel subassemblies ready for transport to the FFTF. This option requires FFTF restart, which would utilize a combination of the existing unirradiated FFTF MOX fuel and the partially irradiated FFTF MOX fuel stored currently in the Canister Storage Building (CSB) near the FFTF on the Hanford site. Use of the unirradiated and partially irradiated MOX fuel helps to address these legacy materials, for which the Office of Environmental Management has yet to identify a final disposition path. The spent fuel would be stored at the CSB for the life of the PMDA.

The key attributes of Option III include:

- Restart of FFTF and operation with a plutonium disposition rate of approximately 0.3 MT/yr;
- Initial disposition in five years, continuing for the next thirty years (i.e., through the design life of the FFTF);
- Processing of pits into declassified metal ingots in PF-4 at LANL. Transport of metal ingots from PF-4 and existing clean metal stored in KAMS to the FMF at INL for fabrication into fuel;
- Fuel fabrication in the existing FMF; and
- Optional increased disposition rate, as required, once additional fuel fabrication capacity were made available (e.g. at SRS).

Two variants of Option III, denoted Option III-SP and Option III-SP-Rev, were assessed to understand the cost impacts of reducing the disposition criteria to the self-protection standard. The latter also includes the incorporation of a power-generation capability as part of the FFTF restart.

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<sup>6</sup> Optional production in the KAFF facility was also considered. A modular approach to KAFF facility development was considered in which the initial capacity would match the needs of the FFTF. The configuration would enable ready addition of a second fabrication line to expand capacity to support an ADR unit as well.

## Results of Assessment

The options described in the preceding chapter – Options I, II, and III for application to the 34-MT PMDA commitment– were analyzed to determine the throughputs (disposition rates) that could be achieved, as well as the capital, operating, and overall life-cycle costs, and the schedules for implementation. These results, summarized below in Figure 9 and Figure 10, contain uncertainties as described in more detail in the subsections that follow.

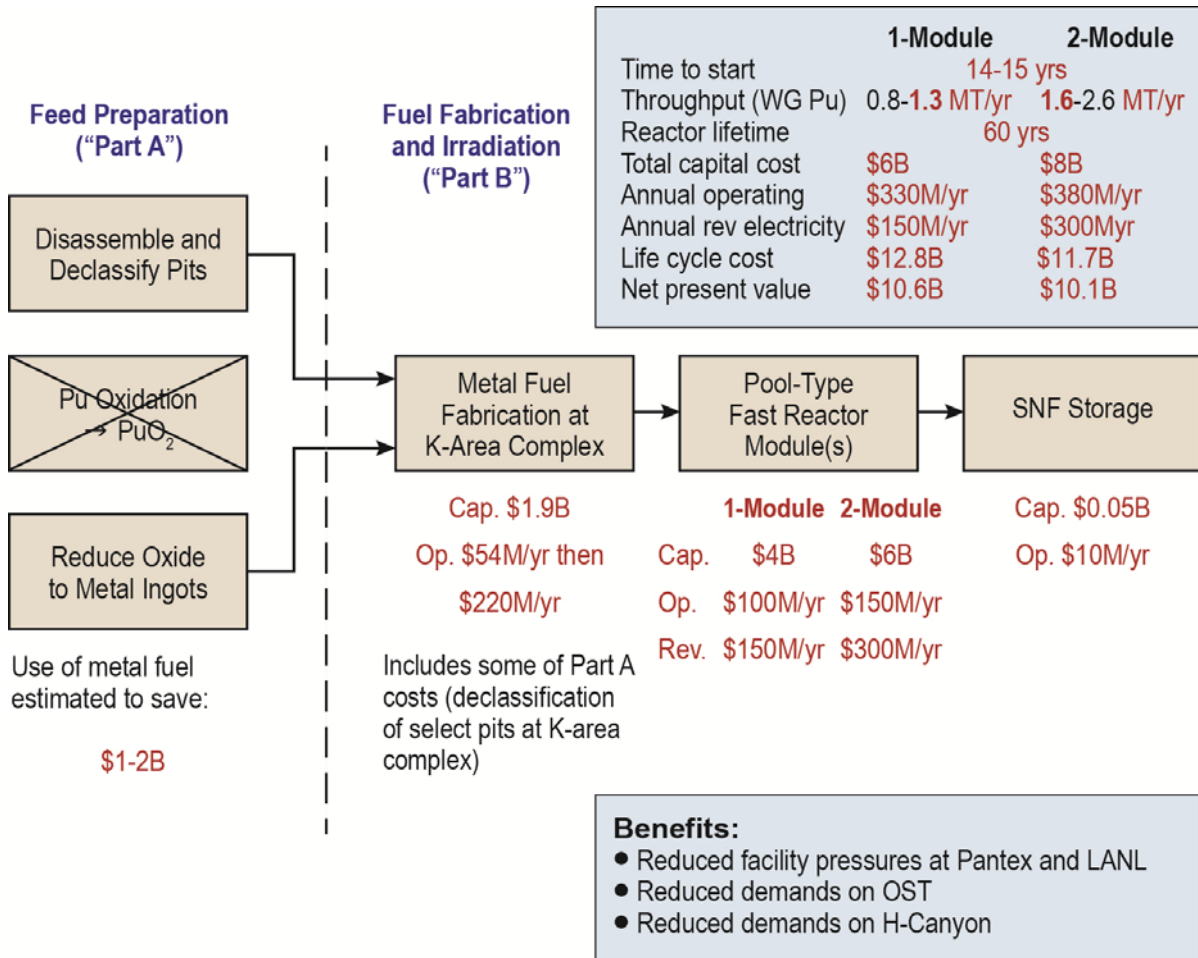


Figure 9. Results of Assessment for Options I and II

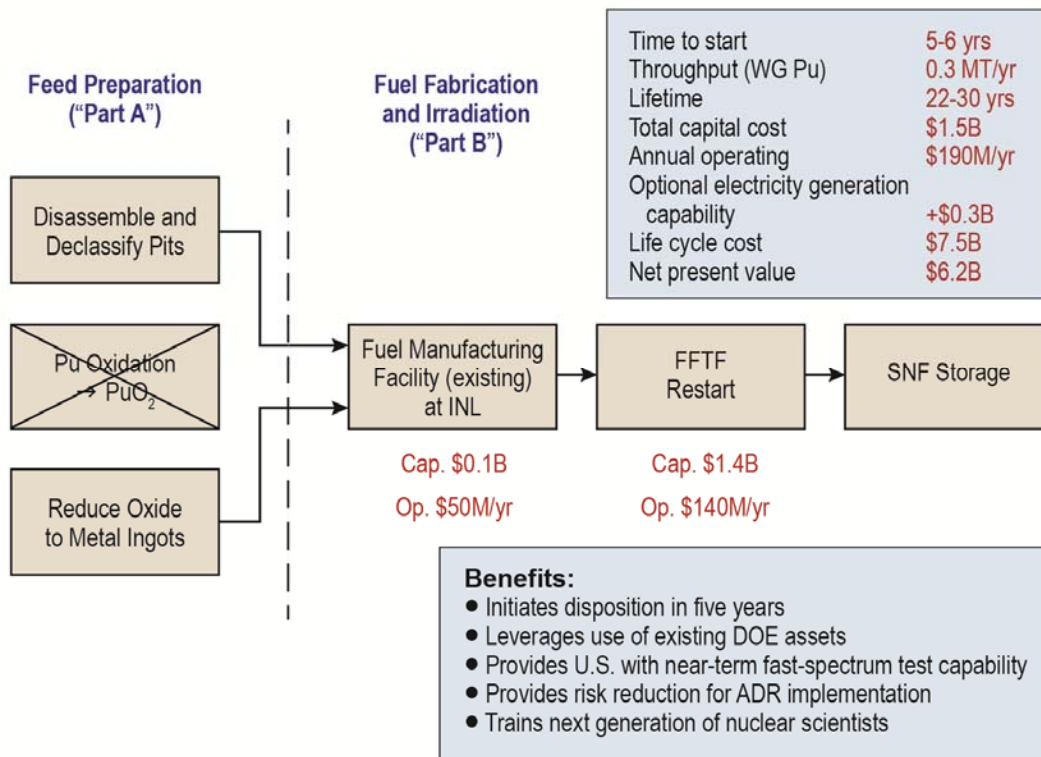


Figure 10. Results of Assessment for Option III

## Disposition Rates

The disposition rates that are achievable depend on the specific characteristics of each option. As discussed previously, scoping calculations for a wide range of potential options were initially performed, and the results of these scoping calculations were used to reduce the set of ADR-Study options to a more manageable number. Conventional fast-reactor fuel management computer models were used to obtain the plutonium throughput values and spent fuel characteristics for the options being considered; these values then dictated the sizes and throughputs for front-end feed preparation, fuel fabrication, and spent fuel storage.

### Front-end Feed Preparation and Metal Fuel Fabrication Facility Throughput

It was determined early in the study that the minimum plutonium throughput target should be 1.3 MT/yr, consistent with the PMDA requirement. Conceptual layouts for a facility with this throughput were developed for a green-field facility, for the KAFF facility, and for the MFFF. As part of this process, it was determined that the principal throughput-limiting step in the fuel fabrication process is the casting furnace. A single furnace would not be capable of producing fuel slugs containing 1.3 MT-Pu/yr, so the layouts developed incorporate two casting furnaces. Such a configuration is capable of achieving an overall plutonium throughput of significantly more than 1.3 MT/yr, but detailed throughput analysis of the facility was not performed given the preliminary stage of design development. Preliminary estimates suggest it could be as high as 2 MT/yr – more than adequate to provide fuel for the options analyzed. This



result applies to the reference conceptual layouts for the KAFF facility, as well as to the layouts for the MFFF building and the green-field facility.

A conceptual arrangement for the front-end feed preparation and fuel fabrication processes was developed using repurposed areas of the K-Area Complex at SRS. Approximately 50,000 ft<sup>2</sup> of process area, with up to an additional 100,000 ft<sup>2</sup> of support area, could be made available within and adjacent to the K-reactor building, leveraging the significant investment previously made in security infrastructure to meet requirements for protection of Category-I materials. It was estimated that about 80,000 ft<sup>2</sup> of space would be required for the KAFF facility. About 60,000 ft<sup>2</sup> of space within the K-Area Complex contains existing infrastructure and operations that would be continued to support the KAFF facility. Thus, a similar green-field facility would need about 140,000 ft<sup>2</sup> in total.

### Single 840-MWt ADR Module Throughput

Each ADR module operates independently with respect to plutonium disposition, so the disposition rates for only a single module were studied; the combined disposition rate for a two-module power block would be exactly double the rates provided below.

To meet the PMDA requirements, disposition fuel must be irradiated to 6.0% burnup, averaged across the fuel batch. At this burnup level, sufficient Pu-239 fission and transmutation occur to achieve a Pu-240/Pu-239 ratio greater than 0.1 without the need for isotopic blending and denaturing of plutonium in the fresh fuel to effect a higher isotopic ratio in the spent fuel. In the ADR, a fuel irradiation time of roughly 27 months is needed to reach this burnup level. A two-batch fuel management scheme was identified, refueling half of the core (96 fuel subassemblies) on a 16-month refueling interval.

A single 840-MWt ADR module operating on this fuel management scheme would have an estimated annual plutonium disposition rate of 785 kg/yr (at 85% capacity factor). Thus, two modules would be required to meet the 1.3 MT/yr minimum plutonium disposition rate specified in the PMDA.<sup>7</sup> The average discharged fuel assembly discharged after the 27-month irradiation period would have a Pu-240/Pu-239 ratio > 0.13 and a centerline dose rate 30 years after discharge of more than 2.4 Sv/hr, thereby meeting the PMDA criteria. This fuel cycle was used as the basis for the two-module Option II.

The disposition rate through a single ADR module could be increased if the fuel were irradiated just long enough to meet the self-protection standard. The 1.0 Sv/hr mid-plane dose rate after 30 years cooling would be attained at an assembly-average burnup of about 2.7%, requiring a 15-month irradiation time. Such a short residence time would be best achieved with a single-batch fuel management scheme, refueling the entire core (192 fuel subassemblies) on a 17.5 month refueling interval. At such a low burnup, insufficient Pu-239 fission and transmutation would occur to achieve a Pu-240/Pu-239 ratio greater than 0.1 as required by the PMDA, so isotopic blending in the fresh fuel would be required. Under such conditions, a single ADR module would have an annual plutonium disposition rate of 1299 kg/yr (at 85% capacity factor) for the weapons plutonium, or 1443 kg/yr including the fuel-grade or reactor-grade blendstock.<sup>8</sup> This fuel cycle was used as the basis for the one-module Option I.

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<sup>7</sup> For this reason, the one-module Option I was designed to meet the self-protection standard rather than the PMDA 6 wt.% burnup criteria.

<sup>8</sup> Even though the PMDA authorizes blending of up to 12 wt.% blendstock plutonium into the disposition plutonium, the actual amount that can be added is often limited by the requirement that the resulting blend, referred to as conversion product, have a Pu-240/Pu-239 ratio < 0.1; considering the fuel-grade and reactor-grade stocks available to the U.S. for blending, it was decided to limit the blendstock to 10% in this study.

Another technique that has been considered as a method of increasing disposition rates is simply to load more plutonium than is needed for reactivity into each assembly. However, the disposition rates analyzed for this ADR Study were constrained by the assumed limit on plutonium concentration in the U-Pu-10Zr alloy fuel of 20 wt.% (22 wt.% HM) or less; this limit was imposed because most of the applicable irradiation database is associated with this plutonium content. However, U-Pu-10Zr alloys containing up to 28 wt.% plutonium have been tested. Were such higher plutonium content fuel to be utilized, the annual disposition rate for a single ADR module could be increased to roughly 2 MT/yr of total plutonium while still meeting the self-protection standard.

#### **400-MWt Fast Flux Test Facility Throughput**

As in the case of the ADR reactors, disposition fuel must be irradiated to 6.0% burnup, averaged across the fuel batch to comply with the PMDA disposition criteria. In the FFTF, a fuel irradiation time of roughly 25 months is needed to reach this burnup level. Unlike the ADR options, however, the throughput for the FFTF option is not limited by the reactor but rather by the availability of fuel. The net result is that the FMF is capable of producing fuel containing only about 330 kg of plutonium per year. This is roughly equivalent to the disposition rate of the FFTF at 6.0 wt.% burnup.

The FFTF disposition rate could be increased were the fuel to be irradiated just long enough to meet the self-protection standard. The 1.0 Sv/hr mid-plane dose at 30 years cooling is attained at a 2.7% assembly burnup, requiring a 11.4 month irradiation time. The short residence time is achieved with two-batch fuel management, refueling half of the core (45.5 fuel subassemblies) on a 7.6 month refueling interval. At such a low burnup, however, insufficient Pu-240 would be generated to achieve the required Pu-240/Pu-239 ratio greater than 0.1, so isotopic blending in the fresh fuel would be necessary. Using blended plutonium feed and using the self-protection standard as the disposition criterion, the FFTF would have an annual plutonium disposition rate of 610 kg/yr for the weapons plutonium (or 678 kg/yr including the fuel-grade or reactor-grade blendstock). Core designs with plutonium concentrations greater than 20 wt.% were not considered, but their use could further increase the disposition rate.

#### **Disposition Rate Summary**

A summary of the disposition rate configurations is provided in Table 1. All of the listed configurations assume weapon plutonium feed. It should be noted that the throughputs listed may be simply doubled for a two-module power block.

**Table 1. Calculated Disposition Rates for a Single ADR Module and FFTF as a Function of Disposition Criteria**

<b>Configuration</b>	<b>Weapons Plutonium Disposition Rate** [kg/yr]</b>	<b>Total Plutonium Disposition Rate** [kg/yr]</b>	<b>Batch-Average Burnup [atom % HM]</b>	<b>Batch-Average Pu-240/Pu-239 Ratio [must be &gt;0.1]</b>	<b>30-Year Dose Rate [Sv/hr @ 1 meter] [must be &gt; 1.0]</b>
ADR – PMDA	785	785	6.1	0.13	2.4
ADR – Self-protection	1299	1440	2.7	0.12*	1.1
FFTF – PMDA	330	330	~ 6.0	> 0.12	> 2.0
FFTF – Self-protection	610	678	2.7	0.12*	1.0

\* Assumes blending with reactor-grade or fuel-grade plutonium during fuel fabrication to ensure isotopic denaturing such that the spent fuel has a higher Pu-240/Pu-239 ratio.

\*\* The listed rates are for a single ADR module. The rates for two-module options are simply double the rates listed.

## Life Cycle Cost Estimates

An important criterion for the evaluation of disposition options is economics, which this study addressed by estimating the projected life cycle costs (LCCs) of all new or modified facilities required to complete the plutonium disposition mission. Due to time and resource constraints, the conventional method of having an architect-engineering firm prepare pre-conceptual designs with new “bottom-up” cost estimates for each of the facilities was not feasible, so parametric “top-down” cost estimating methods were used. For LCC estimate categories, the activities were divided into the three key elements of the Part “B” activities described in the *Key Elements of the Advanced Disposition Reactor Approach* section above. The cost results for each of these categories are presented below, followed by an overall summary for all options.

### Metal Fuel Fabrication Costs for Options I and II

The capital cost for KAFF, including the limited front-end feed preparation activities to be performed within the K-Area Complex, was developed through a Comparative Cost Analysis (CCA) based on a comparison to similar process layouts and functions developed for CD-1 submittal within the Pit Disassembly and Conversion (PDC) project. Many elements of the PDC estimate were based on common functions from the earlier green-field Pit Disassembly and Conversion Facility (PDCF) project which was at the CD-2 submittal stage when it was halted. KAMS storage vault expansion costs were based on recent studies and existing estimates. Minor adjustments were made to the previously estimated values in cases where clear differences are understood (e.g., automation not needed).

The CCA resulted in a single point cost of \$1.9B for the KAFF facility. An additional \$0.1B was estimated for equipment and engineering development costs. Also, because the K-Area Complex is an operational facility, some additional operating expenses would be incurred during the construction phase. These additional operating expenses were estimated to be \$540M by taking a percentage of the total project cost (TPC), and are distributed over the construction phase into the operating costs for the KAFF

facility. The CCA also resulted in a single-point cost for the reduced-capacity, single-line KAFF facility used as part of the Option III-SP and Option III-SP-Rev analyses of \$1.5B. Using engineering scaling factors, a single-point cost of \$2.9B was estimated for the higher-capacity KAFF facility used as part of the Option II-SP analysis.

As an independent check on the CCA results, a separate estimate was prepared by scaling from historical and current construction and operational data (such as \$/ft<sup>2</sup> of building footprint and ft<sup>2</sup> per unit of heavy metal throughput) for special nuclear material Category-I facilities and conceptual design reports for similar proposed plutonium-handling facilities and operations. This somewhat cruder methodology resulted in an estimate for the KAFF facility of \$1.7B as a single point value.

Part of the CCA effort involved an initial review of the potential for the KAFF facility to be designed and constructed in a modular or phased approach. Specifically, expanded plutonium storage capability, pit disassembly/declassification, and slug fabrication operations would be needed before the reduction to metal, pin fabrication, and fuel fabrication processes would be needed. Because the 34 MT of plutonium associated with the PMDA commitment is primarily in the form of pits and clean metal, implementation of the oxide-to-metal reduction capability could be deferred for many years. As a result, it would be possible to execute the project in several phases, which could be authorized and funded separately. It should be noted that the overall total cost would increase if a modular or phased approach is used.

The CCA for an initial phase containing expanded pit/plutonium storage, pit disassembly/declassification, and slug production resulted in a single point cost of \$1.3B. The additional operating expenses were estimated to be \$375M, by taking a percentage of the TPC. It may be possible to subdivide the design and construction of the KAFF facility into smaller phases, as required.

As discussed previously, detailed consideration of the front-end feed preparation (Part "A") activities was impossible because not all required data were available. In addition, front-end feed preparation activities are binned differently for the ADR and the reference LWR MOX approaches. This lack of data also precluded detailed comparison of the ADR Study results with the reference MOX option. However, several opportunities for significant cost savings resulting from implementation of ADR Study options were identified and the overall potential savings were estimated. It may be possible to reduce or eliminate Hydride/De-Hydride (HDH) processing in PF-4 at LANL, but it is more likely the HDH processes would remain but the Direct Metal Oxidation (DMO) processes would be eliminated. Based on the reduced number of operations in PF-4 at LANL, the reduced amount of material to be processed in PF-4 at LANL, the avoidance of purification in H-Canyon, the elimination of the DMO operations in the MFFF, the reduced burdens on the Office of Secure Transport (OST), the avoidance of capital projects at Pantex, and the elimination of the aqueous polishing and oxidation steps, the cost savings were conservatively estimated at \$1B-2B. It is recognized that the uncertainties in this area should be reduced through further analyses, which are included as recommended follow-on activities.

The operating costs for the KAFF facility were estimated based on the current \$125M/yr O&M costs for the K-Area Complex. The incremental staffing cost required to operate the KAFF facility, over and above the baseline staff currently at the K-Area Complex, was estimated to be about \$25M/yr. An additional \$20M/yr was estimated to cover the incremental security costs associated with KAFF facility operation. Another \$50M/yr was estimated to cover the indirect costs of the KAFF facility operations, for laboratory support, and for the support of other organizations not directly associated with the KAFF facility. Thus,

the incremental O&M costs for the KAFF facility is estimated to be \$95M/yr. Combining the current K-Area Complex O&M costs with these incremental KAFF-facility O&M costs, a total O&M cost of \$220M/yr was estimated. This total O&M cost was used in the LCC development, despite the fact that baseline O&M costs for KAMS are nominally covered through the early 2030s by the Office of Environmental Management. This total O&M cost equates to a specific cost of about \$17,000/kgHM for the fuel, when excluding the separate security costs for the K-Area Complex. This specific cost is consistent with, and in fact higher than, the specific cost estimated by Generation 4 – EXCEL Calculation of Nuclear Systems cost calculation tool for metal fuel fabrication (OECD/NEA 2007).

### **Front-end and Fuel Fabrication Costs for Option III**

Until 1994, the FMF was used to fabricate metal alloy fuel for EBR-II. Since that time, options for the use of FMF to fabricate plutonium bearing metal fuel for FFTF and other reactors have been examined. The cost estimate used in this ADR Study was developed based on these earlier studies. The estimate to restart FMF operations, treated as a capital cost, is approximately \$100M, spread over a three-year period. An additional \$20M is included in the LCC estimate for equipment and engineering development costs.<sup>9</sup> The O&M cost was estimated, based on previous experience and current costs, to be \$50M/yr. This O&M cost equates to a specific cost of about \$30,000/kgHM for the fuel, which is much higher than that calculated for the KAFF facility. Higher specific cost would be expected for a smaller facility.

### **Reactor Irradiation Costs**

Detailed design and cost data were developed for the ALMR Mod B under the ALMR program in the early 1990s. These estimates were subjected to multiple reviews by industry and by DOE reviews. They were further refined annually from 1987 to 1995. A more recent unpublished review also confirmed the earlier results. Most of the cost estimates cover a two-module power block, but one cost estimate was prepared for a single prototype module as well.

For this ADR Study, the one-module ADR prototype cost estimate was developed by inflating the ALMR Mod B prototype cost estimate to current dollars by applying the Consumer Price Index (CPI) to the design costs and the Consumer Confidence Index (CCI) to the overnight capital cost. In addition, a \$400M additional fee (beyond the 1992 estimate) for first-of-a-kind (FOAK) licensing was included.<sup>10</sup> The resulting cost is \$3.1B for a single-module prototype.

A separate estimate was also developed by adjusting the same ALMR Mod B one-module prototype design and construction costs by applying the *Handy-Whitman All Steam and Nuclear Index, South Atlantic Region* values. This estimate also resulted in a cost of \$3.1B for a single-module prototype.

The cost for the two-module prototype was estimated similarly. The differential cost between the one-module prototype and the two-module FOAK prototype was escalated using the *Handy-Whitman All Steam and Nuclear Index, South Atlantic Region* values, and estimated to be \$0.8M. This was conservatively rounded to be a \$1B incremental cost for the second module of the two-module power block.

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<sup>9</sup> A lower cost is assumed for FMF because the FMF would be for the most part reconstructed much as it was previously configured without the equipment and engineering development planned for the much larger KAFF facility.

<sup>10</sup> Informal reactor vendor cost estimate for licensing a new reactor, based on recent experience.

Two decades have passed since the original estimates were developed. Thus, it is reasonable to expect that some additional design and construction costs would be incurred due to changing regulatory requirements, including design basis threat changes and post-Fukushima considerations and requirements. Furthermore, the ADR must incorporate one of the possible engineering solutions for handling additional quantities of spent fuel as compared to the baseline ALMR Mod B. Due to the time and resource constraints on this ADR Study, these changes to the design and their impacts on the cost could not be evaluated specifically. To address these unknowns, additional contingencies of \$0.9B and \$1.9B were added to the single-module and two-module cost estimates, respectively. Thus, the LCC estimates are based on a capital cost of \$4B for a one-module prototype and \$6B for a two-module prototype. Costs and schedule for the ADR options were predicated on electricity production, and the overall reactor system was based on a commercial reactor design.

The cost estimate for FFTF is based on the 2007 restart proposal (Columbia Basin Consulting Group 2007). In a similar manner to that described above, the costs were escalated to 2013, resulting in a \$1.4B estimate for FFTF restart including the design, DOE licensing, construction, procurement, and startup costs. The addition of a turbine-generator, incorporated into Option III-SP-Rev, was estimated at \$300M.

### **Spent Fuel Storage Costs**

For the spent fuel storage activities, neither detailed design nor cost data specific to the spent fuel resulting from ADR operation are available to support a “bottoms-up” estimate. The LCC data for Options I and II were developed by examining analogous LWR spent fuel ISFSI projects; an initial capital cost for the ISFSI of \$50M was estimated, with an additional annual O&M cost of \$10M/yr. Because the FFTF already includes a spent fuel handling capability with a capacity comparable to the proposed throughput rate, no additional costs were estimated for FFTF spent fuel storage. The spent fuel would be stored in the existing and operating CSB on the Hanford site and the O&M costs for the CSB are already covered by other programs.

### **Life Cycle Cost Summary**

Table 2 provides a summary of all the options by LCC category for each of the three major cost phases. The total cost for each option is summed and the net present value (NPV) is also provided. Lump-sum costs are expressed in 2013 constant dollars and assume that facilities are operated (after design, construction, and startup) long enough to accomplish the disposition mission. The schedule estimates provided in the next section were used to distribute the costs in time and were combined with a real discount rate of 1.1% to obtain the total NPV of each option.<sup>11</sup>

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<sup>11</sup> The discount rate utilized, 1.1%, is lower than the 1.9% rate that is currently specified by OMB Circular No. A-94 for application to a program with a duration greater than 30 years. Use of the higher discount rate would reduce the calculated NPVs.

**Table 2. Details of Life Cycle Costs and Net Present Values**

LCC Category	Front End Fuel Fabrication	Reactor(s)	Spent Fuel Storage	Total* (2013 \$M)
<b>Option I</b>				
RD&D	\$100	\$600		\$700
Capital	\$1,900	\$4,000	\$50	\$5,950
O&M	\$6,920	\$2,900	\$270	\$10,090
D&D/Closure	\$57	\$400		\$457
Subtotal	\$8,977	\$7,900	\$320	\$17,197
Net Total	\$8,977	\$3,550	\$320	\$12,847
NPV of Net Total				\$10,626
<b>Option II</b>				
RD&D	\$100	\$600		\$700
Capital	\$1,900	\$6,000	\$50	\$7,950
O&M	\$5,820	\$3,600	\$220	\$9,640
D&D/Closure	\$57	\$600		\$657
Subtotal	\$7,877	\$10,800	\$270	\$18,947
Net Total	\$7,877	\$3,600	\$270	\$11,747
NPV of Net Total				\$10,124
<b>Option III</b>				
RD&D	\$20	\$50		\$70
Capital	\$100	\$1,400		\$1,500
O&M	\$1,500	\$4,260		\$5,760
D&D/Closure	\$10	\$140		\$150
Subtotal	\$1,630	\$5,850	\$0	\$7,480
Net Total	\$1,630	\$5,850	\$0	\$7,480
NPV of Net Total				\$6,197
* Costs for combination of Option III with Option I or II are not simply additive, unless the mission is 44 MT.				

## Schedule Estimates

### Options I and II

For Options I and II, a reference schedule was constructed assuming January 1, 2015 as the official start date.<sup>12</sup> The approach taken for the schedule was to put the major activities anticipated to be on or near the critical path into Primavera Project Manager, along with their associated logic and activity durations.

The first major category of activities are the programmatic environmental impact statement (EIS) leading to a record of decision (ROD), policy activities, and procurement (for reactor vendor and NRC licensee)

<sup>12</sup> If one is interested in a Fiscal Year Schedule, the dates quoted here can simply be moved one quarter earlier.

activities.<sup>13</sup> This category also covers the programmatic decision-making process and associated PMDA negotiations (which are assumed neither to drive the critical path nor alter the option specifics).<sup>14</sup>

A second major activity category includes the design and construction of facilities for declassification and associated fuel supply production (e.g. a production facility for declassification, blending, any required oxide reduction, and production of declassified metal slugs and fuel rods). It was assumed that this production facility would be built and licensed in the K-Area Complex per the DOE Order 413.3 (Acquisition of Major Capital Assets) and that the facility's operation would be authorized by DOE.

