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Summary of Plutonium-238 Production Alternatives Analysis Final Report

March 2013

Idaho National Laboratory

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Prepared by the Plutonium-238 Production Alternatives Analysis Team

March 2013

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EXECUTIVE SUMMARY

This report contains an unclassified summary of the opinions and recommendations of the plutonium-238 (Pu-238) Supply Program Alternatives Analysis Team related to the current plan for production of Pu-238 in the United States. The Team was chartered in June 2012 to provide an experienced and independent comparative evaluation of the various potential options the Department of Energy (DOE) could consider for resuming production of Pu-238.

The time available for the review was limited, and the information from which to draw conclusions was not of a homogeneous nature. As a consequence, cost and schedule data for evaluation on a one to one basis were limited. Because of the lack of uniform information, the Team opinions and recommendations expressed are based on evaluations that were more qualitative and subjective than quantitative.

During the course of this review, the Team visited and reviewed facilities under consideration at the Idaho National Laboratory (INL), Oak Ridge National Laboratory (ORNL), Savannah River Site (SRS), and Babcock and Wilcox (B&W). At each site, discussions were held with the operating staff and management. The purpose of these visits was to form a first-hand opinion of the operational status, the condition, the adaptability, and the long-range operability of those facilities.

The Team implemented a two-phase evaluation process. During the first phase, a wide variety of past and new candidate facilities and processing methods were assessed against the criteria established by DOE for this assessment. Any system or system element selected for consideration as an alternative within the project to reestablish domestic production of Pu-238 must meet the following minimum criteria:

- Any required source material must be readily available in the United States, without requiring the development of reprocessing technologies or investments in systems to separate material from identified sources.
- It must be cost, schedule, and risk competitive with existing baseline technology.
- Any identified facilities required to support the concept must be available to the program for the entire project life cycle (notionally 35 years, unless the concept is so novel as to require a shorter duration).
- It must present a solution that can generate at least 1.5 Kg of Pu-238 oxide per year, for at least 35 years.
- It must present a low-risk, near-term solution to the National Aeronautics and Space Administration’s urgent mission need. DOE has implemented this requirement by eliminating from project consideration any alternative with key technologies at less than Technology Readiness Level 5.

The Team evaluated the options meeting these criteria using a more detailed assessment of the reasonable facility variations and compared them to the preferred option, which consists of target irradiation at the Advanced Test Reactor (ATR) and the High Flux Isotope Reactor (HFIR), target fabrication and chemical separations processing at the ORNL Radiochemical Engineering Development Center, and neptunium-237 storage at the Materials and Fuels Complex at INL. This preferred option is consistent with the Records of Decision from the earlier National Environmental Policy Act (NEPA) documentation.

The Team considered the following options:

Option 1a: Target fabrication and target processing at ORNL, irradiation at HFIR at ORNL and ATR at INL, neptunium storage at INL

Option 1b: Target fabrication at B&W facility, target processing at ORNL, irradiation at HFIR and ATR, neptunium storage at INL

Option 2a: Target fabrication and target processing at INL, irradiation at HFIR and ATR, neptunium storage at INL

Option 2b: Target fabrication at B&W facility, target processing at INL, irradiation at HFIR and ATR, neptunium storage at INL

Option 3a: Target fabrication at ORNL and target processing at SRS, irradiation at HFIR and ATR, neptunium storage at INL

Option 3b: Target fabrication at B&W facility, target processing at SRS, irradiation at HFIR and ATR, neptunium storage at INL

The evaluation factors addressed in this second phase, listed in random order, are:

- Cost
- Schedule
- Risk to all project objectives, including initial startup, long-term availability, product quality, and future operating costs
- Environmental impact
- Worker and public safety
- Scalability
- Ability to function within a system evaluated according to the above criteria, if the alternative consists of system element(s).

Table ES-1 (and Table 6-3 in Section 6) summarizes the final comparative rankings of options against Option 2 (base case). Table ES-2 (and Table 6-4 in Section 6) summarizes the projected initial project, operations, total project, and total life-cycle costs for the various options.

Table ES-1. Summary Pu-238 production options evaluation.

Evaluation Factors	Options					
	1a	1b	2a	2b	3a	3b
Cost						
Schedule					1	1
Risk to all Project Objectives		2		2	3	2
Environmental Impact			4		4	
Worker and Public Safety						
Scalability						
Transportation/System Elements			5			

Notes:
1. Start of SRS will be dependent on completion of NEPA activities. However, target fabrication and irradiation in HFIR and ATR in a production mode could begin 2018. Because of the capacity of the SRS H-B Line, any initial delay in production schedule could be quickly regained within a short operational period.
2. Installing target fabrication and processing at B&W is judged to increase the risk to the project in each case due to the facility upgrades needs and associated training for operational staff relative to the expertise at the national laboratories being considered.
3. All operations and procedures have been established and demonstrated. Sufficient capacity exists so that most normal or unplanned operational downtime events would be able to be handled without affecting long-term production quantities
4. Facilities provide excellent containment and isolation of processes. INL and SRS sites have larger boundary areas to general public.
5. INL would have a reduced transportation link because the neptunium and ATR are all on one site.

Substantially Better	Marginally Better	Comparable	Marginally Worse	Substantially Worse

Table ES-2. Cost evaluation comparison for Pu-238.

Cost Categories	1a	1b	2a	2b	3a	3b
Initial Project Funding	$92,000					
Operations Cost	$25,000					
Total Project Cost	$1,540,000					
Total Life-Cycle Cost Discounted	$674,000					

Substantially Better	Marginally Better	Comparable	Marginally Worse	Substantially Worse

The Team observes that any of the six options can be made to work. However, there are more cost, schedule, and project risk uncertainties associated with the various options as compared to the preferred option (1a). It is the collective opinion of the Team that continuing with Option 1a: "Target fabrication and target processing at ORNL, irradiation at HFIR and ATR, neptunium storage at INL" provides the lowest cost and lowest risk to the DOE. It also reestablishes Pu-238 production in the shortest time.

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ACRONYMS AND ABBREVIATIONS

ANL-W	Argonne National Laboratory-West
ATR	Advanced Test Reactor
B&W	Babcock and Wilcox
CDE-1	Critical Decision Equivalent-1
CLWR	Commercial Light Water Reactor
DOE	Department of Energy
DOE-NE	Department of Energy Office of Nuclear Energy
EBR	Experimental Breeder Reactor
FDPF	Fluorinel Dissolution Process Facility
FFTF	Fast Flux Test Facility
FMEF	Fuels and Materials Examination Facility
FMF	Fuel Manufacturing Facility
FY	fiscal year
GPHS	general purpose heat source
HFIR	High Flux Isotope Reactor
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
LTC	Lynchburg Technology Center
LWR	light water reactor
MFC	Materials and Fuels Complex
NASA	National Aeronautics and Space Administration
NEPA	National Environmental Policy Act
NI-PEIS	Nuclear Infrastructure Programmatic Environmental Impact Statement
NOG-L	Nuclear Operations Group – Lynchburg
Np-237	neptunium-237

NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
Pa-233	protactinium-233
PEIS	Programmatic Environmental Impact Statement
Pu-238	plutonium-238
R&D	research and development
RAL	Remote Analytical Laboratory
REDC	Radiochemical Engineering Development Center
ROD	Record of Decision
RPS	Radioisotope Power System
RTG	radioisotope thermoelectric generator
SNM	special nuclear material
SRS	Savannah River Site
TRU	transuranic
U-233	uranium
VXF	vertical experiment facility

Summary of Final Plutonium-238 Production Alternatives Analysis Report

1. INTRODUCTION

The U.S. Department of Energy (DOE) is currently evaluating options for future production of the isotope plutonium-238 (Pu-238). In accordance with the requirements of the National Environmental Policy Act (NEPA) to consider potential environmental effects before taking major federal actions, DOE began this effort in the late 1990s. The NEPA process culminated in 2000 with publication of the *Final Programmatic Environmental Impact Statement for Accomplishing Expanded Civilian Nuclear Energy Research and Development and Isotope Production Missions in the United States, Including the Role of the Fast Flux Test Facility* (DOE 2000a), or Nuclear Infrastructure Programmatic Environmental Impact Statement (NI-PEIS). A subsequent Record of Decision (ROD) in January 2001 (66 FR 7877) identified a preferred alternative, including a decision regarding resumption of producing Pu-238.

A number of years have passed since DOE completed this NEPA documentation. Therefore, DOE assembled an Alternatives Analysis Team – a group of subject matter experts – to consider any additional options, facilities, or sites that would be better-suited or more cost-effective alternatives to implement the preferred approach as described in the project execution plan Critical Decision Event-1 (CDE-1) review. The facilities must be capable of annually producing and processing at least 1.5 Kg of Pu-238 oxide. DOE also considered the ability to scale up to larger quantities (up to 5 Kg of Pu-238 oxide).

DOE is responsible for maintaining the necessary nuclear material and infrastructure required to deliver Pu-238 fueled radioisotope power systems to various federal users, primarily the National Aeronautics and Space Administration (NASA) for space exploration, and to other federal users for terrestrial applications. Radioisotope Power Systems (RPSs) are used when conventional power systems (e.g., chemical or solar) cannot reliably provide electric power to support mission requirements. The properties of the Pu-238 isotope make it ideal for use in applications requiring a long-term, reliable heat source.

The shutdown of the last Savannah River Site (SRS) plutonium production reactor in 1992 eliminated the capability of the United States to produce Pu-238. Since then, the source of Pu-238 for heat sources has been recovering it from purchased foreign-produced material, recycled heat sources, and processing equipment residues. However, available existing domestic sources and foreign supplies of Pu-238 are no longer sufficient to meet future national needs. Furthermore, only domestically produced material may be used for national security missions.

The Pu-238 production technology and process steps are as follows:

- A sufficient quantity of target material that can be irradiated to produce Pu-238
- Facilities to build target rods
- Nuclear reactors or neutron irradiation sources to irradiate the target rods
- Process facilities to treat the irradiated target rods to separate the Pu-238 product from the remaining target material

The following components of Pu-238 production currently exist in the United States:

- The neptunium-237 (Np-237) storage facility housing the target material, located at the Materials and Fuels Complex (MFC) at the Idaho National Laboratory (INL)

- Two reactors – the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL) and the Advanced Test Reactor (ATR) at INL – for irradiating targets. (Note: These reactors are not currently being used for this purpose.

- Facilities for the production of targets for irradiation and postirradiation processing. (New equipment or processing capabilities will have to be established within the existing facilities)

1.1 Previous Analyses

Tables 1-1 and 1-2 summarize the environmental analyses provided in the NI-PEIS to support the ROD. DOE evaluated three existing nuclear reactors as irradiation facility candidates: (1) ATR at INL (formerly Idaho National Engineering and Environmental Laboratory); (2) HFIR at ORNL; and (3) Fast Flux Test Facility (FFTF) at Hanford. Environmental impacts were also estimated for a generic Commercial Light Water Reactor (CLWR), as well as a new research reactor and one or two new accelerators at unspecified DOE sites. DOE also evaluated three facilities as candidates for Pu-238 production: (1) the Radiochemical Engineering Development Center (REDC) at ORNL, (2) Fluorinel Dissolution Process Facility (FDPF) at INL, and (3) the Fuels and Materials Examination Facility (FMEF) at Hanford.

Table 1-1. NI-PEIS alternatives and options.

Alternative*	Pu-238 Production Mission			
	Option Number	Irradiation Facility	Storage Facility	Target Fabrication and Processing Facility
Alternative 2: Use Only Existing Operational Facilities	1	ATR	REDC	REDC
	2	ATR	CPP-651	CPP-651
	3	ATR	FMEF	FMEF
	4	CLWR	REDC	REDC
	5	CLWR	CPP-651	CPP-651
	6	CLWR	FMEF	FMEF
	7	HFIR and ATR	REDC	REDC
	8	HFIR and ATR	CPP-651	CPP-651
	9	HFIR and ATR	FMEF	FMEF
Alternative 3: Construct New Accelerator(s)**	1	New	REDC	REDC
	2	New	CPP-651	CPP-651
	3	New	FMEF	FMEF
Alternative 4: Construct New Research Reactor***	1	New	REDC	REDC
	2	New	CPP-651	CPP-651
	3	New	FMEF	FMEF

Notes:
* Alternative 1 in the NE-PEIS was the "No Action Alternative" (i.e., no new production occurs).
** For target irradiation for an evaluation period of 35 years. Also includes decontamination and decommissioning of accelerator(s) and the processing facility when missions are over, as well as deactivation of FFTF.
*** To be constructed at an existing DOE site to irradiate all isotope production targets for an evaluation period of 35 years. Target material (Np-237) would be processed and transported from SRS to the fabrication facility for storage pending fabrication; irradiated targets would be transported back to the fabricating facilities for postirradiation processing. This scenario was later modified to describe storage at MFC at INL and shipment of Np-237 to a target fabrication facility.

Table 1-2. Irradiation facilities considered but dismissed from further evaluation in the NI-PEIS.

Why Dismissed?	Facility
Facilities lacking sufficient neutron production capacity to support the proposed action without impacting existing missions	Neutron Radiographic Reactor Argonne National Laboratory-West (ANL-W) (now part of INL)
	Brookhaven Medical Research Reactor Brookhaven National Laboratory
	National Bureau of Standards Reactor National Institute of Standards and Technology
	General Atomics Training, Research, and Isotope Production Reactors
	University Small Research Reactors
	University Large Research Reactors (i.e., Massachusetts Institute of Technology and University of Missouri)
	ATLAS Heavy Ion Facility Argonne National Laboratory
	Holifield Radioactive Ion Beam Facility ORNL
	Heavy Ion Linear Accelerator Lawrence Berkeley National Laboratory
	Alternating Gradient Synchrotron Heavy Ion Facility Brookhaven National Laboratory
	Continuous Electron Beam Accelerator Facility Thomas Jefferson National Accelerator Facility
	Electron Linear Accelerator Lawrence Livermore National Laboratory
	University Linear Accelerators
Facilities with capacity fully dedicated to existing missions	Annular Core Research Reactor Sandia National Laboratories
	Brookhaven LIN AC Isotope Producer Brookhaven National Laboratory
Facilities not capable of steady-state neutron production	Sandia Pulse Reactor II and III Sandia National Laboratories
	Transient Reactor Test Facility ANL-W (now part of INL)
	Zero Power Physics Reactor Idaho National Engineering and Environmental Laboratory (now INL)
	Power Burst Facility Idaho National Engineering and Environmental Laboratory (now INL)
	Intense Pulsed Neutron Source Argonne National Laboratory
	Flash X-Ray Facility Lawrence Livermore National Laboratory
Facilities with insufficient power to sustain adequate steady-state neutron production	Brookhaven Medical Research Reactor Brookhaven National Laboratory
	Los Alamos Critical Assembly Facility Los Alamos National Laboratory (LANL)
	General Atomics Training, Research and Isotope Production Reactors
	University Small Research Reactors
	Booster Applications Facility Brookhaven National Laboratory
	Cyclotron Facility Brookhaven National Laboratory

The NI-PEIS considered multiple facility options under each alternative for irradiation, storage, and target fabrication/processing. Scenarios for various options evaluated transportation of nonirradiated targets, irradiated targets, and processed materials between the locations selected for storage, target fabrication, target irradiation, postirradiation processing, and final destination of the Pu-238.

Other facilities were also considered but dismissed from further evaluation (Table 1-2). In developing a range of reasonable alternatives, DOE examined the capabilities and available capacities of 30 facilities at existing and planned nuclear research facilities that could potentially support one or all of the isotope production and research missions. Numerous existing U.S. processing hot cell facilities have the capabilities and capacity to support the nuclear infrastructure, but the NI-PEIS considered only those collocated at the three candidate irradiation-facility sites (and only those most suitable in terms of capability, capacity, and availability).

After considering the environmental impacts, costs, public comments, nonproliferation issues, and programmatic factors, DOE decided to implement the Preferred Alternative identified in Section 2.8 of the NI-PEIS (Alternative 2, Option 7). Under the Preferred Alternative, domestic production of Pu-238 will be reestablished to support U.S. space exploration. For this purpose, the ATR at INL and HFIR at ORNL in Tennessee will be used to irradiate Np-237 targets. Pu-238 production will not interfere with existing primary missions at ATR and HFIR. The REDC at ORNL will be used for fabricating targets and isolating Pu-238 from the irradiated targets.

On August 13, 2004, DOE amended the ROD for the Nuclear Infrastructure PEIS, identifying a decision to transport Np-237 oxide from SRS to the ANL-W site, now known as the MFC at INL. This amendment, which enabled DOE to meet the security requirements for storage of special nuclear material (SNM), followed heightened security concerns following the attacks of September 11, 2001.