The reactor(s) constitute a third major category of activities. The ADR is assumed to be a class-103 reactor licensed under the two-step NRC licensing process defined in 10CFR50 that is typically used for power reactors. The assumption is made that the first (and second if applicable for the option) unit would be started up using U-Pu-10Zr metal alloy fuel and tested under 10CFR50.43 (as a prototype plant)<sup>15</sup>. Once a licensee and vendor were procured, the reactor's critical path would be driven by the NRC licensing process (up through a construction authorization), then by the reactor construction period, and finally by startup and testing for the prototype module. A Part-50 license could be used to license one or two modules (e.g. a two-module "power block"). Because the two-module power block powers a single turbine, it would seem reasonable to start both units simultaneously. *At the level of detail provided in this analysis, the schedule differences between startup of a one-module or two-module ADR were negligible. Therefore, a single schedule that addressed both Options I and II was developed.* A more detailed schedule approach would be required to discern scheduling differences between these two options.

The schedule estimates summarized in the following figures include a mix of "optimistic" and "best estimate" assumptions. For the NEPA activities and the time required to procure the reactor vendor and licensee, the schedule was based on what the actual schedule durations were for the current PMDA LWR MOX program (the best analogy). For the KAFF facility, the durations were derived by comparison with schedules for reuse of existing portions of the K-Area Complex for other projects and are expected to be achievable. The reactor schedules are generally consistent with First of a Kind (FOAK) fast reactor construction schedules and other modular reactor licensing schedules. The schedules derived in this document may be longer than what a reactor vendor's optimistic schedule would be. For the reactor, optimistic assumptions are made concerning the durations of certain activities such as fuel and clad qualification (especially for the high-burn up Option II case)<sup>16</sup> and overall engineering and regulatory development. It was assumed that these schedule elements would not be on the critical path. Thus, in summary, the schedules presented here *are judged to be optimistic but achievable*.

The major scheduling milestones for Options I and II are shown in Figure 11. Reactor criticality (when PMDA disposition begins) occurs in June 2030. The first core is expected to be available approximately

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<sup>13</sup> These categories, in Primavera Project Management schedules, are referred to as "Work Breakdown Structures."

<sup>14</sup> History has shown that PMDA bilateral negotiations can be time consuming-this is an assumption.

<sup>15</sup> Under 10CFR50.43, the NRC will assure that "there is acceptable testing of a prototype plant over a sufficient range of normal operating conditions, transient conditions, and specified accident sequences, including equilibrium core conditions. If a prototype plant is used to comply with the testing requirements, then the NRC may impose additional requirements on siting, safety features, or operational conditions for the prototype plant to protect the public and the plant staff from the possible consequences of accidents during the testing period."

<sup>16</sup> An optimistic assumption was made that the data generated for ternary U-Pu-10Zr metal alloy fuel supplemented with data from binary U-10Zr metal alloy fuel derived from FFTF and EBR II irradiations were adequate to meet NRC fuel qualification requirements. If this assumption proves not to be valid, fuel qualification is likely to be a critical path activity – possibly requiring fast-spectrum irradiation tests that cannot currently be performed domestically.



18 months before it is needed to support the reactor. Therefore, if the reactor schedule could be compressed (e.g., by formulating approaches to support a more optimistic timeline for critical activities than the timeline identified herein), then reactor criticality and initial disposition could occur as soon as January 2029.

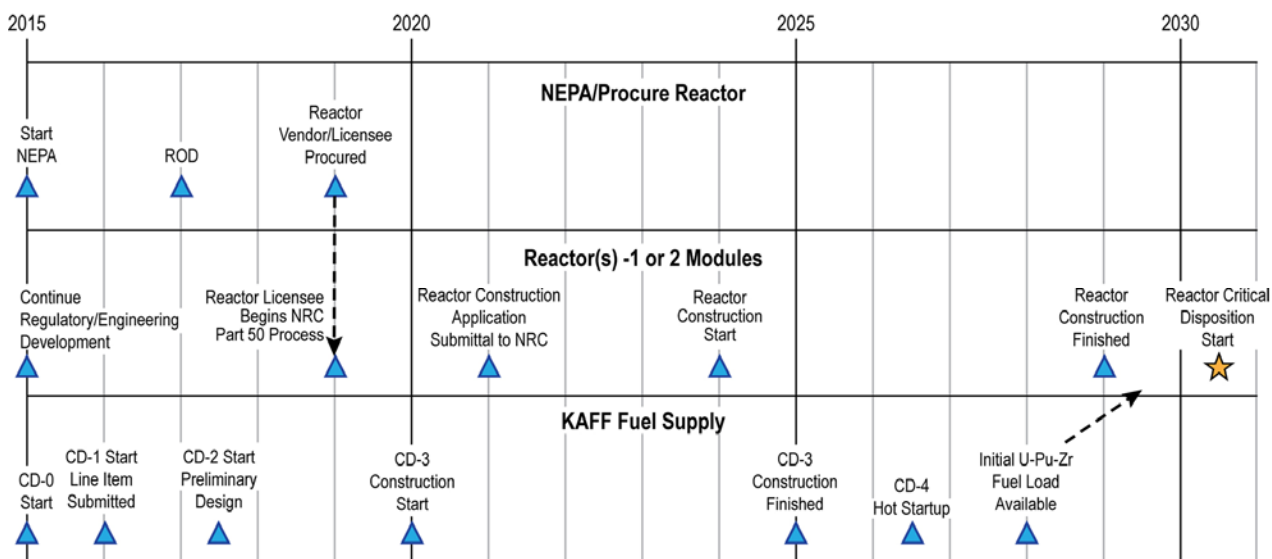


Figure 11. Milestone Schedule for Options I and II

### Option III

In January 1997, the decision was made to place the FFTF in hot standby while evaluations of its future were performed. The restart of FFTF was studied for the purpose of isotope production missions (e.g., tritium and medical isotopes). NEPA evaluations were also performed for these alternative missions. In January 2001, Secretary Richardson made the decision not to restart the FFTF, and the FFTF was placed into a deactivation status. In January 2007, DOE awarded a grant to the Tri-City Development Council to manage an effort to evaluate the FFTF as a potential location for critical fuels and advanced reactor facilities to support the Global Nuclear Energy Partnership. The associated examination by the Columbia Basin Consulting Group (CBCG) of the schedule for restart of FFTF and options for its fuel supply forms the basis of the schedule analysis presented here (Columbia Basin Consulting Group 2007).

The CBCG report stated that the FFTF could be ready to perform fuel testing in 5 to 5.5 years. The time and resource constraints on this ADR Study permitted neither a thorough critical review of the CBCG report, nor a current assessment and walk down of the plant to see if the CBCG conclusions and estimates remain valid. There are a number of other uncertainties specific to the FFTF that should be addressed to obtain a more robust schedule estimate. These issues include, but are not limited to:

- The NEPA strategy for plutonium disposition and the effort required to obtain a positive ROD in light of questions concerning ultimate disposal of sodium bonded spent metal fuel;
- Arrangements with state and local authorities;
- The time required for rebuilding the operational infrastructure;
- The time required for rebuilding the DOE regulatory infrastructure for oversight of FFTF;

- Evaluation of the facility for the design basis threats;
- Evaluations of the condition of many supporting plant systems;
- Fuel and core consumable supply (control rods, new PMDA fuel, and possible reuse of existing FFTF fresh fuel);
- Post-Fukushima safety requirements; and
- Relicensing and recertification by DOE of the FFTF use of metal fuel.

In light of these issues, the schedule results for Option III discussed below should be considered “optimistic.” Figure 12 shows a milestone schedule for Option III. The fabrication of disposition fuel under the PMDA was scheduled to be started in the FMF in approximately three years. The restart date using the CBCG schedule was estimated to be June 2020. This option, even with potential schedule delays resulting from issues noted previously, would provide the earliest potential disposition capability of the ADR options studied.

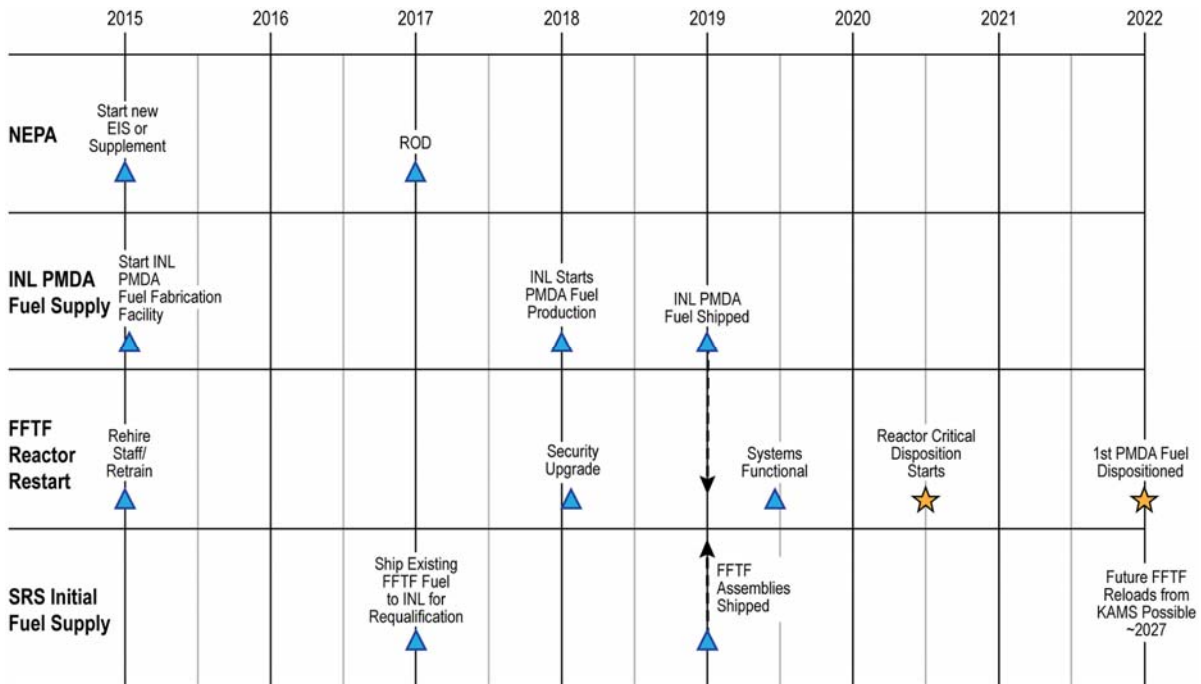


Figure 12. Milestone Schedule for Option III

## Discussion of Results

The results of this ADR Study have highlighted three main options that were used to understand the option space with respect to the current excess weapons plutonium disposition mission. Leveraging use of existing facilities such as KAMS and the FFTF in combination with one or more ADR modules would provide the most attractive approach for feed material preparation, fuel fabrication, irradiation, and spent fuel storage. The advantages, benefits, and risks of the options based on their technical characteristics including disposition rate, cost, and schedule analyses described above are summarized below. In addition, strategies and tradeoffs for maximizing benefits and minimizing risks for plutonium disposition are described.

### Option Results and Comparisons

The following observations were made in considering the disposition scenarios and their associated cost and schedule attributes described in the previous section.

***Options I and II similar life cycle costs but different cash flow profiles.*** While the two options were calculated to have similar LCCs (within 10% of one another), key differences in capital and operating costs occur. Option I has lower capital costs, but higher net operational costs. Option II has higher capital costs, but lower net operational costs. Furthermore, building a two-module ADR is expected to provide more benefit and flexibility in the following manner:

- Double the disposition rate, which would halve the mission duration;
- Reduce capital cost for the additional unit (\$4B for one module versus \$6B for two modules); and
- Reduce the cost of disposition per capital dollar invested through sharing common infrastructure.

Construction of two modules would increase the capital at risk, but would not increase the schedule risk significantly.

***Leveraging the existing K-Area Complex facilities to provide fuel supply is cost effective and can support plutonium disposition for several ADR scenarios.*** Use of metal fuel is very compatible with most of the PMDA metal feed stocks, requiring only declassification and little to no purification of feed material. Collocation with the existing plutonium storage in KAMS facility optimizes use of existing capabilities while minimizing security risks. Oxide reduction could be incorporated through relatively minor facility additions. The aqueous polishing required in the current reference MOX program would not be required.

***PMDA disposition could be initiated in the early 2020s (Option III).*** An important aspect of Option III is that the facilities already exist, and have adequate remaining lifetime to support several decades of operation. Use of the existing inventory of unirradiated MOX fuel for the FFTF restart provides a disposition path for this material, for which the Office of Environmental Management has yet to identify a preferred disposition pathway.

***PMDA disposition could be initiated in the early 2020s (Option III) followed by a major increase in disposition rate in 2030 (Option I or II).*** Option III would provide an early start to disposition. A longer-term higher capacity disposition capability could be phased in as part of a multi-pronged approach. Implementation of this multi-pronged approach would require a concerted U.S. government effort over the next 15 years devoted to implementation of the ADR concept and a significant capital expense

(\$1.9B) for the KAFF facility. Getting started with an early disposition capability through implementation of Option III would be key to promoting overall forward momentum. Implementation of Option III would also reduce the technical risks associated with implementation of Option I or II.

***If the disposition criteria were relaxed to the self-protection standard, higher throughputs would enable a larger disposition capacity per capital dollar expended.*** The results of the ADR Study demonstrate the significant impact that the PMDA disposition criteria have on disposition rates. This is important when considering cost and schedule. Higher disposition rates would enable the mission to be completed faster, resulting in the reduction of operating costs and thus LCCs.

An illustration of this strategy would be to combine Option I (operating to the self-protection standard) with Option III (also operating to the self-protection standard); this combined approach would provide a disposition rate of ~ 2 MT of weapons plutonium per year, which is significantly in excess of the PMDA goal of 1.3 MT/yr. Achievement of this disposition rate would require only one green-field facility, a single ADR prototype module, which translates to less capital at risk. (Even if the PMDA criteria were to be retained, a combined single-module ADR and the FFTF could disposition 1.1 MT/yr.) If Options II and III were combined, the plutonium disposition rate would increase to 1.9 MT/yr [(1.6+0.3) if meeting current PMDA criteria] and to over 3 MT/yr [(2.6+0.6) if meeting the self-protection standard).

The specific disposition costs, that is, the costs per kg of disposition plutonium converted into spent fuel, are summarized for the options in Table 3 below. Options I, II, and III were *not* optimized for specific disposition costs, but parametric studies were performed and summarized in Table 3 specifically to assess the cost impacts of relaxed disposition criteria (self-protection or SP) and extended missions (EXT). Options I and II are capable of dispositioning far more than 34,000 kg of plutonium, but only this reference amount was analyzed to enable cross-comparison of all the PMDA options. The two ADR modules are capable over their 60-year design life of dispositioning approximately 156 MT of disposition plutonium, or 175 MT total plutonium. Were this quantity of plutonium to be dispositioned, the specific disposition costs would be reduced to \$132/kg LCC and \$101/kg NPV. The results for Option II-SP show that for the fixed 34 MT mission, adoption of the self-protection standard would shorten the disposition schedule significantly but would reduce the specific disposition cost; savings would accrue only if the mission were to be expanded to larger stockpiles.

The single-module Option I is also capable of dispositioning significantly more plutonium than the 34 MT PMDA commitment – in fact, 76.7 MT of disposition plutonium or 85.9 MT total plutonium – over its 60-year design life. Were this quantity of plutonium to be dispositioned, the specific disposition costs would be reduced to \$242/kg LCC and \$178/kg NPV.

For the FFTF-based options, cost advantages accrue with adoption of the self-protection standard because the total plutonium that can be dispositioned is limited by the remaining lifetime of the FFTF. The cost savings are not as dramatic as one might expect because the FMF is not capable of producing sufficient fuel to support Option III-SP and thus a second fabrication facility, a reduced capacity KAFF facility, is included in the analysis. The incorporation of a turbine-generator also improves the specific costs.

**Table 3. Summary of Specific Disposition Costs**

Option	Disposition Criteria	Disposition Rate [kg-Pu/yr]	Total Plutonium Dispositioned [kg]	LCC	NPV	Specific LCC [\$K/kg-Pu]	Specific NPV [\$K/kg-Pu]
Option I	Self-protection	1299	34,000	\$12,847	\$10,626	\$378	\$313
Option I-Ext	Self-protection	1299	76,700	\$18,557	\$13,671	\$242	\$178
Option II	PMDA	1570	34,000	\$11,747	\$10,124	\$346	\$298
Option II-SP	Self-protection	2598	34,000	\$13,367	\$11,602	\$393	\$341
Option II-SP-Ext	Self-protection	2598	156,000	\$20,627	\$15,825	\$132	\$101
Option III*	PMDA	330	9900	\$7,480	\$6,197	\$756	\$626
Option III-SP	Self-protection	610	16760	\$12,555	\$10,419	\$749	\$622
Option III-SP-Rev	Self-protection	610	16760	\$10,905	\$9,155	\$651	\$546

\* Costs for combination of Option III with Option I or II are not simply additive, unless the mission is 44 MT.

### Additional Advantages and Benefits

*Accelerated reduction of surplus inventory at Pantex through dual-path pit processing at LANL and SRS would enable avoidance of construction of the Material Staging Facility at Pantex, a future large capital expenditure for the Office of Defense Programs (likely > \$1B).* Pantex has submitted a Critical Decision-0 package for a Material Staging Facility to NNSA Headquarters (Office of Inspector General Office of Audits and Inspections 2013). Accelerated shipments of surplus pits would help alleviate Pantex’s infrastructure challenges by supporting consolidation efforts.

*Transfer of some pit disassembly work from PF-4 to the KAFF facility would reduce the production challenges in PF-4 arising from the deferral of the Chemistry and Metallurgy Research Replacement – Nuclear Facility (CMRR-NF) project and the projected increased pit-production demands.* The CMRR-NF project has been deferred at least five years. The operations currently conducted in the aging and increasingly unsupportable Chemistry and Metallurgy Research facility support pit manufacture conducted in PF-4, and are being transferred to PF-4 and to the Radiological Laboratory, Utility, and Office Building as the laboratory wings in the Chemistry and Metallurgy Research facility are shut down. Simultaneously, pit production demands are projected to increase by the latter part of the decade. These simultaneous demands on PF-4 facility are anticipated to result in production challenges. Transferal of a portion of the pit disassembly work to the KAFF facility would reduce these production challenges, not only in terms of the actual disassembly but also in the receipt, unpacking, characterization, repackaging, and shipment of these materials. This approach would eliminate single-point failure by having two sites capable of pit receipt and pit disassembly.

*Use of metallic fuel in the ADR approach would eliminate the cost of purifying and converting the metallic weapons pits to oxide fuel.* Because the metal fuel is more tolerant of americium and other impurities in the feed, the ADR approach would enable elimination of the aqueous polishing operations, the associated waste solidification operations, production of approximately 1000 transuranic waste drums per year, and disposal of this waste in WIPP. These savings are estimated at \$1-2B.

*The ADR approach would support multi-program users of the K-Area Complex by enabling expanded storage capacity and an extended operating period. Utilizing KAMS for an ADR option would provide a longer life-cycle for the facility, extending the opportunities for NNSA and other agencies and offices to archive and perform forensics on Category-I quantities of SNM and to expand receipt of foreign SNM if pursued by the U.S. government. Depending on the form of incoming material, KAMS could provide a one-stop processing option for a reactor disposition pathway. This could avoid multiple shipments of products prior to disposition.*

The ADR options reduce the demand on the Office of Secure Transport by minimizing shipments of plutonium. Under the reference PMDA, all pits and clean metal will be transported from Pantex to LANL for processing. The recovered plutonium would be subsequently transported to the KAMS facility at SRS. Because the ADR approach can accommodate direct processing of certain pits and clean metal into fuel without prior processing at LANL, approximately 20-25% of the excess inventory at Pantex could be shipped directly to KAMS. While the OST workload would not be significantly reduced, it is likely that efficiencies can be realized in the eastbound convoys.

*The ADR approach would eliminate the reliance on H-Canyon for processing of surplus plutonium, thereby freeing H-Canyon to focus on disposition of used nuclear fuel and highly enriched uranium blend-down. The planned processing of surplus plutonium in H-Canyon will limit the processing of used nuclear fuel and the associated blend-down of highly enriched uranium. Eliminating this planned processing will free up the H-Canyon facility and allow expedited processing of the existing and future inventories of used nuclear fuel without the addition of new dissolvers. This approach would also beneficially enable a reduced security posture in the H-Canyon facility.*

*In addition to meeting the PMDA disposition requirements, the ADR approach provides plutonium disposition capacity beyond the 34 MT identified for the reference program. Having the capability to disposition much larger inventories of plutonium could enable the U.S. to negotiate with the RF for increased disposition rates, or for increased total quantities to be dispositioned, or both. Cooperation with Russia in advanced disposition technologies could represent an important area of scientific collaboration of mutual interest to both countries.*

*The ADR approach may enable the U.S. to obtain PMDA credit for several more tons of plutonium. Several metric tons of plutonium that do not meet the current MFFF acceptance criteria could be used in the ADR. In addition, the pyrometallurgical fabrication process is more forgiving of halide contamination<sup>17</sup> and would be able to disposition portions of the surplus weapons plutonium inventory that are not currently considered suitable for MOX. This “non-MOXable” inventory could be available as matching material for use in future international treaty or agreement negotiations. The ability to disposition through an ADR option would also preserve valuable space in WIPP because plutonium inventories that would otherwise be sent to WIPP for disposal could be beneficially used in the ADR.*

There is also a possible benefit due to the potential for industry and international cost-sharing for implementation of the ADR approach. Other countries (Russia, India, China, South Korea, and Japan)

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<sup>17</sup> Some of the oxide feed materials are contaminated with chloride salts, which are problematic for aqueous purification systems because the chlorides cause increased corrosion.

have expressed interest in pursuing fast-spectrum reactors for a variety of reasons. Cost-sharing on the ADR could provide an industry leader or consortium with first-mover advantages.

### **Technical, Cost, and Schedule Risks**

The ADR Study options, based on metal fuel and fast reactors, differ from those employed for the PMDA LWR reference program. Implementation of an ADR option would provide opportunity for significant benefits as outlined in the previous section, but would also carry with it new and additional technical and implementation risks. Identified major challenges associated with the ADR option are described below. These aspects can only be qualitatively highlighted at this stage. A disciplined analysis of the technical, cost, and schedule risks of these options could be performed but it was beyond the scope of this initial examination.

#### **Declassification and Metal Fuel Fabrication in the K-Area Material Storage and Fuel Manufacturing Facility**

The ADR approach requires a \$1.9B modification to an existing plutonium storage facility, creating a combined storage and fuel fabrication processing facility. While this activity was addressed in the cost and schedule analysis, there are recognized challenges in executing the construction and authorization basis changes necessary to transform K-Area Complex into this configuration.

The fuel production process and its operational experience were successfully demonstrated (both fuel fabrication and fuel performance) at the prototypic level at INL. However, the fuel fabrication process has not reached full industrial maturity. The capacity to support ADR options will have to undergo a large scale up beyond the current experience base, by roughly an order of magnitude (depends on the exact scenario). Specific risk reduction strategies must be identified and employed for engineering a reliable, high-capacity production line that produces nuclear fuel qualified for use in an NRC-licensed power reactor (i.e., qualified as a supplier under 10CFR50 Appendix B). Past experience with many nuclear technologies has demonstrated that a large scale up of a process can introduce new operational problems and concerns that were not an issue during the laboratory or pilot-scale operations.

#### **NRC (or DOE) Reactor Licensing**

This is an obvious challenge for both metal fuel fabrication technology and fast-spectrum burner reactor technology overall. Experimental facilities to support fast-reactor R&D in the U.S. have been limited for some time (and nearly non-existent following the closures of EBR-II and FFTF). Many of the computer codes used for modeling and designing advanced fast-spectrum reactors would require upgrading and experimental validation to obtain NRC acceptance. The design and licensing infrastructure and expertise for such work is dispersed among the U.S. government, its laboratories, and some reactor vendors. While there has been some interest and initial effort by the NRC to develop capabilities and processes for design and licensing different reactor technologies, the NRC has not had a strong focus on these types of technologies, because the vast majority of their regulatory responsibilities are with light-water reactors.

Building the required vendor, licensee (operator), and NRC regulatory infrastructure to support the licensing of U-Pu-10Zr metal alloy fuel and the reactor would be a large endeavor. DOE would likely have to bear most of the technical risk for the front-end, fuel fabrication, and fuel qualification activities. It would be important to get the fuel qualification and licensing paths established as early as possible to prevent them from impacting the overall critical path. Some of the activities associated with engineering

and regulatory development are not on the critical path, but it is important that the majority of these activities be performed in parallel with NEPA activities and procurement of the vendor. The overall outcome of these efforts must enable the NRC to provide a clear licensing path to help guide the licensee, otherwise cost and schedule problems will ensue.

### **Construction and Operation of a First-of-a-Kind Reactor**

Construction and operation of a first-of-a-kind (FOAK) reactor represents a technical, licensing, and project management challenge (which translates into cost and schedule risk). Developing of reliable, qualified supply chains for the reactor's components and minimizing the number of long lead items on the critical path are important issues that must be managed. Construction of a FOAK fast-spectrum NRC-licensed reactor technology would require significant and sustained long-term financial support by the U.S. government. Some reactor licensing risk could potentially be shared between the vendor and the U.S. government, depending on the business model. *These major issues are also relevant significant issues for many other current large nuclear projects in the U.S., including the construction of the MFFF and new reactors.*

### **Fast Flux Test Facility Restart**

The major issues related to restart have been identified and were addressed in an earlier study (Columbia Basin Consulting Group 2007). An obvious overall risk for Option III is that no fast reactor facility has ever been reactivated and relicensed for operations after removing the sodium coolant. Thus, it would be prudent to review and validate all aspects of the previous study in light of present information. Qualification of the existing fuel for initial core loading also needs to be addressed. To help reduce these and other identified risks, the overall cost and schedule for the FFTF restart should be reviewed by an Independent Review Team (IRT). It is recommended that this team be staffed primarily by DOE personnel with reactor regulatory experience, architectural/engineering experts from industry, and knowledgeable retired FFTF staff. This would better identify risks, help validate cost and schedule, and define the path forward.



## Conclusions

The initial technical analyses conducted as part of this study indicate that advanced fast-spectrum burner reactors are technically viable options for use in plutonium disposition. Advanced fast-spectrum burner reactors can meet the current PMDA requirements; the costs of these options could be reduced if the PMDA burnup criteria were to be eliminated, leaving as the primary disposition criterion only the self-protection requirement. These technical results could help to inform broader policy analyses on the possible roles of fast-spectrum burner reactor options for plutonium disposition.

### **Advanced Disposition Reactor Options**

For the purpose of this study, the ADR was defined as a Nuclear Regulatory Commission (NRC) licensed advanced pool-type fast-spectrum liquid-metal cooled burner reactor using metal fuel. Metal fuel was chosen because of the extensive U.S. data, operational experience, passive safety characteristics, and compatibility with the surplus-pit feed form.

Two ADR implementation options were studied: Option I (a single-module ADR prototype) and Option II (a two-module ADR prototype). A key benefit identified for these options is the significant estimated savings [of at least \$1B for feed preparation (“Part A”) costs] derived from use of metal feed (thus avoiding oxidation and aqueous polishing steps). Additional benefits include (1) surplus inventory reduction at Pantex would be accelerated through dual-path pit processing at LANL and SRS, enabling avoidance of construction of the Material Staging Facility at Pantex; (2) production challenges at Los Alamos National Laboratory (LANL) arising from deferral of the CMRR-NF project and projected increased pit-production demands would be reduced through transfer of some pit-disassembly work to the Savannah River Site (SRS) K-Area Complex; (3) demands on Office of Secure Transport (OST) resources would be reduced; and (4) demands on the SRS H-canyon would be reduced, potentially allowing accelerated processing of other spent fuel inventories stored at SRS.

Specific outcomes for Option I and Option II include:

- Capital cost for fuel production facility (KAFF facility) - \$1.9B (\$1.1B less than for a green-field fuel fabrication facility)
  - Use of the MFFF at SRS was considered but K-Area complex was more cost effective
- ADR can be operational in 14-15 years (aligned with the operational readiness of the KAFF facility)
  - Option I (\$4B), a single-module ADR, fulfills the 1.3 MT/yr throughput criteria only if the disposition criteria are reduced to the requirement for self-protection; the throughput is reduced to 0.8 MT/yr if the current PMDA burnup criteria are used
  - Option II (\$6B), two-module ADR, fulfills the current PMDA criteria at 1.6 MT/yr throughput; throughput increases to 2.6 MT/yr if only the requirement for self-protection is used
- Cost for ISFSI - \$50M capital, plus \$10M/yr for O&M
- For Option II, net estimated annual operating costs less than \$100M/yr over 30 years

## Fast Flux Test Facility Option

Restarting the FFTF, a fast-spectrum test reactor closed in 1994, enables initiation of PMDA disposition in five years with a throughput of 330 kg/yr. In addition, FFTF restart reduces technical risks for implementation of options that include new ADR reactors.