In support of this decision, DOE prepared a Supplemental Analysis for the PEIS (DOE 2000b) for the change of storage location of Np-237 oxide from REDC to MFC to determine whether further NEPA review was required. DOE determined that no additional NEPA review was necessary because the relocation and change in storage location did not constitute a substantial change in the original proposed action, and the impacts analyzed in the NI-PEIS bounded the impacts of transfer to and storage at the new proposed storage location.

1.2 Alternatives Analysis Screening Criteria

Any system or system element selected for consideration as an alternative within the project to re-establish domestic production of Pu-238 must meet the following minimum criteria:

- Any required source material must be readily available in the United States, without requiring the development of reprocessing technologies or investments in systems to separate material from identified sources.
- It must be cost, schedule, and risk competitive with existing baseline technology.
- Any identified facilities required to support the concept must be available to the program for the entire project life cycle (notionally 35 years, unless the concept is so novel as to require a shorter duration).
- It must present a solution that can generate at least 1.5 Kg of Pu-238 oxide per year, for at least 35 years.
- It must present a low-risk, near-term solution to NASA's urgent mission need. DOE has implemented this requirement by eliminating from project consideration any alternative with key technologies at less than Technology Readiness Level 5 (DOE Guide 413.3-4A).

2. ALTERNATIVES ANALYSIS PROCESS DESCRIPTION

To conduct the Alternatives Analysis, the Team developed a clear problem statement. Based on the problem statement, the team identified the necessary process steps for producing Pu-238 and potential technologies, and evaluated the alternatives against the established criteria.

2.1 Team Selection and Capabilities

The first step in the alternative evaluation process was to select a Team that would ensure broad and technically competent representation of all aspects of the process. Team members brought extensive experience from a variety of backgrounds. Table 2-1 presents the Team members selected with their affiliation and area of expertise. Appendix A contains detailed descriptions of their qualifications.

Table 2-1. Voting members of the Team.

Name	Affiliation	Expertise
Wade E. Bickford	Savannah River National Laboratory	Reactor analysis and isotope production planning
Chadwick D. Barklay	University of Dayton	Senior Research Scientist
David B. Lord	INL	Project Construction Management
James E. Werner	INL	Isotope and Nuclear Material Technology

2.2 Problem Statement Formulation

The Team, with input from DOE personnel, developed the following problem statement:

> The Alternatives Analysis Team will identify known Pu-238 production alternatives that have a reasonably mature technical basis and provide a sound discussion, including technical and cost factors, as to whether the alternatives will produce a satisfactory amount of Pu-238 for the program, as well as why or why not. The group will include an analysis of alternative technologies and innovations that may provide cost and quality benefits for future Pu-238 production. Those identified as being worthy of engineering trade studies will be identified. The Team will identify and assess the necessary infrastructure to accomplish the Pu-238 isotope production mission with the following goals:
>
> - Provide 1.5 - 2 Kg of Pu-238 per year by 2018
> - The capability to produce larger quantities for a limited period (surge capacity).

2.3 Identify Technologies and Process Steps

The first action of the Team was to identify the production steps for producing the Pu-238 isotope to be used ultimately in the production of heat sources, as follows. The steps described below assume Pu-238 production from neutron irradiation of Np-237 and subsequent chemical separation of the plutonium and neptunium.

2.3.1 Neptunium Storage

The neptunium feedstock material to be used to fabricate targets for irradiation and production of Pu-238 came from SRS to INL, where it is currently stored at the Fuel Manufacturing Facility (FMF). It will be removed from storage as needed and transferred to the target fabrication facility.

2.3.2 Precursor (Np-237 Oxide) Cleanup

Np-237 undergoes decay to produce protactinium-233 (Pa-233); protactinium further beta decays to uranium-233 (U-233), emitting an energetic gamma ray that is a radiological concern.

The decay process in the Np-237 decay chain is interesting because the parent and subsequent daughter products, in this case Np-237 and U-233, have very long half-lives, as well as a very short-lived intermediate product, Pa-233. This results in secular equilibrium between Np-237 and its short-lived Pa-233 decay product. This equilibrium develops quickly (within months). The associated gamma-ray field resulting from Pa-233 decay becomes a radiological concern within weeks. Depending on the capabilities of the target fabrication facility, it may or may not be economically justifiable for the neptunium to be decontaminated by separating out the Pa-233 before target fabrication. The base case assumption is that it will be cleaned up; however, this issue requires further analysis.

2.3.3 Target Fabrication

Neptunium targets must be manufactured to survive the irradiation environment without the release of fission products. They must also be clad, and the cladding should not fail during irradiation.

The baseline target design is pressed pellet rod targets manufactured by pressing individual Np-237 oxide and aluminum pellets, inserting them in a cladding tube, welding the tube closed, and swaging or hydrostatically pressing the tube to achieve a mechanical bond with the pellets.

2.3.4 Irradiation

The target elements are neutron irradiated in a nuclear reactor where the reaction shown below takes place:

$$^{237}\mathrm{Np}\ (n,\gamma \longrightarrow {}^{238}\mathrm{Np} \xrightarrow[2.1\ \mathrm{day}]{\beta^-} {}^{238}\mathrm{Pu}$$

Exposures of neptunium targets in a reactor are optimized to limit the production of other isotopes of plutonium.

2.3.5 Separation of Pu-238

Pu-238 heat source production requires the efficient and reliable recovery of Pu-238 and unconverted Np-237 from irradiated targets. For irradiated target processing, SRS developed and operated a Pu-238 and unconverted Np-237 recovery program based on anion exchange separation. In this process, irradiated Np-237 oxide targets are dissolved. The dissolved solution undergoes a process where the actinides are separated from fission products and other impurities. The Pu-238 is then separated from Np-237 using additional separation cycles effect a clean separation.

Once the plutonium is extracted from irradiated targets, several processing steps are required before the plutonium is suitable for heat source fabrication. The purified plutonium must be converted to the thermodynamically stable oxide form.

2.3.6 Waste Processing and Handling

Systems for waste stream processing will be able to provide complete management of all waste generated. These wastes include sanitary and industrial, hazardous, radioactive (both low-level and transuranic [TRU]), and mixed (radioactive and hazardous). Sanitary, industrial, low-level, and hazardous quantities are anticipated to be minimal and will be managed with existing host site waste streams. Radioactive gaseous emissions will be filtered and monitored by building exhaust systems. The predominant waste streams will be radioactive liquid waste (primarily remote-handled TRU and contact-handled TRU) from processing and radioactive solid waste (contact-handled TRU, remote-handled TRU, and solid low-level waste) from repair, decontamination, and maintenance.

Tanks will collect effluent from the irradiated neptunium target dissolution and protactinium waste (as decayed to U-233 after several months) from the neptunium separation. The liquid waste will be neutralized, concentrated, and stabilized to meet appropriate disposal requirements.

Solid radioactive waste will be segregated to the extent possible as determined by operational constraints. The majority of solid radioactive waste will be classified as TRU and disposed of at the Waste Isolation Pilot Plant in Carlsbad, New Mexico.

2.3.7 Storage and Shipment of Special Nuclear Material

Storage, packaging, and shipment preparation facilities are needed to prepare for shipment of the Pu-238 material to LANL. Areas and equipment used for packaging, preparation, and receipt operations are needed. Equipment and tools used for handling and storage operations will be kept in this area.

2.4 Approach

The Team determined that, first, a general assessment including as wide a set of options and processes as possible would be generated. From this set of options, the Team then culled the number of options down to a more reasonable set for a more detailed assessment development and analysis of variations. Based on the initial screening criteria, the Team quickly developed a short list of facility/option combinations for analysis, as detailed in the following sections. The DOE Oak Ridge Operations provided the criteria by which to judge options and a prioritization of the evaluation factors, but not specific weighting factors.

The Team noted that quantitative data on all options and criteria were not available. Costs, in particular, were missing for pairings of facility options such as target fabrication at Babcock and Wilcox (B&W) facilities paired with the processing at SRS facilities. The Team noted that subjective engineering judgment and expert opinion would have to be used in some cases, resulting in the expectation that the final matrix comparison of options would contain largely subjective, qualitative opinions. The Team agreed to document the basis for such subjective expert judgment whenever possible. In discussions with the DOE Oak Ridge lead, the objective of the Team was defined to rank the options against the stated screening criteria, and then evaluate the remaining options according to their merits against a set of evaluation factors and documenting the basis for the Team's judgment.

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3. PREFERRED OPTION DESCRIPTION

The Program Management Plan for the Pu-238 Restart Program identified the preferred option as conducting the target irradiation at ATR and HFIR, target fabrication and chemical separations processing at ORNL REDC, and Np-237 storage at MFC (DOE 2011). This is consistent with the ROD from the earlier NEPA documentation, as described above.

3.1 Advanced Test Reactor and High Flux Isotope Reactor Irradiation

3.1.1 Advanced Test Reactor (ATR)

The ATR at INL was designed to optimize fuel and material testing for the Navy's nuclear propulsion program. It began operation in 1967 and has operated continuously since, averaging approximately 250 operating days per year. Irradiation of material and fuel in ATR can simulate many years of prototypical operation in a few months or years of testing. This capability is valuable for testing materials and fuels to support light water reactor (LWR) and more advanced reactor designs. Unlike U.S. commercial LWRs, ATR has no established lifetime or shutdown date. All core internal components are removed and replaced every 8 to 10 years during a core-internals change-out outage, typically of about 6 months.

The ATR is a pressurized, light-water moderated and cooled, beryllium-reflected, enriched-uranium-fueled reactor with a maximum operating power of 250 megawatts. The ATR core cross-section (Figure 3-1) consists of 40 curved aluminum-plate fuel elements in a serpentine configuration around a three-by-three array of large irradiation locations in the core or flux traps. The peak thermal flux can reach 1.0×10^{15} n/cm^2-sec, and peak fast flux (E>1.0 MeV) 5×10^{14} n/cm^2-sec.

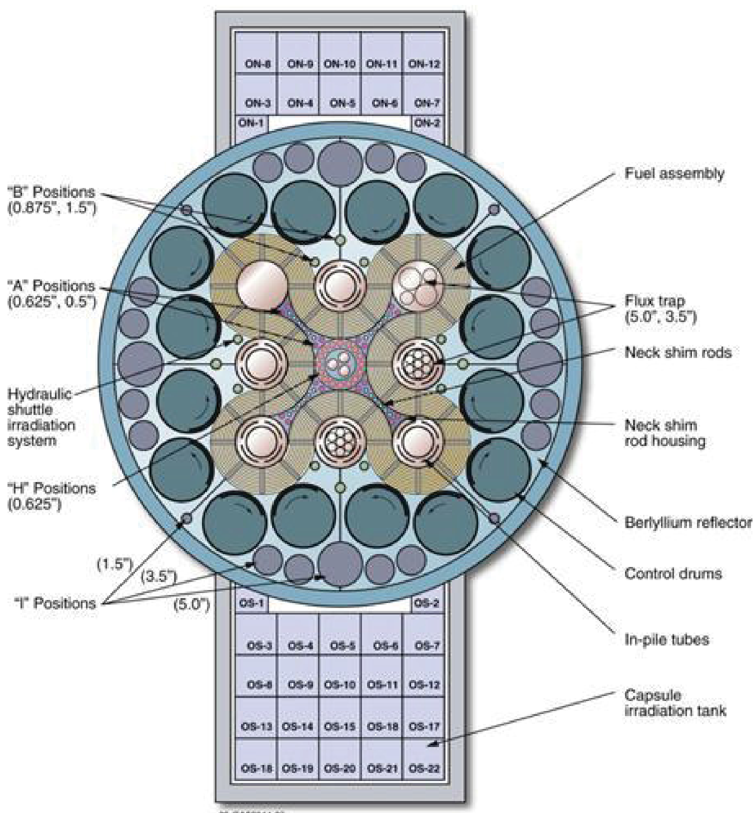


Figure 3-1. Cross-section view of the ATR.

This core configuration creates five main reactor power lobes (regions) that can be operated at different powers during the same operating cycle. Along with the nine flux traps, there are 68 irradiation test positions ranging in diameter from 1.27 to 12.7 cm and all 122 cm long, and the irradiation tanks outside the core reflector tank have 34 low-flux irradiation positions.

There are three primary experiment configurations in ATR: (1) static capsule, (2) instrumented lead, and (3) pressurized water loop. Experiments must remain in ATR for the duration of the operating cycle (average 49 days).

3.1.2 High Flux Isotope Reactor (HFIR)

The HFIR at ORNL is a versatile 85-megawatt, pressurized, light-water-cooled and -moderated flux trap type research reactor. The primary function of HFIR is cold and thermal neutron scattering, but other capabilities include materials irradiation, materials production, and neutron activation analysis.

The core consists of two fuel elements, an inner fuel element and an outer fuel element, each constructed of involute fuel plates. An over-moderated flux trap is located in the center of the core, a large beryllium reflector is located on the outside of the core, and two control elements are located between the fuel and the reflector. The flux trap and reflector house numerous experimental facilities used for isotope production, material irradiation, and cold/thermal neutron scattering. The active fuel height is 20 in., and the outer diameter of the outer fuel element is approximately 16.5 in.

At HFIR, Pu-238 production could occur in the vertical experiment facilities (VXFs) in the HFIR permanent beryllium reflector. Sixteen small-radius (2.012 cm) and six large-radius (3.599 cm) VXFs are located within the reflector. Conceptually, both small and large VXF Np-237 target rod bundles are to be assembled, as illustrated in Figure 3-2. The figure shows an example of where they could be located in the HFIR reflector.

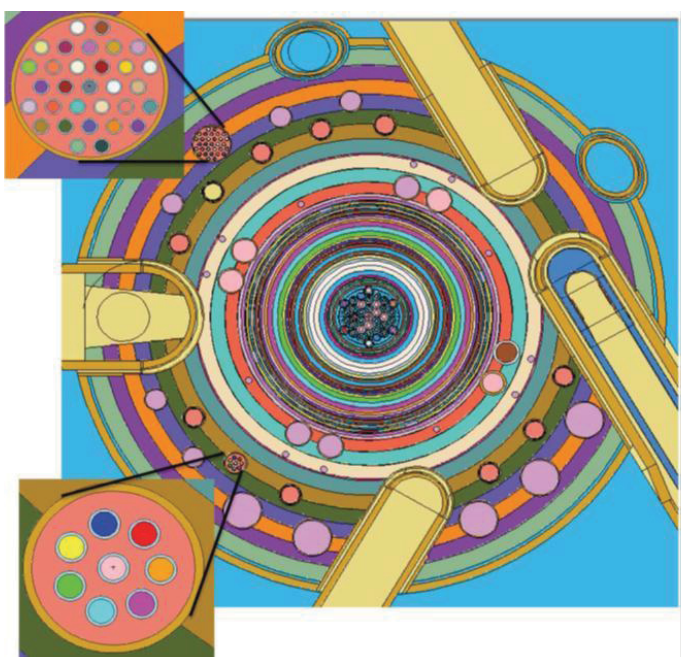


Figure 3-2. Cross-section view of the HFIR illustrating the small (lower left) and large (upper left) VXF target arrays.

3.2 ORNL Radiochemical Engineering Development Center (REDC) for Combined Target Fabrication and Processing

The REDC is a hot cell facility that currently operates as a Safety Category 2, Nonreactor Nuclear Facility. The following sections describe the facility (ORNL 2011).

Figure 3-3 depicts the anticipated use of REDC for target fabrication and irradiated target processing. Neptunium purification will be performed in an existing glovebox laboratory in REDC, and a method for target fabrication will be developed in REDC as well when full-scale targets must be produced to support regular operations. Full-scale target fabrication and inspection will be performed in a new target fabrication glovebox that will be procured and installed in the REDC. The target irradiation to produce the radioisotope will be performed in both ATR and HFIR. The processes to dissolve and separate the irradiated targets, as well as to recover the neptunium and plutonium, will be performed in the ORNL REDC hot cells.

After chemical separations, the solutions are transferred to separate neptunium and plutonium lines for precipitation, calcination, and packaging. The neptunium line will be located in an existing space in REDC.

Numerous facility support systems, including utilities, safeguards and security, ventilation, and environmental monitoring, are already in place at participating work sites to ensure safe and secure operation. The project will leverage existing infrastructure at participating sites.

A design study was performed to assess the REDC to fabricate neptunium targets for irradiation in the ATR and HFIR and recover the Pu-238 from irradiated targets. The facility has hot cell processing equipment used for similar radioisotope recovery missions. Expansion from the pilot scale to a production scale would require facility modifications. Testing and validating process flow sheets would also be required.

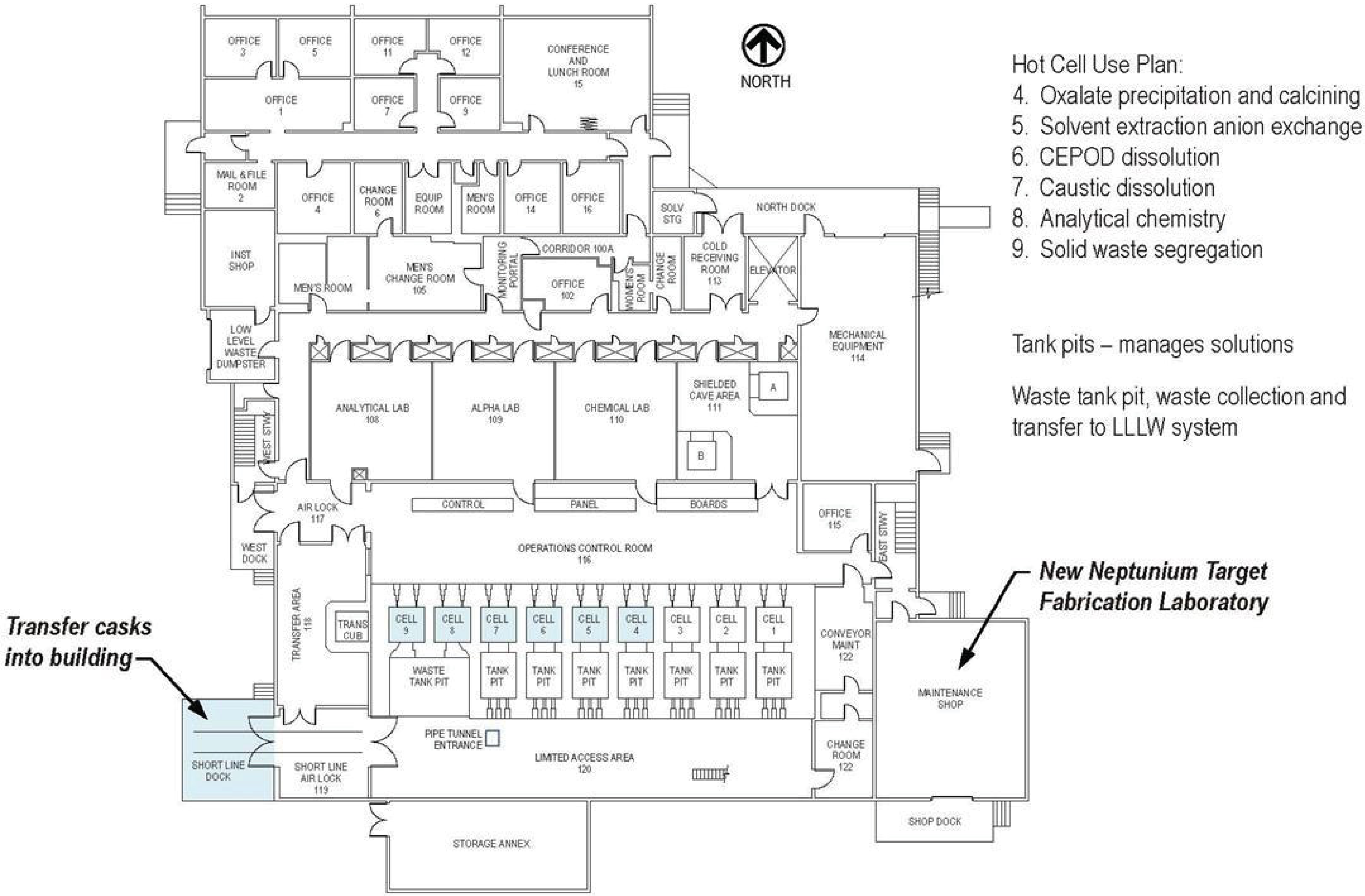


Figure 3-3. First floor layout of REDC showing areas to support Pu-238 production.

3.3 Neptunium-237 Oxide Stored at the Materials and Fuels Complex (MFC)

The majority of the DOE supply of Np-237 oxide was shipped from SRS to INL between 2005 and 2008 to support future production of Pu-238. The Np-237 was converted from liquid to a solid Np-237 oxide form, packaged into primary and secondary containment vessels at SRS, and then shipped to INL in 9975 Type B casks. The containers of Np-237 oxide were removed from the casks and placed in storage racks for secure storage in the FMF vault at MFC. The storage configuration was designed to meet requirements for structural integrity, criticality safety, radiation safety, safeguards and security, and shielding effectiveness.

The FMF was constructed in 1986 for the purpose of housing binary (i.e., uranium and zirconium) fuel and its associated manufacturing equipment to sustain a fuel manufacturing operation for Experimental Breeder Reactor (EBR)-II (INL 2011a). EBR-II fuel is no longer manufactured in FMF. Activities conducted as part of the FMF mission include:

- Processing fuel currently stored at MFC for use elsewhere in the DOE complex.
- Research and development (R&D) on new fabrication methods for high-density, low-enrichment fuel forms.
- Fuel fabrication for the advanced fuel cycle initiative to investigate options for actinide transmutation fuels and targets.
- Storage of uranium and TRU elements, including plutonium and neptunium.
- FMF operations associated with these activities include receipt, storage, handling, inspection, and processing of uranium, plutonium, and other TRU materials. There are several gloveboxes and operational hoods in FMF. Processing of plutonium-bearing materials and other TRU materials is performed in these gloveboxes and hoods, depending on quantity.

FMF is currently a DOE Hazard-Category 2 Nonreactor Nuclear Facility. A storage rack specifically designed for Np-237 oxide storage is located in the FMF vault.

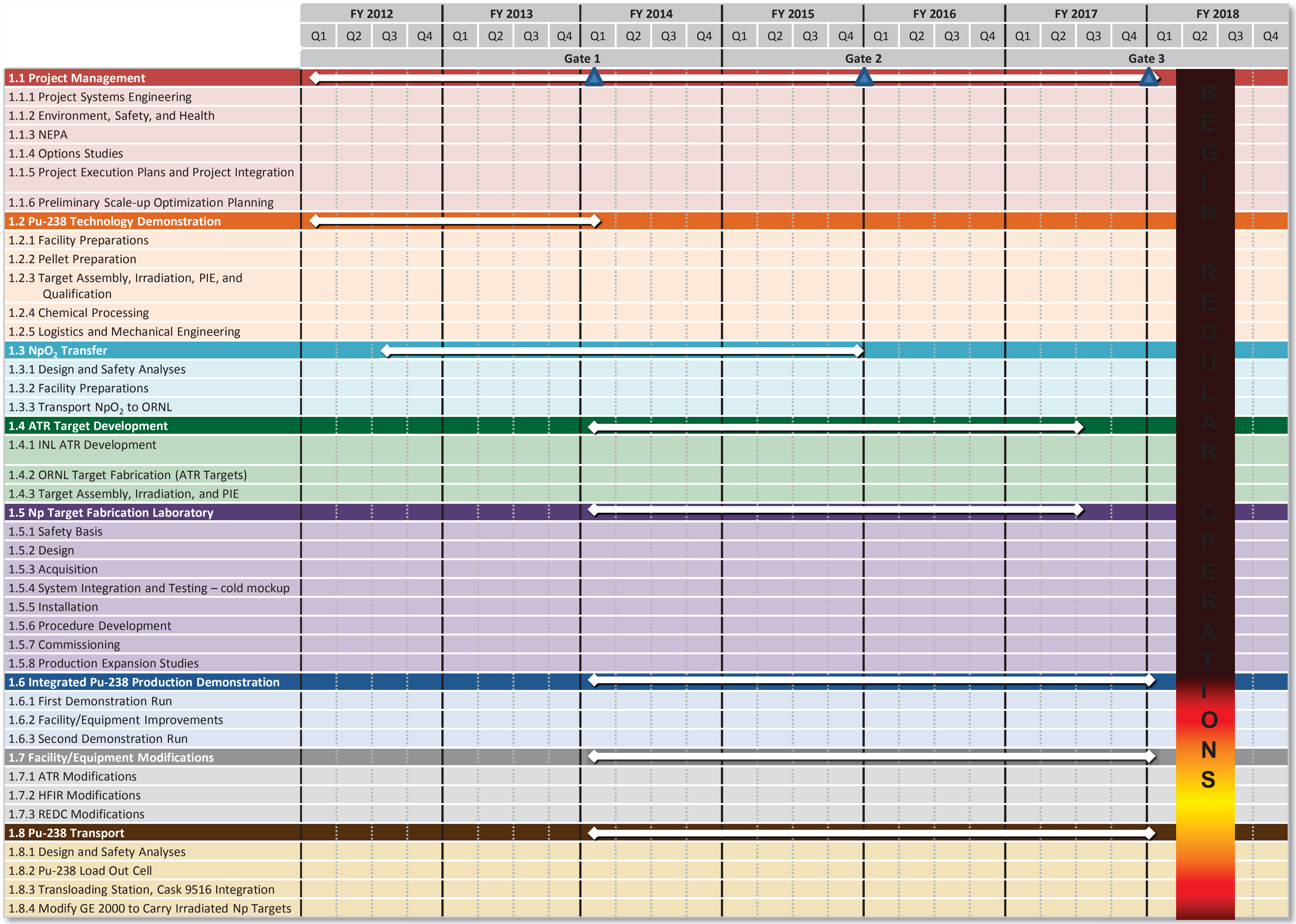
3.4 Preferred Option Cost and Schedule

The notional high-level spending profile for Fiscal Year (FY) 2012 through FY 2017 for the Preferred Option is included in Table 3-3. This profile is based on the midpoint of the preliminary project cost range, which will be refined and reviewed at formal points throughout the project. Table 3-4 summarizes the schedule for the preferred option.

Table 3-3. High-level spending profile for the preferred option ($M).

Project	FY 2012	FY 2013	FY 2014	FY 2015	FY 2016	FY 2017	Totals
1.1 Project Management	2.0	2.5	1.7	1.7	1.7	1.8	11.4
1.2 Pu-238 Technology Demonstration	8.1	10.0	1.3				19.5
1.3 Np-237 Oxide Transfer	0.3	1.5	1.7	1.9			5.3
1.4 ATR Target Development			0.5	2.8	1.6	0.9	5.8
1.5 Neptunium Target Fabrication Laboratory			1.4	1.3	8.0	2.6	13.3
1.6 Integrated Pu-238 Production Demonstration		0.2	5.5	3.5	5.3	6.6	21.1
1.7 Facility/Equipment Improvements			1.1	1.1	4.2	3.2	9.7
1.8 Pu-238 Transfer			1.2	2.2	1.6	0.9	5.8
Totals	**10.5**	**14.2**	**14.5**	**14.5**	**22.3**	**15.9**	**91.9**

Table 3-4. High-level project schedule for the preferred option.



4. CANDIDATE OPTION FACILITY IDENTIFICATION

The facilities discussed in this section have been identified for further consideration because they met the initial Alternatives Analysis screening criteria identified in Section 1.1.

4.1 Babcock and Wilcox Facility, Mt. Athos, Virginia

At the request of DOE, B&W performed a study assessing the capability of setting up a production line at the Mt. Athos Site to fabricate Np-237 oxide targets. The study included assessments of the receipt of the material, facilities and processes, licensing, safeguards and security, radiation safety/health physics, quality assurance, and transportation to reactors (Babcock & Wilcox, 2012). Both the Lynchburg Technology Center (LTC), an R&D laboratory Nuclear Regulatory Commission (NRC) licensed Category 3 facility, and the Nuclear Operations Group-Lynchburg (NOG-L), a high security NRC-licensed Category 1 manufacturing facility, are located at the Mt. Athos Site.

B&W proposed that this project be performed using existing facilities and processes that are well within the site experience base. The project would not require any new construction. The material procurement and nonradioactive fabrication would be performed within the existing NOG-L facility that is currently set up for research and test reactor fuel fabrication. The target fabrication would be performed at the LTC, which would require upgrades, including laboratory renovation and heating, ventilation, and air conditioning system improvements to accommodate the process line. An assessment of the security and safeguards requirements indicated that the Mt. Athos site has the necessary accounting systems and security programs in place to store and process the Np-237 oxide material.

Waste management is an important component of the NEPA process. A major concern identified in the study is disposal of the greater-than-Class-A TRU waste that would be generated; handling and disposing of greater-than-Class-A TRU waste is an issue that requires DOE guidance as to the preferred disposal route. According to B&W, the environmental impact of this project would be minimal, and it is expected that any assessment would result in a Finding of No Significant Impact.

B&W also provided an estimate of the annual production costs for a 5 Kg/year rate to be $2.25 million per year (in current-year dollars) in the study. Four phases were identified in setting up a production line for this project:

- Phase 1 consists of performing the design/installation/construction, which will take place over a 1-year period. This phase includes all costs for facility upgrade and production line design and equipment.
- Phase 2 consists of the preoperational actions, which are expected to take place over a 6-month period. The goal of this phase is to develop and qualify operational procedures for all of the process lines, train the line operators, and demonstrate the final product.
- Phase 3 is the initial production phase. Initial operations to approach an annual production rate of 2 Kg/year are expected to take place over a period of 18 months. The operations phase consists of the production of deliverable targets. The 18-month initial production period anticipates potential start up inefficiencies. Subsequent production campaigns could be performed over 1-year periods.
- Phase 4 is transportation of the targets to the reactor.

The project schedule identifying the four phases is included as Figure 4-1.

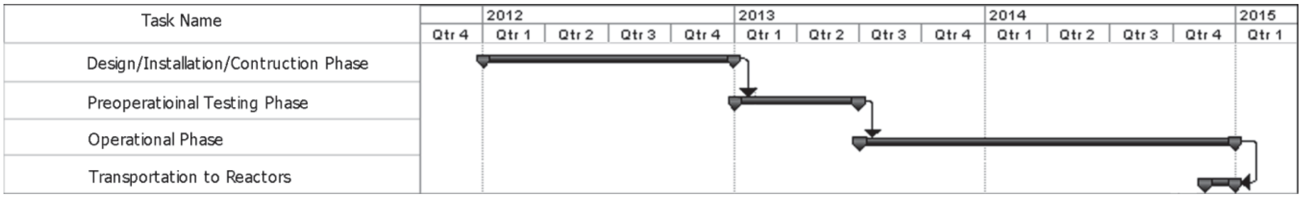


Figure 4-1. B&W project schedule.

Implementation of this option would require construction of additional facilities (as well as associated costs) to build the capability at ORNL to ship the recovered Np-237 oxide target material to B&W to continue the target manufacture. Initial estimates for setting up this operation are assumed to be similar to the estimates for transferring the Np-237 oxide from INL: $5.7 million within the first 3 years before shipment as well as $350,000 per year to cover packaging and shipping charges. In addition, DOE would have to secure a disposal pathway for the greater-than-Class-C TRU waste.

It is anticipated that greater-than-Class-C TRU waste would be generated if B&W fabricated the targets, and that the Department of Energy Office of Nuclear Energy (DOE-NE) would have to identify a pathway to dispose of the waste. Additional investigations and analysis would be needed to identify disposal options.

From a NEPA perspective, the additional mileage in shipping the neptunium from INL to B&W rather than to ORNL could be addressed in a supplemental assessment to the existing NEPA record. However, current NEPA documentation does not address transport of TRUs from B&W or shipments of neptunium from ORNL. These issues would require further investigation to determine an appropriate level of additional NEPA documentation.

4.2 SRS H-Canyon Facilities

The SRS produced all the Pu-238 used in radioisotope thermoelectric generators (RTGs) for deep space missions up to the Cassini Mission and, in the 1980s, had full Pu-238 production cycle capabilities, including:

- Neptunium recovery from irradiated uranium fuel rods (H-Canyon)
- Fabrication of Np-237 targets
- Irradiation of Np-237 targets (SRS reactors)
- Dissolution of irradiated Np-237 target material, separation and purification of Np-237 and Pu-238 product streams (H-Canyon frames process)
- Conversion of Np-237 and Pu-238 to oxide
- Recovery of primary Frames and HB-Line losses (H-Canyon frames waste recovery process)
- Pressing of Pu-238 oxide into general purpose heat source (GPHS) pellets and encapsulation into iridium metal claddings (235-F Facility)
- Recovery and purification of off-specification Pu-238/Np-237 or broken GPHS pellets (HB-Line scrap recovery, frame waste recovery).