Specific outcomes for Option III include:

- Near-term disposition capability
  - Initiates disposition in 5 years using restarted FFTF (\$1.4B to restart)
  - Fulfills the current PMDA criteria for 0.3 MT/yr throughput; throughput increases to 0.6 MT/yr if only the requirement for self-protection is used
- Low upfront cost, \$1.4B for FFTF restart and \$0.1B for restart of the FMF at INL (0.3 MT/yr throughput)
- Net estimated annual operating costs less than \$200M/yr
- Option for electricity generation (additional \$300M capital), for on-site use

## Cost Summary

Comparison of the costs among the options requires noting the differences in duration, total plutonium dispositioned, and the assumed spent-fuel disposition criteria. Both Options I and II are able to disposition the 34 MT of excess plutonium associated with the PMDA commitment. However, the cost calculations for Option I are based on the assumption that only the requirement for self-protection is used.

Furthermore, for Option I the excess weapons plutonium would be blended with approximately ten percent reactor-grade plutonium to ensure that required plutonium isotopic ratio in the spent fuel would be met. Because of this blending step, nearly 38 MT of plutonium would be dispositioned for Option I. Blending would not be required for Option II and the costs are calculated for operation using the PMDA spent fuel disposition criteria. The two-module Option II would have higher initial costs (primarily due to the additional \$1B capital cost for the second module), but these higher initial costs would be more than offset by the lower net operating costs. As Table 4 shows, the LCCs for Options 1 and 2 are very similar. In Option III, the total quantity of plutonium dispositioned (to the PMDA criteria) is limited to just less than 10 MT by the lifetime of the FFTF reactor. The LCC and NPV for Option III are also shown in Table 4 below.

**Table 4. Summary of Life Cycle Costs and Net Present Values**

<b>LCC Category [2013 \$M]</b>	<b>Front-end Fuel Cycle</b>	<b>Reactor(s)</b>	<b>Back-end Fuel Cycle</b>	<b>Total</b>
Option I (Self-protection)				
LCC w/o Revenues	\$8,877	\$7,700	\$330	\$17,007
Net Total	\$8,977	\$3,650	\$330	\$12,957
NPV of Net Total				\$10,710
Option II (PMDA)				
LCC w/o Revenues	\$7,877	\$10,500	\$280	\$18,657
Net Total	\$7,877	\$3,900	\$280	\$12,057
NPV of Net Total				\$10,344
Option III (PMDA)				
LCC w/o Revenues	\$1,630	\$5,850	\$0	\$7,480
Net Total	\$1,630	\$5,850	\$0	\$7,480
NPV of Net Total				\$6,197

## Next Steps

These preliminary technical results justify a more in-depth analysis of once-through fast-spectrum burner reactor options for plutonium disposition. A comprehensive list of the next steps to further define the technical role of ADRs in plutonium disposition has been prepared; the key next steps include:

- Performing detailed analysis of the mission requirements for the KAFF facility;
- Engaging industry in defining required attributes of a fast-spectrum burner reactor; and
- Refining construction and operating cost estimates for the ADR approach in the context of current safety, security, and licensing requirements.

These technical results could help to inform broader policy analyses on the possible roles of fast-spectrum burner reactor options for plutonium disposition.

## Appendices

## Appendix A. Background to the Advanced Disposition Reactor Study

As the Cold War ended, retirements associated with implementation of the Strategic Arms Reduction Treaties I and II were projected to render tens of metric tons of plutonium excess to defense needs. In his capacity as President Bush's National Security Advisor, Brent Scowcroft requested that the National Academy of Sciences' Committee on International Security and Arms Control (CISAC) study the possible options for management and disposition of the projected excess plutonium stocks. The study was ultimately commissioned through the U.S. Department of Energy's Office of Nuclear Energy. In parallel with the CISAC study commissioning, DOE/NE initiated several studies by the leading nuclear steam supply system vendors to evaluate the various reactor-based disposition options including the ALMR. These efforts were continued and supported by the incoming Clinton administration.

In September 1993, President Clinton issued the U.S. Nonproliferation and Export Control Policy,<sup>1</sup> which committed the United States to undertake a comprehensive management approach to the growing accumulation of fissile materials from dismantled nuclear weapons. Following this announcement, an Interagency Working Group (IWG) was established to conduct a comprehensive review of the options for disposition of surplus plutonium from nuclear weapons activities of the United States and the former Soviet Union. The IWG was co-chaired by the White House Office of Science and Technology Policy and the National Security Council. In response to the President's nonproliferation policy, Secretary O'Leary created a department-wide project for control and disposition of surplus fissile materials on January 24, 1994. Later that year, this project became the Office of Fissile Materials Disposition (DOE/MD). The DOE had a lead role within the IWG for evaluating technical options and developing analyses of economic, schedule, environmental, and other aspects of potential disposition options.

The CISAC report, *Management and Disposition of Excess Weapons Plutonium*, was released in 1994 and covered aspects of disarmament up to and including options for long-term disposition (Committee on International Security and Arms Control, National Academy of Sciences 1994). This seminal report introduced several concepts including the "Spent-fuel standard" (SFS), which postulates that the immediate goal should be to make excess weapons plutonium "roughly as inaccessible for weapons use as the much larger and growing quantity of plutonium that exists in spent fuel from commercial reactors." Options that leave the plutonium more accessible than the spent fuel would mean that the material would continue to pose a unique safeguards problem indefinitely. It was acknowledged that steps beyond the SFS would be necessary over the long term for plutonium.<sup>18</sup> The report discussed intrinsic and extrinsic barriers associated with disposition forms.

The CISAC report outlined the general world overview in regards to plutonium stocks. The concept of spiking plutonium (which does not meet the SFS) was also discussed, but found not to provide an adequate barrier over the long run unless the spiked fuel is ultimately reused. The two most promising alternatives were identified to be utilization of plutonium as fuel in reactors and vitrification. Deep boreholes were also noted to be potentially attractive. The use of advanced reactors and fuels to achieve high plutonium consumption without reprocessing was deemed not to be worthwhile in terms of altering

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<sup>18</sup> Interestingly, cost was considered to be important, but the CISAC stated that it should not be the primary criterion in light of the security objectives.

the security risk. However, it was recognized that the best means of disposition might well differ between the U.S. and the RF due to the different infrastructures and plutonium policies.

One of the key inputs to the CISAC report was a subsidiary report by the Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium (Committee on International Security and Arms Control, National Academy of Sciences 1995). The subsidiary report, which was published about a year later than the primary report but which dates to the same original request from Scowcroft, contains more complete information on the reactor options.

In January 1995, joint efforts were undertaken between U.S. and Russian experts to perform a comprehensive examination of options for long-term plutonium disposition. These efforts culminated in a series of joint reports issued in 1996. Joint studies and analyses continued through the negotiation of the PMDA, which is discussed in the following appendix.

In 1999, an Interim Report was provided to DOE by the Panel to Review the SFS. This report also used the example of the 20-30 years in their arguments about the variability over time when considering the SFS. The committee reinforced the point that the SFS depends only on intrinsic properties (e.g., dose, isotopics, mass, etc.) of the final form of the disposition option, institutional and other safeguards are not per se part of the standard. The standard's meaning is in terms that the form would not add significantly to the security risks associated with plutonium in spent fuel, given comparable engineered and institutional protections for both types of material. Significantly, the committee stated that *it has not constructed a formula that can be mechanistically applied to determine compliance with the standard, and the committee remained unconvinced that it was practical or desirable to do so*. Rather the recommendation was to examine the various barriers in terms of proliferation threat forming a matrix to inform the judgment process.

In 2000, the panel was charged by the Office of Fissile Material Disposition in the U.S. DOE to 1) amplify and clarify the SFS and the considerations to be taken into account in its application and 2) using results of 1, determine whether the final forms of can-in-canister immobilization, irradiation of MOX in commercial LWRs, and irradiation of MOX in CANDU reactors would meet the SFS. The basis of comparison was 30-year-old spent uranium LWR fuel irradiated to 33,000 MWd/MTHM. The LWR weapons-plutonium MOX (40,000 MWd/MTHM) met the standard. Individual CANDU MOX bundles at 9700 MWd/MTHM did not meet the standard. CANDU CANFLEX MOX bundles at 25,000 MWd/MTHM (assuming a large agglomeration) were judged as marginal. For the can-in-canister, it was concluded that additional investigation would have to be performed and that a testing and development program might lead to identification of specific various forms that could meet the spent-fuel standard. This report showed the process (in essence a non-proliferation type of assessment) that the panel went through and the resulting conclusions about applying the criteria (Committee on International Security and Arms Control, National Academy of Sciences 2000).

These efforts culminated in the signing of the PMDA in September 2000, which set the U.S. firmly on a path towards use of LWRs and immobilization for long-term disposition. With the change of administration in 2001, these decisions were re-evaluated. As part of that re-evaluation, the Office of Nuclear Energy developed a technical approach for enhancing the Department's ongoing surplus weapons plutonium disposition activity that included use of advanced fast reactor technology (Magwood-2001).

The proposed alternative approach was not implemented at that time, but recent events have resulted in re-evaluation of the Department's approach for disposition of surplus weapons plutonium.

During the years since the current weapons plutonium disposition program (PDP) inception, the stockpiles of plutonium have continued to grow such that the relevant problem may no longer be limited to the initial 68 MT of excess weapons plutonium, 34 MT each for the U.S. and Russia. With the evolution of threat considerations including possible use of improvised nuclear devices, large stocks of plutonium are now considered more of a liability than an asset. Thus, this study addresses the 34 MT of excess U.S. weapons plutonium as only the initial step along a path to address these much larger international stocks. Implementation of the ADR-based alternative disposition path may help to influence plutonium management worldwide through U.S. leadership and demonstration of a viable disposition pathway.

Large quantities of weapons plutonium currently exist; one open-source estimate places the worldwide stockpile at 240 MT of military weapons material, of which approximately 80 MT have been declared excess to weapons needs (The Nuclear Threat Initiative 2012).

In this light, the Office of Nuclear Energy was recently tasked by Secretary Chu to do a new evaluation of advanced fast reactors for plutonium disposition – one of the pillars of the approach proposed in 2001. The purpose of this ADR Study is to revisit the 2001 proposal, completing an evaluation of the technical, financial, and schedule aspects of plutonium disposition using one or more advanced fast reactors.

## Appendix B. Constraints on Implementation Imposed by the Plutonium Management and Disposition Agreement and Other Considerations

### Disposition Criteria Codified in the Plutonium Management and Disposition Agreement

The current Plutonium Disposition Program (PDP), managed by the Office of Fissile Materials Disposition within the National Nuclear Security Administration (NNSA), is being implemented in accordance with the *Plutonium Management and Disposition Agreement*, signed on September 1, 2000 (U.S. and Russian Federation 2000) and amended in 2010 (U.S. and Russian Federation 2010). This intergovernmental agreement requires that the U.S. and Russia each dispose of 34 metric tons of weapons plutonium at a minimum rate of 1.3 metric tons per year. The agreement specifies that this disposition be accomplished in the U.S. by irradiating the material as mixed oxide fuel (MOX) in existing commercial light water nuclear reactors and in Russia by irradiating the material as MOX fuel in the BN-600 and BN-800 advanced fast reactors.

The verb “to disposition” was effectively created to describe the approach developed to deal with the quantities of surplus plutonium released from military programs in the U.S. and Russia. The definition is codified in the PMDA, as amended:

*Disposition plutonium shall be considered disposed if the spent plutonium fuel resulting from irradiation in the BN-600 and BN-800 reactors meets the four criteria below.*

*Each spent plutonium fuel assembly contains a unique identifier that demonstrates it to be a fuel assembly produced with conversion product.*

*Each spent plutonium fuel assembly is irradiated to an average fuel burn-up level of no less than:*

- a) five (5) percent of heavy-metal atoms for assemblies from the BN-600 reactor;*
- b) three and nine-tenths (3.9) percent of heavy-metal atoms for assemblies from the BN-800 reactor during the two-to-three year reactor commissioning stage; and*
- c) four and one-half (4.5) percent of heavy-metal atoms for assemblies from the BN-800 reactor during the stage of operation of the reactor with rated parameters.*

*The average fuel burn-up level of any batch of such spent plutonium fuel assemblies discharged during the same refueling outage from the reactor core is no less than:*

- a) six and one-half (6.5) percent of heavy-metal atoms for the BN-600 reactor;*
- b) five (5) percent of heavy metal atoms for the BN-800 reactor during the two-to-three year reactor commissioning stage; and*
- c) six (6) percent of heavy metal atoms for assemblies from the BN-800 reactor during the stage of operation of the reactor with rated parameters.*

*The radiation level from each spent plutonium fuel assembly is such that it will become no less than 1 Sievert per hour one meter from the accessible surface at the centerline of the assembly 30 years after irradiation has been completed.*



Neither the ADR nor any other sodium-cooled advanced fast reactor is defined in the PMDA for use as a U.S. disposition reactor. However, because Russia's two disposition reactors, the BN-600 and BN-800, are sodium-cooled fast reactors, Rosatom as the Russian executive agent for implementation of the PMDA would likely accept application of the burnup limits for the BN-800 to the ADR. *Thus, the disposition limits for the BN-800 were assumed to be the baseline limits for the ADR.* The burnup criteria set for the BN-800 and used as the assumed criteria for the ADR are much more restrictive than the other PMDA disposition criteria. The disposition rates per ADR module per year could be increased significantly if the PMDA burnup criteria were to be eliminated, leaving as the primary disposition criterion only the self-protection requirement.<sup>19</sup>

### Self-Protection Requirement

The final criterion quoted above from the PMDA, as amended, is adapted in part from an interpretation of the SFS defined in the CISAC reports and in part from the IAEA and NRC requirements for self-protection. The dose equivalent rate is taken from the IAEA and NRC specifications for a self-protecting gamma dose rate.

The IAEA guidance document *The Physical Protection of Nuclear Material and Nuclear Facilities* has long been considered the internationally accepted standard for physical protection. It is not a legally binding instrument as such, but can be given a legally binding effect in some bilateral nuclear safeguards agreements that prescribe INFCIRC/225 as the standard to be applied to nuclear material supplied under such agreements. According to this document, a fresh MOX fuel assembly would be Category-I because it contains more than two kilograms of plutonium. Spent weapons-plutonium MOX fuel starting at Category-I can be reduced to Category-II if its radiation level exceeds 1 Gy/hr (or 100 R/hr) at 1 meter unshielded per INFCIRC/225.

The INFCIRC/225 requirements are codified in the NRC's categorization of materials for physical protection. At the time of the NAS studies and continuing up to today, the NRC specification for the self-protection standard is 1 Gray/hr (100 R/hr) at 1 meter.<sup>20</sup> If material is considered to be self-protecting, then the physical protection requirements per 10CFR73 are more relaxed.

The thirty year requirement is taken indirectly from the NAS's explanations of the SFS. CISAC noted that accessibility of plutonium in commercial spent fuel is quite variable (because the radiation barrier naturally falls over time). The panel stated the if inaccessibility of weapons plutonium were to be made comparable to that of plutonium contained in spent fuel in the middle of the age distribution (20-30 years old), existence of weapons plutonium in that form would not markedly increase the security risks already associated with civilian fuel. The thirty-year value was also taken in part from the recognition that the mission duration would be on the order of thirty years. It was and is desirable that the material initially dispositioned would not itself again become a proliferation risk prior to the completion of the program.

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<sup>19</sup> The core analyses performed in support of this ADR Study in fact demonstrated that the isotopic degradation requirement is more limiting than the self-protection requirement for the ADR fuel design; thus, options in which the burnup requirement is assumed eliminated incorporate blending of the weapons plutonium with fuel or reactor grade plutonium to ensure that the final Pu-240/Pu-239 isotopic ratio in the spent fuel is > 0.1.

<sup>20</sup> It should be noted that minor changes in specified dose units have been changed over the years by the NRC, the bottom line however is that the INFCIRC 225 and the NRC self-protection limits have been generally consistent.

The burnup at which a fuel assembly achieves this level of self-protection has been commonly referred to by those familiar with the PDP as the “spent-fuel standard burnup,” but this shorthand notation is not entirely faithful to the original formulation of and subsequent elaborations on the definition of the SFS. This shorthand terminology has therefore been avoided in this document in favor of the term “self-protection requirement.” It is by no means certain that the CISAC, if commissioned to perform an evaluation, would determine that any given fuel assembly with a radiation level exactly as described above (1 Sv/hr at 1 meter distance from the centerline after 30 years of cooling) actually meets the SFS.

### **Isotopic Degradation**

An additional consideration, which is not codified in the PMDA but which underlies the actual disposition criteria, is isotopic degradation. The batch-average burnup values were included in the disposition criteria in part to ensure isotopic degradation significantly beyond the PMDA definition for weapons plutonium (Pu-240/Pu-239 ratio  $< 0.10$ ).<sup>21</sup> The BN-800 chief designer estimated that the Pu-240/Pu-239 isotopic ratio averaged over any given discharged batch of BN-800 fuel would be about 0.17. This number was also officially reported by Rosatom. Thus, an additional implicit requirement beyond the specific requirements codified in the PMDA is that the Pu-240/Pu-239 isotopic ratio averaged over a given batch of discharged spent plutonium fuel assemblies should be  $\geq 0.17$ . For the BN-800 oxide fuel, the isotopic degradation criterion is roughly equivalent to the minimum burnup criterion, but this would not necessarily be the case for another sodium-cooled reactor such as the ADR.

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<sup>21</sup> Although isotopic degradation is not included in the explicit conditions for disposition codified in the PMDA, as amended, it was one of the key considerations in the negotiation of burnup limits for the Russian sodium-cooled fast reactors. “Spiking” options that would leave the plutonium with a Pu-240/Pu-239 ratio  $< 0.1$  were never seriously considered during the PMDA negotiations. Isotopic degradation occurs so much faster in light-water cooled reactors that it was effectively ignored as a consideration in setting the 20 MW-d/kgHM burnup limit for LWRs.

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## **Appendix C**

# **Analysis of Non-Reactor-Based Options to Dispose of 34 Metric Tons of Surplus Weapon-Grade Plutonium**





**ANALYSIS  
OF NON-REACTOR-BASED OPTIONS  
TO DISPOSE OF 34 METRIC TONS  
OF SURPLUS WEAPON-GRADE PLUTONIUM**

**Prepared by the  
National Nuclear Security Administration's  
Office of Fissile Materials Disposition**

**April 2014**

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## ACRONYMS

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ALMR	Advanced Liquid Metal Reactor
ARIES	Advanced Recovery and Integrated Extraction System
CCC	Criticality Control Container
CCO	Criticality Control Overpack
CIM	Cylindrical Induction Melter
DNFSB	Defense Nuclear Safety Board
DOE	Department of Energy
DWPF	Defense Waste Processing Facility
EIS	Environmental Impact Statement
EPA	Environmental Protection Agency
FGE	Fissile Gram Equivalent
FMD	Fissile Materials Disposition
FY	Fiscal Year
GWSB	Glass Waste Storage Building
HEU	Highly Enriched Uranium
HLW	High-Level Waste
HRP	Human Reliability Program
HSS	Office of Health, Safety, and Security
IAEA	International Atomic Energy Agency
INL	Idaho National Laboratory
KG	Kilogram
KIS	K-Interim Surveillance
LaBS	Lanthanide-Borosilicate
LANL	Los Alamos National Laboratory
LEU	Low Enriched Uranium
LLNL	Lawrence Livermore National Laboratory
LLW	Low Level Waste
LWR	Light Water Reactors
MFFF	Mixed Oxide Fuel Fabrication Facility
MHR	Modular Helium Reactor
MLLW	Mixed Low Level Waste
MOX	Mixed Oxide

MSA	Material Storage Area
MT	Metric Ton
NAS	National Academy of Sciences
NDA	Non-Destructive Analysis
NEPA	National Environmental Policy Act
NNSA	National Nuclear Security Administration
NOI	Notice of Intent
NPT	Nuclear Nonproliferation Treaty
NRC	Nuclear Regulatory Commission
OST	Office of Secure Transportation
PDCF	Pit Disassembly and Conversion Facility
PEIS	Programmatic Environmental Impact Statement
PF-4	Plutonium Facility 4
PIP	Plutonium Immobilization Project
PMDA	United States-Russia Plutonium Management and Disposition Agreement
Pt/Rh	Platinum/Rhodium
RD&D	Research, Development, and Demonstration
RFETS	Rocky Flats Environmental Technology Site
ROD	Record of Decision
SNF	Spent Nuclear Fuel
SNM	Special Nuclear Material
SPD	Surplus Plutonium Disposition
SRS	Savannah River Site
STA	Secure Transportation Asset
TA-55	Technical Area 55
TPA	Tri-Party Agreement
TRU	Transuranic
U.S.	United States
WIPP	Waste Isolation Pilot Plant
WTP	Waste Treatment and Immobilization Plant Project

# *Analysis of Non-Reactor-Based Options to Dispose of 34 MT of Surplus Weapon-Grade Plutonium*

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## **INTRODUCTION**

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The United States (U.S.) Fissile Materials Disposition (FMD) Program is an important element of our national commitment to meet the requirements of the Nuclear Nonproliferation Treaty (NPT). It serves both the disarmament and nonproliferation pillars of the NPT by rendering Highly Enriched Uranium (HEU) and plutonium that have been declared excess as no longer suitable for weapons. For HEU, this is done by downblending the material to low enriched uranium (LEU). For plutonium, the U.S.-Russia Plutonium Management and Disposition Agreement (PMDA) calls for each nation to dispose of no less than 34 metric tons (MT) of surplus weapon-grade plutonium by irradiating it as mixed oxide (MOX) fuel in nuclear reactors, with the United States using light water reactors (LWR) and the Russian Federation using fast reactors, or by any other methods that may be agreed by the Parties in writing. The President's Fiscal Year (FY) 2014 budget request for the Department of Energy (DOE) stated that, due to cost increases associated with the MOX fuel approach, DOE would assess plutonium disposition strategies in FY2013 and would identify options for FY2014 and the out-years.

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## 1. BACKGROUND AND PREVIOUS CONSIDERATIONS

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The end of the Cold War left a legacy of surplus weapon-grade fissile materials both in the U.S. and the former Soviet Union, with substantial quantities of plutonium no longer needed for defense purposes. Global stockpiles of weapon-grade fissile materials pose a danger to national and international security in the form of potential proliferation of nuclear weapons and nuclear terrorism as well as the potential for environmental, safety, and health consequences if the materials are not properly secured and managed. In September 1993, in response to these concerns, President Clinton issued a Nonproliferation and Export Control Policy which committed the U.S. to seek to eliminate, where possible, the accumulation of stockpiles of HEU or plutonium, and to ensure that where these materials already exist, they are subject to the highest standards of safety, security, and international accountability.

The U.S. has conducted numerous evaluations of plutonium disposition strategies beginning in the early 1990s, when a National Academy of Sciences (NAS) review contributed to the identification of viable options to address the “*clear and present danger*” posed by excess weapon-grade plutonium in the U.S. and Russia. The 1994 review recommended that disposition should meet the spent fuel standard, i.e., “*...result in a form from which the plutonium would be as difficult to recover for weapons use as the larger and growing quantity of plutonium in commercial spent fuel.*” [NAS 1994] The review indicated that the two most promising alternatives were immobilization of plutonium in combination with high-level waste (HLW) and irradiation of plutonium as MOX fuel in commercial reactors. These alternatives were preferred since they created physical, chemical, and radiological barriers to the retrieval of the material and would meet the spent fuel standard, thus reducing the risk of recovery.

On March 1, 1995, the U.S. declared 38.2 MT of weapon-grade plutonium as surplus to defense needs. In addition, DOE announced that it had 14.3 MT of non-weapon-grade plutonium that was no longer needed. The following year, at the April 1996 Moscow Nuclear Safety and Security Summit, the leaders of the seven largest industrial countries and Russia issued a joint statement endorsing the need to make excess fissile materials in the U.S. and Russia unusable for nuclear weapons.

In January 1997, after examining 37 different plutonium disposition technology options and completing a Final Programmatic Environmental Impact Statement (EIS) [DOE/EIS-0229], DOE decided to pursue a hybrid U.S. plutonium disposition strategy that allowed immobilization and irradiation of MOX fuel in existing LWRs. [Record of Decision (ROD), 62 FR 301] [See Attachment A: Summary of National Environmental Policy Act (NEPA) Documents Related to Surplus Plutonium Disposition, and Attachment B: Technology Options Previously Considered in the 1995 Screening Process] Following this announcement, in September 1997, former Russian President Yeltsin declared up to 50 MT of Russian plutonium as surplus to defense needs.

In January 2000, after completing the Surplus Plutonium Environmental Impact Statement [DOE/EIS-0283], DOE decided to immobilize some of the plutonium using the can-in-canister approach (imbedding the plutonium in a ceramic matrix emplaced in cans, placing the cans in canisters and surrounding each can with vitrified HLW to provide a radiological barrier and deter theft or diversion) and to fabricate some of the plutonium into MOX fuel, in facilities to be located at the Savannah River Site (SRS). [ROD 65 FR 1608]

In September 2000, the U.S. and the Russian Federation signed the PMDA, which calls for each country to dispose of at least 34 MT of excess weapon-grade plutonium. According to the agreement, Russia would dispose of its material by irradiating it as MOX fuel in LWRs, and the U.S. would dispose of the majority of its material by irradiating it as MOX fuel in LWRs. In addition, some U.S. material would be disposed of through immobilization using the can-in-canister system. [PMDA 2000] During the PMDA negotiations, Russian officials made it clear they did not consider immobilization as an acceptable disposition approach since it did not degrade the isotopic composition of the plutonium and thus could potentially be retrieved in the future.<sup>1</sup> However, they eventually agreed that approximately 9 MT of U.S. plutonium produced as part of the weapons program (not in pit form, but rather metal and oxide forms) could be immobilized. [See Attachment C: Immobilization Provisions of the 2000 U.S.-Russia PMDA]

In 2002, the Bush Administration directed a review of nonproliferation programs that included the plutonium disposition program. The review considered more than 40 approaches for plutonium disposition, with twelve (12) distinct options selected for detailed analysis. Following this review, DOE cancelled immobilization due to budget constraints, and announced that DOE was conducting further reviews of a MOX-only approach and making no decision on the plutonium disposition program until those reviews were completed. [ROD 67 FR 19432] Cancellation of the immobilization approach was meant to save time and money over the previous hybrid strategy, and was acceptable to Russia, whereas an immobilization-only approach was not acceptable based on Russia's concerns regarding the recoverability of the plutonium. At the time, the revised MOX-only approach was estimated to cost \$3.8 billion (in constant FY2001 dollars) to implement over approximately 20 years. [NNSA 2002]

In addition to the progress regarding the 34 MT of plutonium under the PMDA, between 1998 and 2002 DOE announced a series of decisions to dispose of a variety of plutonium residues stored at Rocky Flats Environmental Technology Site (RFETS) as transuranic (TRU) waste at the Waste Isolation Pilot Plant (WIPP) near Carlsbad, New Mexico. These materials were originally part of a set of materials designated to be repackaged and sent to the Savannah River Site (SRS) in South Carolina for storage and subsequent disposition. This action paved the way for disposal of surplus plutonium as TRU waste at WIPP from

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<sup>1</sup> *Isotopic composition is the percent of each plutonium isotope within a given quantity of plutonium. The PMDA defines weapon plutonium as plutonium with an isotopic ratio of plutonium 240 to plutonium 239 of no more than 0.10. The only feasible disposition methods that degrade the isotopic composition of weapon-grade plutonium are reactor-based options that are not addressed in this analysis.*



other DOE Sites including the Hanford Site, SRS, Los Alamos National Laboratory (LANL), Idaho National Laboratory (INL), and Lawrence Livermore National Laboratory (LLNL).

Thereafter, DOE stated that it had completed its evaluation of changes entailed by a MOX-only disposition strategy, and decided to fabricate 34 metric tons of surplus plutonium into MOX fuel, including 6.5 metric tons originally planned for immobilization. [Amended ROD, 68 FR 20134]

In 2006, at the request of Congress, DOE again analyzed its strategy for disposing of surplus plutonium in a report entitled “*Disposition of U.S. Surplus Materials: Comparative Analysis of Alternative Approaches.*” [DOE 2006] In addition, in 2007 DOE submitted to Congress a report entitled “*Business Case Analysis of the Current U.S. Mixed Oxide (MOX) Fuel Strategy for Dispositioning 34 Metric Tons of Surplus Weapon-Grade Plutonium*”, which reconfirmed the MOX approach. [DOE 2007a]

In 2007, DOE announced its decision to consolidate the remaining surplus non-pit plutonium at SRS since the majority of the facilities supporting the plutonium disposition mission would be located there. [ROD 72 FR 51807] DOE consolidated surplus plutonium from the Hanford Site, LANL, and LLNL, saving millions of dollars by avoiding the cost of operating numerous high security facilities. The secure plutonium storage facility at the Hanford Site was shut down, and is no longer operating due to the consolidation of its plutonium at SRS.