SRS has since shut down or dismantled a number of these capabilities; however, the following capabilities and equipment still exist and could be put back into service if needed:

- Recovery and purification of off-specification Pu-238/Np-237 or broken GPHS pellets (HB-Line scrap recovery, frame waste recovery)
- Conversion of Np-237 and Pu-238 to oxide
- Dissolution of irradiated Np-237 target material, separation, and purification of Np-237 and Pu-238 product streams (H-Canyon frames process).

4.2.1 HB-Line Facility

The HB-Line Facility consists of three distinct processes: (1) the scrap recovery process, (2) the Np-237 oxide conversion process, and (3) the Pu-238 oxide process. These operations are located in Building 221-H at SRS. A brief description of each process is provided below.

Scrap Recovery Process

Scrap recovery process operations include opening, screening, size-reducing, and dissolving scrap. The initial scrap recovery process mission was to dissolve off-specification Pu-238 oxide or broken GPHS pellets and transfer to H-Canyon for recovery of the plutonium. The HB-Line Facility also contains a waste handling line that prepares contaminated items for TRU waste disposal and an analytical laboratory for analyzing samples.

Np-237 Oxide Process

The HB-Line Np-237 oxide process was designed to produce Np-237 oxide powder. Neptunium in solution was received from H-Canyon. The solution was then processed and rinsed with a decontamination wash to remove contaminants. Once washed, the neptunium was eluted as a concentrate. The neptunium concentrate was then precipitated, filtered, and washed. It was then converted to a dioxide. The neptunium dioxide product was then packaged for storage or shipment.

Pu-238 Oxide Process

The HB-Line Pu-238 oxide process was designed to produce Pu-238 oxide powder. The original mission for the Pu-238 oxide process was to receive purified Pu-238 solution from H-Canyon, precipitate the plutonium, and calcine the plutonium to form an oxide powder.

HB-Line Historical Process Production Rates

- Scrap Pu-238 was dissolved at a rate of ~3 Kg/month
- Np-237 was recovered, purified, precipitated, and calcined at a rate of ~20 Kg/month
- Pu-238 oxide was produced at a rate of ~ 2 Kg/month.

HB-Line Needed Modifications

Use of the HB-Line Facility for Pu-238 recovery would require the following modifications and upgrades:

- Documented safety analysis modifications

- Replace dissolvers
- Checkout/repair/replace chiller
- Upgrade distributed control systems
- Cleanout/decontaminate gloveboxes
- Replace glovebox glass panels as needed
- Replace instruments/probes
- Replace pumps, manual valves, and auto-valves
- Replace furnaces
- Procure product calorimeters and electrical standards
- Procure filter boats and screens
- Procure and install equipment for opening and sealing nuclear materials shipping containers
- Other preparations (e.g., training, procedures, emergency preparedness hazards assessment, fire hazards analysis, etc.).

4.3 INL Remote Analytical Laboratory

A preconceptual design study was performed to assess the Remote Analytical Lab (RAL), Building CPP-684, to fabricate neptunium targets for irradiation in ATR and HFIR and recover the Pu-238 from irradiated targets (INL 2011b). Applicable performance, design, documentation, project risks, and quality assurance requirements were identified within this assessment, and designs and layouts were prepared to determine the viability and cost of reconfiguring RAL to support this mission. Because RAL has been operating in support of other missions for the past 20 years, it would be necessary to remove existing equipment and modify or reconfigure the facility to meet target fabrication and Pu-238 production goals.

The RAL is a two story, metal-clad, steel-framed building constructed in 1984. It houses an analytical laboratory that contains a conventional chemical analysis laboratory, an analytical hot-cell, and a waste handling hot-cell. The first and second floors have approximately 7,600 ft^2 and 3,500 ft^2, respectively. The facility would have to be reconfigured to support processing of Np-237 oxide targets and Pu-238 oxide. The facility also contains approximately 1,400 ft^2 of warm laboratory space and 1,500 ft^2 of cold laboratory and office space.

One advantage of using RAL is that it is collocated with CPP-651, a facility certified for storage of Special Nuclear Material (SNM). No modifications to CPP-651 would be needed to support Np-237 oxide target and Pu-238 oxide storage needs.

The RAL functioned as a facility that processed radioisotopes and, as such, has regions that are radioactively contaminated. Efforts must be undertaken to decontaminate the facility, remove existing equipment no longer needed, and remove existing structures inside the facility to make room for new structures and equipment that would be installed once the facility interior decontamination and demolition are complete. The facility must also be reconfigured to support the identified neptunium target and Pu-238 oxide processing objectives.

5. CANDIDATE FACILITIES DISMISSED

The Team reviewed the various facility options identified in Tables 1-1 and 1-2 against the screening criteria identified in Section 1.1. The Team concluded that the decisions and rationale made at the time of the EIS remain valid for these facilities and was dismissed for further analysis in this report.

A number of other facilities or concepts not addressed in the EIS assessment (Table 1-2) were identified by the Team. Some of these facilities were not considered to be viable at the time of the EIS ROD and others have had some development work or studies completed since the ROD was published. These facilities are identified in Table 5-1. The facilities were dismissed from the more detailed assessment because they did not meet one or more of the screening criteria identified in Section 1.1. However, a more detailed description of the facility or concept and a Team assessment is provided in Appendix B for completeness.

Table 5-1. Candidate facilities dismissed.

Irradiation Facilities Dismissed from Further Consideration	Alternative Target Fabrication and Processing Facilities Dismissed from Further Consideration
High Temperature Gas Reactor	Liquid Target Loop and Online Processing
Molten Salt Reactor	Universal Target Design
Small Modular Reactor	
Commercial Light Water Reactor	
National Reactor Universal, Canada	
Annular Core Research Reactor, Sandia National Laboratories	
Accelerators	

6. ALTERNATIVE EVALUATION

The project alternatives that passed the screening process described previously were evaluated according to their relative merits in the following areas. The evaluation factors are listed in random order:

- Cost
- Schedule
- Risk to all project objectives, including initial startup, long-term availability, product quality, and future operating costs
- Environmental impact
- Worker and public safety
- Scalability
- Ability to function within a system evaluated according to the above criteria, if the alternative consists of system element(s).

Appendix D provides a more detailed list of items that were considered under the basic evaluation factors. Also provided in the appendix is a list of specific questions the Team developed to aid in understanding and evaluating the options as they pertain to the evaluation factors.

6.1 Proposed Pu-238 Production Options for Evaluation

The guidance provided to the Team led to considering a matrix of options (see Table 6-1). The Team toured specific facilities at INL, SRS, B&W, and ORNL, and held discussions with representatives from the various sites to understand better the options available and the sites' responses to the evaluation factors provided above. The following options are being considered:

Option 1a: Target fabrication and target processing at ORNL, irradiation at HFIR and ATR, neptunium storage at INL

Option 1b: Target fabrication at B&W facility, target processing at ORNL, irradiation at HFIR and ATR, neptunium storage at INL

Option 2a: Target fabrication and target processing at INL, irradiation at HFIR and ATR, neptunium storage at INL

Option 2b: Target fabrication at B&W facility, target processing at INL, irradiation at HFIR and ATR, neptunium storage at INL

Option 3a: Target fabrication at ORNL and target processing at SRS, irradiation at HFIR and ATR, neptunium storage at INL

Option 3b: Target fabrication at B&W facility, target processing at SRS, irradiation at HFIR and ATR, neptunium storage at INL

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Table 6-1. Proposed Pu-238 production options for evaluation.

Option 1a:	Target Fabrication and Target Processing at ORNL, Irradiation at HFIR and ATR, Neptunium Storage at INL
Summary	The Team considers the base case, which collocates the target fabrication and processing function at ORNL, to have the lowest installation costs, earliest schedule for achieving production status (by 2018), and lowest project risk of all the options considered. Collocation of these functions is very compatible with the TRU actinide mission ongoing at the ORNL REDC. Therefore, the program could be beneficial in maintaining and expanding core technical capabilities in this area, as well as retaining and attracting new staff for careers in actinide research, both of which will be critical to the future success of the program.
Cost	
Team Comments	• Because of the ORNL Team's work to develop and understand the cost basis and apply the appropriate levels of contingency to their estimates, the risk and uncertainty levels are well defined. • Few modifications or equipment design are needed in this option. • The Team expects the program to be able to respond to and adapt to changes in facilities or process technology for the duration of the project. Changes may be necessary to the target design and or product requirements depending on unknown future events (i.e., a change in the reactor driver fuel at ATR or HFIR). The Team considers that having a central location responsible for developing and implementing modifications is more cost efficient in executing program goals in a timely fashion than parsing out requirements to separate facilities. • Supporting the long-term viability of the program will require a cohesive, critical core of expertise. Given the limited scope of the program, it is unlikely that this critical mass of expertise can be maintained at more than one location. Pooling limited program resources also offers more diverse technical assignments and challenges, which is critical to attracting new talent.
Advantages	• ORNL is already the national resource for higher actinide research, development, and production. Collocating the Pu-238 production mission at ORNL offers the potential for cost savings and synergy with related programs. • ORNL has experience in TRU target development. • ORNL has existing processing equipment. • INL has storage facilities operational. • ORNL has begun developing targets for irradiation qualification and thus target production specifications and procedures. • ORNL has developed detailed information regarding facility modifications and process equipment. ORNL has identified areas of potential risk and has developed plans and testing to reduce development or implementation risk.
Disadvantages	• ORNL is a laboratory environment and may be challenged to transition to a production mission for annual production. Other facilities may be more cost-effective for mass production of targets. However, the lower product demand for the base case reduces the potential impact of this concern. In any event, the HFIR at ORNL or ATR at INL will be performing irradiations; thus, the laboratories will be involved in at least one or more of the process steps. • REDC is an established operational facility that does not easily accommodate changes to the process or facility layout.

Table 6-1. (continued).

Option 1a:	**Target Fabrication and Target Processing at ORNL, Irradiation at HFIR and ATR, Neptunium Storage at INL**
Schedule	
Team Comments	ORNL has been supporting the planning of this program for most of a decade. The test irradiation and processing plan currently being implemented will provide the technical basis for defining eventual production target requirements. Provided minimal “unknown-unknowns” are encountered, the Team has high confidence in the project baseline.
Advantages	• The ORNL schedule supports the irradiation of production targets by FY 2018 and initial processing of the targets to make Pu-238 oxide. • ORNL has developed a detailed schedule and identified development and testing needs.
Disadvantages	• It is unlikely that the ORNL could accelerate production of Pu-238 product earlier than FY 2018. • The Team is not confident that ORNL would be able to successfully scale-up production if required or recover the production schedule if a technical issue forced an operation shutdown.
Risk to All Project Objectives	
Team Comments	• The program as currently defined assumes use of the irradiation services of HFIR and ATR, which requires that ORNL develop and qualify a compatible target. • This approach imposes a production mission onto aging (e.g., ~50 years old) research reactors, which have historically had a variety of customers with varying requirements. There is no guarantee that the needs of new production mission would receive priority over those of an existing client.
Advantages	• ORNL has begun looking at process and facility risks and has identified a well thought-out methodology to reduce project cost and schedule risks. • ORNL is the center for TRU isotope production, with experience in target development, processing, and isotope recovery. Locating the mission at ORNL gives a high confidence in success at the 2 Kg/year product level.
Disadvantages	• ORNL indicated confidence in process capacity at the defined 2 Kg/year product level. However, for quantities higher than 2 Kg/year, ORNL indicated that uncertainty increased. Thus, the base case constrains DOE and NASA to a 2 Kg/year level. • One concern is the process represents a potential single point failure. The only means of mitigating this is to procure replacement hardware in advance, rather than waiting until a failure occurs. ORNL does have plans to procure replacement hardware, but this could be insufficient if a larger problem should occur in the cell. Overall, ORNL is a laboratory and not a production facility, which represents an inherent risk. • Because of the lack of excess capacity in REDC, a technical issue that halts production could compromise the ability to meet schedule at the 2 Kg/year product level.
Environmental Impact	
Team Comments	ORNL is the center for TRU isotope production for DOE. This mission would represent a significant jump in annual mass throughput. However, ORNL indicates that past target processing (e.g., curium targets from SRS) did involve comparable quantities of byproducts requiring treatment and disposal.

Table 6-1. (continued).

Option 1a:	**Target Fabrication and Target Processing at ORNL, Irradiation at HFIR and ATR, Neptunium Storage at INL**
Advantages	ORNL has a well-defined waste disposition pathway for all waste streams. ORNL has, through past operation, identified the disposition pathway for all products and byproducts expected with the implementation of this mission. Waste disposal pathways are in place and permitted. Collocating the target fabrication and processing functions at ORNL will reduce transportation of rejected targets and recycled neptunium recovered from reprocessed targets.
Disadvantages	The ORNL site has a small boundary area compared to Idaho or SRS. However, the physical separation has been analyzed and deemed adequate for the proposed activities.
Worker and Public Safety	
Team Comments	Purification of the neptunium would be within the capabilities demonstrated in the past at ORNL in association with the TRU actinide program. Fabrication of the neptunium targets would be functionally similar to past activities, but would require a scale up in volume produced. How this production activity would be integrated into a laboratory environment is unknown.
Advantages	• ORNL has established operation and processing procedures, operations, and emergency response support. • ORNL has an established review process for all stages of development (target fabrication, irradiation, and processing). • ORNL has professional staff experienced in the fabrication of aluminum-based actinide targets.
Disadvantages	ORNL is a laboratory environment, but will have to maintain industrial and radiological safety successfully in a production environment.
Scalability	
Team Comments	• The Team's impression is that the base case itself is inflexible to change. The available space in the REDC is allocated to the base target production rate; there is little or no room for expansion in processing capability. • Any significant changes to production capability would require the use of new floor space and processes.
Advantages	None specifically identified.
Disadvantages	• The available space in the REDC is allocated to the base target production rate; there is little or no room for expansion in processing capability.
Transportation/System Elements	
Team Comments	Collocation of the target fabrication and processing functions at ORNL would eliminate the transportation link for recycle of target rejects, and recycle of neptunium recovered from reprocessing.
Advantages	Collocation of the target fabrication and processing functions at ORNL would eliminate the transportation link for recycle of target rejects, and recycle of neptunium recovered from reprocessing.
Disadvantages	The base case assumes that neptunium storage will remain at INL; thus, all options have this disadvantage of a long transportation link. However, the defined product demand is low enough that several commercial shipments per year will suffice to provide the necessary neptunium feedstock for target production.

Table 6-1. (continued).

Option 1b:	**Target Fabrication at B&W Facility, Target Processing at ORNL, Irradiation at HFIR and ATR, Neptunium Storage at INL**
Summary	• The commercial and regulatory environment in which B&W operates may offer the potential for options that translate into program cost savings and no schedule impact. However, higher uncertainties in the cost estimate and unknown contingency assessments exist in the B&W estimate. Further study and analysis are needed to gain a better confidence in the cost, schedule, and associated risk estimates. With respect to life-cycle project costs, the overall savings of this alternative were judged by the Team to be minimal, within the uncertainty in the project costs. • B&W has proposed the elimination of the neptunium cleanup step prior to pellet fabrication. This step has the positive aspects of eliminating a wet chemistry waste stream. However, it can also result in the increase in radiation exposure to line workers in pellet fabrication. B&W operates to higher allowable worker exposure limits than ORNL, which makes this option possible. B&W is not penalized in the comparative ranking of options for proposing this option. However, direct consequences of each approach must be recognized. • The present staff has little experience with neptunium or neptunium contaminated with Pu-238; therefore, additional effort would be needed to train and qualify a Team that could enter into a safe, successful target production operation. • Additional studies would be needed to provide a better understanding of the cost basis and to determine if there are acceptable disposal pathways for all waste streams. Certain material streams might need to be returned to ORNL. This could include waste from neptunium purification and target rejects produced in the course of target fabrication. A clearer understanding would also help to ensure disposal of contaminated equipment and to avoid generation of legacy wastes. • Finally, Np-237 is currently treated as a byproduct material per the B&W NRC license; however, DOE treats the material as SNM. This would necessitate the establishment of special provisions requiring augmentation of the B&W accountability system to interface properly with the level of material accountability expected by DOE for receipt of the neptunium.
Cost	
Team Comments	• ORNL must develop target specifications before B&W can order equipment and develop processing techniques. • B&W offers two options: (1) with neptunium purification wet chemistry and (2) no neptunium purification with dry blending of oxides in targets. The elimination of the wet chemistry step offers the potential for some short-term savings. However, with respect to life-cycle project costs, the overall savings projected for eliminating purification were judged minimal, within the uncertainty in project costs. • The regulatory environment in which B&W operates may offer the potential for program cost savings without an impact on the overall project schedule. However, higher uncertainties in the cost estimate and needed contingency exist in the B&W estimate. Further study and analysis are needed to gain a better confidence in the cost and schedule estimates.
Advantages	• ORNL has installed processing equipment. • INL has operational storage facilities. • The option for eliminating the neptunium purification step offers the potential for a short-term reduction in costs associated with establishing the target fabrication line. • The facility modifications required to locate the project at the B&W facility appear to be minimal. • The B&W facility and management is tailored to production runs. Operating under a commercial NRC license provides greater flexibility

Table 6-1. (continued).

Option 1b:	**Target Fabrication at B&W Facility, Target Processing at ORNL, Irradiation at HFIR and ATR, Neptunium Storage at INL**
	and ability to lower unit costs than operating under DOE regulations.
Disadvantages	B&W had experience in the past with TRUs (e.g., fabrication of FFTF fuel); however, the current staff expertise appeared to center on materials examination and metallurgy. Costs would have to reflect the effort to hire and train a cadre of staff familiar with handling and processing TRUs.
Schedule	
Team Comments	• B&W presented a project schedule responsive to the project, indicating that a target fabrication line could be installed and operational in the required time. • Early target production using B&W is unlikely.
Advantages	• Operation under NRC license provides more flexibility to meet schedule challenges. • The facility modifications required to locate the project at the B&W facility appear to be minimal, and could likely be performed within the schedule. B&W indicated that modifications to operational permits for byproduct materials would be required, but could be handled at the state level and would be completed within the schedule constraints.
Disadvantages	Implementation would require target development by ORNL, and then characterization and specification of target requirements for the purpose of defining contractual terms for an outside party. A second set of validation testing would likely be required at both HFIR and ATR for targets manufactured at the B&W facility before starting production campaigns. Establishing contractual requirements with a second organization for target production would require additional time in the schedule.
Risk to All Project Objectives	
Team Comments	• B&W has TRUs experience (e.g., FFTF fuel production), but these facilities and missions are in the past. B&W health physics support expressed some concerns, indicating that B&W did not really understand the hazards associated with neptunium contaminated with Pu-238. The staff that developed the proposal appears to have technical experience primarily in materials-related research (fuel examination, metallurgy). The involvement of technical staff with experience in fuel fabrication (HFIR and ATR fuel) appeared minimal. The fuel production staff appeared to have minimal involvement in the proposal. B&W indicated that additional DOE support would be required to bring the proposal up to a standard that B&W management would stand behind. • There was some indication that fuel fabrication staff had a firm reluctance to introduce neptunium into the fuel fabrication areas; thus, the neptunium target line was proposed to go into a corner of the LTC building. The concern is that introduction of a neptunium processing line into a portion of the LTC may not be compatible with its historic mission, and may impact historical customers.
Advantages	B&W offers the potential to bring its resources in fuel fabrication to the program, with experience in a variety of fuel forms, and in producing production-level quantities of items to specified levels of quality.
Disadvantages	• B&W facility would require modifications to remove equipment and add ventilation. • B&W would be introducing TRUs into a facility not accustomed to such activity. The group believes this would add schedule risk to the project. • Introducing TRUs under NRC license may adversely impact other site operations if an event occurred, thus adding additional risk to the

Table 6-1. (continued).

Option 1b:	**Target Fabrication at B&W Facility, Target Processing at ORNL, Irradiation at HFIR and ATR, Neptunium Storage at INL**
	balance of other B&W plant operations. • B&W did not demonstrate any technical capability with respect to TRUs or to wet chemistry separation processes. • B&W link to operational support appeared minimal. • The discussions with B&W personnel lead the Team to question whether the neptunium project would be fully capable of tapping into the considerable B&W experience in fuel fabrication. The proposed target fabrication line would be physically isolated in an area that appears more related to metallurgy and material examination, which may impact the historical function and customers. Concerns were expressed at B&W that the present staff had little experience with neptunium or neptunium-contaminated with Pu-238. • The Np-237 is currently treated as a byproduct material per the B&W NRC license. However, DOE treats the material as SNM comparable to U-233. Special provisions would have to be put in place to require the augmentation of the B&W accountability system to interface properly with the level of material accountability expected by DOE for receipt of the neptunium.
Environmental Impact	
Team Comments	• B&W is uncertain if the waste from wet chemistry processing of the neptunium could fit within its current operational envelope for waste disposal. The option for return of process wastes (solutions, spent resin) needs further assessment to determine viability or the need for B&W to store the waste until a disposal pathway is established. • If B&W performed only the dry target fabrication option, it would not be in a position to deal with target rejects. The aluminum-neptunium oxide pellets would thus require a transportation route back to ORNL for disposition. ORNL flow sheets would have to be modified. The contractual arrangements between ORNL and B&W would have to address a return stream of target material that has not yet been quantified.
Advantages	None were identified over the base case.
Disadvantages	• B&W may require the return of waste streams and contaminated equipment, which would be difficult to authorize. • B&W may generate waste that may have to be stored at facility until a disposal pathway is developed. • The disposal of process wastes from B&W may require alternations to the site operating permit. Cleanup of the project upon completion (all boxes, etc.) and waste disposition would have to be determined. • There has been no public discussion of introducing TRUs back into the B&W facility.
Worker and Public Safety	
Team Comments	The regulatory environment in which B&W operates may offer the potential for program cost savings without an impact on the overall project schedule. Specifically, B&W has proposed the elimination of the neptunium cleanup step prior to pellet fabrication. This step may eliminate wet chemistry waste streams. However, it can also result in the increase in radiation exposure to line workers in pellet fabrication. B&W operates to higher allowable worker exposure limits than compared to ORNL, thus making this option possible. B&W is not penalized in the comparative ranking of options for proposing this option. However, there are direct consequences of each approach that must be recognized.

Table 6-1. (continued).

Option 1b:	**Target Fabrication at B&W Facility, Target Processing at ORNL, Irradiation at HFIR and ATR, Neptunium Storage at INL**
Advantages	The B&W option offers the potential to bring experience related to operating a fuel production line to the program.
Disadvantages	• The proposed B&W building was judged by the Team to be less robust than ORNL base case. • Implementation of the dry option (i.e., no neptunium purification) would likely translate into higher worker exposure for B&W workers when compared to DOE laboratories. B&W would still have the opportunity to improve on shielding based on operational experience. However, modifications subsequent to startup would be reflected in higher costs. Any worker exposure at B&W would still be within its operational limits. • There is a shorter/smaller boundary to public than the DOE laboratory options. • Additional transportation of rejects would be realized between B&W and ORNL.
Scalability	
Team Comments	If sited at B&W, the target fabrication function would be highly specified, in terms of product specification, quality, and quantity. The presumption is that the line would incorporate only such additional capacity that DOE was willing to contract for up front.
Advantages	None identified over the baseline.
Disadvantages	The presumption is that the target fabrication process at B&W would be highly specified with respect to quality and quantity. The initial perception of the evaluation panel is that this situation is more likely to introduce a production line with less flexibility than compared to centralizing activities at ORNL, especially if a change to the target specification was required.
Transportation/System Elements	
Team Comments	• As noted above, B&W may want to explore options to return certain material streams to ORNL. This could include waste from neptunium purification, and target rejects produced in the course of target fabrication. • B&W will require modification to the state license for byproduct materials; however, that is considered straightforward.
Advantages	The B&W facility is located relatively close to ORNL, when compared to the ORNL-to-INL link or ORNL-to-SRS link. In either case the volume of shipments is assumed to be within the use of commercial services.
Disadvantages	There may be the need to return certain material streams to ORNL. This could include waste from neptunium purification and target rejects produced in the course of target fabrication.

Table 6-1. (continued).

Option 2a:	Target Fabrication and Target Processing at INL, Irradiation at HFIR and ATR, Neptunium Storage at INL
Summary	Reconfiguring an existing INL facility for Pu-238 production offers a viable option of cost-effective delivery per Kg of product in addition to establishing a new facility dedicated to the Pu-238 project. Performing Pu-238 production at INL would combine existing facilities, security systems, and operations while supporting DOE's emphasis on consolidating nuclear material, increasing the security of nuclear material, reducing nuclear risks, and addressing issues surrounding the secure transportation of nuclear material. An all-INL option would reduce the number of times that material would have to be transported from one DOE site to another DOE site; however, it has higher costs and a longer schedule than the ORNL base case. These result primarily from (1) the need to clean up the proposed facility (RAL), and (2) the need to install new processing equipment. Also, the INL option would not allow production of Pu-238 by 2018. The remote location of the proposed INL site (RAL) offers better separation of the proposed activities from the public than other options. Further, the RAL hot cell environment should provide a high assurance of containment over the project life. The all-INL option eliminates the shipment of Np-237 oxide to an off-site location for processing into targets. On-site shipments would only be subject to on-site transportation requirements.
Cost	
Team Comments	The all-INL option has higher costs and a longer schedule than the ORNL base case. This results primarily from (1) the need to clean up the proposed facility (RAL), and (2) the need to install new processing equipment. (The base case program demand currently fits within the capacity of existing ORNL processing equipment.)
Advantages	• The program would acquire a dedicated facility for the activity proposed. • The annual production throughput could be higher, potentially reducing per-unit costs.
Disadvantages	Significant cost would go into facility preparation (i.e., cleanup from previous use).
Schedule	
Team Comments	INL has laid out a schedule that would allow for start of target fabrication in mid-FY 2018. Targets could be ready for irradiation in FY 2018, with irradiation complete at some point in FY 2019. Actual separation and recovery of Pu-238 would be presumed to begin following a cooling period of several months. Processing of the targets would begin no sooner than FY 2020.
Advantages	None identified over the baseline.
Disadvantages	• INL representatives indicate that it would be unlikely that the INL option could support an accelerated case (i.e., production 1 or 2 years earlier). This is driven primarily by the time currently estimated to clean up of RAL. • The INL schedule and availability to begin production would take longer than the base case. Some form of a DOE Order 413.3B process would be required for the modifications needed to establish target production and processing facilities at RAL. • INL options would not allow production of Pu-238 by 2018. • ORNL would have to develop targets and fabrication specification, and transfer technology to an alternate site.
Risk to All Project Objectives	
Team Comments	INL has experience in the separation and handling of TRUs, primarily from fuel cycle work in support of research reactor operations. INL also has extensive experience in chemical separations, primarily associated with reprocessing of naval fuels. However, INL has limited

Table 6-1. (continued).

Option 2a:	**Target Fabrication and Target Processing at INL, Irradiation at HFIR and ATR, Neptunium Storage at INL**
	experience in the preparation of TRU targets to support irradiation and operation of a research reactor in a materials production mode.
Advantages	INL has extensive experience in radiochemistry, reprocessing of irradiated fuels, and separation of products. INL is proposing the use of a shielded remote hot cell facility for processing, which would provide high assurance of containment. The facility proposed for use currently has no direct customers and would be dedicated to this program.
Disadvantages	• The facility proposed for use (RAL) has extensive contamination and will require cleanup for use. An unresolved question is whether unforeseen contamination could derail the proposed schedule for cleanup and refurbishment with new equipment. RAL is located in an area of the site slated for decommissioning. The cost of providing area infrastructure (security, utilities, etc.) may go up in the future. • The mission would not be directly related to historical site missions. This may tend to isolate the function within the laboratory organizational structure, and restrict opportunities for personnel advancement or attraction of new talent. • INL would be installing the fabrication and processing lines in a small footprint, limiting flexibility or expansion of the process if needed. • INL technical capability with respect to TRUs limited.
Environmental Impact	
Team Comments	The INL option would generate radioactive wastes for disposal associated with cleanup of the RAL facility.
Advantages	• The remote location of the proposed INL site (RAL) offers better separation of the proposed activities from the public than other options. (All options, however, are presumed to be within proscribed environmental requirements.) Further, the RAL hot cell environment should provide a high assurance of containment over the project life. • Collocation of major operations would likely lead to reduced transportation needs.
Disadvantages	The cleanup of RAL will produce waste streams not associated with other options. The waste should be low level, however, within the receipt limits of currently operational burial sites.
Worker and Public Safety	
Team Comments	• If target production and processing were implemented in RAL, the potential exists for a high degree of isolation from the public. • The down-side to concentrating all activities in one building is that contamination events or facility upsets could impact all facility operations.
Advantages	The use of the remote hot cell environment in RAL for target processing offers the potential for excellent isolation and worker shielding.
Disadvantages	Portions of RAL high radiation levels. Workers will take occupational exposure to clean up the RAL facility prior to modifications. A number of potential waste streams have been identified by INL that will be generated in the cleanup of RAL.
Scalability	
Team Comments	The Team's impression from INL Team members is that the RAL concept is limited to the ~2 Kg/year production scenario.
Advantages	None identified over the baseline.

Table 6-1. (continued).

Option 2a:	**Target Fabrication and Target Processing at INL, Irradiation at HFIR and ATR, Neptunium Storage at INL**
Disadvantages	The space in RAL appears to be highly constrained. The assumption here is that it constrains INL to the ~2 Kg/year option. The space within RAL for fabricating targets is also constrained. Little space would be available to explore alternate targets designs or fabrication.
Transportation/System Elements	
Team Comments	The all-INL option eliminates the shipment of Np-237 oxide from INL to any off-site location. On-site shipments would only be subject to on-site transportation requirements.
Advantages	Consolidating activities at INL, with neptunium storage also at INL, would reduce the impact of the transportation link.
Disadvantages	This option would have a longer route to HFIR for unirradiated and irradiated targets. However, the route to ATR could be proposed as the primary path over use of HFIR, reducing the transportation impact.

Table 6-1. (continued).

Option 2b:	**Target Fabrication at B&W Facility, Target Processing at INL, Irradiation at HFIR and ATR, Neptunium Storage at INL**
Summary	This option has higher costs and the schedule is longer than the ORNL baseline. The commercial and regulatory environment in which B&W operates may offer the potential for options that translate into program cost savings and no schedule impact. However, higher uncertainties in the cost estimate and unknown contingency assessments exist in the B&W estimate. While some advantages for additional space availability in RAL could be realized to offer additional flexibility or an increase in the available processing throughput, it does not significantly enhance option 2a. The same issues and concerns identified in option 1b would need to be addressed to understand the potential savings and associated program risks.
Cost	
Team Comments	This option combines the potential or reduced target fabrication costs at B&W with the projected higher up-front costs to ready RAL at INL. The costs would be driven by the costs to prepare and operate RAL. The costs would still be higher than the baseline option.
Advantages	None identified over the baseline.
Disadvantages	If INL only performs processing, the RAL will still require cleanup and removal of equipment for reuse. The total costs would still be higher than the baseline option.
Schedule	
Team Comments	The subjective conclusion of subject matter experts is that it would take longer to establish target fabrication operations at B&W. This option would be limited by the schedule at INL to ready RAL.
Advantages	Space utilization at INL may improve with the elimination of target fabrication.
Disadvantages	• Early schedule unlikely due to refit of RAL. • ORNL would have to develop target then transfer technology to alternate site. • INL would have to develop new process flow sheet and equipment. • B&W would require facility modifications, and RAL would require decontamination and contaminated equipment removal.
Risk to All Project Objectives	
Team Comments	• This option combines the programmatic risk associated with B&W with additional risk associated with cleanup and new construction at RAL. • B&W has experience in the past with TRUs (e.g., FFTF fuel production). However, these facilities and missions are the past. B&W health physics support expressed some concerns, indicating that B&W did not really understand the hazards associated with neptunium contaminated with Pu-238. The staff that developed the proposal appears to have technical experience primarily in materials-related research (e.g., fuel examination, metallurgy, etc.). The involvement of technical staff with experience in fuel fabrication (HFIR and ATR fuel) appeared minimal. The fuel production staff appeared to have minimal involvement in the proposal. B&W indicated that additional DOE support would be required to bring the proposal up to a standard that B&W management would stand behind.
Advantages	• Process facility at INL would be dedicated to the Pu-238 program. Space at B&W appears to be divorced from specific program uses. • The base case appears to use up the process capacity of the existing equipment at ORNL; use of RAL facilities may provide more availability to plutonium production and not have to compete for time from other committed project campaigns.

Table 6-1. (continued).