In 2007, former Secretary of Energy Bodman declared an additional 9 MT of U.S. weapon-grade plutonium as surplus to defense needs. [DOE 2007b] Secretary Bodman stated that the additional plutonium would be removed in the coming decades from retired, dismantled nuclear weapons, and was planned to be eliminated by fabrication into MOX fuel that would be irradiated in commercial nuclear reactors to produce electricity. [NNSA 2012]

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## 2. RECENT DEVELOPMENTS

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There have been many changes to the plutonium disposition program since the 2002 and 2003 decisions to pursue a MOX-only approach. One of the major changes is that the Russian Government undertook a reassessment of technical options for disposing of its plutonium. As a result of its reassessment, Russia stated its preference to disposition its material in fast reactors instead of LWR, an approach that is more consistent with Russia's national energy strategy. The decision led to a renegotiation of a number of key provisions of the PMDA. During the April 2010 Nuclear Security Summit in Washington, DC, former Secretary of State Hillary Clinton and former Russian Foreign Minister Sergey Lavrov signed a protocol amending the PMDA to formalize the shift to fast reactors for Russian plutonium disposition. The protocol also established a number of nonproliferation conditions under which Russia could operate its fast reactors for plutonium disposition that limit the ability to produce additional weapon-grade plutonium. In July 2011, after ratification by the Russian Duma and formal approval of both governments, the PMDA with its protocols was entered into force. [See Attachment D: Summary of Key Changes to the PMDA Resulting from the 2010 Protocol] This action has set the precedent for incorporating another disposition method under the PMDA based on each nation's interests.

In addition to the evolution of the Russian program, the U.S. program has also changed significantly. In 2008, the cost and schedule baseline for the U.S. Mixed Oxide Fuel Fabrication Facility (MFFF) that will produce MOX fuel for irradiation in reactors was established at \$4.8 billion with a hot start-up date of November 2016. In August 2012, the contractor submitted a baseline change proposal for the facility that would increase its cost to \$7.7 billion and extend the schedule by 3 years. [BCP 12-121]

In addition, the estimates to operate the MOX facility after construction have continued to rise, as well as the cost of other related activities, such as a facility to treat the waste from the MOX facility. According to a recent independent review of the MOX facility operating costs by the National Nuclear Security Administration (NNSA) Office of Defense Programs' Office of Analysis and Evaluation, the estimated annual operating cost of approximately half a billion dollars may be low. [NNSA 2013] Because of the rising costs, in January 2012, DOE decided to pursue cancelling one of its planned plutonium disposition projects at SRS, a stand-alone facility to disassemble nuclear weapons pits and convert the plutonium metal into an oxide to be used as feedstock the MOX facility. [EXEC-2012-000647] Instead, due to changes in the operating plans for other facilities in the DOE complex, DOE's preferred alternative is to use existing facilities to accomplish this part of the plutonium disposition mission.

However, the potential savings resulting from the cancellation of a stand-alone pit disassembly facility are not enough to halt the overall rising costs of the program. As a result of the cost increases, and the current budget environment, DOE announced in 2013 that it would assess alternatives to the current plutonium disposition approach.

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## 3. TECHNICAL APPROACH

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### 3.1 DESCRIPTION OF APPROACH

The purpose of this document is to analyze non-reactor-based options that could potentially provide a more cost effective approach to dispose of at least 34 MT of U.S. surplus weapon-grade plutonium to meet international commitments. This analysis does not include evaluation of any long-term storage options since storage does not constitute disposition and therefore would not meet long-standing U.S. government policy objectives and international commitments. Rather, this analysis focuses on options that could either alone, or in combination with others, address at least 34 MT of U.S. surplus weapon-grade plutonium. There may be hybrid approaches that merit further study, that could combine different disposition options, possibly at different times, and still achieve the disposition of at least 34 MT of plutonium. For example, an optimal approach might be to pursue multiple options or begin disposition with one option and then transition to another. All of the non-MOX options may require further development and/or analysis (e.g., technology development, discussions with Russia, modification of federal legislation) during a standby period.

For all options, this analysis assumes that plutonium metal is oxidized through pit disassembly and conversion processes at LANL in New Mexico and at SRS in South Carolina, as appropriate. Since 1995, numerous options have been analyzed and dismissed. After careful consideration, the following three options were deemed the most reasonable to reassess based on further development of the technology from when they were originally assessed. The analysis focuses on the advantages and disadvantages of these three (3) primary options:

- Option 1: Immobilization (Ceramic or Glass Form)
- Option 2: Downblending and Disposal
- Option 3: Deep Borehole Disposal

The following criteria were used to determine the advantages and disadvantages of the various options in this non-reactor-based analysis:

- Meeting international commitments
- Cost effectiveness
- Duration to complete the 34 MT mission
- Technical viability
- Legal, regulatory and other issues

Separately, DOE is analyzing reactor-based disposition options, including the current approach of irradiation of MOX fuel in LWRs and any potential cost efficiencies, as well as

irradiation of plutonium fuel in fast reactors. These reactor-based options are not included in this analysis.

### **3.2 DESCRIPTION OF OPTIONS**

This section provides a summary description of each option. All of the options maximized the use of existing facilities to the greatest extent possible. For further details, see Attachment E for Option 1, Immobilization; Attachment F for Option 2, Downblending and Disposal; and Attachment G for Option 3, Deep Borehole Disposal.

#### **3.2.1 IMMOBILIZATION (CERAMIC OR GLASS FORM)**

This option involves immobilizing plutonium oxide using a “can-in-canister” facility that would need to be constructed. The plutonium would be immobilized into either a ceramic or glass form, placed into a can, and then surrounded with HLW glass in a glass waste canister, hence the term can-in-canister. The immobilization process would begin by milling plutonium oxide to reduce the size of the powder and achieve faster and more uniform distribution of the plutonium for processing. Although some milling would be performed at LANL during oxide production, additional milling would be required to ensure the plutonium and the glass frit are both milled to similar particle sizes.

For a glass process, the milled plutonium oxide would be blended with borosilicate glass frit containing neutron absorbers (e.g., gadolinium, boron, hafnium). The mixture would be melted in a platinum/rhodium (Pt/Rh) melter vessel, and drained into stainless steel cans. The cans would be sealed, leak-tested, assayed, and transferred out of the immobilization facility.

A ceramic process would produce a titanate-based ceramic that immobilizes the weapon-grade plutonium. The ceramic would be produced by mixing the plutonium feed stream with oxide precursor chemicals (e.g., pyrochlore and rutile in addition to neutron absorbers such as hafnium and gadolinium), forming the mixed powder into “pucks” and sintering the pucks in a resistively heated furnace. The ceramic pucks would be placed in stainless steel cans, sealed, leak-tested, assayed, and transferred out of the immobilization facility.

The cans filled with either the ceramic or vitrified plutonium would then be loaded into long stainless steel cylinders called magazines, and loaded into empty HLW canisters. The canisters containing the cans of immobilized plutonium would then be filled with HLW that has been melted into glass to complete the process and produce a waste form suitable for repository disposal. The plutonium would be disposed of once the HLW canister containing the immobilized plutonium is placed in a geologic repository.

There are only two U.S. DOE sites that have significant quantities of HLW and that have, or will have, the capability to encapsulate HLW into glass logs for ultimate disposal: SRS and the Hanford Site. The first site, SRS, has been using its Defense Waste

Processing Facility (DWPF) since 1996 to vitrify HLW into glass logs. However, since nearly half of SRS's HLW has already been remediated, there is not enough HLW remaining to dispose of 34 MT of surplus plutonium. In addition, DWPF is scheduled to complete operations by 2032, which would likely be before a new immobilization facility could be designed and constructed. [SRR-LWP-2009-00001]

An alternative of pursuing this immobilization option would be sited at the Hanford Site which based on this analysis is not viable. It would require a new secure plutonium storage facility or repurposing an existing facility, a new plutonium immobilization facility and modifications to the current Waste Treatment Plant (WTP), which is under construction to vitrify 56 million gallons of HLW. Both of these facilities would be secure Hazard Category 2 facilities, which would require meeting stringent security and safety regulations.<sup>2</sup> Modifications would also be needed to the Waste Treatment Plant, which is currently under construction for the tank waste disposition mission. Building a new immobilization facility at the WTP and modifying WTP for the plutonium disposition mission is not a viable option as the Department needs to maintain its focus and resources at Hanford on completing the WTP for the tank waste immobilization. It would introduce unacceptable technical, regulatory, and financial and other risks to the completion of WTP. These risks are discussed later in the report.

Two potential variants of the immobilization option that were considered during the early stages of this analysis were:

1. The use of H-Canyon at SRS to dissolve the plutonium and then transfer it to the HLW system for vitrification into glass through the DWPF, and
2. Direct injection of plutonium into the DWPF or WTP melter process for HLW.

Both of these variants would avoid the need to construct a stand-alone immobilization facility, but have significant obstacles. Regarding the first variant, there is not enough HLW at SRS to vitrify the full 34 MT of plutonium with the limitations of the H-Canyon dissolution process and the waste transfer capabilities. The second variant, direct injection of the plutonium, although technically feasible, would require significant research, development, and demonstration (RD&D) to determine the loading limits of each glass canister, determine the controls required to prevent criticality during the injection process, and develop the design modifications required for the injection process. [Vitreous Laboratory 2013] Both of these variants are discussed further in Attachment E.

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<sup>2</sup> In accordance with DOE-STD 1027-92, each DOE nuclear facility is characterized by the level of hazard it presents to the public and workers from the amount and type of nuclear materials present at the facility. Hazard Category 2 is assigned when an on-site consequence is significant, i.e., facilities with the potential for a nuclear criticality event or with sufficient quantities of hazardous material and energy which would require on-site emergency planning activities.

### 3.2.2 DOWNBLENDING AND DISPOSAL

This option would involve downblending plutonium oxide with inhibitor materials, packaging it into approved containers, and shipping the downblended plutonium to a repository for permanent disposal. A reference case analysis for the downblending option is based on utilizing information on technical feasibility, cost and schedule impacts, and regulatory considerations gained from the operating experience at the Waste Isolation Pilot Project (WIPP) in Carlsbad, New Mexico.

The WIPP facility began receipt and disposal of Contact Handled TRU waste in March 1999 and Remote Handled TRU waste in January 2007. Currently, it is the only underground repository in the U.S. authorized to dispose of TRU waste generated by defense activities. Established over the course of a twenty year time period, the siting, construction, and authorization to operate WIPP required significant Congressional action, approval by the EPA, public input and consent from the State of New Mexico. In 1979, WIPP was authorized by Congress through annual authorization. [Public Law 96-164]

The Waste Isolation Pilot Plant Land Withdrawal Act of 1992 allowed DOE to withdraw the land around WIPP from general use and put it under exclusive use of DOE. The Act contained specific limitations on the quantity of transuranic waste that could be disposed of in WIPP and limitations on the overall capacity. It also provided that the facility comply with EPA regulations for disposal (Solid Waste Disposal Act).

While technically feasible, pursuing an option such as WIPP or an alternate location today for 34 MT of surplus plutonium would require significant engagement with federal, state, and local representatives. Disposal of these additional materials in WIPP would require amendment of the WIPP Land Withdrawal Act as well as federal and state regulatory actions. For an alternate site, a new TRU-waste repository would need to be established. The additional costs for such an option are not included in the downblending reference case analysis since they would be site specific and depend on the inventories of materials to be disposed.

To downblend the plutonium, material would be added to plutonium oxide to inhibit recovery. This downblending process would involve mixing the plutonium with inhibitor materials to reduce the plutonium content to less than 10 percent by weight. Downblending would be conducted at SRS. Two additional gloveboxes would be installed for this option. The containers of downblended plutonium would be characterized (non-destructive assay, digital radiography, and headspace gas sampling) to ensure that they meet waste acceptance criteria prior to shipment to a TRU-waste repository. Once shipped to a repository, the packages containing the plutonium would be emplaced in the salt bed. Over time, high pressure on the salt formation would cause the salt to creep, filling in the voids in the disposal rooms, and entombing the packages permanently. This disposal method has been proven, and continues to be used to dispose of surplus plutonium from various DOE sites. Approximately 4.8 MT of

plutonium that was downblended have been shipped to WIPP, mostly from six sites: RFETS, Hanford, INL, LLNL, LANL, and SRS.

For the downblending effort at SRS, this analysis assumes existing infrastructure and capabilities are used to the maximum extent possible, and addresses the enhancements that would be needed. For the disposal as TRU in a repository, it also takes advantage of a large body of actual cost data on operations, and estimates the additional resources that would be required to dispose of 34 MT. The analysis also identifies the additional staff required to accommodate increased throughput. As such, the costs are the incremental costs and do not include the sunk costs associated with existing infrastructure. The cost of constructing WIPP was approximately \$700 million (1986).

Two variants of the downblending option were considered in this analysis:

1. Downblending plutonium oxide at SRS and LANL with inhibitor material, and packaging into approved containers, prior to shipment of downblended plutonium to a repository.
2. Downblending plutonium oxide at SRS with inhibitor material, increasing plutonium loading within each can, and packaging into approved containers prior to shipment of downblended plutonium to a repository.

The first variant is comparable to the option described above, but involves downblending plutonium at both SRS and LANL. The second variant could be used to enhance this option overall and involves further increasing the plutonium loading within each can at SRS. Both of these variants carry additional risks and are discussed further in Attachment F.

### **3.2.3 DEEP BOREHOLE DISPOSAL**

This option involves direct disposal of surplus plutonium in a deep geologic borehole. Direct disposal in a deep geologic borehole could involve the disposal of plutonium metal and/or oxide in suitable canisters. The concept consists of drilling boreholes into crystalline basement rock to approximately 5,000 meters deep. The canisters would be emplaced into the lower 2,000 meters of the borehole. The upper borehole would be sealed with compacted clay or cement. A liner casing would be in place for the emplacement of waste canisters. To emplace the waste canisters, one proposal is to establish a device that would rotate the shipping cask at the surface to a vertical position then lower it into the borehole remotely. Multiple "strings" of canisters would be lowered to the disposal zone, and each canister string would be separated from the overlying canister string using a series of plugs. After the waste canisters are emplaced and the overlying plugs have been set, the guide casing would be removed and the borehole sealed. [SAND2011-6749] Based on the 1996 estimates used to support the Programmatic Plutonium Storage and Disposition EIS, this analysis assumes that 3 deep boreholes would be required to emplace 34 MT of surplus plutonium. [DOE/EIS-0229] This concept would require further RD&D to resolve uncertainties and to allow for a more comprehensive evaluation.

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## 4. ANALYSIS

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This section summarizes the results of the options analysis. When compared against one another, the ratings were based on “+” positive rating annotating that the option is more advantageous, “O” neutral rating annotating that the option is medium or neutral, or “-” negative rating annotating that the option is less advantageous.

### 4.1 MEETING INTERNATIONAL COMMITMENTS

The U.S.-Russia PMDA specifically calls for each nation to dispose of no less than 34 MT of surplus weapon-grade plutonium by “*irradiation of disposition plutonium as fuel in nuclear reactors or any other methods that may be agreed by the Parties in writing*”, with the U.S. using LWRs and Russia using fast reactors. Under the provision related to the irradiation method of disposition the PMDA requires that the plutonium in the spent fuel is no longer weapon-grade (i.e., changing the isotopic composition so that the ratio of the isotope 240 to isotope 239 is greater than 0.10), and has other criteria to determine that the plutonium has been dispositioned (e.g., long-term radiation levels). [See Attachment D: Summary of the PMDA Criteria for Determining that Plutonium is Dispositioned]

While none of the options presented in this analysis change the isotopic composition of the weapon-grade plutonium, the 1994 NAS report on the *Management and Disposition of Excess Weapon Plutonium* discussed other ways to minimize accessibility of the plutonium by creating physical, chemical, or radiological barriers. Examples of the barriers include: physical -- burial significantly below the ground surface, chemical -- downblending the plutonium with other materials, and radiological -- mixing it with HLW. [NAS 1994] Each of the non-reactor-based options would provide barriers to retrieval of the plutonium. The immobilization option rated the highest of the three options, with the least risk when judged against this criterion.

Option 1, immobilization, meets all three attributes (physical, chemical, and radiological barriers), and therefore would be the most difficult to retrieve. Option 2, downblending, meets two of the attributes (chemical and physical barriers). Option 3, deep borehole, contains, as a minimum the physical barrier; if the plutonium were buried with other materials, could also include a radiological and a chemical barrier. For Option 3 to meet all three attributes, however, it would require significantly more research and development to determine and to approve this waste form.

Although none of these options meets the irradiation criteria in the PMDA, Article III of the PMDA states that disposition can also be “*any other methods that may be agreed by the Parties in writing*”. Although Russia previously expressed concerns regarding the potential retrieval of immobilized plutonium, recent discussions with Russia regarding the U.S. consideration of a non-reactor-based option indicates that such a change would require agreement by both Parties but could then be incorporated into the existing PMDA. Key provisions of the PMDA were renegotiated to allow Russia to disposition its plutonium in



fast reactors instead of LWRs after the reassessment of its strategy. Beginning in 2006, the United States undertook a major effort to update the 2000 agreement, primarily at Russia's request that it conduct its entire disposition in fast reactors to fit with its nuclear energy strategy. In contrast to the current U.S. review, this earlier effort to update Russian and U.S. program elements entailed a wide range of substantial changes to the PMDA (including new nonproliferation provisions). Still, this effort exemplified a willingness to accommodate each Party's national interests.

The PMDA requires both Parties to take all necessary steps to complete an appropriate verification agreement with the International Atomic Energy Agency (IAEA). This requirement would be applicable to all options.

The following are the key points that led to the rating of each alternative.

**Option 1: Immobilization - Ceramic or Glass Form (+Single Positive Rating)**

- Would require supplemental U.S. Russian agreement pursuant to Article III of the PMDA – In the past Russia has expressed concerns about potential retrieval of immobilized plutonium.
- Previous 2000 PMDA included immobilization as an element of U.S. plutonium disposition, but limited the quantity to 9 MT of plutonium material not from pits.
- Would meet all three attributes for minimizing accessibility through physical, chemical, and radiological barriers.

**Option 2: Downblending and Disposal (O Neutral Rating)**

- Would require supplemental U.S. Russian agreement pursuant to Article III of the PMDA.
- Currently meets two of the attributes for minimizing accessibility through physical and chemical barriers as an approved waste form for the reference case WIPP.
- Although all three options include IAEA monitoring and inspection, the reference case WIPP is the only facility of the three currently on the list of potential DOE sites for future IAEA monitoring and inspection.
- Plutonium currently disposed of at WIPP meets DOE Order 474.2 which requires meeting certain conditions before nuclear materials are considered sufficiently unattractive for illicit purposes.

**Option 3: Deep Borehole Disposal (O Neutral Rating)**

- Would require supplemental U.S. Russian agreement pursuant to Article III of the PMDA.
- At a minimum, meets the physical barrier by itself; if buried and/or mixed with other materials, could also include a radiological and a chemical barrier but would require significant development and approval of this waste form.

## 4.2 COST EFFECTIVENESS

A comparative evaluation was performed to analyze the cost effectiveness of the options. The downblending option rated the highest with the least risk when judged against this criterion which used WIPP as a reference case. The cost for disposal would be higher for an alternate TRU-waste repository. Deep borehole was also favorable, but not as attractive due to significant uncertainties.

Option 1 Immobilization, requires construction of a multi-billion dollar immobilization facility, and potential construction or significant modification of a storage facility. In 1999, the cost to design and construct the immobilization facility was comparable to the MOX facility, with the cost estimates within \$100 million of each other. The total lifecycle cost to operate the immobilization facility was slightly less than the cost to operate the MOX facility. Since then, the immobilization project was cancelled, and the MOX project has experienced significant cost growth with the latest contractor-submitted baseline change proposal at \$7.7 billion, with an estimated annual operating cost of over \$500 million. This analysis uses a parametric comparison between the MOX facility and immobilization to estimate the immobilization costs. Historically, the estimated costs for the projects were comparable.

As previously discussed, the immobilization option would be at the Hanford Site using WTP as the source for the HLW mixture that surrounds the inner cans of immobilized plutonium. Integrating this process into WTP would impact the current cost and schedule of WTP, its future operations, and overall tank waste disposition mission. Additionally, the secure plutonium storage facility at the Hanford Site was shutdown years ago and, as a result, this capability would need to be reconstituted.

The estimate for Option 1 includes construction and operation of a secure Hazard Category 2<sup>3</sup> immobilization facility; construction or significant modification and operation of a secure Hazard Category 2 plutonium storage facility; security costs; potential modifications to WTP to complete the can-in-canister process; and a glass waste storage building for the additional HLW canisters produced. The total cost to construct and operate these facilities for the plutonium disposition mission is estimated at \$12.6 billion to \$20.6 billion (\$6.5 billion to \$13 billion in capital costs and \$6.1 billion to \$7.6 billion in operating costs) in constant FY2014 dollars.

Option 2, downblending and disposal is currently a disposal method used by DOE sites for kilogram (kg) quantities of surplus plutonium. For the purposes of this analysis, using WIPP as a reference case, the total cost for capital upgrades and to operate the SRS facilities for downblending, packaging, and shipping and for the repository to receive 34 MT of surplus plutonium is estimated at \$2.3 billion to \$3 billion in constant FY2014 dollars, \$212

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<sup>3</sup> In accordance with DOE-STD 1027-92, each DOE nuclear facility is characterized by the level of hazard it presents to the public and workers from the amount and type of nuclear materials present at the facility. Hazard Category 2 is assigned when an on-site consequence is significant, i.e., facilities with the potential for a nuclear criticality event or with sufficient quantities of hazardous material and energy which would require on-site emergency planning activities.

million to \$262 million in capital enhancements based on a 380 fissile gram equivalent (FGE) loading limit per can. These costs assume adding two additional gloveboxes at SRS to increase downblending, packaging, and certification rates, and additional costs at WIPP for increased receipts above the current plutonium and TRU waste processing and receipt rates.

Option 3, deep borehole disposal, has the potential for a very long site selection and characterization process, and the need to obtain permits and licenses to operate the facility. In 2011, Sandia National Laboratory estimated the cost to drill each borehole at approximately \$40 million. [SAND2011-6749] However, the cost for site characterization, licensing and certification of a qualified plutonium waste form is unknown at this time, and will be dependent on completion of the RD&D activities to help resolve key uncertainties. A 2012 Sandia report on deep borehole research, development and demonstration indicates that the preliminary estimates for the RD&D activities (without the use of radioactive waste or materials) would require approximately 5 years and \$75 million. The subsequent costs to deploy full-scale operational facility(ies) is yet to be defined. [SAND2012-8527P] While the cost for a deep borehole disposition option cannot be estimated to the same degree as the other options, it is believed that this method of disposition would fall between the immobilization option cost range and the downblending option cost range. Based on the similarities between disposition of plutonium in a deep geologic repository and disposition of plutonium in a deep borehole, the costs for disposition in a deep borehole would be closer to the downblending option. As a comparison, the 1986 cost to construct and start-up WIPP was approximately \$700 million, or \$1.47 billion in 2013 (escalated). The cost of constructing and licensing a new repository today would cost substantially more than this due to today's design, construction, and operations standards.

**Table 4-1: Cost Comparison of Options**

	Low Range (Constant FY 2014 Dollars)	High Range (Constant FY 2014 Dollars)	Low Range (Escalated 2% Ops, 4% Cap Annually)	High Range (Escalated 2% Ops, 4% Cap Annually)	Low Range (Net Present Value)	High Range (Net Present Value)
<b>Immobilization Capital Cost</b>	\$6.5B	\$13B	\$8.3B	\$16.6B	\$5.7B	\$11.4B
<b>Downblending Capital Cost</b>	\$0.2B	\$0.3B	\$0.3B	\$0.4B	\$0.2	\$0.2
<b>Immobilization Ops Cost</b>	\$6.1B	\$7.6B	\$10.4B	\$12.8B	\$4.6	\$5.7
<b>Downblending Ops Cost</b>	\$2.1B	\$2.7B	\$3B	\$4.5B	\$1.6	\$2.1
<b>Immobilization Total Cost</b>	\$12.6B	\$20.6B	\$18.7B	\$29.4B	\$10.3 B	\$17.1B
<b>Downblending Total Cost</b>	\$2.3B	\$3B	\$3.3B	\$4.9B	\$1.8B	\$2.3B
<b>Deep Borehole Total Cost</b>	Not Estimated	Not Estimated	Not Estimated	Not Estimated	Not Estimated	Not Estimated

The following are the key points that led to the rating of each alternative.

**Option 1: Immobilization - Ceramic or Glass Form (- - Double Negative Rating)**

- New, multi-billion dollar capital project for the immobilization facility, secure storage facility and modifications to WTP, most likely resulting in cost and schedule impacts to the WTP project and operations.
- Construction and operating costs could be similar to MOX facility.
- \$12.6 billion - \$20.6 billion in constant FY2014 dollars (on the high end of the range: \$13 billion for capital/enhancements, \$7.6 billion in operating costs).

**Option 2: Downblending and Disposal (++ Double Positive Rating)**

- Relatively cost effective under the reference case since it would utilize existing, operating infrastructure – (based on currently shipping surplus downblended plutonium to WIPP).
- Small incremental annual operational funding for increased downblending throughput and repository disposal, under the reference case based on use of current WIPP operating data.
- \$2.3 billion - \$3 billion in constant FY 2014 dollars (on the high end of the range: \$262 million for capital/enhancements, \$2.7 billion in operating costs).

### **Option 3: Deep Borehole Disposal (+ Single Positive Rating)**

- Cost for site characterization, licensing and certification of a qualified plutonium waste form is unknown at this time and would be dependent on completion of the RD&D to help resolve key uncertainties.
- Cost for disposition in a deep borehole would be closer to the downblending option than the immobilization option.

#### **4.3 DURATION TO COMPLETE THE 34 MT MISSION**

All of the options would be completed in approximately the same time period (between 2045 and 2057). However, when comparing the ranges, the downblending option rated slightly favorable over the other two options because it carries the least risk when judged against this criterion.

The duration for MOX facility design was approximately 10 years, construction is assumed to be approximately 10 years, and operations is assumed to be 15 years. For the immobilization option, the design and construction was assumed to be 20 years and the operating duration 15 years consistent with the MOX facility. The completion of the 34 MT mission was estimated to be approximately 2045-2050. This analysis assumes the Option 1 end date to be when all of the plutonium is immobilized and placed in an interim storage location as opposed to final disposition in a geologic repository. The schedule range moves to 2054-2061 if the project costs are constrained to \$500 million annually at 4% escalation and the operating costs are escalated at 2% annually.

For Option 2, the duration is estimated to take 32-43 years, completing between 2046 and 2057, assuming enhancements to increase throughput and increase staffing to minimize conflicts with other missions. This analysis assumes packaging into the recently certified criticality control overpack (CCO) package which has a maximum limit of 380 FGE per package. If the project or capital costs are constrained to \$500 million annually, the schedule does not change since the annual capital outlays do not approach the \$500 million constraint.

Option 3, deep borehole disposal, has the highest uncertainty in duration for site selection, characterization process, licensing, construction and start-up, and was therefore assessed with the lowest rating. For comparative purposes, the timeline for the deep borehole option was assumed to be similar to the timeline for a geologic repository for spent fuel outlined in the January 2013 *Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Radioactive Waste*. The timeline assumes having a repository sited by 2026, the site characterized and the repository designed and licensed by 2042, and the repository constructed and operations started by 2048. [DOE 2013] Assuming one year to drill each borehole (3 would be needed), the surplus plutonium would be disposed of by 2051.

Although all three options appear to be of similar duration, immobilization carries the highest risk due to the high upfront capital requirements and significant risks in completing the capital asset projects in the assumed duration. In addition, given that this

option depends on HLW as feed for the can-in-canister approach this option introduces potentially significant, and thus unacceptable, schedule risk to the Hanford tank waste immobilization mission, particularly if it were to impede or delay the tank waste immobilization. Hanford is not a viable option for the mission of disposing of 34 MT of weapon grade plutonium and will not be considered. Deep borehole disposal also carries significant risk due to unknown requirements for siting, licensing and certification of the waste form. Under the reference case, the downblending option carries the least technical risk. However, an alternate TRU-waste repository would add cost and schedule delay to the reference case, since a new repository could not be operational by 2019.

The following are the key points that led to the rating of each alternative.

**Option 1: Immobilization: Ceramic or Glass Form (- Single Negative Rating)**

- Would complete immobilizing 34 MT of plutonium in 2045-2050, but has significant risks due to construction of major capital projects.

**Option 2: Downblending and Disposal (+ Single Positive Rating)**

- Known and ongoing process with estimated completion between 2047 and 2057 loaded at 380 FGE limit.

**Option 3: Deep Borehole Disposal (0 Neutral Rating)**

- Unknown but lengthy process expected for licensing, start-up, and certification of the waste form – estimated to be completed by 2051-2056.

#### **4.4 TECHNICAL VIABILITY**

The primary considerations for the technical viability rating were process maturity (whether or not the process is proven) and the risk of successful implementation and execution. The downblending option rated the highest of the three options because WIPP currently receives plutonium as an approved TRU waste form for disposal and has the least risk when judged against this criterion.

Option 1, immobilization of plutonium in ceramic or glass form, would require further development to qualify the can in canister technology and throughput. Essentially all of the process steps have been previously demonstrated in a variety of applications; however, validation testing would be needed to integrate the process steps for this application and demonstrate that a reasonable throughput can be achieved with the appropriate nuclear safety controls. Additional testing would also be necessary to demonstrate the variety of plutonium feeds can be effectively processed.

Option 1 also requires qualification of the waste form for a potential geologic repository. Although the technical requirements for the certified waste form are yet to be defined, previous efforts to qualify HLW glass for repository disposal could be leveraged for qualification of the can-in-canister waste form. Extensive work was completed for HLW borosilicate glasses to develop appropriate acceptance criteria and to develop means to

demonstrate that these criteria were met during production of the HLW glass waste form. An effort was initiated in FY2000 under the ceramic Plutonium Immobilization Project (PIP) to accomplish this task, and was still in the preliminary stages when cancelled. A second immobilization project separate from the PMDA mission (the Plutonium Vitrification Project) was authorized in 2005 [Sell 2005], but was subsequently cancelled in 2007. [DOE 2007c] During that time, the project began the waste form performance testing and qualification program. This vitrified glass can-in-canister waste form was identified as a potential waste form in the Yucca Mountain License Application.