Option 2b:	**Target Fabrication at B&W Facility, Target Processing at INL, Irradiation at HFIR and ATR, Neptunium Storage at INL**
Disadvantages	• B&W would be introducing TRUs into a facility that currently does not have any. • B&W link to operational support appeared minimal. • Target fabrication operations at B&W may cause unintended constraints or impacts on other plant operations that are in close proximity to the proposed facility.
Environmental Impact	
Team Comments	The same aspects and comments identified in options 2a and 1b would apply for this option.
Advantages	The RAL facility is open for reuse with no impact on other programs.
Disadvantages	• B&W would be introducing TRUs into a facility not accustomed to such activity. • B&W may require the return of waste streams, which would be difficult to authorize.
Worker and Public Safety	
Team Comments	• This option combines the environmental impact of radioactive waste returns from B&W with the wastes associated with cleanup of RAL. • The regulatory environment in which B&W operates may offer the potential for options that translate into program cost savings. Specifically, B&W has proposed the elimination of the neptunium cleanup step prior to pellet fabrication. This step may eliminate wet chemistry waste streams. However, it can also result in the increase in radiation exposure to line workers in pellet fabrication. B&W operates to higher allowable worker exposure limits than compared to ORNL, making this option possible. B&W is not penalized in the comparative ranking of options for proposing this option. However, direct consequences of each approach must be recognized.
Advantages	None identified over the baseline.
Disadvantages	• There has been no public discussion of introducing TRUs back into the B&W facility. • Smaller boundary to public. • Additional transportation of rejects between B&W and INL. • Proposed B&W building judged less robust than ORNL base.
Scalability	
Team Comments	• This option combines the limited scalability of B&W with the limited scalability of the space limitations within RAL. • Additional effort is needed to better define the scope, schedule, and cost for the B&W proposal especially looking at increasing production or fabricating longer target rods.
Advantages	None identified over the baseline.
Disadvantages	• B&W would accept the target design from ORNL, with little apparent flexibility for subsequent development. • The space shown for INL and B&W appeared very limited, with little room for expansion.
Transportation/System Elements	

Table 6-1. (continued).

Option 2b:	**Target Fabrication at B&W Facility, Target Processing at INL, Irradiation at HFIR and ATR, Neptunium Storage at INL**
Team Comments	• There is a slight increase in transportation for rejects back to INL, but normal commercial transport is sufficient and no special vehicles are required. • B&W will require modification to the state license for byproduct materials; however, that is seen as straightforward.
Advantages	None identified over the baseline.
Disadvantages	• B&W has handled TRUs at this location in the past, but it has been several decades and the project required extensive remediation. • Compared to the baseline, there are inherent risks when shipping due to schedule delays or problems with shipping. Given the fact that the Nuclear Materials & Inspection Service group in the LTC has no experience in handling Np-237 or residual quantities of Pu-238 in the reprocessed Np-237 additional risk to the cost, schedule, and installation would be expected.

Table 6-1. (continued).

Option 3a:	**Target Fabrication at ORNL and Target Processing at SRS, Irradiation at HFIR and ATR, Neptunium Storage at INL**
Summary	• The SRS option has a proven historical record of processing Pu-238. All of the equipment and facilities remain in some form on the site. The SRS Team has high confidence that the separation function could be brought on line to operate within the cost and schedule timeframes provided to DOE. However, the costs are higher and the schedule would be longer relative to ORNL baseline option. The SRS cost is primarily the costs to re-establish the frames operation. The frames are already procured and on site. Predominate cost is associated with fabricating the jumpers needed to make the frames operational. Since H-Canyon is currently in operation, the program does not have to be burdened with the total cost of facility operation or waste disposal. • The H-Canyon and HB-Line have a limited projected lifetime. Current projects extend operations 7-8 years. Beyond that, projecting canyon lifetime and costs become more uncertain. • The capacity of the SRS equipment is large per the Pu-238 project needs (i.e., 2 Kg/month vs. 2 Kg/year). The capacity would be idle most of the year, with qualification runs required. The SRS option would be much better suited to an option with 20 Kg/year production rate or more. • All other evaluation factors are considered by the Team to be better or the same as the ORNL baseline option.
Cost	
Team Comments	This cost would be primarily the costs at SRS to re-establish the frames operation. However, since the frames are already procured and on site, the predominant cost is associated with fabricating the jumpers needed to make the frames operational. Since H-Canyon is currently in operation, the program does not have to be burdened with the total cost of facility operation or waste disposal.
Advantages	None identified over the baseline.
Disadvantages	• High costs relative to ORNL. The H-Canyon and HB-Line have a limited projected lifetime. Current projects extend operations 7-8 years. Beyond that, projecting canyon lifetime and costs becomes more uncertain. • The capacity of the SRS equipment is large per program needs (i.e., 2 Kg/month vs. 2 Kg/year). The capacity would be idle most of the year, with qualification runs required.
Schedule	
Team Comments	• A limiting factor is target development to get a production run of targets into the reactor by 2018. If target production occurs in 2018, the score is the same as the base case. The excess capacity represented by the SRS canyon would only be an advantage if target processing were delayed and larger batches of targets accumulated. Once initiated, the capacity of the canyon could rapidly consume any backlog, minimizing the potential for additional program delays in receiving product. • SRS has had the equipment in storage for years. The issues would be verifying that the frames are ready for installation, and that they can operate efficiently at the material levels proposed for the program. There is a relatively high level of confidence that SRS could complete re-installation of equipment in support of the proposed schedule.
Advantages	• If ORNL focused on target development and qualification, SRS could support earlier processing. • SRS has high confidence that the function could be brought on line within the proposed schedule. • Possibly better, if reduced ORNL mission accelerated target development.

Table 6-1. (continued).

Option 3a:	**Target Fabrication at ORNL and Target Processing at SRS, Irradiation at HFIR and ATR, Neptunium Storage at INL**
Disadvantages	The H-Canyon and HB-Line have a limited projected lifetime. Current projects extend operations 7-8 years. Beyond that, projecting canyon lifetime and costs becomes more uncertain.
Risk to All Project Objectives	
Team Comments	SRS has high confidence that the separation function could be brought on line and operate as advertised.
Advantages	• Separation factors and recovery fractions are well defined for SRS process. • SRS has a high degree of technical assurance in program success for reprocessing and recovery of product and recycle of neptunium with the SRS technology. • SRS has a high degree of technical assurance that neptunium recycle and plutonium product will meet programmatic expectations for purity, trace constituents, and minimal loss to waste. • SRS has equipment in storage that would require reinstallation and instrumentation. • SRS has high technical competence at SRS in TRUs. • This option would free ORNL process for higher-actinide program, and SRS process has demonstrated history of meeting Pu-238 needs.
Disadvantages	Limited projected life and large scale capability of the canyon makes an ill-fit with the proposed small annual production rate. SRS option would be much better suited to an option with 20 Kg/year production or more (e.g., with qualification of a target for commercial irradiation, and irradiation of 100 Kg/year or more of neptunium targets).
Environmental Impact	
Team Comments	The disposition paths for waste streams from processing at SRS are highly defined and operational. SRS has the only high-level waste system integrated with a waste vitrification system.
Advantages	Wastes from processing at SRS would be directed to the high-level waste system, with subsequent vitrification in the Defense Waste Processing Facility. The volume of wastes that would be generated is incrementally small compared to the waste volume already awaiting vitrification at SRS.
Disadvantages	None identified over the baseline.
Worker and Public Safety	
Team Comments	H-Canyon has operated for over 50 years with high assurance of safety to workers and the public.
Advantages	The H-Canyon environment provides a high degree of assurance that process materials will be maintained within the boundaries of the canyon, and that releases and exposure to workers and the public will be held to historically low levels.
Disadvantages	None identified over the baseline.
Scalability	

Table 6-1. (continued).

Option 3a:	**Target Fabrication at ORNL and Target Processing at SRS, Irradiation at HFIR and ATR, Neptunium Storage at INL**
Team Comments	The scale disadvantage of H-Canyon for the base case becomes an advantage when considering scalability. H-Canyon and HB-Line could accept material flows producing 2 Kg/month.
Advantages	SRS capacity in H-Canyon and HB-Line could readily accept scale-up of program demands by a factor of 10 or more (in excess of 2 Kg/month). This, however, would require consideration of neptunium target flows on the order of 100 Kg/year, which would exceed the capacity of DOE irradiation facilities assumed for the base case (HFIR and ATR). This would imply the development of a suitable target for commercial irradiation (i.e., Np-237 oxide clad in zirconium or stainless steel) and large-scale use of commercial reactors for target irradiation.
Disadvantages	Up-front program costs would be increased. However, such a program could provide DOE and NASA with an order of magnitude more plutonium over the next 5 years (i.e., 25 Kg vs. 7.5 Kg). While the initial costs would be higher, the Team thinks that this option should still be able to generate the product on a comparable or lower $/Kg basis. Further analysis is needed to verify this assumption.
Transportation/System Elements	
Team Comments	Transportation would be comparable to the base case. SRS, however, is experienced in the packaging and shipping of the Pu-238 product in oxide form.
Advantages	None identified over the baseline.
Disadvantages	None identified over the baseline.

Table 6-1. (continued).

Option 3b:	Target Fabrication at B&W Facility, Target Processing at SRS, Irradiation at HFIR and ATR, Neptunium Storage at INL
Summary	• The SRS option has a proven historical record of processing Pu-238. The commercial and regulatory environment in which B&W operates may offer the potential for options which translate into program cost savings and no schedule impact. However, the costs for this option are higher and the schedule would be longer relative to ORNL baseline option. The SRS cost is primarily the costs to re-establish the frames operation. • Higher uncertainties remain in the cost estimate and unknown contingency assessments exist in the B&W estimate. Further study and analysis are needed to gain a better confidence in the cost, schedule, and associated risk estimates. With respect to life-cycle project costs, the overall savings of this alternative were judged by the Team to be minimal, within the noise of the uncertainty in the project costs. • The H-Canyon and HB-Line have a limited projected lifetime. Current projects extend operations 7-8 years. Beyond that, projecting canyon lifetime and costs become more uncertain. • The capacity of the SRS equipment is large per the Pu-238 project needs (i.e., 2 Kg/month vs. 2 Kg/year). The capacity would be idle most of the year, with qualification runs required. The SRS option would be much better suited to an option with 20 Kg/year production rate or more. • Finally, the Np-237 is currently treated as a byproduct material per the B&W NRC license. However, DOE treats the material as a SNM comparable to U-233. Special provisions would have to be put in place to require the augmentation of the B&W accountability system to properly interface with the level of material accountability expected by DOE for receipt of the neptunium.
Cost	
Team Comments	This option is the same as option 3a with the exception that the target fabrication would be done at the B&W facility. The same findings and discussions found in options 1b, 2b, relative to utilizing the B&W facilities, and the 3a options remain valid for this option.
Advantages	The regulatory environment in which B&W operates may offer the potential for program cost savings without an impact on the overall project schedule.
Disadvantages	SRS will require significant up-front costs to re-establish the frames. Note that capacity of equipment is large per program needs (i.e., 2 Kg/month). The capacity would be idle most of the year, with qualification runs required. However, higher uncertainties in the cost estimate and needed contingency exist in the B&W estimate. Further study and analysis is needed to gain a better confidence in the cost and schedule estimates.
Schedule	
Team Comments	The limiting factor is target development to get a production into the reactor by 2018. As with option 3a, the excess capacity represented by the SRS canyon would only be an advantage if target processing were delayed and larger batches of targets accumulated. Once initiated, the capacity of the canyon could rapidly consume any backlog, minimizing the potential for additional program delays in receiving product.
Advantages	SRS could support earlier processing, provided a target could be qualified and sufficient material irradiated. The confidence that target fabrication could be initiated early at B&W is lower. The facility modifications required to locate the project at the B&W facility appeared to be minimal, and could likely be performed within the schedule. B&W indicated that modifications to operational permits for byproduct materials would be required, but could be handled at the state level and would be completed within the schedule constraints.

Table 6-1. (continued).

Option 3b:	Target Fabrication at B&W Facility, Target Processing at SRS, Irradiation at HFIR and ATR, Neptunium Storage at INL
Disadvantages	The disadvantages would be comparable to option 1b with respect to target fabrication.
Risk to All Project Objectives	
Team Comments	Risks would be the same as identified in options 1b and 3a.
Advantages	• Option may possibly be better than baseline option, in that separation factors and recovery fractions are well defined for SRS process. • SRS has equipment in storage that would require reinstallation and instrumentation. • High technical competence at SRS in TRUs. • SRS process has demonstrated history of meeting Pu-238 needs.
Disadvantages	B&W facility would require modifications to remove equipment, add ventilation. B&W would be introducing TRUs into a facility not accustomed to such activity.
Environmental Impacts	
Team Comments	Environmental assessment would be the same as identified in options 1b and 3a.
Worker and Public Safety	
Team Comments	Worker and public safety assessment would be the same as identified in options 1b and 3a.
Scalability	
Team Comments	Scalability assessment would be the same as identified in options 1b and 3a.
Transportation/System Elements	
Team Comments	• There is a slight increase in transportation for rejects back to SRS, but normal commercial transport is sufficient and no special vehicles are required. • B&W will require modification to the state license for byproduct materials; however, that is considered straightforward. • The distance between the B&W facility and SRS is considered a negligible factor compared to other option. • Other transportation/system assessment would be the same as identified in options 1b and 3a.

The site facilities and function associated with each option are identified in Table 6-2.

Table 6-2. Proposed Pu-238 production options for evaluation.

Function / Location	Options					
	1a	1b	2a	2b	3a	3b
Neptunium Target Fabrication/Modified ORNL Facility	◎				◎	
Irradiated Target Processing/ORNL REDC Facility	◎	◎				
Neptunium Target Fabrication/B&W Facility		◎		◎		◎
Irradiated Target Processing/SRS Facility					◎	◎
Neptunium Target Fabrication/Modified INL Facility			◎			
Irradiated Target Processing/Modified INL Facility			◎	◎		
Neptunium Storage/INL*	◎	◎	◎	◎	◎	◎
Target Irradiation/HFIR and ATR	◎	◎	◎	◎	◎	◎

*Cost analysis performed by INL for the storage and transport of Np-237 Oxide (INL 0211a) has shown that the most economical pathway for the project is to utilize the storage facilities at INL and ship neptunium to the designated fabrication site in a "just-in-time" or "as needed" manner. Therefore, the assessment did not address alternate storage options such as complete transfer of the Np-237 oxide to ORNL or SRS as no alternative indicated that cost savings would result.

6.2 Team Evaluation

Table 6-3 summarizes the Team's assessment. Each option was compared to the Baseline Option 1a using the evaluation factors discussed above. Detailed comments from the Team are captured in Table 6-1, where the option's advantages and disadvantages are identified as compared to the base option as well as the Team overall assessment of the option.

Table 6-3. Summary Pu-238 production options evaluation.

Evaluation Factors	Options					
	1a	1b	2a	2b	3a	3b
Cost						
Schedule					1	1
Risk to all Project Objectives		2		2	3	2
Environmental Impact			4		4	
Worker and Public Safety						
Scalability						
Transportation/System Elements			5			

1. Start of SRS will be dependent on completion of NEPA activities. However, target fabrication and irradiation in HFIR and ATR in a production mode could begin 2018. Because of the capacity of the SRS H-B Line, any initial delay in production schedule could be quickly regained within a short operational period.
2. Installing target fabrication and processing at B&W is judged to increase project risk in each case due to the facility upgrades needs and associated training for operational staff relative to the expertise at the national laboratories being considered.
3. All operations and procedures have been established and demonstrated. Sufficient capacity exists so that most normal or unplanned operational downtime events would be able to be handled without affecting long term production quantities
4. Facilities provide excellent containment and isolation of processes. INL and SRS sites have larger boundary areas to general public.
5. INL would have a reduced transportation link because the neptunium and ATR are all on one site.

Substantially Better	Marginally Better	Comparable	Marginally Worse	Substantially Worse

6.2.1 Summary Pu-238 Production Options Cost Evaluation

The Team developed life-cycle cost elements of the various options to provide some information for cost comparisons. The Team did not adjust any of the cost figures provided by the various candidate facilities, but are presented as provided by the facility option sponsor. The Team did provide some estimates on values when they were not provided by the facility estimate. It should be noted that options 1a and 2a do provide contingency in their cost estimates. The others do not include any contingency factors or costs in their estimate.

Comments were provided by the Team in the individual cost assessment sections for the option to provide some additional perspective regarding the cost evaluation.

Table 6-4 is a summary table showing a relative comparison of the initial project costs, operations cost, total project costs, and total life-cycle cost for the various options.

Table 6-4. Cost evaluation comparison for Pu-238.

Cost Categories	1a	1b	2a	2b	3a	3b
Initial Project Funding	$92,000					
Operations Cost	$25,000					
Total Project Cost	$1,540,000					
Total Life-Cycle Cost Discounted	$674,000					

Substantially Better	Marginally Better	Comparable	Marginally Worse	Substantially Worse

7. RECOMMENDATIONS

After reviewing the data and analyzing the options, the Team developed the following recommendation: The Team recommends continuing with Option 1a: "Target fabrication and target processing at ORNL, irradiation at HFIR and ATR, neptunium storage at INL." This option provides the lowest cost and lowest risk to the DOE. It also re-establishes Pu-238 production in the shortest time.

8. REFERENCES

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Appendix A

Team Makeup and Qualifications

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Wade E. Bickford
(803) 725-7346
Savannah River National Laboratory, Aiken, SC 29803

Summary

Mr. Bickford has over 35 years of experience in nuclear reactor safety, design, and nuclear materials stewardship. He entered the Reactor Physics Group at the Savannah River Laboratory in 1988, coming from an Advanced Reactor Concepts Group at the Pacific Northwest Laboratory at Hanford. His career has spanned topics ranging from reactor analysis and isotope production, to safety, thermal hydraulics, and materials disposition. Highlights are summarized below by position.

2005 – Present — Principal Technical Advisor, National Security Studies. Mr. Bickford provides intelligence analysis to DOE Office of Intelligence and Counterintelligence. The emphasis is on analyzing reactor technology for plutonium and tritium production capabilities. Support has also been provided to the International Atomic Energy Agency in safeguards analysis of heavy water research reactors.

1992 – 2005 — Advanced Planning and Analysis.

Pu-238 Program – Mr. Bickford has been the technical lead to coordinate exchanges with the Idaho National Laboratory on proposed Pu-238 options at INL. He has participated in the program design and options reviews at INL's request. Mr. Bickford was the principal author for complex-wide material management plans for highly enriched uranium, Np-237 and Pu-238, Pu-242, and Am-241. He coordinated input from experts at ORNL, LANL, Y-12, and INEEL. At LLNL request, he has examined options for large scale production of Pu-238, and use in denaturing weapons grade plutonium.

Legacy Special Target Materials – Mr. Bickford provided leadership to define physical characteristics and radiation histories for legacy special materials, including the Mk-18A, US1, and US2 targets. Information on disposition options has been coordinated with Oak Ridge National Laboratory.

Disposition of Highly Enriched Uranium – Mr. Bickford was the co-technical leader with Y-12 of a DOE complex-wide study for NNSA (NA-26) David Huizinga to determine options for ~40 metric tons of surplus highly enriched uranium (HEU) that does not meet commercial specifications (i.e., off-spec). Technical analysis demonstrating feasibility supported the successful program to down-blend off-spec HEU for use in commercial power reactors. Mr. Bickford has been a member of the monitoring teams which make on-site visits to Russia to verify the blend down of HEU.

1988 – 1992 — Reactor Physics and Thermal Hydraulics – Mr. Bickford supported initial conceptual work on the proposed heavy water new production reactor, and co-authored the SRL System Requirements Document for the new reactor. He also participated in thermal hydraulics code development and qualification while on assignment at Babcock and Wilcox in Lynchburg, VA.

1974 – 1988 — Battelle Pacific Northwest Laboratory, Senior Research Scientist, Advanced Nuclear Concepts Group – Mr. Bickford advanced through a number of positions from 1974 to 1988, with time off for graduate studies. This included an initial assignment in Fusion Systems, and a Nuclear Safety and Risk Analysis Section performing studies for the Nuclear Regulatory Commission.

Education/Professional

1973 B.A. Mathematics, Washington State University

1973 Phi Beta Kappa honorary

1977 M.S. Nuclear Engineering, University of Washington

1987 Licensed Professional Engineer (Mechanical)

David B. Lord

(208) 526-0706

Idaho National Laboratory, Idaho Falls, ID 83415

Summary

Mr. Lord has over 38 years of varied industrial experience primarily in project management, with special skills in long distance driving and copying and pasting from various documents. He came to the Idaho National Laboratory in 1990 after previously working in the electric utility, petroleum refining, and petro chemical industries. His career has ranged from maintenance of large chemical processing equipment, large construction projects to increase the efficiency of petroleum refining equipment, construction and planning of electric utility generating plants, and varied nuclear and non-nuclear infrastructure projects to support the research work at INL. Highlights are summarized below by position.

1990 – Present	Idaho National Laboratory, Project Manager, Infrastructure Projects. Mr. Lord provides project management support from initial planning studies through construction and final testing and turnover for a wide variety of projects to support the Nuclear Energy mission of INL. Pu-238 Program – Mr. Lord has been involved intermittently with the Pu-238 program since 2005 when the Argonne National Laboratory - West was merged into INL. At that time, Mr. Lord was named as the project manager for the proposed project to consolidate all of the Pu-238 production functions at INL. Land Mobile Radio Project – Mr. Lord is the project manager for a managed service contract to provide a P-25 compliant emergency radio system to INL's emergency response organizations as well as providing interface with cooperating outside agencies. Radiological and Environmental Sciences Laboratory – Mr. Lord is the project manager for the construction of a new RESL building. The RESL building is designed to meet LEED gold requirements. The facilities include radiochemistry, organic chemistry, inorganic chemistry, and instrumentation laboratories. The facility also houses shielded "iron rooms" made of pre-World War II steel for the low background required for radiological counting operations. EROB Data Center – Mr. Lord was the project manager to provide a modern data center capable of supporting current and near-term, INL high-performance computing (HPC) equipment. The data center includes the complex electrical power and HVAC systems to support the HPC equipment.
1980 – 1990	Alabama Electric Cooperative, Generation Projects and System Planning – Mr. Lord was the project manager for projects to rebuild the coal handling system at a major generating station, to rebuild a 1920s vintage hydroelectric plant, and numerous other generation facility projects. He was later in charge of the System Planning Department that included load forecasting, transmission planning, and generation planning. This included the planning, justification, and sizing for the only utility Compressed Air Energy Storage facility in the United States.
1978 – 1980	Exxon Company, USA, Refinery Projects and Support Operations – Mr. Lord was the project manager for a major upgrade to the refinery pipestills to increase the energy efficiency by recovering waste heat from the stack exhaust systems. He was also the mechanical support engineer for the refinery utility systems including upgrades to the refinery air and wastewater systems.
1974 – 1978	Dow Chemical Company, Technical Maintenance Group – Mr. Lord worked a s a mechanical engineer to provide technical services to analyze and correct problems with complex chemical plant processing equipment.

Education/Professional

1974 B.S. Mechanical Engineering, Auburn University

1974 Pi Tau Sigma, Tau Beta PI honoraries

1993 M.S. Mechanical Engineering, University of Idaho

1979 Licensed Professional Engineer (Mechanical)

James E. Werner
(208) 526-8378
Idaho National Laboratory, Idaho Falls, ID 83415

Summary

James Werner is a staff nuclear engineer with 24 years of experience in the Space Nuclear Systems and Technology development and advanced reactor design activities. He serves as Idaho National Laboratory program manager for the labs efforts in support of developing and testing space nuclear reactor technology for NASA and DOE. His current research interests include development and testing of high temperature fuels and materials, evaluation and design of high temperature liquid metal pumps and design and construction of test capabilities to support testing of reactor components and systems for the Fission Surface Power (FSP) project.

2004 – Present Serves as program manager for the In the Space Nuclear Systems and Technology Division for projects involved in developing and testing space nuclear reactor technology for NASA and DOE-NE. His current research interests include development and testing of high temperature fuels and materials, evaluation and design of high temperature liquid metal pumps and design and construction of test capabilities to support testing of reactor components and systems for the FSP project and production of Pu-238 material.

40 Kwe Fission Surface Power – Mr. Werner participation in the design and development on the 40 Kwe Fission Surface Power system. Tasks included design and fabrication of prototypic electro magnet pumps and test planning for fuels development and zero power critical testing. Mr. Werner also participated in the conceptual design of a 1-2 Kw Fission Power System.

Nuclear Thermal Propulsion – Mr. Werner lead the INL technology effort to recapture fabrication of high temperature CERMET fuel for NTR systems.

1988 – 2004 Director, Energy R&D Division, Office of Research and Development U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho. Mr. Werner has been actively involved in nuclear space system development. In the past he has served as the DOE Nuclear Engineer Division Manager, Energy R&D Division at the Idaho Operations Office during that time he served as:

Deputy Manager for the Jupiter Icy Moons Orbiter (JIMO) project. Tasks included planning and coordinating DOE laboratory support for the government trade studies as well as support NASA's procurement activities for an industry system design team. Supported DOE-NE 34 in development of JIMO design reference missions and coordinated DOE laboratory input into trade studies for a Nuclear Electric Propulsion systems.

DOE-ID lead for coordinating and providing input into Space Nuclear Thermal Propulsion. Activities included development and assessment of environmental impacts from doing ground tests on a Nuclear Thermal Reactor (NTR) system as well as contributing to development of a conceptual design of a ground test facility for NTR systems. Managed INEEL involvement and activities associated with the Space Exploration Initiative and Multi Megawatt Program.

Project Manager, NPR-MHTGR. Managed DOE laboratory and industry contract effort to design and test HTGR UCO fuel and tritium target using SiC – Triso-Carbide-coating technology.

Education/Professional

1978 Bachelor of Science, Nuclear Engineering, University of Arizona, Tucson, AZ

1979 System Safety Certificate DARCOM Training Center Texarkana, TX

1982 Licensed Professional Engineer (Mechanical)

Member, American Nuclear Society and Idaho Section of the American Nuclear Society

Chadwick D. Barklay
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University of Dayton Research Institute, Dayton, OH 45469

Summary

Dr. Barklay has 20 years of experience in conducting research for the U.S. Department of Energy (DOE), the Department of Defense (DOD), and NASA on metallic and ceramic materials. As an employee of Argonne National Laboratory-West, Idaho National Laboratory, and Mound Laboratories, Dr. Barklay was responsible for the assembly of encapsulated Plutonium heat sources into Fine Weave Pierced Fabric (FWPF) modules, which were further assembled into various types of Radioisotope Power Systems RPS units. Currently Dr. Barklay is responsible for leading the Advanced High Temperature Materials Group at the University of Dayton Research Institute. In this position he performs research, development, and testing on a number of materials based projects for various sponsors including DOE, DOD, NASA, and industrial partners. Highlights are summarized below by position.

2004 – Present University of Dayton Research Institute – Dr. Barklay is a Senior Research Scientist and Group Leader for the Advance High Temperature Materials Group. Dr. Barklay and his group provide technical expertise to DOE-NE Space and Defense Power Systems regarding technical materials related issues associated with the fabrication, testing, assembly, and disassembly of RPSs.

Pu-238 Program – Dr. Barklay has extensive experience in the determination of low-level neutron radiation effects on refractory materials. His research and development activities have supported many materials based technologies including ^{238}Plutonium dioxide fueled RPSs employed on various missions (i.e., Cassini, New Horizons, and the future Mars Science Laboratory mission); and identifying replacement materials for FWPF currently being used in the GPHS. Dr. Barklay also has extensive experience in the development, production, and shipment of radioisotope thermoelectric generators. In this capacity he has participated in multi-disciplined technical efforts with LANL, ORNL, ANL-West, INL, NASA-KSC, the Russian Mayak Productions Association, and various program contractors. He has consulted with DOE in a number of areas including the effect of radiation on the mechanical and physical properties of materials and the high-temperature interfacial reactions between materials.

Radioisotope Power Systems – Dr. Barklay served as the Chairman of the Preliminary and Final Design Review (FDR) Board for the Advanced Stirling Radioisotope Generator (ASRG) program, which were multi-disciplined process assessments to demonstrate that the maturity of the design of the system under review is ready for full-scale fabrication, assembly, integration, and testing.

2002 – 2004 Argonne National Laboratory – West/Idaho National Laboratory – Dr. Barklay was responsible for the relocation of critical Radioisotope Power Systems assembly equipment and processes from the DOE Mound Laboratory in Ohio to Argonne National Laboratory in Idaho. Additionally, Dr. Barklay had an instrumental role in the oversight of the procurement, packaging, and transportation of Russian plutonium procured by the Department of Energy (DOE), which was critical to the execution of future deep space exploration programs.

1988 – 2002 Mound Laboratory – Babcock & Wilcox, Lead Engineer, **Isotope Power Systems Program** – Dr. Barklay advanced through a number of positions from 1988 to 2002, which culminated with the responsibility for the assembly of encapsulated Plutonium heat sources into graphite modules that were further assembled into various Radioisotope Power Systems.

Education/Professional

1987 B.S. Materials Science Engineering, Wright State University

2004 M.S. Materials Science Engineering, University of Dayton

2007 Ph. D. Materials Science Engineering, University of Dayton

2008 M.A. National Security and Strategic Studies, Naval War College

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Appendix B

Dismissed Alternatives

B.1 Irradiation Facilities

The following facilities were dismissed for further consideration because they did not meet one or more of the screening criteria identified in Section 1.2.

B.1.1 High Temperature Gas Reactor

DOE is currently developing the technology and design and analysis tools for a High Temperature Gas Reactor (HTGR). Some of the distinguishing features of the HTGR are the coated fuel particle, helium coolant, graphite moderator, and high temperatures compared to other reactor concepts. These unique traits give the HTGR both advantages and disadvantages over other nuclear plant designs. In terms of advantages, the high temperatures enable the generation of high-quality process heat that has a number of industrial uses beyond electricity generation. HTGR designs use passive heat removal systems, protecting the reactor from accidents even in the event of prolonged station blackout. Many HTGR technologies and materials have been developed. Technologies such as helium coolant and coated fuel particles have been used extensively in HTGRs (i.e., Fort St. Vrain) in the past and are still being employed in HTGRs (i.e., HTR-10) today.

A full system design and an approved licensing process for the HTGR do not currently exist. As with many fuel cycles, reprocessing and long-term waste disposal do not have the same operational track record as fuel fabrication and reactor operation, and an initial demonstration unit or licensed reactor remains many years away. Also, significant investment and testing of an acceptable neptunium target would be required before any determination of cycle times, production rates, and quality of product could be ascertained – none of which would be compatible with current target designs.

Conclusion: While the HTGR system has received extensive development funding, it is years away from the demonstration stage. In addition, a completely new target design and target fabrication and processing facilities would have to be researched, designed, and developed, requiring both additional time and funding. Based on technical maturity, stage of development, availability, timeliness, and cost considerations, this alternative does not represent a credible option.

B-1.2 Molten Salt Reactor

Molten-salt reactors (MSRs), both fast and thermal spectrum, have been the subject of periodic investigations since the early 1960s. An experimental MSR operated at ORNL to research this technology through the 1960s; constructed by 1964, it went critical in 1965 and operated until 1969. Further investigations have not proceeded beyond high-level material balance, heat transfer, and chemistry exploration. While the principal concepts underlying MSRs have not changed over the years, much of the underlying technology base has evolved. Fast spectrum MSRs can be employed to consume actinides from LWR fuel or, alternatively, to extend fissile resource availability through uranium-to-plutonium breeding. MSRs can operate with salt processing and fuel addition taking place in either continuous or batch operations. For thermal-spectrum systems, it is important to remove the fission products from the salt to minimize the parasitic neutron capture that results from fission products with large capture cross sections. In a fast-spectrum system, these parasitic losses are lower because the fission-product capture cross sections are lower in fast-spectrum energy range.

MSRs have the potential for incorporating excellent passive safety characteristics. They have a negative salt-void coefficient (expanded fuel is pushed out of the core) and a negative thermal-reactivity feedback that avoids a set of major design constraints in solid-fuel fast reactors. Thus, a fast spectrum MSR can provide a high-power density while maintaining passive safety. The liquid state of the core also enables a passive, thermally triggered (melt plug) core draining into geometrically subcritical tanks that are passively thermally coupled to the environment. Fast spectrum MSRs have a low operating pressure even at high temperatures, and fast spectrum MSR salts are chemically inert, thermodynamically lacking the energetic reactions with environmental materials seen in other reactor types (e.g., hot zirconium or sodium with water). MSR technology with a thorium fuel cycle also offers attractive characteristics to destroy or transmute long-lived radionuclides, particularly TRU actinides, into short-lived isotopes. It also offers the capability during fuel processing of extracting the isotopes Pu-238 and Np-237 for further enhancement of the production of Pu-238 material.

This concept remains in the in the early proof-of-concept and conceptual stages. A full system design or approved licensing process does not currently exist. An initial demonstration unit or a licensed reactor remains many years away. Extensive research and demonstration efforts are also needed on the fuel processing technology – not only to meet acceptable design aspects but also to ensure acceptable proliferation resistance requirements. Also, significant investment, development, and testing of a Pu-238 production process would be required before any determination as to cycle times, production rates, and quality of product could be ascertained – none of which would be compatible with current target designs.