To implement an immobilization option at the Hanford Site, modifications to the WTP would be required to support receipt of the immobilized plutonium cans. The specific modifications to WTP would not be known until the design is completed, however, based on the DWPF changes that were identified during the cancelled Plutonium Vitrification Project, it is expected that WTP would require receipt and handling capabilities for the canisters filled with immobilized plutonium. The plutonium filled canisters differ from typical DWPF/WTP canisters in that they contain significant quantities of Special Nuclear Material (SNM), emit a significant amount of radiation, and weigh significantly more. Security measures, including the potential use of a protective force would be necessary for receipt and movement of the immobilized plutonium canisters. Specific shielding and/or remote operation measures would be required to handle the canisters. Due to the weight of the can-in-canister assembly, modifications to existing canister handling equipment (loading dock, forklift, crane, etc.) would likely be required.

For Option 2, downblending and disposal, as proven by WIPP, the technology maturation is advanced; however, this option is not without technical risk, primarily due to facility enhancements to increase throughput capacity. This option assumes two additional gloveboxes would be installed in K-Area Material Storage Area. Each glovebox would be from 4 to 6 feet long, and seismically qualified with fire suppression and detection. Each glovebox would require the following equipment: DOE-STD-3013 can opener, scale, blender, canning area to crimp-seal the cans, and a bag out port. The additional gloveboxes would be required to handle the increased downblending and packaging operations. The technology and process steps are simple and known, however, additional controls may be required to the facility safety basis that could limit operations and potentially impact other missions in K-Area. Additional analysis also would be required to understand whether any design enhancements over the reference case at WIPP would be needed.

Similar to Option 1, the technical requirements for the certified waste form for Option 3, deep borehole disposal, are yet to be defined. Until such time that the RD&D for deep borehole disposal is authorized and nears completion, and DOE decides whether or not to proceed with this technology, the scope of this project (i.e., facilities, utilities, support systems and infrastructure) are yet to be defined. The RD&D would demonstrate the feasibility of deep borehole disposal and would be focused on completing conceptual design analysis and demonstrating key components of borehole drilling, borehole construction, waste canisters, handling, emplacement, and borehole sealing operations. Planning for drilling a deep demonstration borehole would concentrate on using existing technology. The RD&D would also focus on the data gaps in the borehole geological,

hydrological, chemical, and geophysical environment important to post-closure safety of the system, materials performance at the depths that the material would be emplaced, and construction of the disposal system. [SAND2012-8527P]

The following are the key points that led to the rating of each alternative.

**Option 1: Immobilization: Ceramic or Glass Form (- Single Negative Rating)**

- Technical uncertainty of the can-in-canister technology and throughput.
- Technological uncertainty of the glass can-in-canister form for disposal in a geologic repository.
- Specific modifications and impacts to WTP are yet to be fully defined. WTP, itself, is still under construction. This is not a viable option for the Hanford Site.

**Option 2: Downblending and Disposal (++) Double Positive Rating)**

- Least risk under the reference case.
- Two additional gloveboxes would be installed to increase throughput, however the technical requirements are known and in use today.

**Option 3: Deep Borehole Disposal (- Single Negative Rating)**

- Drilling the deep boreholes would be technically viable.
- Technical requirements for the certified waste form are yet to be defined.
- Concept is still under development.

**4.5 LEGAL, REGULATORY, AND OTHER ISSUES**

All three options have legal and regulatory issues and were all rated low.

Option 1 would adversely impact the tank waste disposition mission at the Hanford Site, further slowing the completion of WTP and delaying treatment of the 56 million gallons of high level waste stored at Hanford, which would be unacceptable. For context, construction has been suspended on the Pretreatment Facility, the facility through which all the waste would be processed, due to technical issues. As a result, DOE has notified the State of Washington that it is as serious risk of missing the milestones associated with WTP that are contained in Consent Decree in State of Washington v. United States Department of Energy, No. 08-5085-FVS (E.D. Wash.). DOE's recently submitted proposal to the State of Washington to amend the Consent Decree does not contemplate modifications to WTP for the plutonium disposition mission. Additionally, DOE went through great efforts to consolidate storage of non-pit plutonium at SRS, and within the past 5 years has deinventoried the surplus plutonium from the Hanford Site to SRS. Furthermore, shipping the plutonium back to the Hanford Site would face strong State and public opposition.

Option 2, downblending and disposal in a repository would raise legal and regulatory issues that would require resolution prior to any serious consideration of WIPP or another location. The Waste Isolation Pilot Plant Land Withdrawal Act of 1992 contained specific limitations on the quantity of transuranic waste that could be disposed of in WIPP and



limitations on the overall capacity of the facility. Disposal of the entire 34 MT of material in WIPP would require amendment of the WIPP Land Withdrawal Act as well as federal and state regulatory actions. As with any location considered for this disposal mission, significant engagement with federal, state, and local representatives would be required. Implementing such an option would require Congressional action.

For Option 3, deep borehole disposal, permitting, licensing, establishing performance requirements, and developing a suitable waste form for disposal are regulatory steps that would require further development.

Extensive NEPA process (2 years or more) would be required for all of these options, and therefore was not a discriminator in this evaluation.

The following are the key points that led to the rating of each alternative.

**Option 1: Immobilization: Ceramic or Glass Form (- - Double Negative Rating)**

- Option is not contemplated under current agreements with Washington State, and potential implications associated with changes to WTP scope and schedule.
- Would require qualification and permitting of this waste form in a geologic repository.
- Strong opposition likely from the State of Washington.
- Opposition by State regulators; significant involvement with the DNFSB.
- Not viable option for the Hanford Site.

**Option 2: Downblending and Disposal (- Single Negative Rating)**

- Would require significant engagement with federal, state, and local representatives before any decision to go forward with this option.
- Implementation would require Congressional action, including amendment to existing legislation or enactment of new legislation.

**Option 3: Deep Borehole Disposal (- - Double Negative Rating)**

- Significant regulatory challenges in licensing, permitting, and establishing the requirements for the certified waste form.

**4.6 KEY POINT SUMMARY**

Table 4-2 provides a summary of the key points and ratings identified in the analysis for each option and criteria.

**Table 4-2: Key Point Summary / Ratings**

<p><b>Key:</b>                      + More Advantageous                      O Medium/Neutral                      -- Less Advantageous</p>	<p><b>Meeting International Commitments/Russian Cooperation</b></p>	<p><b>Cost Effectiveness</b></p>	<p><b>Duration to Complete</b></p>	<p><b>Technical Viability</b></p>	<p><b>Legal, Regulatory, and Other Issues</b></p>
<p><b>Immobilization - Ceramic or Glass Form</b></p>	<p style="text-align: center;"><b>+</b></p> <ul style="list-style-type: none"> <li>• Would require supplemental U.S.-Russian agreement pursuant to Article III of the PMDA – Russia expressed concerns about potential retrieval of immobilized plutonium.</li> <li>• Previous 2000 PMDA included immobilization as an element of U.S. plutonium disposition but limited the quantity to 9 MT of plutonium material not from pits.</li> <li>• Would meet all three attributes for minimizing accessibility through physical, chemical, and radiological barriers.</li> </ul>	<p style="text-align: center;"><b>--</b></p> <ul style="list-style-type: none"> <li>• New, multi-billion dollar capital project for the immobilization facility, secure storage facility and modifications to WTP, most likely resulting in cost and schedule impacts to the WTP project and operations.</li> <li>• Construction and operating costs could be similar to MOX facility.</li> <li>• \$12.6 billion - \$20.6 billion in constant FY2014 dollars (on the high end of the range: \$13 billion for capital/enhancements, \$7.6 billion in operating costs).</li> </ul>	<p style="text-align: center;"><b>-</b></p> <ul style="list-style-type: none"> <li>• Would complete immobilizing 34 MT of plutonium in 2045-2050, but has significant risks due to construction of major capital projects.</li> </ul>	<p style="text-align: center;"><b>-</b></p> <ul style="list-style-type: none"> <li>• Technical uncertainty of the can-in-canister technology and throughput.</li> <li>• Technological uncertainty of the glass can-in-canister form for disposal in a geologic repository.</li> <li>• Specific modifications and impacts to WTP are yet to be fully defined. WTP, itself, is still under construction. This is not a viable option for the Hanford Site.</li> </ul>	<p style="text-align: center;"><b>--</b></p> <ul style="list-style-type: none"> <li>• Option is not contemplated under current agreements with Washington State, and potential impacts associated with changes to WTP scope and schedule.</li> <li>• Would require qualification and permitting of waste form in a geologic repository.</li> <li>• Strong opposition likely from State of Washington.</li> <li>• Opposition by State regulators; significant involvement with the DNFSB.</li> <li>• Not viable option for the Hanford Site</li> </ul>

**Table 4-2: Key Point Summary / Ratings (Continued)**

<p><b>Key:</b>                      + More Advantageous                      0 Medium/Neutral                      -- Less Advantageous</p>	<p><b>Meeting International Commitments/Russian Cooperation</b></p>	<p><b>Cost Effectiveness</b></p>	<p><b>Duration to Complete</b></p>	<p><b>Technical Viability</b></p>	<p><b>Legal, Regulatory, and Other Issues</b></p>
<p><b>Downblending and Disposal</b></p>	<p><b>0</b></p> <ul style="list-style-type: none"> <li>• Would require supplemental U.S.-Russian agreement pursuant to Article III of the PMDA - based on previous Russian concerns about immobilized plutonium, Russia may also express concerns about retrieval of plutonium in this form.</li> <li>• Currently meets two of the attributes for minimizing accessibility through physical and chemical barriers for the reference case WIPP.</li> <li>• Although all three options include IAEA monitoring and inspection, the reference case WIPP is the only facility of the three currently on list of potential DOE sites for future IAEA monitoring and inspection.</li> <li>• Plutonium currently disposed of at WIPP meets DOE Order 474.2 which requires meeting certain conditions before nuclear materials are considered sufficiently unattractive for illicit purposes.</li> </ul>	<p><b>++</b></p> <ul style="list-style-type: none"> <li>• Relatively cost effective under the reference case (based on currently shipping surplus downblended plutonium to WIPP).</li> <li>• Small incremental annual operational funding for increased downblending throughput and repository disposal, under the reference case based on use of current WIPP operating data.</li> <li>• \$2.3 billion - \$3 billion (on the high end of the range: \$262 million for capital / enhancements, \$2.7 billion in operating costs).</li> </ul>	<p><b>+</b></p> <ul style="list-style-type: none"> <li>• Known process with estimated completion between 2047 and 2057 loaded at 380 FGE limit.</li> </ul>	<p><b>++</b></p> <ul style="list-style-type: none"> <li>• Least risk under the reference case.</li> <li>• Two additional gloveboxes would be installed to increase throughput, however the technical requirements are known and in use today.</li> </ul>	<p><b>-</b></p> <ul style="list-style-type: none"> <li>• Would require significant engagement with federal, state, and local representatives before any decision to go forward with this option.</li> <li>• Implementation would require Congressional action, including amendment to existing legislation or enactment of new legislation.</li> </ul>

**Table 4-2: Key Point Summary / Ratings (Continued)**

<p><b>Key:</b>                      + More Advantageous                      0 Medium/Neutral                      -- Less Advantageous</p>	<p><b>Meeting International Commitments/Russian Cooperation</b></p>	<p><b>Cost Effectiveness</b></p>	<p><b>Duration to Complete</b></p>	<p><b>Technical Viability</b></p>	<p><b>Legal, Regulatory, and Other Issues</b></p>
<p><b>Deep Borehole Disposal</b></p>	<p><b>0</b></p> <ul style="list-style-type: none"> <li>• Would require supplemental U.S.-Russian agreement pursuant to Article III of the PMDA, - based on previous Russian concerns about immobilized plutonium, Russia may also express concerns about retrieval of plutonium in this form.</li> <li>• As a minimum, would meet the physical barrier by itself; if buried other materials, could also include a radiological and a chemical barrier but would require significant development and approval of this waste form.</li> </ul>	<p><b>+</b></p> <ul style="list-style-type: none"> <li>• Cost for site characterization, licensing and certification of a qualified plutonium waste form is unknown at this time and would be dependent on completion of the RD&amp;D to help resolve key uncertainties.</li> <li>• Cost for disposition in a deep borehole would be closer to the downblending option than the immobilization option.</li> </ul>	<p><b>0</b></p> <ul style="list-style-type: none"> <li>• Unknown but lengthy process expected for licensing, start-up, and certification of the waste form –estimated to be completed by 2051-2056.</li> </ul>	<p><b>-</b></p> <ul style="list-style-type: none"> <li>• Drilling the deep boreholes would be technically viable.</li> <li>• Technical requirements for the certified waste form are yet to be defined.</li> <li>• Concept is still under development.</li> </ul>	<p><b>--</b></p> <ul style="list-style-type: none"> <li>• Concept is still under development. Regulatory challenges in licensing, permitting, and establishing the requirements for the certified waste form.</li> </ul>

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## SUMMARY

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The purpose of this document was to analyze non-reactor-based options that could potentially provide a more cost effective approach to dispose of at least 34 MT of U.S. surplus weapon-grade plutonium to meet international commitments. The options that were analyzed included immobilization of plutonium in glass or ceramic form in combination with HLW, downblending and disposal of the plutonium at WIPP, and disposal of plutonium in a deep borehole. Although this analysis focused on options that could address all 34 MT, there may be hybrid options that could combine different disposition options to achieve the disposal of 34 MT that merit further study. The options analyzed in this document are at varying stages of development, from an early pre conceptual thought through currently implemented and operating processes; therefore, the certainty and risk within each option varies considerably. This analysis should be independently validated prior to making a final decision on a specific option.

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## ATTACHMENT A: SUMMARY OF NATIONAL ENVIRONMENTAL POLICY ACT (NEPA) DOCUMENTS RELATED TO SURPLUS PLUTONIUM DISPOSITION

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**December 1996** – DOE issued the *Final Storage and Disposition of Weapons-Usable Fissile Materials Final Programmatic Environmental Impact Statement (PEIS)*. [DOE/EIS-0229] The preferred alternative was a combination of reactor and immobilization alternatives including vitrification, ceramic immobilization, and existing reactors.

**January 1997** – In the *Storage and Disposition PEIS* Record of Decision (ROD), DOE announced its decision to pursue a hybrid strategy for disposition that would allow immobilization of some or all of the surplus plutonium in glass or ceramic material for disposal in a geologic repository, and fabrication of some surplus plutonium into MOX fuel for irradiation in existing domestic commercial nuclear power reactors, with subsequent disposal of the used fuel in a geologic repository. [ROD 62 FR 3014]

**August 1998** – In an amended *Storage and Disposition PEIS* ROD (ROD 63 FR 43386), DOE decided to proceed with accelerated shipment of surplus non-pit plutonium from RFETS to SRS, as well as the relocation of all the Hanford Site surplus non-pit plutonium to SRS, pending disposition. DOE decided to only implement the movement of the RFETS and the Hanford Site surplus non-pit plutonium inventories to SRS, if SRS were selected as the immobilization site.

**November 1999** – DOE issued the *Final Surplus Plutonium Disposition EIS* (SPD EIS) tiering from the analysis presented in the *Storage and Disposition PEIS* and focusing on sites where disposition activities would take place. The preferred alternatives were pit conversion at SRS in a new stand-alone facility (PDCF); MOX fuel fabrication at SRS in a new facility (MFFF); and immobilization at SRS in a new facility using a ceramic can-in-canister technology.

**January 2000** – DOE issued a ROD for the *SPD EIS*, announcing its decision to implement a hybrid approach to surplus plutonium disposition, wherein approximately 17 MT of surplus plutonium would be immobilized in a ceramic form and up to 33 MT of surplus plutonium would be fabricated into MOX fuel and irradiated in existing domestic commercial nuclear power reactors. The ROD also announced that the three facilities needed to implement this approach, PDCF, MFFF, and the immobilization facility would be constructed and operated at SRS. [ROD 65 FR 1608]

**April 2002** – DOE amended the *Storage and Disposition PEIS* and *SPD EIS* RODs, which announced the cancellation of the immobilization portion of the disposition strategy; selection of the immediate implementation of consolidated long-term storage at SRS of surplus non-pit plutonium then stored separately at RFETS and SRS; and authorization of consolidated long-term storage at SRS in K-Area Material Storage. The amended ROD also stated that DOE was evaluating changes to the MOX portion of the surplus plutonium

disposition program, including a revised strategy to dispose of 34 MT of surplus plutonium in a MOX-only approach and was making no decision on the MOX program until those review were completed. [ROD 67 FR 19432]

**April 2003** – DOE issued the *Supplement Analysis and Amended Record of Decision, Changes Needed to the Surplus Plutonium Disposition Program* and made the associated determination that no additional NEPA analysis was needed to process into MOX fuel 6.5 MT of non-pit plutonium originally intended for immobilization (referred to as “alternate feedstock”) or to implement the MFFF design changes identified during the detailed-design process. [DOE-EIS-0283-SA1] The amended ROD announced DOE’s decision to disposition as MOX fuel 34 MT of surplus plutonium, including the alternate feedstock. [ROD 68 FR 20134] The supplement analysis and amended ROD did not address the remaining surplus non-pit plutonium that had been intended for immobilization.

**March 2007** – DOE issued a Notice of Intent (NOI) to prepare the *SPD Supplemental EIS* to evaluate the potential environmental impacts of surplus plutonium disposition capabilities that would be constructed and operated at SRS to provide a disposition pathway for surplus non-pit plutonium originally planned for immobilization. [NOI 72 FR 14543] DOE stated that its preferred alternative was to construct and operate a new vitrification capability within an existing building at SRS to immobilize most of the surplus non-pit plutonium, and to process some of the surplus non-pit plutonium in the existing H-Canyon/HB-Line and Defense Waste Processing Facility (DWPF) at SRS. The NOI also stated that DOE would analyze the impacts of fabricating some surplus non-pit plutonium into MOX fuel.

**December 2008** – In an interim action determination, DOE decided to process approximately 180 kg of surplus plutonium through H-Canyon/HB-Line for vitrification in DWPF.

**September 2009** – In an interim action determination, DOE decided to process up to 420 kg of plutonium materials comprised of plutonium-enriched uranium mixtures, plutonium-contaminated HEU, and fuel grade plutonium metal not suitable for MFFF feed or disposal at WIPP through H-Canyon/HB-Line for vitrification in DWPF.

**July 2010** – DOE issued an amended NOI announcing its intent to modify the scope of the SPD Supplemental EIS. [NOI 75 FR 41850] DOE revised the scope of the SPD Supplemental EIS to refine the quantity and types of surplus plutonium, evaluate additional alternatives (disposal of some of the surplus non-pit plutonium as TRU waste at WIPP and establishing pit disassembly and conversion capabilities in existing facilities in K-Area at SRS), and no longer consider in detail one of the alternatives identified in the 2007 NOI (ceramic can-in-canister immobilization). In addition, DOE had identified a glass can-in-canister immobilization approach as its preferred alternative in the 2007 NOI for the non-pit plutonium then under consideration; the 2010 amended NOI explained that DOE would evaluate a glass can-in-canister immobilization alternative in this *SPD Supplemental EIS*, but that DOE no longer had a preferred alternative.

**March 2011** – In an interim action determination issued in December 2008, DOE decided to process 180 kg of surplus plutonium removed from 3013 containers through H-Canyon/HB-Line for vitrification in DWPF. The interim action determination issued in March 2011 evaluated the option of preparing and packaging about 85 kilograms of this material at HB-Line for disposal as TRU waste at WIPP.

**October 2011** – In an interim action determination, DOE decided to process an additional 0.5 MT of surplus non-pit plutonium through H-Canyon/HB-Line for disposal at WIPP.

**January 2012** – DOE issued a second amended NOI announcing its intent to modify the scope of this *SPD Supplemental EIS*. [NOI 77 FR 1920] New alternatives were added to include the capability to conduct pit disassembly and/or conversion at one or more of the following locations: the Plutonium Facility (PF-4) at LANL, H-Canyon/HB-Line at SRS, K-Area at SRS, and the MFFF at SRS. The amended NOI announced that the MOX Fuel Alternative was DOE's preferred alternative for surplus plutonium disposition; DOE's preferred alternative for pit disassembly and conversion was to use some combination of facilities at LANL, H-Canyon/HB-Line at SRS, K-Area at SRS, and the MFFF at SRS; and DOE's preferred alternative for disposition of plutonium that is not suitable for MOX fuel was disposal at WIPP.

**July 2012** – DOE announced the availability of the *Draft SPD Supplemental EIS*, which included five alternatives: No Action, Immobilization to DWPF, MOX Fuel, H-Canyon/HB-Line to DWPF, and WIPP. The preferred alternatives were the MOX fuel for surplus plutonium disposition; some combination of facilities at LANL (PF-4), H-Canyon/HB-Line at SRS, K-Area at SRS, and the MFFF at SRS for pit disassembly and conversion; and disposal at WIPP for plutonium that is not suitable for MOX fuel.

**References:**

DOE/EIS-0229, *Storage and Disposition of Weapons-Usable Fissile Materials Final Programmatic Environmental Impact Statement*, Office of Fissile Materials Disposition, Washington, DC, December 1996.

DOE/EIS-0283-SA1, *Supplement Analysis and Amended ROD, Changes Needed to the Surplus Plutonium Disposition Program*, April 17, 2003.

ROD 62 FR 3014, *Record of Decision for the Storage and Disposition of Weapons-Usable Fissile Materials Final Programmatic Environmental Impact Statement*, January 21, 1997.

ROD 63 FR 43386, *Amended Record of Decision for the Storage and Disposition of Weapons-Usable Fissile Materials*, August 13, 1998.

ROD 65 FR 1608, *Record of Decision for the Surplus Plutonium Disposition Final Environmental Impact Statement*, January 11, 2000.

ROD 67 FR 19432, *Amended Record of Decision for the Storage and Disposition of Weapons-Usable Fissile Materials and the Surplus Plutonium Disposition Final Environmental Impact Statement*, April 19, 2002.

ROD 68 FR 20134, *Amended Record of Decision for the Surplus Plutonium Disposition Program*, April 24, 2003.

NOI 72 FR 14543, *Notice of Intent to Prepare a Supplemental Environmental Impact Statement of Surplus Plutonium Disposition at the Savannah River Site*, March 28, 2007.

NOI 75 FR 41850, *Amended Notice of Intent to Modify the Scope of the Surplus Plutonium Disposition Supplemental Environmental Impact Statement and Conduct Additional Public Scoping*, July 19, 2010.

NOI 77 FR 1920, *Amended Notice of Intent to Modify the Scope of the Surplus Plutonium Disposition Supplemental Environmental Impact Statement and Conduct Additional Public Scoping*, January 12, 2012.

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## **ATTACHMENT B: TECHNOLOGY OPTIONS PREVIOUSLY CONSIDERED IN THE 1995 SCREENING PROCESS**

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### **STORAGE OPTIONS**

- No Disposition Action (Continued Storage)
- Radiation Barrier Alloy (Storage)

### **DISPOSAL OPTIONS**

- Direct Emplacement in HLW Repository
- Deep Borehole (Immobilization)
- Deep Borehole (Direct Emplacement)
- Discard to WIPP
- Hydraulic Fracturing
- Deep Well Injection
- Injection into Continental Magma
- Melting in Crystalline Rock
- Disposal Under Ice Caps
- Seabed (Placement on Ocean Floor)
- Sub-Seabed Emplacement
- Ocean Dilution
- Deep Space Launch

### **IMMOBILIZATION WITH RADIONUCLIDES OPTIONS**

- Underground Nuclear Detonation
- Borosilicate Glass Immobilization (DWPF)
- Borosilicate Glass Immobilization (New Facility)
- Ceramic Immobilization
- Electrometallurgical Treatment
- Borosilicate Glass Oxidation / Dissolution

### **REACTOR AND ACCELERATOR OPTIONS**

- Euratom MOX Fabrication / Reactor Burning
- Existing Light Water Reactors (LWR)
- Partially Completed LWRs
- Evolutionary or Advanced LWRs
- Naval Propulsion Reactors
- Modular Helium Reactors
- Candu Heavy Water Reactors
- Advanced Liquid Metal Reactors (ALMR) with Pyroprocessing
- Accelerator Conversion / Molten Salt
- Accelerator Conversion / Particle Bed
- Existing LWRs with Reprocessing
- Advanced LWRs with Reprocessing
- Molten Salt Reactors
- ALMRs with Recycle
- Particle Bed Reactors
- Accelerator-Driven Modular Helium Reactors (MHR)

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**ATTACHMENT C: IMMOBILIZATION PROVISIONS OF THE 2000  
U.S. RUSSIA PLUTONIUM MANAGEMENT AND DISPOSITION  
AGREEMENT**

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*The following are excerpts from the 2000 PMDA:*

**Article I**

For the purposes of this Agreement, the terms specified below are defined as follows:

5. "Immobilized forms" means plutonium that has been imbedded in a glass or ceramic matrix and encapsulated with high-level radioactive waste in a can-in-canister system suitable for geologic disposal, or any other immobilization system agreed by the Parties.
6. "Disposition facility" means any facility that stores, processes, or otherwise uses disposition plutonium, spent plutonium fuel, or immobilized forms, including fuel fabrication facility, immobilization facility, nuclear reactor, and storage facility.

**Article III**

1. Disposition shall be by one or more of the following methods:
  - a) irradiation of disposition plutonium as fuel in nuclear reactors;
  - b) immobilization of disposition plutonium into immobilized forms; or
  - c) any other methods that may be agreed by the Parties in writing.

**Article VI**

3. Neither Party shall separate disposition plutonium contained in immobilized forms.

**Article VII**

1. Each Party shall have the right to conduct and the obligation to receive and facilitate monitoring and inspection activities in order to confirm that the terms and conditions of this Agreement with respect to disposition plutonium, blend stock, spent plutonium fuel and immobilized forms, and disposition facilities are being met.

**Article XIII**

5. Notwithstanding termination of this Agreement:
  - c) neither Party shall (i) use any plutonium separated from spent plutonium fuel for the manufacture of nuclear weapons or any other nuclear explosive device, for research, development, design or testing related to such devices, or for any other military purpose, or (ii) export spent plutonium fuel, immobilized forms, or any plutonium separated from spent plutonium fuel to a third country.;
  - d) each Party shall continue to effectively control and account for spent plutonium fuel and immobilized forms, as well as to provide effective physical protection of such material.

**ANNEX ON  
QUANTITIES, FORMS, LOCATIONS, AND METHODS OF DISPOSITION**

**Section I -- Quantities and Methods of Disposition**

For the United States of America:

<b>Quantity (metric tons)</b>	<b>Form</b>	<b>Method of Disposition</b>
25.00	Pits and Clean Metal	Irradiation
0.57	Oxide	Irradiation
2.70	Impure Metal	Immobilization
5.73	Oxide	Immobilization

**ANNEX ON TECHNICAL SPECIFICATIONS**

**Section II -- Immobilization**

1. Each can containing disposition plutonium immobilized in a glass or ceramic form designated to be inserted into a canister is marked with a unique identifier that allows for confirming the presence of the can as it is inserted into the canister;
2. Each canister containing cans of disposition plutonium is marked with a unique identifier that allows it to be identified during and after the immobilization process;
3. Each canister does not contain more than 30 kilograms of disposition plutonium; and
4. The radiation level from each canister is such that it will become no less than 1 sievert per hour one meter from the accessible surface at the centerline of the canister 30 years after the canister has been filled with high-level radioactive waste.

**ANNEX ON MONITORING AND INSPECTIONS**

**Section I -- Definitions**

For purposes of the Agreement, the following definitions shall apply:

1. "Monitoring" means a set of measures and activities that together provide data to the monitoring Party on disposition plutonium, blend stock, spent plutonium fuel, immobilized forms, or disposition facilities.
2. "Inspection" means a monitoring activity conducted by the monitoring Party on-site at a facility in order to obtain data and make observations on disposition plutonium, blend stock, spent plutonium fuel, immobilized forms, or disposition facilities.

**Section II -- General Principles**

1. *Scope:* Monitoring and inspection activities shall be conducted in accordance with the Agreement, this Annex, and procedures to be agreed by the Parties pursuant to Section V of this Annex.
2. *Purpose:* Monitoring and inspection activities shall be designed and implemented to ensure that the monitoring Party has the ability independently to confirm that the

terms and conditions of the Agreement with respect to disposition plutonium, blend stock, spent plutonium fuel, immobilized forms, and disposition facilities are being met.

9. *Pu-240/Pu-239 Ratio*: The monitoring Party shall be allowed to confirm that the Pu-240/Pu-239 ratio of the disposition plutonium is no greater than 0.10. Confirmation shall occur after receipt but before processing of disposition plutonium at a conversion facility, or upon receipt at a fuel fabrication facility or immobilization facility.

#### **Section IV -- General Approach to Confirm Disposition of Disposition Plutonium**

1. The monitoring Party shall have the right, using agreed procedures, to confirm that spent plutonium fuel assemblies and immobilized forms meet the criteria specified in the Annex on Technical Specifications.
2. Monitoring rights on spent plutonium fuel and immobilized forms shall include procedures, designed with a view to minimize costs that will allow confirmation that such fuel and forms remain in their declared locations.



## ATTACHMENT D: SUMMARY OF KEY CHANGES TO THE PMDA RESULTING FROM THE 2010 PROTOCOL

General Provisions	2000 PMDA	2010 Amended PMDA
Funding Russian Federation Disposition program	U.S. and international donors to fund all Russian costs (\$2.5+B)	<ul style="list-style-type: none"> <li>• U.S. contribution capped at \$400M.</li> <li>• No U.S. funding for BN-800 construction.</li> <li>• If assistance is not provided Russia has the right to terminate its activities under the Agreement.</li> </ul>
Method of disposition	U.S.: Immobilization (9 MT) and LWRs (25 MT) RF: 34 MT in BOR-60, BN-600 and LWR	<ul style="list-style-type: none"> <li>• U.S.: LWR (34 MT).</li> <li>• RF: BN-600 and BN-800 Fast Reactors (34 MT).</li> </ul>
Annual Disposition Rate	2MT per year	<ul style="list-style-type: none"> <li>• 1.33 MT per year.</li> </ul>
Key Program Elements	Not applicable	<ul style="list-style-type: none"> <li>• U.S.: Disposition by irradiating plutonium as MOX fuel in at least 4 LWRs.</li> <li>• RF: Disposition by irradiating plutonium as MOX fuel in the BN-600 and BN-800 reactors.</li> </ul>
Nonproliferation Conditions	2000 PMDA	2010 Amended PMDA
Fast reactors in Russia	BN-600 blanket removal in Joint Statement to PMDA. No reference to BN-800 in PMDA.	<ul style="list-style-type: none"> <li>• BN-800 Breeding ratio less than one.</li> <li>• Removed BN-600 blanket.</li> </ul>
Reprocessing limits on Non-Disposition MOX Fuel	Non-disposition MOX fuel not permitted at a disposition reactor	<ul style="list-style-type: none"> <li>• In disposition reactors, no reprocessing of <b><u>non-disposition MOX fuel</u></b> during the Agreement. (Exception: Limited amount of test fuel in the LWRs and BN-800 reactor, provided such reprocessing does not result in new separated weapon-grade plutonium).</li> </ul>

**Nonproliferation Conditions that carried forward from 2000 PMDA to 2010 Amended PMDA**

- Monitoring and inspection activities of disposition in both countries. [Note: Following signing of the 2010 Protocol, the U.S. and Russia began negotiations with the IAEA for international monitoring of both Parties' disposition programs]
- Any plutonium, once received at any disposition facility, shall not be used for the manufacture of nuclear weapons or any other military purpose.
- Disposition plutonium, once received at any disposition facility, shall not be exported to a third country, except by agreement of the Parties.
- Neither Party shall reprocess spent plutonium fuel containing disposition plutonium during the life of the Agreement (Approximately 40 years).
- Notwithstanding termination of the Agreement:
  - a) neither Party shall use plutonium, once it is received at any disposition facility, for nuclear weapons or any other military purpose;
  - b) neither Party shall export to a third country plutonium, once it is received at any disposition facility, except by agreement of the Parties;
  - c) neither Party shall use any plutonium separated from spent plutonium fuel for nuclear weapons or any other military purpose, or export such material to a third country, except by agreement of the Parties;
  - d) each Party shall continue to effectively control and account for spent plutonium fuel and provide effective physical protection of such material;
  - e) Spent plutonium fuel shall remain subject to international monitoring.
- No spent plutonium fuel shall be reprocessed after termination of the Agreement unless such reprocessing is subject to international monitoring.

**Summary of PMDA Criteria for Determining That Plutonium is Dispositioned**

	<b>Light Water Reactors</b>	<b>BN-600 Fast Reactor</b>	<b>BN-800 Fast Reactor</b>
Fuel Assembly ID	Each plutonium fuel assembly must contain unique identifiers	Each plutonium fuel assembly must contain unique identifiers.	Each plutonium fuel assembly must contain unique identifiers.
Required heavy-metal atom burn-up level for each assembly	No less than 20,000 megawatt days thermal.	Not less than five (5) percent.	No less than three and nine-tenths (3.9) percent during commissioning stage (2-3 years) and four and one-half (4.5) percent thereafter.
Additional heavy-metal atom burn-up levels requirements	None	For all assemblies discharged during the same refueling outage, no less than an average of 6.5% percent.	For all assemblies discharged during the same refueling outage, no less than an average of 5% (commissioning stage) and 6% thereafter.
Long-term irradiation levels	No less than 1 sievert per hour one meter from the accessible surface at the centerline of the assembly 30 years after irradiation.	No less than 1 sievert per hour one meter from the accessible surface at the centerline of the assembly 30 years after irradiation.	No less than 1 sievert per hour one meter from the accessible surface at the centerline of the assembly 30 years after irradiation.

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## ATTACHMENT E: IMMOBILIZATION - CERAMIC OR GLASS

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### **E.1 IMMOBILIZATION AT THE HANFORD SITE - BASE APPROACH**

Given that this option depends on HLW as feed for the can-in-canister approach this option introduces potentially significant, and thus unacceptable, schedule risk to the Hanford tank waste immobilization mission, particularly if it were to impede or delay the tank waste immobilization. Although Hanford is not a viable option for the mission of disposing of 34 MT of weapon grade plutonium, it was included for completeness of this options study and to document the activities necessary to implement such an option.

#### ***E.1.1 FACILITY DESCRIPTION***

##### **Hanford**

The Hanford Site is located in southeastern Washington State along the Columbia River. The site was established in the 1940's to support the development and production of the U.S. weapons program. This involved the operation of nine nuclear reactors, plutonium and spent fuel processing facilities, and numerous associated support facilities. The site generated several hundred thousand MT of chemical and radioactive waste from these processing activities including high-level waste (HLW), transuranic (TRU) waste, low level waste (LLW), mixed low level waste (MLLW), and hazardous waste. Initially the waste management process involved neutralizing the acidic waste with sodium hydroxide and sodium carbonate and storing the resulting caustic waste in large underground tanks until long term disposition solutions were established. To store the liquid waste, 177 stainless steel tanks were constructed from 1943 - 1980s in the 200 Areas at the Hanford Site. Today, the Hanford Site also processes its contact-handled TRU waste through shipment to the Waste Isolation Pilot Plant (WIPP), whereas the low level waste and mixed low level waste are disposed of on site.

DOE is currently constructing the Waste Treatment and Immobilization Plant Project (WTP), depicted in Figure E1, at the Hanford Site to process and stabilize 56 million gallons of radioactive and chemical waste. WTP will cover 65 acres in the 200 East Area and is comprised of four main nuclear facilities (pretreatment, HLW vitrification, low activity waste vitrification, and an analytical lab) as well as operations and maintenance buildings, utilities, and office space. WTP will use a vitrification technology to blend the waste with glass-forming materials in a melter system and pour the resulting glass into stainless steel canisters to cool and solidify. [DOE 2012]

**Figure E1: Hanford Site - Waste Treatment and Immobilization Plant under Construction**



Much of DOE's environmental management work at the Hanford Site is governed by the Consent Decree in the case of the State of Washington v. Chu, Case No. 08-5085-FVS and the Hanford Federal Facility Agreement and Consent Order (TPA or Tri-Party Agreement). DOE has informed the State of Washington that the achievement of a number of Consent Decree milestones is at serious risk.

### ***E.1.2 TECHNICAL APPROACH***

In the Record of Decision (ROD) for the Surplus Plutonium Disposition (SPD) Environmental Impact Statement (EIS), DOE decided to implement the hybrid approach for the disposition of up to 50 MT of surplus plutonium by fabricating up to 33 MT into mixed oxide (MOX) fuel and immobilizing approximately 17 MT. [ROD 65 FR 1608] SRS was selected as the location for the 3 disposition facilities: the Pit Disassembly and Conversion Facility (PDCF), Plutonium Immobilization Facility, and Mixed Oxide Fabrication Facility (MFFF). Subsequently, in 2002, DOE announced its decision to cancel the immobilization portion of the disposition strategy due to budgetary constraints. [ROD 67 FR 19432] At the time of cancellation the Plutonium Immobilization Project (PIP) was in the early stages of design and was finalizing the conceptual design report. DOE was 2 years into a projected

5-year development and testing program that included waste form performance testing and qualification for licensing the waste form in the geologic repository.

As a result of the 2002 decision to cancel PIP, DOE had about 13 MT of surplus plutonium without a defined disposition path.<sup>4</sup> In 2007, DOE announced its intention [NOI 72 FR 14543] to prepare a Supplement EIS for Surplus Plutonium Disposition at SRS [DOE/EIS-0283-S2] to evaluate the potential environmental impacts for alternatives to dispose of this material. This Notice of Intent identified DOE's preferred alternative to construct and operate an immobilization facility within an existing building at SRS. This facility, known as the Plutonium Vitrification Project, would immobilize plutonium within a Lanthanide-Borosilicate glass inside stainless steel cans. The cans then would be placed within larger canisters to be filled with vitrified HLW in the Defense Waste Processing Facility (DWPF) at SRS. The canisters would be suitable for disposal in a geologic repository.

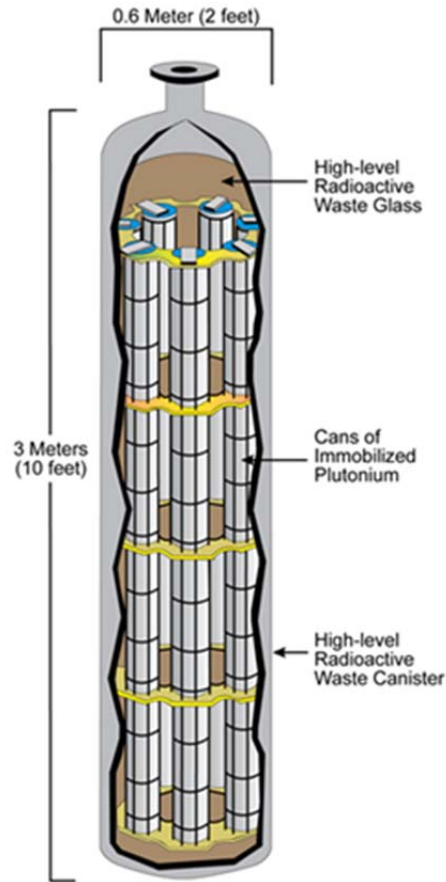
Since the glass vitrification technology was advanced in the 1990's and early 2000 through the operational experiences of DWPF and through developmental testing associated with an americium vitrification project at SRS, it was selected as a preferred form for the Plutonium Vitrification Project over the ceramic form identified in PIP. The Plutonium Vitrification Project was authorized in 2005 to dispose of the up to 13 MT of plutonium at SRS. [Sell 2005] During this time, the project developed the conceptual design for the vitrification process, further developed the can-in-canister technology from the PIP project, and began the waste form performance testing and qualification program for licensing the waste form in the geologic repository. This vitrified glass can-in-canister waste form was identified as a potential waste form in the Yucca Mountain License Application. (See Figure E2) The project was subsequently cancelled in 2007.

The only two U.S. DOE sites that have significant quantities of HLW or that have the capability to encapsulate the waste into glass logs for ultimate disposal are SRS and the Hanford Site. The first site, SRS, has been using DWPF since 1996 to vitrify HLW into glass logs. Because a significant amount of SRS's HLW has already been remediated, there is not enough HLW remaining to dispose of 34 MT of surplus plutonium. In addition, DWPF is scheduled to complete operations by 2032, well in advance of designing and constructing an immobilization facility to perform this mission.

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<sup>4</sup> *Approximately 4 MT of unirradiated Zero Power Physics Reactor fuel at the Idaho National Laboratory (INL) was part of the original 17 MT considered for immobilization and excess to weapons programs. For several years DOE set aside this material for other potential other uses, therefore this material was excluded from the scope of the SRS Plutonium Vitrification Project.*

**Figure E2: High-Level Waste Can-In-Canister Diagram**



The second location, the Hanford Site, is where DOE is constructing a new facility, the WTP, to vitrify its waste into glass logs. While there is enough HLW available to complete the 34 MT disposition mission, the Hanford Site deinventoried its plutonium not in fuel form in 2009, and its secure plutonium storage facility has been shut down. As a result, an immobilization option at the Hanford Site would require a new plutonium storage facility to be constructed or an existing facility significantly modified in addition to the new plutonium immobilization facility. Both of these facilities would be secure Hazard Category 2 facilities, which would require meeting stringent security and safety regulations.

### ***E.1.3 FACILITY CONSTRUCTION/MODIFICATION***

The Hanford Site construction/modification scope of work is broken out into projects: 1) Storage; 2) Immobilization; and 3) WTP Modification.

#### **Storage**

A new plutonium storage facility or modification to an existing facility would have to be constructed to receive and store the plutonium oxide from SRS and LANL. The Hanford Site would have to reconstitute a security program to protect significant quantities of weapon-grade plutonium including reconstituting a Human Reliability Program (HRP) to ensure the

reliability of the workers with access to this material. The building blocks of the storage facility would include:

Material receipt capability for "Secure Transport" vehicles: The plutonium would be transported to the Hanford Site using the NNSA's Office of Secure Transportation (OST). An enclosed off-loading area would be required that provides sufficient security features during receipt of the transport vehicles. Equipment required for shipping container receipts would include a fork lift, drum hoist, drum scale, barcode reader, non-destructive analysis (NDA) confirmatory measurement device, and instruments for radiological control personnel. Backup power supply would also be required for the transportation vehicles.

Vault storage: A 10,000 position secure Hazard Category 2 plutonium vault that can store either DOE-STD-3013 cans or shipping containers such as the 9975, 9977, or ES-3100 would be needed. The vault or vaults must meet nuclear safety, life safety, and fire protection codes including independent and redundant nuclear safety systems where appropriate, fire suppression and detection systems, and multiple egress paths. DOE safeguards and security features would also be required. International Atomic Energy Agency (IAEA) safeguards most likely would also be required for a minimum of 3 MT of plutonium which is currently under IAEA safeguards at SRS. The IAEA material would have to be in a segregated area with cameras and tamper indicating devices for IAEA monitoring.

Material surveillance program: The Hanford Site would need to reconstitute a plutonium surveillance program in accordance with DOE-STD-3013 to verify corrosion and pressurization conditions would not occur over a 50-year period that might compromise the integrity of the cans during storage. The standard requires both destructive and non-destructive examination of the cans in storage. The glovebox for the destructive analysis must have a can puncture device with gas sampling capability, can opener, can cutter to take samples for corrosion testing, scales, and a method to sample the plutonium. In a separate area, the Hanford Site would need to reconstitute the capability to perform destructive analysis of the can itself for corrosion testing, and analytical analysis of the plutonium. For non-destructive surveillance, a digital radiography system (x-ray capability) would be required to observe the amount of pressurization within each inner can. This option assumes that LANL would continue with the shelf life program as required by DOE-STD-3013 and that this function would not transfer to the Hanford Site.

DOE-STD-3013 packaging capability: To meet the 50-year storage criteria for plutonium as required by DOE Order, the Hanford Site would need to reconstitute the DOE-STD-3013 packaging capability to repackage plutonium prior to start-up of the immobilization capability. This would include an inert glovebox with furnaces to stabilize the plutonium to 950° Celsius, driving off moisture that might be absorbed on the plutonium and a DOE-STD-3013 canning system.

Material control and accountability measurement area: Measurement area would be required, including drum counting and can counting capabilities. If IAEA safeguards were required, a separate IAEA counting area and equipment might also be needed.

*Balance of plant:* This would include the support functions, e.g., electrical systems, fire systems, building and process ventilation systems, and diesel generator building.

*Security:* Significant security upgrades would be required since the Hanford Site no longer stores large quantities of SNM other than in fuel form. These upgrades would include, for example, reactivating or establishing a new intrusion detection system, alarm stations, surveillance systems, entry control facility, security vehicles, weapons armory, and weapons training facility.

### **Immobilization**

A plutonium immobilization facility would need to be constructed at the Hanford Site. The throughput required for 34 MT over a 15-year period would be approximately 100 cans per week (rounded conservatively), resulting in 4,000 cans per year over the 15-year period, resulting in approximately 60,000 cans based on a 10-month production year. The actual total number of cans required is 56,667 (rounded to 60,000) to dispose of 34 MT, therefore with each WTP canister containing 28 cans, approximately 2,024 HLW canisters would be required to package the plutonium. Based on the amount of HLW displaced per canister due to the immobilized plutonium, the vitrification plant at WTP would create approximately 250 additional HLW canisters, about an additional half-year of production at WTP.<sup>5</sup> Similar security features would be required for this facility, as would be in the storage facility. The immobilization process, as depicted in Figure E3, is broken down into the following building blocks and is based on the now cancelled Plutonium Vitrification Project.

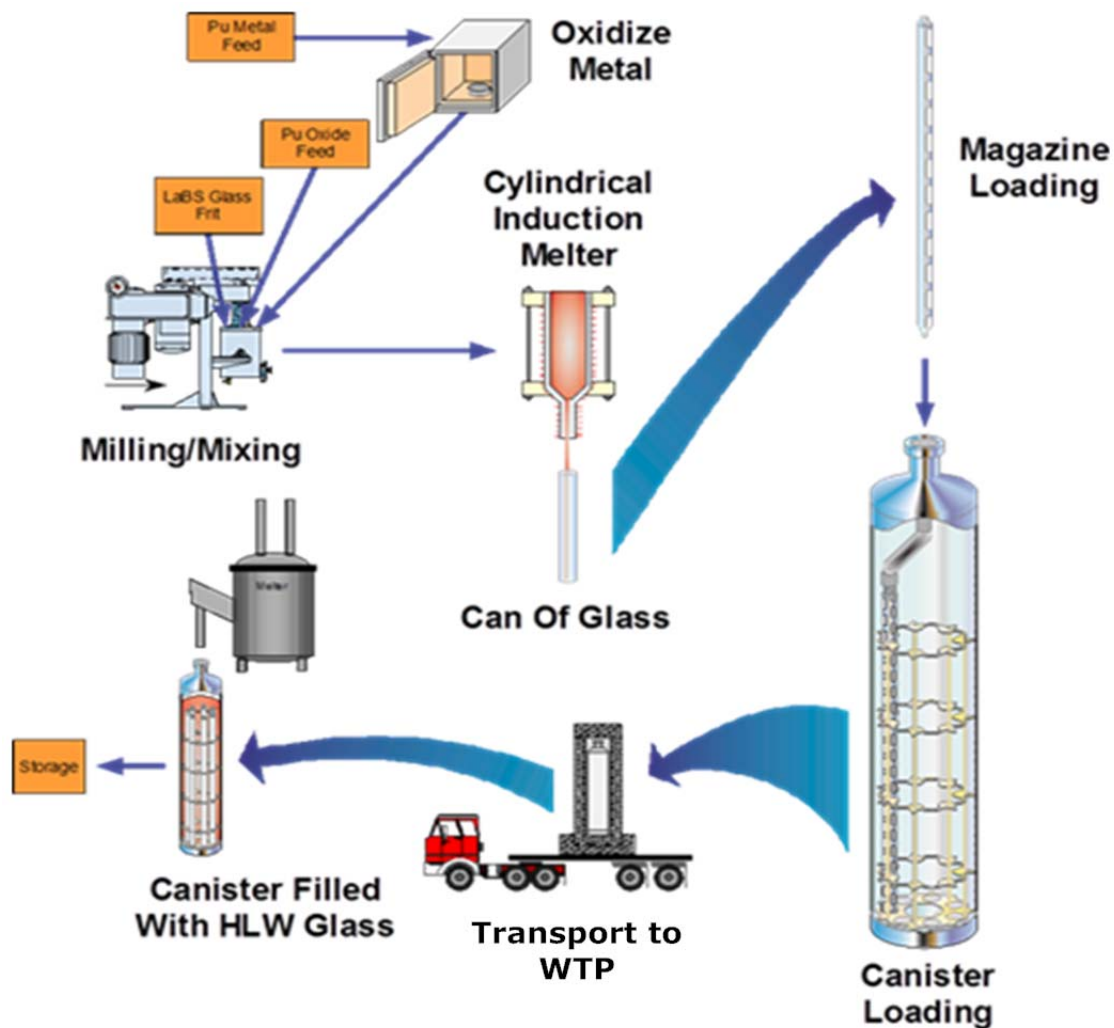
*Material receipt capability for "Secure Transport" vehicles:* The plutonium would be transported within the Hanford Site, from the vault storage facility to the immobilization facility using the onsite security force. An enclosed off-loading area would be required that provides sufficient security features during receipt of the transport vehicles. Equipment required for shipping container receipts includes a fork lift, drum hoist, drum scale, barcode reader, non-destructive analysis (NDA) confirmatory measurement device, and instruments for radiological control personnel. An area will need to be established to house the on-site transport vehicle with a power source.

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<sup>5</sup> Currently, it is estimated that WTP will produce approximately 10,600 HLW canisters at a rate of 400 canisters per year. The operation life is approximately 25-27 years.



Figure E3: Immobilization Process Flow Diagram\*



\*Note: Oxidize metal step is not required at the immobilization facility since all material received into the facility will be in oxide form.

**Interim vault storage:** Interim or lag storage area for up to 500 DOE-STD-3013 cans would be required to remove the DOE-STD-3013 cans from the shipping containers and provide storage until ready for the processing steps.

**Feed preparation:** Feed preparation would receive the DOE-STD-3013 cans of oxide from material receipt storage and prepares the plutonium for processing. The plutonium would be crushed and screened to a particle diameter less than 1 mm and placed into cans loaded at 2 kg per can.

**Milling and mixing:** The milling and mixing process step would combine the plutonium feed with Lanthanide-Borosilicate (LaBS) glass frit. Plutonium oxide feed would be received into the milling and mixing glovebox from the feed preparation glovebox. Milling and mixing would be accomplished using an attritor mill to produce the necessary particle size

to ensure dissolution and incorporation of the plutonium into the glass and a homogenous mixture. The resulting mix would be loaded into melter batch cans and sent to immobilization.

Immobilization: In immobilization, the plutonium feed/LaBS frit mixture would be vitrified into glass cans using a Cylindrical Induction Melter (CIM). The CIM is a compact, high temperature (1600° Celsius capability) melter. A platinum/rhodium (Pt/Rh) vessel would be used to contain the melt and a Pt/Rh drain tube would be used to discharge the molten glass into cans. It is estimated that 20 melter units would be required. The resultant glass cans would be transported to the bagless transfer unit.

Bagless transfer: The bagless transfer would allow the glass can to be removed from the glovebox in a non-contaminated state by emplacing the glass can in a bagless transfer can. It is estimated that three bagless transfer units would be required to obtain the throughput requirements. The bagless transfer cans would be transported to magazine loading/storage, canister load/ship.

Magazine loading/storage, canister load/ship: This area would receive the bagless transfer cans, assemble cans into magazines (long stainless steel cans containing 4 bagless transfer cans per magazine), store the magazines in an area capable of storing a minimum of 400 magazines, and assemble the can-in-canister assemblies that are suitable for filling with HLW glass. The empty WTP canister would be shipped to this plutonium immobilization facility where 7 magazines containing 28 immobilized plutonium cans would be placed into the empty WTP canisters. A temporary plug would be inserted over the opening and the canisters would be loaded into a shielded shipping cask for transport to WTP.

Non-nuclear material handling: Non-nuclear material handling would provide for the receipt and storage of non-radioactive materials and containers used in the process. A storage building outside of the Security Area would be provided to facilitate off-site vendor receipts. This building would supply approximately a one-month supply of materials.

Waste handling/loading: The waste handling/loading would remove waste generated from the process. This building block removes waste from the generation point, performs the appropriate measurements, packages waste, and prepares waste for shipment to the disposal location.

Balance of plant: The balance of plant would comprise of the support functions required by the immobilization process, e.g., electrical systems, fire systems, building and process ventilation systems, diesel generator building, and the administrative support building.

## **WTP Modifications**

Modifications to the WTP vitrification plant would be required to support receipt of the immobilized plutonium cans. The specific modifications to WTP would not be known until design of the WTP vitrification plant is completed. However, based on the DWPF changes that were identified during the cancelled Plutonium Vitrification Project, it is expected that WTP would require receipt and handling capabilities for the canisters filled with immobilized plutonium cans. The immobilized plutonium canisters differ from typical DWPF/WTP canisters, in that they contain significant quantities of SNM, emit a significant amount of radiation<sup>6</sup>, and weigh significantly more. Security measures, including the potential use of a protective force would be necessary for receipt and movement of the immobilized plutonium canisters. Specific shielding and/or remote operation measures would be required to handle the canisters. Due to the weight of the can-in-canister assembly, modifications to existing canister handling equipment (loading dock, forklift, crane, etc.) would likely be required. The modified process steps are described below.

- The transport truck would arrive at the WTP vitrification plant at an upgraded/modified canister receipt bay. The shielded transport cask would be opened and a new bridge crane provided by this immobilization project would be used to remove the canister from the cask. It is expected that a “shielded shroud” would be needed for radiation shielding. The shroud could be designed to mate to the cask so the canister can be enveloped by the shroud as it is removed from the cask. The shrouded canister would be loaded onto a transport vehicle (e.g., forklift truck, motorized cart) for transfer through the canister storage area to the existing canister airlock area.
- In the canister airlock, the canister would be removed from the shroud and positioned for transfer to the melt cell using the “existing” monorail from the WTP vitrification plant. The addition of shielding and remote viewing capability would be required in this area. The canister would be grasped by the monorail hoist and taken to the melt cell entry hatch. Additional protective shielding and remote viewing capability would be provided for the operator during this operation. All non-essential personnel must be excluded from the corridor during this evolution. The canister would be lowered through the entry hatch into the transfer cart then into the melt cell using the “existing” canister grapple and in-cell crane.
- In the melt cell, the canister would be placed into existing storage racks for staging to the WTP melter using the in-cell crane. A capability using the existing manipulator would be needed in the melt cell to remove the temporary canister plug from the can-in-canister assembly. These plugs would become waste upon removal. Subsequent processing of the can-in-canister assembly would proceed similarly to processing a standard WTP canister.

With the production of approximately 250 additional HLW canisters, an additional glass waste storage facility was conservatively assumed in this option.

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<sup>6</sup> The combination of the LaBS frit (containing boron) and the plutonium feed materials would generate neutrons in the vitrified plutonium product through the “alpha, n” reaction. The neutron dose from this mixture has not been quantified but it is expected that shielding measures would need to be employed in the immobilization facility and in subsequent canister handling activities.

#### ***E.1.4 KEY ASSUMPTIONS***

- NEPA analysis and ROD completed in a timely manner.
- Staffing available (both operations and security) in particular qualified, cleared, nuclear workers in the HRP.
- Successful negotiations with the State of Washington to ship at least 34 MT of plutonium into Washington pending identification and start-up of the HLW geologic repository.
- Additional glass waste storage building to store the additional glass canisters produced.
- Until a geologic repository is identified, and the waste qualification requirements are established, same waste acceptance requirements as were established for Yucca Mountain assumed.

#### ***E.1.5 COST AND SCHEDULE***

Immobilization requires construction of a multi-billion dollar immobilization facility and potential construction or significant modification of a storage facility. In 1999, the cost to design and construct the immobilization facility was comparable to the MOX facility, with the cost estimates within \$100 million of each other. The total lifecycle cost to operate the immobilization facility was slightly less than the cost to operate the MOX facility. Since then, the immobilization project was cancelled, and the MOX project has experienced significant cost growth with the latest contractor-submitted baseline change proposal at \$7.7 billion with an estimated annual operating cost of more than \$500 million. This analysis uses a parametric comparison between MOX and immobilization to estimate the immobilization costs. Historically the estimated cost for the projects was comparable.

The immobilization project and the MOX project would have parallel processes in many respects, even though the plutonium is encased in glass in the case of immobilization and in a uranium oxide fuel ceramic in the case of MOX fuel. The largest difference in the processes that could drive a difference in relative cost is that the MOX project has an aqueous polishing step and the immobilization project would require changes to WTP. In very rough terms, the capital cost for the aqueous processing part of the MOX facility has been estimated in the past to be approximately 1/3 of the cost of the overall MOX project. The WTP modifications are estimated at \$500 million which would include approximately \$100 million for an additional HLW glass storage capacity. Therefore, the low end of the range for the immobilization project would be 1/3 less than the \$7.7 billion estimate for the MOX project plus \$500 million totaling approximately \$6 billion, and the high end of the range is the \$12 billion based on the MOX project and the additional cost of the glass waste storage building and WTP modifications. The operational costs would depend on the acquisition strategy to operate the facility so this analysis assumes the range of the MOX facility identified by the independent review team conducted for MOX operations and adjusted (reduced) to compensate for not having the aqueous processing operations in the immobilization facility.

The storage facility is estimated at \$500 million to \$1 billion based on the cancelled Actinide Packaging and Storage Facility at SRS and the Highly Enriched Uranium Material Storage Facility at the Y-12 National Security Complex and an annual operating cost of \$50 to \$100 million.

**Table E1: Immobilization Costs**

<b>Constant FY 2014 dollars</b>	<b>Low Range</b>	<b>High Range</b>
Immobilization Facility Capital Costs (2015 – 2035)	\$6 billion	\$12 billion
Storage Facility Capital Costs (2015 – 2025)	\$0.5 billion	\$1billion
<b>Sub-Total</b>	<b>\$6.5 billion</b>	<b>\$13 billion</b>
Immobilization Operations Costs (2035 – 2050)	\$4.9 billion	\$5.1 billion
Storage Operations Costs (2025 – 2050)	\$1.25 billion	\$2.5 billion
<b>Sub-Total</b>	<b>\$6.1 billion</b>	<b>\$7.6 billion</b>
<b>Total</b>	<b>\$12.6 billion</b>	<b>\$20.6 billion</b>

The project estimates include construction and operation of a secure Hazard Category 2, immobilization facility; construction or significant modification and operation of a secure Hazard Category 2 plutonium storage facility; security costs; and modifications to WTP to complete the can-in-canister process. The total cost is estimated at \$12.6 billion to \$20.6 billion in constant FY 2014 dollars (\$6.5 billion to \$13 billion in capital costs and \$6.1 billion to \$7.6 billion in operating costs).

The duration for MOX facility design was approximately 10 years, construction, and operations is assumed to be 15 years. For the immobilization option, the design and construction was assumed to be 20 years and the operating duration 15 years consistent with the MOX facility. The completion of the 34 MT mission was estimated to be approximately 2045-2050. This analysis assumes the Option 1 end date to be when all of the plutonium is immobilized and placed in an interim storage location. The duration of the storage facility is 25 years from start-up through completing the immobilization mission.

### ***E.1.6 PROGRAMMATIC ACTIONS AND CHANGES***

- Negotiate with Russian Government and incorporate an additional disposition method into the existing Plutonium Management and Disposition Agreement (PMDA).
- Negotiate with the State of Washington to ship, immobilize, and store plutonium there pending identification and start-up of the HLW geologic repository. (Note that DOE recently completed removal of the surplus plutonium from the Hanford Site to SRS to reduce security costs across the DOE complex.)
- Perform additional NEPA analysis.
- Work with OST to enable shipment of this material to the Hanford Site.

### ***E.1.7 RISKS***

The major risks in this strategy include:

- Introduces potentially significant, and thus unacceptable, schedule risk to the Hanford tank waste immobilization mission, particularly if it were to impede or delay the tank waste immobilization.
- Shipping the plutonium back to the Hanford Site likely would be problematic with the State or the public since DOE went through great efforts to consolidate storage of non-pit plutonium at SRS and within the past 5 years deinventoried the surplus plutonium from the Hanford Site to SRS.
- Shipping weapon-grade plutonium into the State of Washington for can-in-canister disposition without DOE having identified and started a geologic repository for HLW likely would be problematic with the State or the public.
- Russia may be unwilling to accept this as a disposition method for plutonium.
- Qualified additional staffing who meet the cleared, HRP requirements would be needed.
- Requirements for testing and qualification of the waste form could change significantly once the geologic repository is identified.
- Completion of two major capital projects at Hanford, one related to tank waste and the other on plutonium disposition, on time and within budget would be difficult. Integration of the modifications into the current design build effort on WTP would be difficult.

## E.2 IMMOBILIZATION VARIANT 1: H-CANYON

Two potential variants of the immobilization option were considered during the early stages of this analysis. The first variant uses H-Canyon at SRS to dissolve the plutonium and then transfer it to the HLW system for vitrification into glass through the DWPF.

### E.2.1 FACILITY DESCRIPTIONS

#### H-Canyon

H-Canyon at SRS was built in the 1950s and has been operating since 1955, using a solvent extraction process for recovery of plutonium and uranium from spent nuclear fuel and targets, primarily from SRS nuclear reactors. In 1992, DOE decided to phase out chemical processing for defense purposes and transitioned the mission of H-Canyon to stabilization of nuclear materials.

**Figure E4: H-Canyon and HB-Line Processing Facility**



Material processed in H-Canyon is dissolved in nitric acid before entering the solvent extraction process. The first cycle of the solvent extraction process separates the solution into uranium and plutonium or neptunium product streams. The product stream from the first cycle is sent to subsequent solvent extraction cycles for further purification. Liquid waste from these processes are reduced in volume and eventually neutralized for waste transfer from H-Canyon to H-Area liquid radioactive carbon steel waste tanks.

## **DWPF**

DWPF at SRS was built in S-Area to vitrify the several million gallons of liquid HLW stored in 49 large underground tanks. The DWPF complex consists of the Vitrification Facility and support structures, including the Glass Waste Storage Buildings (GWSBs). Liquid wastes from the H-Canyon and now deactivated F-Canyon separation facilities are stored in tank farms where the liquids are processed to reduce the volume of the waste and separate it into sludge and salt components.

The current waste that is vitrified in DWPF is composed of washed sludge and the high-activity waste streams from salt processing. Sludge washing is performed by adding water to the sludge batch, mixing with slurry pumps, securing the pumps to allow gravity settling of washed solids, and decanting the sodium rich supernate to an evaporator system for concentration. Salt pretreatment includes an actinide removal process and modular caustic-side solvent extraction system that separates the salt waste into a high-activity (high-alpha) stream for vitrification in DWPF and a low-activity stream to be processed at the Saltstone Facility.

Within the DWPF Vitrification Facility, waste is mixed with borosilicate glass frit and used as feed for the melter, where the mixture is heated to form molten glass. Canisters of vitrified waste from DWPF are transferred to Glass Waste Storage Facilities for storage.

### ***E.2.2 TECHNICAL APPROACH***

For this variant, there is not enough HLW at SRS to vitrify the full 34 MT of plutonium. DWPF has been operating since 1996 to vitrify HLW into glass logs. Because a significant amount of SRS's HLW has already been remediated (nearly half), there is not enough HLW remaining to dispose of 34 MT of surplus plutonium. In addition, DWPF is scheduled to complete operations by 2032. [SRR-LWP-2009-00001] However, DWPF and the remaining HLW could be used to immobilize up to 6 MT of plutonium as part of a potential hybrid disposition approach. Since 2002, DOE has utilized this method to dispose of approximately 340 kg of surplus plutonium; however, operations were suspended to minimize impacts to the liquid waste system and to implement the more cost effective method of disposing of the plutonium at SRS through downblending and disposal at WIPP. Since this variant does not disposition all 34 MT of surplus plutonium, it was not fully developed.

In this variant, the plutonium would be dissolved using nitric acid in either the H-Canyon or HB-Line facility, then the solutions would be transferred to the DWPF sludge feed tank in the H-Area waste tank farm pending vitrification at DWPF. The plutonium stream from H-Canyon by-passes the normal receipt tank (Tank 39) from the Canyon and is transferred just-in-time into the sludge processing tanks (Tank 51 or Tank 42) or the DWPF feed tank (Tank 40). This allows for increased plutonium loading while maintaining the proper criticality controls to ensure the neutron absorber stays with the plutonium throughout the process. Processing surplus plutonium through H-Canyon/HB-Line would increase the number of HLW canisters to be generated and stored. The number of additional HLW canisters would depend on the quantity of surplus plutonium processed through H-



Canyon/HB-Line and DWPF and on the plutonium concentration within the feed material. Processing up to 6 MT of surplus plutonium would generate up to 20 to 48 additional canisters depending on the plutonium loading.

### ***E.2.3 FACILITY CONSTRUCTION/MODIFICATION***

The major constraint in this variant is limitations in dissolution operations in H-Canyon, criticality controls during transfer of the plutonium solution, and the limited window to transfer the plutonium solution to DWPF. The plutonium solution must be held in the canyon until transferred “just-in-time” to the sludge processing or DWPF feed tank. This transfer would occur approximately once a year depending on the sludge batch schedule. Minor modifications, such as additional tank storage in H-Canyon and installation of a dedicated transfer line may be made to the H-Area tank farm to support transferring up to 6 MT of plutonium to DWPF. [SRNL-L6000-2013-00002]

## **E.3 IMMOBILIZATION VARIANT 2: DIRECT INJECTION**

The second variant analyzed is direct injection of plutonium into the DWPF or WTP melter process for HLW.

### ***E.3.1 FACILITY DESCRIPTION***

The primary facilities required for this variant are DWPF or WTP. Refer to Sections E.1.1 and E.2.1 for facility descriptions.

### ***E.3.2 TECHNICAL APPROACH***

Direct injection of plutonium into the DWPF or WTP melter process for HLW was identified as a possible immobilization technique by Catholic University [Catholic University 2013] in addition to the first variant described in Section E.2. Although technically feasible, the direct injection variant requires significant RD&D to determine the necessary modifications to the process for the loading limits of each glass canister and to prevent a criticality during the injection process, recognizing that each melter batch contains varying amounts and types of radionuclides. The Catholic University study focused on the technical aspects of the glass and the solubility of plutonium in postulating the plutonium loading limits; however, it did not consider the operational and process design constraints, e.g., melter constraints and criticality safety constraints.

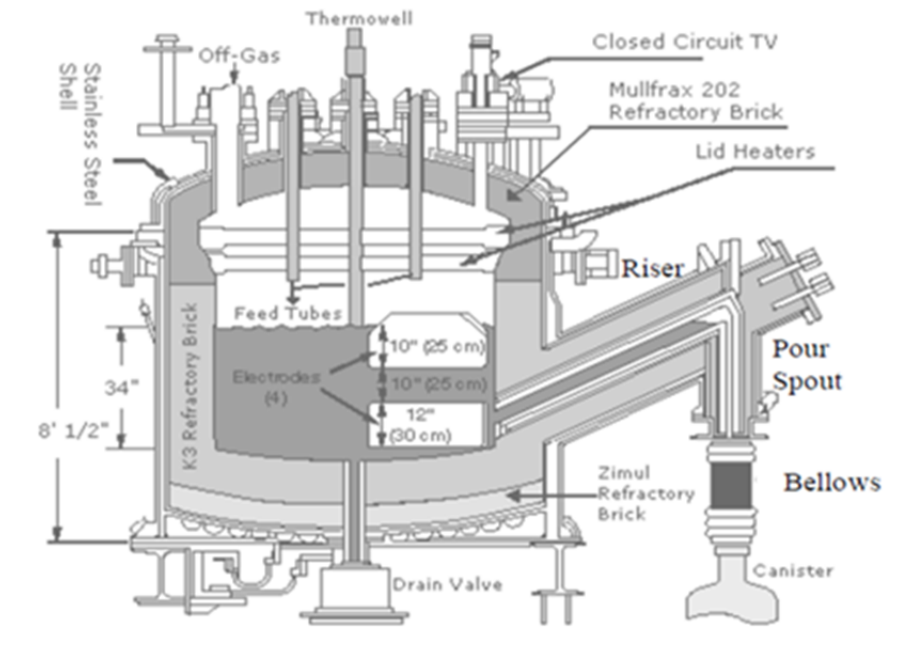
The study suggested directly injecting the plutonium into the glass disposal canister. The pouring process continues to be one of the most challenging aspects for DWPF processing. The bellows/canister region in DWPF has become more complex with the addition of the knife edge inserts and heaters. The melter pouring system relies on pressure differentials between the melter plenum and pour spout. The bellows, attached between the pour spout and canister, ensures the differential pressure is maintained for the glass to pour into the canister, depicted in Figure E5. Keeping the system sealed and controlling the pressure are key to consistent pouring and have not always been easy to maintain. This has become

more difficult to control by adding bubblers in the melter to increase mixing and melting rate. The pressure surges can cause difficulties in controlling the melter pressure control for pouring. Early issues during melter pouring operations included erosion of the "knife edge" where the HLW glass detaches from the pour spout and falls into the canister. After some time, the glass stream did not detach evenly leading to glass stream wavering, wicking and accumulating in the pour spout and bellows. This problem was corrected by using "knife edge inserts" that are periodically replaced to maintain the knife edge. The bellows also was redesigned to allow heating to help mitigate solidified glass build-up (see Figure E6).

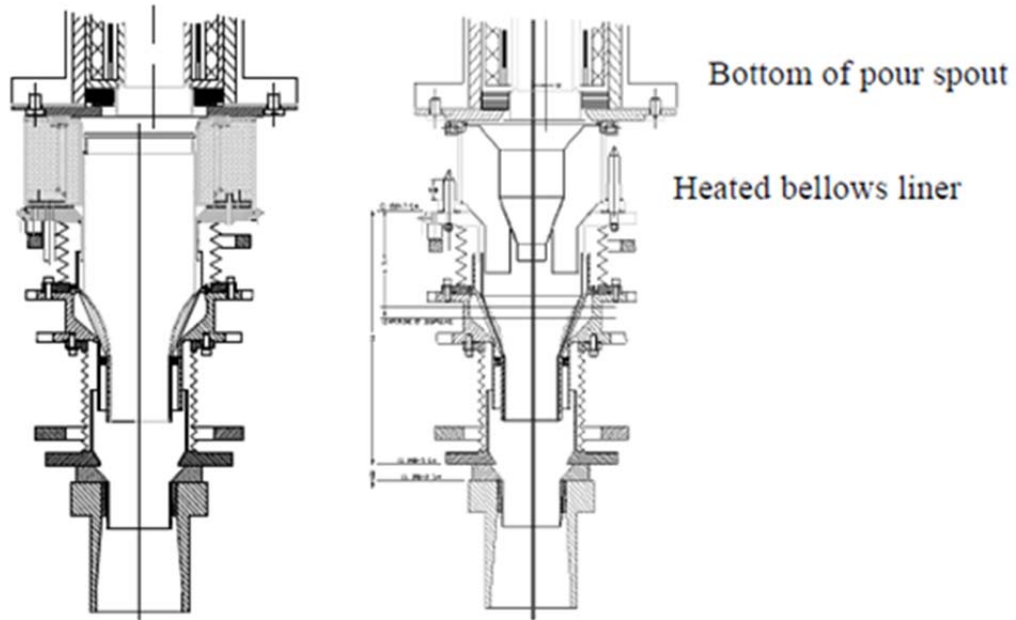
Significant research and development would need to occur to develop a method to inject the plutonium directly into the disposal canister while maintaining the pressure differential and ensuring that the plutonium being added into the canister does not incur a suck back incident back into the melter. Additionally a homogenous mix of the plutonium and neutron absorber would be required for criticality control and would require significant research and development.

The plutonium could potentially be injected into the melter and not the canister but this also would require research and development and design changes to the melter. Since this direct injection variant had so many unanswered technical questions that require significant development, it was not fully developed.

**Figure E5: Cross-Sectional View of the DWPF Melter**



**Figure E6: DWPF Melter Bellows without (left) and with (right) Heated Bellows Liner**



**References:**

Catholic University 2013, "Disposition of Excess Weapons Plutonium" Werner Lutze and Ian L. Pegg, Vitreous State Laboratory at The Catholic University of America, Washington DC, February 12, 3013.

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ROD 65 FR 1608, *Record of Decision for the Surplus Plutonium Disposition Final Environmental Impact Statement*, January 11, 2000.

ROD, 67 FR 19432, *Amended Record of Decision Surplus Plutonium Disposition Program*, April 19, 2002.

ROD, 72 FR 14543, *Amended Notice of Intent to Prepare a Supplemental Environmental Impact Statement of Surplus Plutonium Disposition at the Savannah River Site*, March 28, 2007.

Sell 2005, *Approval of Mission Need (CD-0) for a Plutonium Disposition Project* DOE Memorandum for James A. Rispoli, Assistant Secretary for Environmental Management from Call Sell Deputy Secretary, September 6, 2005.

SRNL-L6000-2013-00002, Final Report, *H-Canyon/HB-Line Data Call to Support the Surplus Plutonium Disposition Supplemental Environmental Impact Statement*, Revision 4, Aiken, South Carolina, March 2013.

SRR-LWP-2009-00001, *Liquid Waste System Plan*, Rev. 18, Savannah River Remediation, LLC, Savannah River Site, Aiken, South Carolina, February 2013.

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## **ATTACHMENT F: DOWNBLENDING AND DISPOSAL**

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### **F.1 DOWNBLENDING AND DISPOSAL - BASE APPROACH**

A reference case analysis for the downblending option is based on utilizing information on technical feasibility, cost and schedule impacts, and regulatory considerations gained from the operating experience at the Waste Isolation Pilot Project (WIPP) in Carlsbad, New Mexico. While technically feasible, pursuing an option such as WIPP or an alternate location today for 34 MT of surplus plutonium would require significant engagement with federal, state, and local representatives. Disposal of these additional materials in WIPP would require amendment of the WIPP Land Withdrawal Act as well as federal and state regulatory actions. For an alternate site, a new TRU-waste repository would need to be established. The additional costs for such an option are not included in the downblending reference case analysis since they would be site specific and depend on the inventories of materials to be disposed.

#### ***F.1.1 FACILITY DESCRIPTION***

##### ***Waste Isolation Pilot Plant***

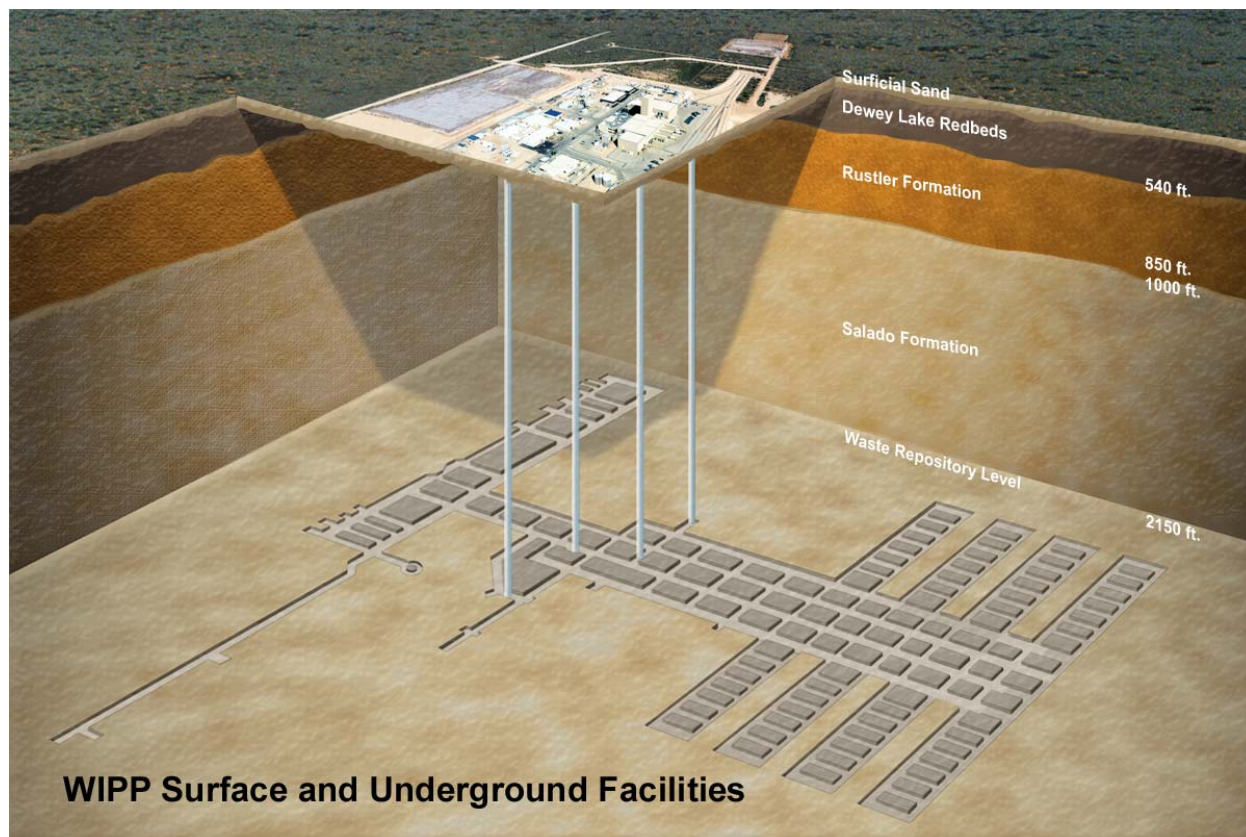
Since WIPP, located near Carlsbad, New Mexico, is currently the only U.S. facility authorized to dispose of TRU waste generated by defense activities, this option utilizes WIPP as a reference case for disposal at a geologic repository. The WIPP repository is located in ancient salt beds, 2,150 feet below the ground surface. The WIPP Land Withdrawal Act [Public Law No. 102-579] authorized the disposal of up to 175,600 cubic meters (6.2 million cubic feet) of TRU waste generated by the nation's atomic energy defense activities. TRU waste is waste that contains alpha particle emitting radionuclides with atomic numbers greater than uranium (92) and half-lives greater than 20 years in concentrations greater than 100 nanocuries per gram of waste.

Current plans reflect that TRU waste will be received and emplaced at WIPP through FY2030. Radioactive waste is received and prepared for underground disposal at the Waste Handling Building. WIPP includes four shafts to the underground, the Exhaust Filter Building, water storage tanks and pump house, trailers and auxiliary buildings for personnel offices, two warehouses, and a Support Building containing laboratory and office facilities, showers, and change rooms for underground workers. WIPP functions as an active mine for the purpose of the permanent disposal of TRU radioactive waste. The underground repository is located 2,150 feet below the surface in a 2,000-foot thick salt formation.

The underground disposal area at WIPP includes the four main entries and cross-cuts that provide access and ventilation and ten disposal areas, referred to as panels, as shown in Figure F1. A typical disposal panel consists of seven disposal rooms. Each room is 33 feet wide, 13 feet high, and 300 feet long. The disposal rooms are separated by pillars of salt 100 feet wide and 300 feet long. Panel entries at the end of each of these disposal rooms

are also 33 feet wide and 13 feet high and will be used for waste disposal, except for the first 200 feet from the main entries. The first 200 feet is used for installation of the panel closure, not disposal. The panel entries are 20 feet wide by 13 feet high for the intake and 16 feet wide by 12 feet high for the exhaust. [DOE 2012]

**Figure F1: Diagram of Waste Isolation Plant**



### ***K-Area at Savannah River Site***

In the April 19, 2002, Amended Record of Decision (ROD), DOE announced its decision to immediately consolidate surplus, non-pit plutonium from the Rocky Flats Environmental Technology Site (RFETS) at SRS in K-Area. [ROD 67 FR 19432] Portions of the K-Reactor building were modified for nuclear material storage to support this consolidation. The former reactor confinement area and adjacent areas were modified to form a large warehouse called the K-Area Material Storage Area (MSA). The plutonium is stored in the K-Area MSA in DOE-STD-3013 compliant containers nested within Type B shipping containers, primarily 9975 shipping containers. This is a robust packaging configuration that serves as confinement against possible release of contamination during transportation and storage. Also included in the modification were shipping and receiving capabilities for DOE's Secure Transportation Asset (STA).

Operating since 2007, K-Interim Surveillance (KIS) provides the capability for destructive and non-destructive examination of stored plutonium materials. Non-destructive

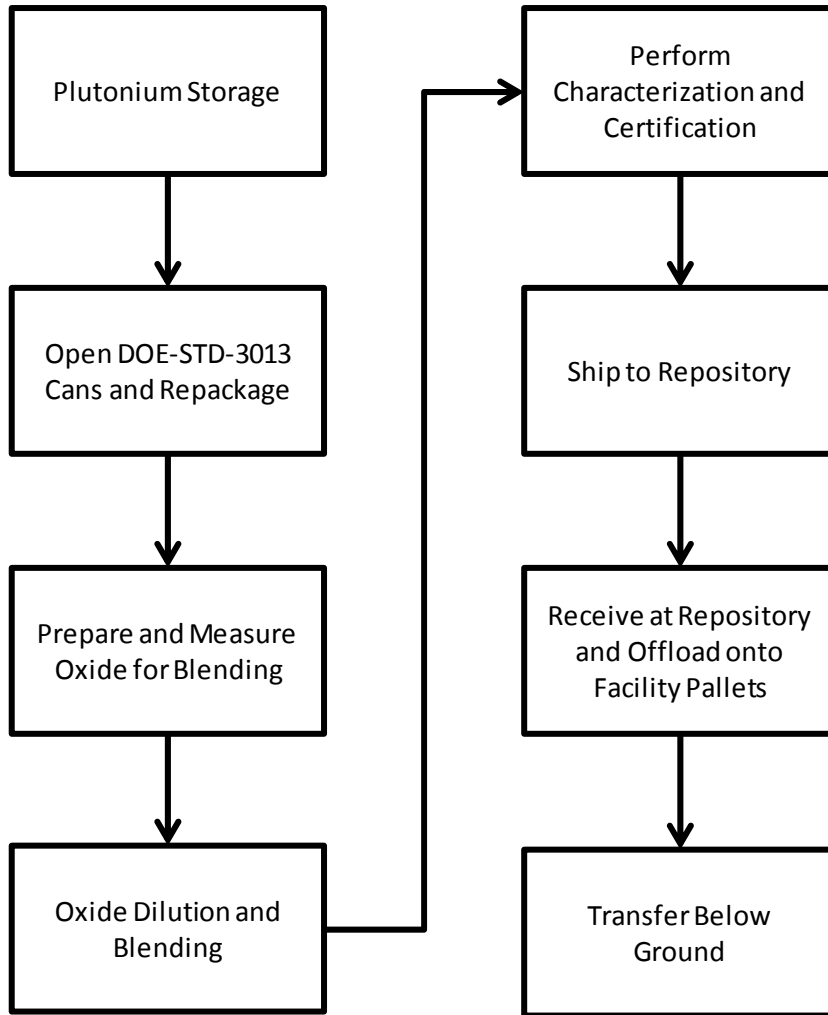
examination capabilities include weight verification, visual inspections, digital radiography, materials control and accountability measurement, and gamma ray analysis, while destructive capabilities include can puncturing for headspace gas sampling and can cutting for oxide sampling. Interim repackaging capabilities are available for safe storage of the material pending eventual disposition. To accommodate KIS, portions of the K-Reactor building were modified to include installation of a glovebox and associated equipment; upgrades of ventilation, filtration, and fire protection systems; and the addition of backup power capability.

### ***F.1.2 TECHNICAL APPROACH***

SRS has the capability to downblend and package surplus plutonium for disposal at WIPP. The material is downblended with inhibitor materials to less than 10 weight percent plutonium and packaged to meet the WIPP acceptance criteria. K-Area at SRS and PF-4 at LANL could be used to prepare surplus plutonium for disposal at a repository. The base option assumes that all of the plutonium oxide would be downblended at SRS, however, a variant that uses both SRS and LANL are also analyzed in section F.2.

Figure F2 illustrates the process that would be used for downblending and packaging the 34 MT of plutonium to a repository. The material would be transferred from the vault into a glovebox where the DOE-STD-3013 containers would be cut open. The plutonium oxide would be repackaged into suitable cans, mixed/blended with inhibitors and loaded into criticality control overpack (CCO) containers. The CCOs have a 380 FGE loading limit. Inhibitors would be added to reduce the plutonium content to less than 10 percent by weight and inhibit plutonium material recovery. Loaded CCOs would then be characterized to demonstrate acceptance at the Repository. These characterization activities include non-destructive assay, digital radiography, and headspace gas sampling for each CCO to be shipped. Once CCOs have successfully passed the characterization process and meet the acceptance criteria they would be shipped in the TRUPACT-II containers (see Figure F3).

**Figure F2: Downblending and Packaging Plutonium Flowchart**





**Figure F3: TRUPACT-II Containers**

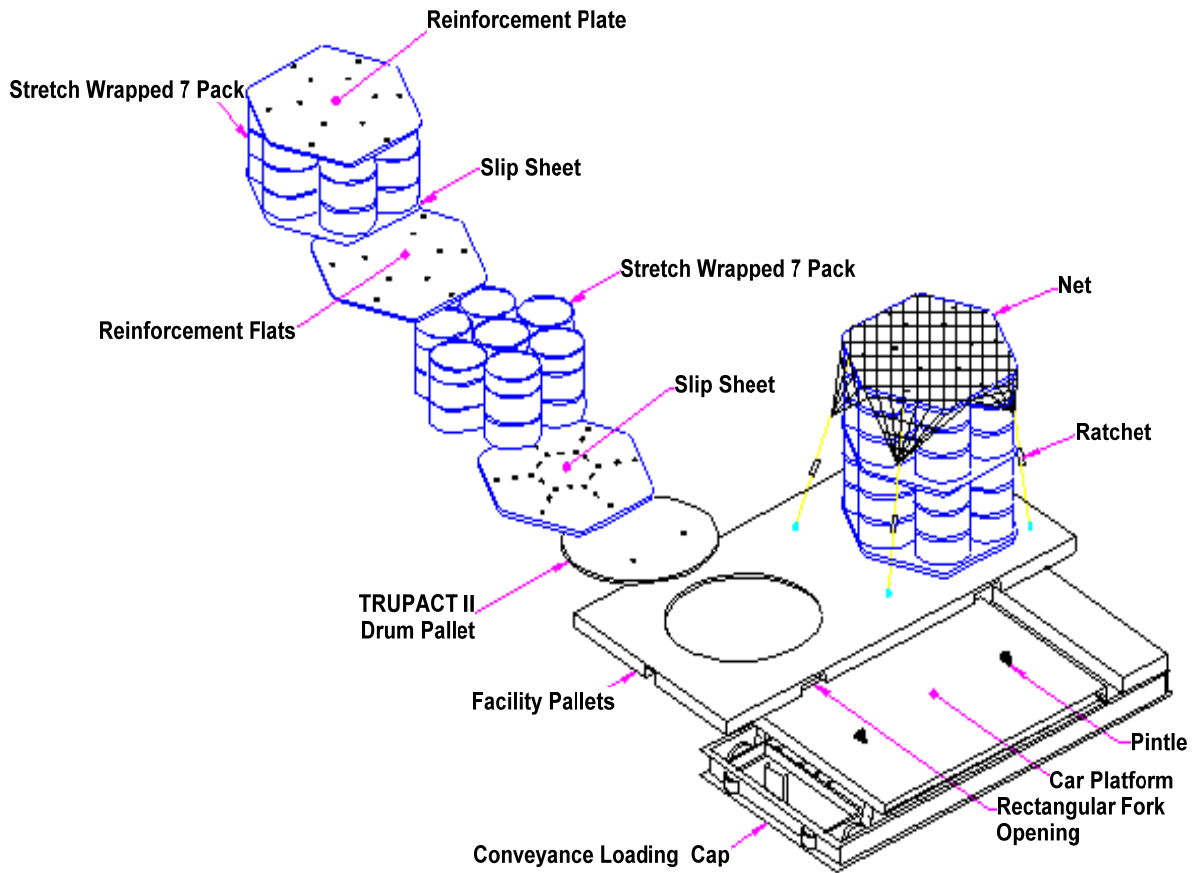


Minor upgrades would be needed to enhance downblending of surplus plutonium at SRS. These upgrades would include two additional gloveboxes (totaling 3 WIPP downblend gloveboxes at SRS), and additional non-destructive assay equipment for increased throughput.

It should be noted that within K-Area, approximately 3 MT of plutonium is currently under IAEA inspection and verification. Prior to disposal at a repository, DOE would need to negotiate the terms for termination of this verification.

The reference case, WIPP, includes surface and underground facilities that support waste handling and emplacement. The principal surface structure at WIPP is the Waste Handling Building where TRU waste is unloaded from the TRUPACT-II containers. The TRU waste containers are then placed onto the 7 pack pallet configuration then transferred to the underground disposal area (otherwise referred to as a “panel”) through a waste shaft for disposal. (See Figure F4)

**Figure F4: WIPP Seven Pack Pallet Configuration**



Over time, high pressure on the salt formation would cause the salt to creep, filling in the voids in the disposal rooms or panels and entombing the packages permanently. This disposal method has already been, and continues to be used to dispose of surplus plutonium from several DOE sites. Approximately 4.8 MT of plutonium has been shipped to WIPP mostly from five different sites: Rocky Flats, Hanford, Idaho, LANL, and SRS.

The volume of space necessary to emplace 34 MT of blended plutonium assuming the CCO packages and the representative seven pack pallet configuration would be approximately 1 full panel at a repository with similar sized panel's as at WIPP. Although WIPP could accept up to 13 MT of plutonium within the current unsubscribed capacity of the WIPP regulatory and statutory limits, disposal of 34 MT would require amendment of the WIPP Land Withdrawal Act as well as federal and state regulatory actions and would likely require a change to the WIPP Land Withdrawal Act to increase the total capacity at WIPP. For an alternate site, a new TRU-waste repository would need to be established.

### **F.1.3 FACILITY MODIFICATIONS AND OPERATIONAL CHANGES**

#### ***Reference Case, Waste Isolation Pilot Plant***

- No modifications.
- Additional handling equipment and consumables may be required for increased number of TRU waste drums.
- Additional analysis would be required to disposition this amount of plutonium.

#### ***Savannah River Site***

- Install 2 additional seismically qualified downblend gloveboxes with fire suppression capability and DOE-STD-3013 can opener and scales, non-destructive assay equipment.
- Documented Safety Analysis change for increased oxide downblending and packaging.
- Additional monitoring equipment and consumables may be required.

### **F.1.4 KEY ASSUMPTIONS**

- NEPA analysis and Record of Decision completed in a timely manner.
- Staffing is available, in particular qualified, cleared nuclear workers in the Human Reliability Program (HRP) at SRS.
- For the reference case, successful amendment of the WIPP Land Withdrawal Act to increase WIPP capacity and negotiations with the State of New Mexico and the Environmental Protection Agency (EPA) to modify permits to allow increased disposal.

### **F.1.5 COST AND SCHEDULE**

#### **Staffing Needs**

#### ***Reference Case, Waste Isolation Pilot Plant***

- 60 additional operations staff for 24/7 operations for above and below ground operations.

#### ***Savannah River Site***

- 60 additional operations staff (cleared, HRP) for 24/7 downblending operations, packaging, and final material control and accountability measurements.
- 30 additional operations staff for characterization for 24/7 TRU waste handling and packaging into TRUPACT-II.
- 40 additional staff located at SRS for characterization for 24/7 operations.

**Table F1: Reference Case Incremental Costs**

<b>Constant FY 2014 dollars</b>	<b>Low Range</b>	<b>High Range</b>
SRS Capital Cost	\$32 million	\$52 million
WIPP Capital Cost	\$180 million	210 million
<b>Sub-Total</b>	<b>\$212 million</b>	<b>\$262 million</b>
SRS Operational Cost	\$1.6 billion	\$2.1 billion
WIPP Operational Cost	\$550 million	\$600 million
<b>Sub-Total</b>	<b>\$2.1 billion</b>	<b>\$2.7 billion</b>
<b>Total</b>	<b>\$2.3 billion</b>	<b>\$3 billion</b>

To complete the entire 34 MT mission at SRS would take 32-43 years with an end date between 2046 and 2057. Each blend line glovebox capacity is 400 kg/year (approximately 1,300 cans per year or 32 cans per week) multiplied by three gloveboxes. Under the reference case, the increased staff is required to operate the additional blend gloveboxes and characterize, package, and ship to WIPP in addition to the increased handling capacity at WIPP.

**F.1.6 PROGRAMMATIC ACTIONS AND CHANGES**

- Modify U.S. / Russian Agreement. [PMDA 2000].
- Under the reference case, work with Congress to change the WIPP Land Withdrawal Act to increase the total capacity at WIPP.
- Perform additional NEPA analysis.

**F.1.7 RISKS**

The major risks in this strategy are listed below:

- Under the reference case, ability to amend the WIPP Land Withdrawal Act in a timely manner to support this option.
- Russia may be unwilling to accept this as a method to dispose of the plutonium.
- Qualified additional staffing unavailable.

**F.2 VARIANT 1: DOWNBLENDING AND DISPOSAL USING SRS AND LANL**

There are two variants of the downblending option, both of which are technically feasible. The first variant is comparable to the base option described in the previous section, but involves downblending plutonium at both SRS and LANL. This variant involves slightly more execution risk than the base option due to the added complexity of managing the critical ongoing missions at PF-4 while performing downblending operations. The advantages of this option are significantly fewer cross-country shipments than the base option, and completing the mission sooner.

### **F.2.1 FACILITY DESCRIPTION**

Refer to Section F.1.1 for WIPP and SRS facility descriptions.

#### ***Los Alamos National Laboratory***

LANL is located in northern New Mexico within Los Alamos County occupying approximately 40 square miles of land along the Pajarito Plateau. Virtually all plutonium operations at LANL occur in Technical Area 55 (TA-55). Located within TA-55, the Plutonium Facility (PF)-4, provides research in and application of chemical and metallurgical processes for recovering, purifying and converting plutonium and other actinides into many compounds and forms in support of multiple programs including defense, nuclear nonproliferation and nuclear energy missions. Anion exchange, solvent extraction, and pyro-chemical processing are the three production scale techniques that are used extensively. (See Figure F5)

**Figure F5: Los Alamos National Laboratory**



In 1998, the Advanced Recovery and Integrated Extraction System (ARIES) began operations to develop the technology to dismantle surplus pits, convert the metal into an oxide form and package for storage pending delivery to the MOX Facility. The technology was planned to be incorporated into the design of the Pit Disassembly and Conversion Facility (PDCF). With the successful demonstration of the ARIES process and delays in the design and construction of the PDCF project, LANL was directed to produce 2 MT of plutonium oxide using the ARIES process as early feedstock for the MOX facility. DOE subsequently decided to pursue cancellation of the PDCF project and began evaluating alternatives for the disassembly and conversion capability through the use of existing

facilities including expanding the ARIES capability at LANL. In 2012, DOE amended the Notice of Intent to the Surplus Plutonium Disposition Supplemental Environmental Impact Statement announcing DOE's intent to evaluate these alternatives. [NOI 77 FR 1920] In 2012, DOE issued the draft SEIS identifying the use of LANL and H-Canyon to perform the oxide production mission. This analysis assumes that LANL will be disassembling all of the pit plutonium, pending completion of the NEPA.

All plutonium operations at TA-55 create low level waste (LLW) and TRU waste. TRU waste is currently characterized at Area G before it is transported to the Radioassay and Nondestructive Testing Facility, also located in TA-54, and loaded into TRUPACT-II packages for shipment to WIPP. [DOE 2013]

### ***F.2.2 TECHNICAL APPROACH***

Similar to the base option, LANL would blend the material in PF-4 using the same process as at SRS. Three downblending gloveboxes would need to be installed in PF 4, or existing gloveboxes would need to be modified to complete this mission. SRS would continue to blend the plutonium as described in the base option above. This option also installs a new TRU waste handling and storage facility at LANL, and also upgrades the PF-4 infrastructure to support increased material downblend, movement, and handling capabilities. These upgrades are straight-forward, however until the safety basis evaluations are complete and the PF-4 seismic upgrades are complete, the facility most likely will be limited in the amount of plutonium allowed in PF-4.

PF-4 has constraints that must be addressed to perform downblending operations. These constraints include limited plutonium vault storage capacity, limited material handling and movement capacity, reduced plutonium inventory limits in PF-4 until seismic upgrades are completed. Additionally, this added mission could impact Defense Program missions due to the inventory constraints and storage constraints.

The primary missions at LANL are defense-related missions, and therefore the site has limited capacity for TRU waste operations. The characterization, storage, and waste handling infrastructure would be upgraded to support this significant increase in TRU waste shipments. A Resource Conservation and Recovery Act permitted pad and trailer would be used for characterization, testing, and certifying the containers to meet the Repository Waste Acceptance Criteria. Certified containers would be transported to Radioassay and a Nondestructive Testing Facility where TRUPACT-II would be loaded for off-site shipment to the Repository.

### ***F.2.3 REQUIRED MODIFICATIONS AND OPERATIONAL CHANGES***

#### ***Reference Case, Waste Isolation Pilot Plant***

- No modifications.
- Additional handling equipment and consumables may be required for increased number of TRU waste drums.

### ***Savannah River Site***

- Install 2 additional seismically qualified downblend gloveboxes with fire suppression capability and DOE-STD-3013 can opener and scales, non-destructive assay equipment.
- Documented Safety Analysis change for increased oxide downblending and packaging.
- Additional monitoring equipment and consumables may be required.

### ***Los Alamos National Laboratory***

- Construct new TRU characterization and storage facility.
- Use existing glovebox or install additional seismically qualified downblend gloveboxes with fire suppression capability and DOE-STD-3013 can opener and scales, non-destructive assay equipment.
- PF-4 enhancements to elevator for material movements.
- Additional monitoring equipment and consumables.
- Documented Safety Analysis change for increased oxide downblending and packaging.

#### ***F.2.4 KEY ASSUMPTIONS***

- NEPA analysis and Record of Decision completed in a timely manner.
- Staffing available, in particular qualified, cleared, nuclear workers in the HRP at LANL and SRS.
- For the reference case, amendment of the WIPP Land Withdrawal Act to increase WIPP capacity and successful negotiations with the State of New Mexico and the EPA to modify permits for disposal.
- Resolution of PF-4 seismic upgrades.
- Vault storage at PF-4 can be managed to support this mission.

#### ***F.2.5 COST AND SCHEDULE***

##### ***Reference case, Waste Isolation Pilot Plant***

- 70 additional operations staff for 24/7 operations for above and below ground operations.

##### ***Savannah River Site***

- 60 additional operations staff (cleared, HRP) for 24/7 downblending operations, packaging, and final material control and accountability measurements.
- 30 additional operations staff for characterization for 24/7 TRU waste handling and packaging into TRUPACT-II.
- 40 additional staff located at SRS for characterization for 24/7 operations.

### **Los Alamos National Laboratory**

- 60 additional operations staff (cleared, HRP) for 24/7 operations.
- 30 additional operations staff in TRU waste characterization and handling facility 24/7 operations.
- 40 additional located at LANL for characterization for 24/7 operations.

**Table F2: Variant 1 Downblending and Disposal using LANL and SRS Costs**

	<b>Low Range</b>	<b>High Range</b>
SRS Capital Cost	\$32 million	\$52 million
LANL Capital Cost	\$100 million	\$150 million
WIPP Capital Cost	\$100 million	\$130 million
<b>Sub-Total</b>	<b>\$232 million</b>	<b>\$332 million</b>
SRS Operational Cost	\$900 million	\$1.2 billion
LANL Operational Cost	\$915 million	\$1.2 billion
WIPP Operational Cost	\$360 million	\$480 million
<b>Sub-Total</b>	<b>\$2.2 billion</b>	<b>\$2.9 billion</b>
<b>Total</b>	<b>\$2.4 billion</b>	<b>\$3.3 billion</b>

To complete the entire 34 MT mission at both SRS and LANL would complete their mission between 2035 and 2041. Each glovebox capacity at SRS is 400 kg/year (approximately 1,300 cans per year or 32 cans per week) multiplied by three glovebox operations. The throughput at LANL was assumed to be the same as SRS (1.2 MT per year). For the reference case, the increased staff is required to operate the additional blend operations and characterize, package, and ship to WIPP in addition to the increased handling capacity at WIPP.

#### **F.2.6 PROGRAMMATIC ACTIONS AND CHANGES**

- Negotiate with Russian Government and incorporate an additional disposition method into the existing PMDA.
- Under the reference case, work with Congress to change the WIPP Land Withdrawal Act to increase the total capacity at WIPP.
- Perform additional NEPA analysis.
- Work with DP to de-conflict space requirements in PF-4.

#### **F.2.7 RISKS**

The major risks in this strategy are listed below:

- Under the reference case, ability to amend the WIPP Land Withdrawal Act in a timely manner to support this option.
- Russia may be unwilling to accept this as a method to dispose of the plutonium.
- Qualified additional staffing unavailable.



- Additional controls may be required by the PF-4 facility safety basis that could limit operations and potentially impact other missions in the facility until seismic upgrades are completed.
- Material handling constraints and limited plutonium vault storage capacity at PF-4 could limit throughput.
- LLW and TRU waste handling and disposal are secondary missions at LANL therefore a production scale TRU waste program could significantly impact the existing waste handling operations and infrastructure at LANL.
- Space available within PF 4 and mission can be de-conflicted with future DP work.

### **F.3 VARIANT 2: DOWNBLENDING AND DISPOSAL WITH INCREASED LOADING**

The second variant is to increase the loading within each can to approximately 1 kg per can at SRS. This is technically feasible, would reduce the number of shipments to the Repository, and would reduce the volume of TRU waste. However, it involves more technology risk than the base option. The advantage of this variant is significantly less material handling at both the shipping and receiving sites, fewer shipments, and reduction in the space required at the Repository.

#### ***F.3.1 FACILITY DESCRIPTION***

Refer to Section F.1.1 for the SRS and WIPP facility descriptions.

#### ***F.3.2 TECHNICAL APPROACH***

DOE would evaluate the potential to increase plutonium loading per package beyond the planned 380 FGE, to minimize space necessary at the Repository. This variant is presented as an opportunity to reduce the total volume of waste emplaced and reduce material handling operations at the shipping and receiving sites.

The process steps would be the same as described in the downblending base option. The differences would be in the shipping method and packaging used to ship to the Repository. The blended plutonium would be packaged in a standard can at higher loading assumed to be 1 kg FGE as opposed to 380 FGE in the base option, then packaged into 9975 shipping containers for shipment in lieu of the CCO/Criticality Control Container (CCC) configuration. These containers would require characterization and certification for shipment to the Repository. The most significant difference, however, is that the quantity of material per shipment would require safeguards and security during shipment and receipt at the Repository. This would complicate shipping and receiving due to limiting the facility to cleared personnel and conflicting with TRU waste receipts. The OST would be used to transport the plutonium oxide. The advantages at the shipping sites are fewer material handling operations and material movements (on the order of 1/2 - 2/3 reduction), and less storage and staging space requirements.

A significant issue of this variant is that due to the operational security requirements of these shipments, DOE would need to change in its policy of transparency on TRU shipments.

Security upgrades also would be necessary. For the reference case, this opportunity for increased loading would require \$50-\$100 million in capital investments at WIPP to support security and operational upgrades, and additional security staff depending on the amount of plutonium per shipment. The advantage of the increased loading would be a substantial reduction in the amount of space required by possibly 1/2 - 2/3 less than the 380 FGE loading in the base option.

### ***F.3.3 REQUIRED MODIFICATIONS AND OPERATIONAL CHANGES***

In addition to the modification and operational changes identified in the downblending base option, the following additional modifications would be required to increase the plutonium loading.

#### ***Reference Case, Waste Isolation Pilot Plant***

- Installation of security modifications to receive quantities of SNM.

### ***F 3.4 KEY ASSUMPTIONS***

In addition to the assumptions identified in the downblending base option, the following assumptions would be required to increase plutonium loading:

- For the reference case, successful negotiations with WIPP Stakeholders with changes in transportation protocol.
- Office of Health, Safety, and Security (HSS) approval to terminate safeguards and security at the Repository.
- Security Vulnerability Assessment completed and no significant unexpected upgrades at the Repository identified.
- DOE approves the use of the existing digital radiography equipment at the shipping sites to certify packages meet acceptance requirements.
- Permit modification approved by state to allow increased loading.

**F.3.5 COST AND SCHEDULE**

In addition to the increased operations staffing identified in the downblending base option, additional security personnel will be required to support receipt.

**Table F3: Variant 2 Downblending and Disposal with Increased Loading Costs**

	<b>Low Range</b>	<b>High Range</b>
SRS Capital Cost	\$32 million	\$52 million
WIPP Capital Cost	\$145 million	\$205 million
<b>Sub-Total</b>	<b>\$177 million</b>	<b>\$257 million</b>
SRS Operational Cost	\$900 million	\$1 billion
WIPP Operational Cost	\$420million	\$476 million
<b>Sub-Total</b>	<b>\$1.3 billion</b>	<b>\$1.5 billion</b>
<b>Total</b>	<b>\$1.5 billion</b>	<b>\$1.8 billion</b>

To complete the entire 34 MT mission with an increased loading per can of 1 kg, SRS could complete in approximately 13-15 years finishing between FY2028 and FY2030; however this variant is constrained by availability of the feedstock from pit disassembly and conversion activities, which are estimated to be completed between 2032 and 2034. For the reference case, increased staff is required to operate the additional blend gloveboxes and characterize, package, and ship to WIPP in addition to the increased handling capacity at WIPP.

**F.3.6 PROGRAMMATIC ACTIONS AND CHANGES**

In addition to the actions and changes identified in the downblending base option, the following actions would be necessary to increase loading:

- For the reference case, permit modifications required for increased loading.
  - New waste forms may need to be established and approved by EPA.
- New disposal container, 9975 shipping container, must added to the compliance envelope, “certified/approved” by NRC/EPA, and added to the Repository permit.
- Conduct performance assessments that reflect the new containers and waste form if required.
- Work with OST to enable shipment of this material to the Repository.
- Engage with State agencies, emergency response agencies, and other stakeholders concerning changes in the notification of shipments via OST – currently all TRU shipments are transparent to State and Local agencies and the public; however utilization of OST assets would not allow for this open transportation protocol.

### ***F.3.7 RISKS***

In addition to the risks identified in the downblending base option, the following additional risks would be necessary to increase loading:

- For the reference case, State of New Mexico and/or EPA do not approve permit modification to allow increased loading as an acceptable waste form.
- Western Governors Association and Stakeholders unsupportive of changes in transportation protocol.
- Approval to terminate safeguards on downblended plutonium oxide at the Repository site cannot be agreed to by HSS.
- Permit, Documented Safety Analysis, or security modifications at the Repository not approved.
- Qualified additional staffing not in place who meet the cleared, HRP requirements.

**References:**

DOE 2012, *Draft Surplus Plutonium Disposition Supplemental Environmental Impact Statement*, DOE/EIS 0283-S2, U.S. Department of Energy Office of Fissile Materials Disposition and Office of Environmental Management, Washington, DC, July 2012.

DOE 2013, Revised Final Report, Data Call to Support the Surplus Plutonium Disposition Supplemental Environmental Impact Statement, LA-UR-12-26497, Surplus Plutonium Disposition Supplemental Environmental Impact Statement Data Call Response, Los Alamos, New Mexico, January 2013.

NOI 77 FR 1920, *Amended Notice of Intent to Modify the Scope of the Surplus Plutonium Disposition Supplemental Environmental Impact Statement and Conduct Additional Public Scoping*, January 12, 2012.

Public Law No. 102-579, *The Waste Isolation Pilot Plant Land Withdrawal Act, as amended by Public Law 104-201 (H.R. 3230, 104<sup>th</sup> Congress)*, October 30, 1992.

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## **ATTACHMENT G: DEEP BOREHOLE DISPOSAL**

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### **G.1 DEEP BOREHOLE DISPOSAL – BASE APPROACH**

#### ***G.1.1 FACILITY DESCRIPTION AND TECHNICAL APPROACH***

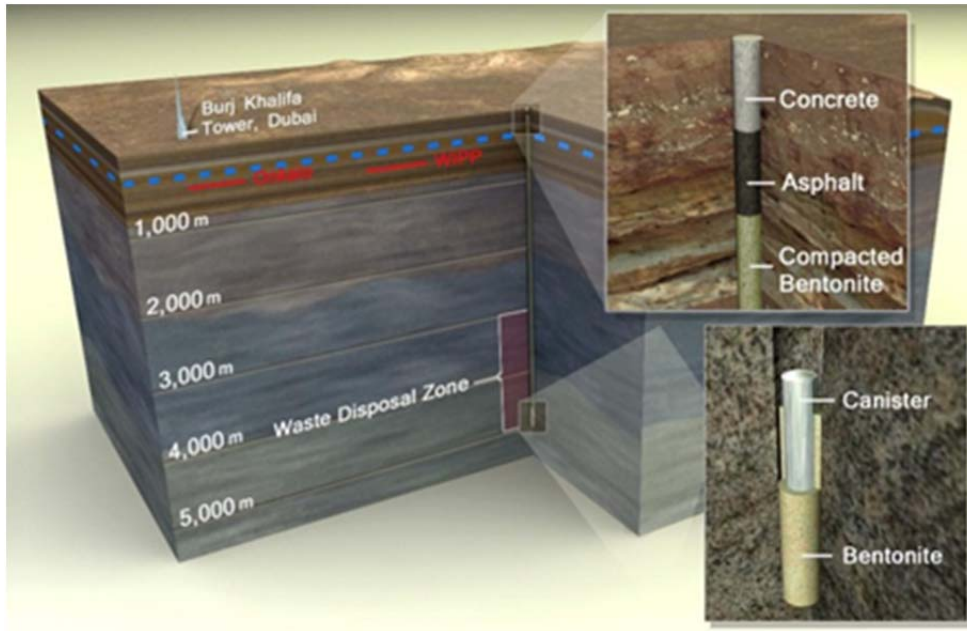
The following information is from the Sandia Research, Development, and Demonstration (RD&D) Plan for deep borehole disposal. [SAND2012-8527P]

Numerous factors suggest that deep borehole disposal of spent nuclear fuel (SNF) and high-level waste (HLW) is inherently safe. Deep borehole disposal of SNF, HLW and excess/surplus fissile materials has been reviewed periodically over the last several decades. Based on the recommendations by the Blue Ribbon Commission, Sandia prepared a roadmap for DOE outlining the activities necessary to advance deep borehole disposal from its current conceptual status. [BRC 2012] Successful completion of these activities could enable future deployment as a disposal system for SNF and HLW.

The RD&D Roadmap describes the activities to help resolve key uncertainties about deep borehole disposal that include a full-scale demonstration for proof of concept without the use of actual radioactive waste or materials. The demonstration would have four primary goals: 1) demonstrate the feasibility of characterizing and engineering deep boreholes, 2) demonstrate processes and operations for safe waste emplacement down hole, 3) confirm geologic controls over waste stability, and 4) demonstrate safety and practicality of deep borehole disposal as a disposal concept. The proposed demonstration would be a key early element of a program and would be focused on demonstrating the viability of the deep borehole disposal concept.

The deep borehole disposal concept consists of drilling boreholes into crystalline basement rock to approximately 5,000 meters deep. The canisters would be emplaced into the lower 2,000 meters of the borehole. The deep borehole disposal would be several times deeper than for typical mined repositories. The upper borehole would be sealed with compacted clay or cement. A liner casing would be in place for the emplacement of waste canisters. To emplace the waste canisters, a device would rotate the shipping cask at the surface to a vertical position then lower it into the borehole remotely. Multiple or “strings” of canisters would be lowered to the disposal zone and each canister string would be separated from the overlying canister string using a series of plugs. After the waste canisters have been emplaced and the overlying plugs have been set, the guide casing would be removed and the borehole sealed. The borehole seal system would consist of alternating layers of compacted bentonite clay and concrete and possibly asphalt in the shallow portion of the seal system. The disposal zone in a single borehole could contain about 400 waste canisters of approximately 5 meters length. Based on the 1996 estimates used to support the Storage and Disposition PEIS, this analysis assumes that 3 deep boreholes would be required to emplace 34 MT of surplus plutonium. [DOE 1996]

**Figure G1: Generalized Concept for Deep Borehole**



### ***G.1.2 FACILITY CONSTRUCTION/MODIFICATION***

Until such time that the RD&D for deep borehole disposal is authorized and nears completion and DOE decides whether or not to proceed with this technology, the scope of this project (i.e., facilities, utilities, support systems and infrastructure) are yet to be defined. The RD&D would demonstrate the feasibility of deep borehole disposal and would be focused on completing conceptual design, analysis, and demonstrating key components of borehole drilling, borehole construction, waste canisters, handling, emplacement, and borehole sealing operations. [SAND2012-8527P]

### ***G.1.3 KEY ASSUMPTIONS***

- NEPA analysis and Record of Decision completed in a timely manner.
- DOE decides where to site the disposal facility for the surplus plutonium and is successful at obtaining approval and licensing of the facility.

### ***G.1.4 COST AND SCHEDULE***

The total cost and schedule are yet to be defined; however the Sandia report indicates that the preliminary estimates for the RD&D activities (without the use of radioactive waste or materials) would require approximately 5 years and \$75 million. [SAND2012-8527P] The subsequent costs to deploy a full-scale operational facility(ies) for radioactive waste or materials are yet to be defined. For comparative purposes, the timeline for the deep borehole option was assumed to be similar to the timeline for a geologic repository for spent fuel as outlined in the January 2013 *Strategy for the Management and Disposal of Used*

*Nuclear Fuel and High-Level Radioactive Waste.* The timeline assumes a repository sited by 2026, the site characterized and the repository designed and licensed by 2042, and the repository constructed and operations started by 2048. [DOE 2013] Assuming 1 year to drill each borehole (3 would be needed), the surplus plutonium would be disposed of by 2051. As a comparison, the 1986 cost to construct and start-up WIPP was approximately \$500 million. While the cost for a deep borehole disposition option cannot be estimated to the same degree as the other options, it is believed that this method of disposition would fall between the immobilization option cost range and the downblending option cost range. Based on the similarities between disposition of plutonium in WIPP (a deep geologic repository) and disposition of plutonium in a deep borehole, the costs for disposition in a deep borehole would be closer to the downblending option.

#### ***G.1.5 PROGRAMMATIC ACTIONS AND CHANGES***

- Negotiate with Russian Government and incorporate an additional disposition method into the existing PMDA.
- Perform additional NEPA analysis including siting determination.
- Complete RD&D for deep borehole disposal.
- Identify the disposal site and establish the waste acceptance criteria to determine the acceptable waste form for disposal.

#### ***G.1.6 RISKS***

The major risks in this strategy are listed below:

- DOE must complete the RD&D activities and select the location(s) for deep borehole disposal.
- Uncertain how long and what requirements would be enforced by the EPA and individual states concerning the regulatory requirements for operating the facility and receiving/emplacing the final waste form.
- Russia may be unwilling to accept this as a method to dispose of the plutonium.
- Requirements for testing and qualification of the waste form could change significantly throughout the developmental process.
- As with any major capital project, a myriad of risks would be identified with the execution and start-up of projects.



**References:**

BRC 2012, *Blue Ribbon Commission on America's Nuclear Future Report to the Secretary of Energy*, Prepared for the U.S. Department of Energy by the Blue Ribbon Commission, Washington, DC, January 2012.

DOE 1996, *Storage and Disposition of Weapons-Usable Fissile Materials Final Programmatic Environmental Impact Statement*, DOE/EIS-0229, Office of Fissile Materials Disposition, Washington, DC, December 1996.

DOE 2013, *Strategy for the Management and Disposal of Used Nuclear Fuel and High Level Radioactive Waste*, Washington, DC, January 2013.

PMDA 2000, *Agreement between the Government of the United States of America and the Government of the Russian Federation Concerning the Management and Disposition of Plutonium Designated as No Longer Required for Defense Purposes and Related Cooperation*, signed at Moscow and Washington on August 29 and September 1, 2000, as amended by the Protocols of September 15, 2006 and April 13, 2010, all three of which entered into force together on July 13, 2011.

SAND2012-8527P, *Research, Development, and Demonstration Roadmap for Deep Borehole Disposal*, Prepared for U.S. Department of Energy, Sandia National Laboratories, August 31, 2012.