Conclusion: While MSR technology offers some potential advantages in producing Pu-238 to acceptable properties at a potentially cheaper unit cost, it is years away from the demonstration stage. In addition, a completely new approach to production design, irradiation calculations, and target fabrication processing facilities would have to be researched, tested, designed, and developed, requiring both additional time and funding. Based its technical maturity, stage of development, availability, timeliness, and cost considerations, this alternative does not represent a credible alternative to the 2001 through 2004 decision.

B-1.3 Small Modular Reactor

The DOE is currently investigating the technology and design and analysis tools for a small modular reactor (SMR). Nearer term SMR designs are variants of Generation III CLWRs. Distinguishing features of SMRs are the smaller size of the plant, which makes it possible to manufacture most of the vessels and systems in a factory and ship them to the operating site. Most near-term designs utilize the same or similar fuel types as existing LWRs.

Modification of SMRs to enable online insertion and retrieval of targets for Pu-238 production would require significant facility modifications to existing designs and would necessarily include penetrations into the reactor vessel. Additional facility modifications would be required to enable loading of the targets into a shielded cask for transport to a processing facility. Performing these facility modifications could require an extended refueling outage (with a resulting loss of power generation revenue to the SMR owner) and could potentially extend subsequent maintenance or refueling outages to inspect, test, and maintain the insertion and retrieval system, reactor vessel penetrations, and potential containment vessel penetrations.

Although some companies have begun early discussions with the NRC on the licensing process, no SMRs are currently being built. Significant investment and testing of an acceptable neptunium target would be required before any determination as to cycle times, production rates, and quality of product could be ascertained – none of which would be compatible with current target designs.

Conclusion: While SMR systems have received extensive development funding, construction of a demonstration plant is years away. In addition, new target designs for SMR reactors and new target fabrication and processing facilities would have to be researched, designed, and developed, requiring both additional time and funding. Based its technical maturity, stage of development, availability, timeliness, and cost considerations this alternative does not provide a credible alternative to the 2001 through 2004 decision.

B-1.4 Existing Commercial Light Water Reactors

Most pressurized water reactors operating in the United States are licensed to operate at thermal power levels of 2,500 to 3,500 megawatts for net station electric outputs of 800 to 1,200 megawatts electric. Since the primary mission of a CLWR is the production of electric power, Pu-238 production would have to be conducted on a noninterference basis. While no specific LWR was selected, irradiation tests of Np-237 targets were conducted at Connecticut Yankee Reactor owned by Connecticut Yankee Atomic Power Company in the 1970s[1]. The results of this study demonstrated that a stable neptunia containing target material could be fabricated and irradiated in commercial nuclear power reactors with no perturbation of reactor operation other than neutron consumption. Pu-238 is produced in these targets in sufficient concentration to project a reasonable cost for the recovered product.

The time and costs to develop and qualify a target design, demonstrate the process for plutonium and neptunium separation and the time to prepare and submit a license modification to the NRC would be significantly more than the project costs for the preferred option. In addition, some significant facility modifications would be required to enable loading of the targets into a shielded cask for transport to a processing facility.

Some additional supportive development effort would be required for the above program. This would entail further delineation of the fabrication parameters and a firming up of the conditions for the reprocessing. Development of an alternative target material that would be soluble in nitric acid is also needed. Existence of such an alternative would permit greater leeway in choice of reprocessing technology, and open up potential participation in the reprocessing operation to a large number of operators.

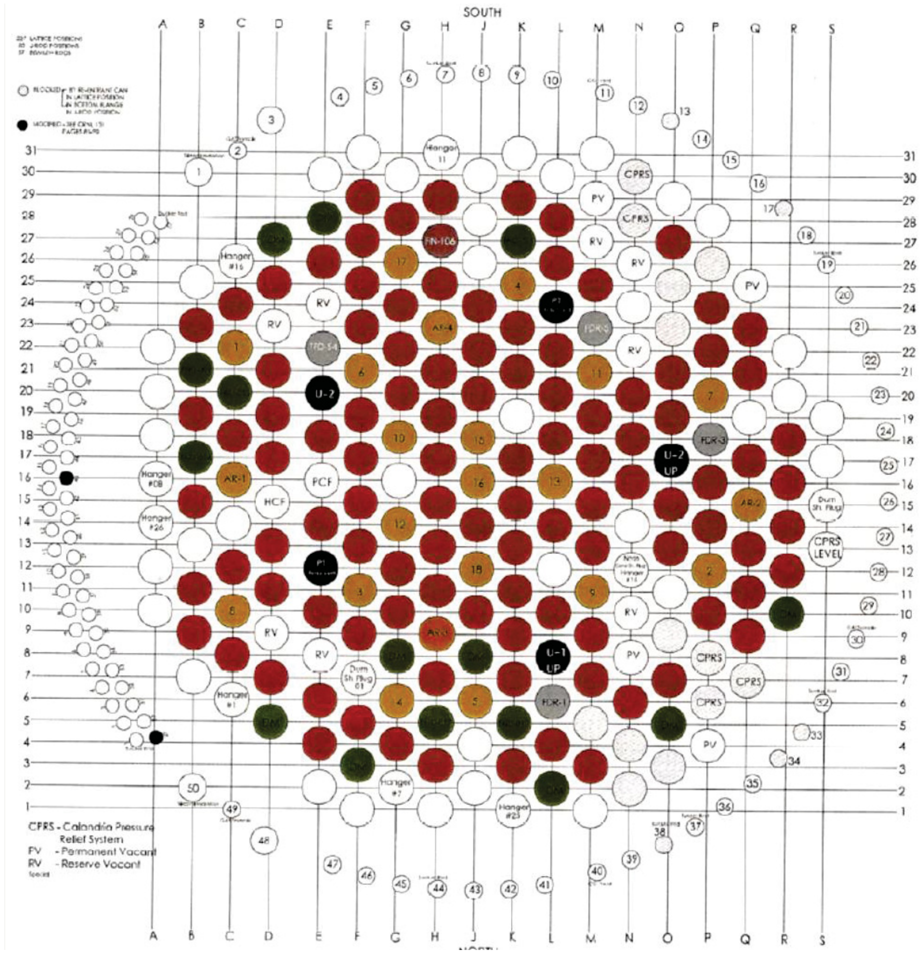
Conclusion: While CLWRs are available, a new target design would have to be developed. This would have to be consistent with existing processing capabilities in the DOE complex. Extensive license modifications and NRC review and approval would also be required. Based its technical maturity, availability, timeliness, and cost considerations this alternative does not provide a credible alternative to the 2001 through 2004 decision.

B-1.5 National Reactor Universal, Canada

The Canadian National Reactor Universal (NRU) is a large heterogeneous, high-flux, thermal-neutron research reactor that is heavy-water- moderated and cooled. It has many irradiation sites, including light-water cooled loops. The reactor is a large tank filled with heavy water contained in a vertical orientation along the driver fuel assemblies, various assemblies for isotope production, experimental sites, and control assemblies. There are 109 fuel assembly locations in the core (Figure B-1): 92 fuel rods generate 116 megawatts, six Mark 4 Fast neutron rods generate 5 megawatts, one Mark 7 Fast neutron rod generates 2 megawatts, and 10 Mo-99 production rods generate 2 megawatts. This represents a total of 125 megawatts. Eleven of these positions are reserved to isotope production assemblies; one of these assemblies is dedicated to I-125 production.

Past studies have indicated that the NRU could produce quantities of Pu-238 in the 1 to 5 Kg range, but it was not clear how many of the available irradiation positions would be needed. Because it is a low temperature system with a large thermal flux, it would appear that current target designs could be incorporated into the reactor with limited additional testing to validate the target. The facility must meet DOE safeguard and security requirements. However, information about additional safeguard and security requirements and additional facility improvements required to handle the receipt, storage, and shipment of unirradiated and irradiated neptunium targets is unknown.

[1] BMI-X-656, 1975, "Final Report Production of Pu-238 in Commercial Power Reactors Target Fabrication, Postirradiation Examination, and Plutonium and Neptunium Recovery," July 31, 1975.



Notation	Color	Significance
	Red	Fuel rod
DM	Green	Dummy rod
U-1, U-2, PT	Black	Loop sites
1 to 18	Tan	Control rods
AR-1, AR-2, AR-4	Tan	Cobalt adjuster rods
AR-3	Orange	Aluminum nitride adjuster rod
FN	Purple	Fast neutron rod
FND	Green	Fast neutron dummy rod
PCF	White	Pneumatic capsule facility
HCF	White	Hydraulic capsule facility
FDR	Grey	Flux detector rod
TFDR	Grey	Traveling flux detector rod
RV	White	Reserve vacant
PV	White	Permanent vacant
CPRS	White	Part of calandria pressure relief system

Figure B-1. NRU core configuration as documented in 2001, in the open literature.

It is known that NRU can receive highly enriched uranium (HEU). Factors such as mass and attractiveness levels of the physical and chemical form of the neptunium would need to be considered in the safeguard and security assessment. An analysis and determination must be made regarding any unreviewed safety questions (USQs) resulting from the introduction of the targets into the reactor.

Assessments of the reactors operating safety basis as well as any adverse environmental impacts from the larger quantities of neptunium and plutonium would also have to be performed and approved.

Transporting the unirradiated and irradiated neptunium targets into Canada would also require that DOE obtain an export license. The NRU produces a significant amount of medical and commercial radioisotopes, and initial estimates indicate that introduction of the neptunium targets in the NRU would adversely affect the reactor's current mission and production rates of other isotopes. The extent of the impact or the quantity of neptunium targets that could be added to the reactor without compromising existing commitments would have to be assessed. The NRU is licensed to operate only to the end of October 2016. The Canadian government would have to take action to extend its operating license beyond that point.

Conclusion: The NRU offers an alternative irradiation facility for potential Pu-238 production; however, it has a number of disadvantages as discussed above. Additional NEPA documentation, potentially including a new Environmental Impact Statement, could be required to address and bound potential environmental impacts. Considering factors such as timeliness and unknown additional risk factors associated with availability, impact to other missions, existing security, material handling capability, and potentially adverse costs, this alternative does not provide a credible enhancement over the 2001-04 decision.

B-1.6 Annular Core Research Reactor, Sandia National Laboratories

The Annular Core Research Reactor (ACRR) at Sandia National Laboratories (SNL) is a water-moderated, pool-type research reactor capable of steady-state, pulsed, and tailored transient operations. In the past, it has been configured for medical isotope production. Other duties for ACRR include reactor-driven laser experiments, space reactor fuels development, pulse reactor kinetics, reactor heat transfer and fluid flow, electronic component hardening, and explosive component testing. It is also routinely used for education and training programs.

Factors such as mass and attractiveness levels of the physical and chemical form of the neptunium would need to be considered in the safeguard and security assessment. An analysis and determination must also be made regarding any USQs as a result of the introduction of the targets into the reactor. Assessments of the reactor's operating safety basis as well as any adverse environmental impacts from the larger quantities of neptunium and plutonium would also have to be performed and approved.

Conclusion: Significant investments would be needed to make the ACRR a viable candidate for use in Pu-238 production. There are several other options that appear to be more economically viable and would produce more flexibility in providing irradiation services. Based on, cost, availability, timeliness, and limited production estimates this alternative does not provide a viable alternative to the 2001 through 2004 decision

B-1.7 Accelerators

The previous NEPA documents considered the use of both low-energy and high-energy accelerators in detail; no substantial changes to their status, availability, or assessment have since taken place.

Conclusion: No perceived improvements or enhancements would alter previous DOE decisions. In addition, a complete new target design and target fabrication and processing facilities would have to be researched, designed, and developed, requiring both additional time and funding. Based on technical maturity, stage of development, availability, timeliness, and cost considerations this alternative does not provide a credible enhancement over the 2001-04 decision.

B.2 Alternative Target Fabrication and Processing Facilities Dismissed

B-2.1 Liquid Target Loop and Online Processing

An alternative irradiation target option of flowing neptunium dissolved in liquid through a nuclear reactor, then separating the plutonium from other components in small, quantified batches using resin columns or some other separations technique has been proposed since the time of the NEPA studies. While some of these concepts show some promise of providing a higher quality product or potentially reducing infrastructure and operational costs, there are no test data to support their viability. All proposed concepts lack the technical maturity required for consideration as viable alternatives; significant R&D time would be needed to conduct to determine viability and associated construction and operational costs. Other factors such as impacts on reactor operating and safety basis, safeguards and security requirements, classification concerns, and other facility or support needs would also have to be understood.

Conclusion: While this novel irradiation target option offers some potential advantages, it is years away from a being demonstration as a viable alternative. A significant effort would be needed to understand both the irradiation characteristics and the separation process before a demonstration plant could be built to determine scaling factors. In addition, a complete new approach to production design, irradiation calculations, and target fabrication processing facilities would have to be researched, tested, designed, and developed. Finally either a new reactor or a complete redesign of an existing reactor would be needed to support a liquid target loop. Based on technical maturity, stage of development, timeliness, and cost considerations, this alternative does not provide a credible enhancement over the 2001-04 decision.

B-2.2 Universal Target Design

This option would include a target design suitable for a variety of irradiation environments (i.e., stainless steel versus aluminum clad). The irradiation source could be an existing or new DOE reactor, and/or access to commercial irradiation (e.g., thiobarbituric acid reactive substances [TBARS]). The target would need to be qualified for a variety of reactor options and be able to be incorporated into an NRC license. Techniques and head-end processes would need to be explored and developed to allow the use of existing processing and separation techniques.

Conclusion: While this alternative could be used in a variety of reactor systems, some basic research would be needed to comprehend the entire irradiation and processing sequence. This would include not only where the target could be placed within a reactor system, but also what processing facilities would be needed to dissolve and recover both the plutonium and the neptunium from the irradiated target rods. Target rods tested in commercial pressurized water reactors in the past have proven to be a viable method of producing Pu-238. However, very high concentrations of Pu-236 were in the recovered product material. Whether this can be reduced by placing the target in a different location in the reactor core or modifying the target design is unknown at this time.

Demonstration of a viable production alternative appears to be years away. Based on technical maturity, stage of development, timeliness, and cost considerations this alternative does not provide a credible enhancement over the 2001 through 2004 decision.

Appendix D

Alternative Evaluation Factors and Questions for Candidate Sites

D.1 Alternative Evaluation Factors

D.1.1 Cost

1. Total Project Cost Estimates: What is the estimated funding needed for engineering, construction, and start-up of a project?
2. Life-Cycle Cost Estimates: What is the estimated funding needed to support the project from start to completion, including construction, maintenance, and employees etc., calculated over 35 years?

D.1.2 Schedule

1. How much time is needed to establish production capability and then transition to a production mode generating Pu-238 fuel forms?
2. Is there an option to achieve an early production start (staying within existing NEPA coverage)?

D.1.3 Risk to all project objectives, including initial startup, long-term availability, product quality, and future operating costs

1. Process Technical Maturity: How developed is the process step for the production of Pu-238 fuel forms?
2. Uncertainty of Redevelopment: Are there unknown problems with reestablishing use of existing buildings, such as residual contamination, deviation from record drawings, undiscovered inadequate construction, and other undocumented conditions?
3. Complexity: What would be the ease of (re)establishing use of a building or buildings for Pu-238 production, and the degree of difficulty in performing a particular evolution?
4. Technical Staff: Are there adequate skills of staff in working with nuclear materials of similar high specific activity?
5. Dependence on Other Programs: Will the operations of other programs affect the implementation of Pu-238 production?
6. Production Flexibility: can the facility be used for other programs during or after use, or is the facility amenable to process improvements during the life of the program?
7. Negative Impact on Other Programs: Will the placement in a retrofitted facility impact existing programs, such as increased risk of contamination, displacement from facilities, or limited time in shared facilities?
8. Robustness of facilities: Is there any single point failure points; are the processes / systems fault tolerant; is there adequate operational support? Are there significant differences in the reliability factors of the processes / systems being proposed?

D.1.4 Environmental Impact

1. Waste (cost/schedule, stakeholder): Can waste be stored and processed on site, are existing facilities available to quantify, package, or treat all wastes generated?
2. Available Disposal Paths: Will there be legacy waste at the end of the program?
3. Stakeholder Acceptance: What is the likelihood that outside parties will be amenable to the production of Pu-238 at the facility (regulatory, public, DOE)?

D.1.5 Worker and Public Safety

1. Off-site Safety:
   - Public safety
   - Containment
   - Transportation safety.

It should be noted that for these key considerations, we will not attempt to quantify the actual on-site or off-site safety risks, but represent relative differences in risk inferred from the differences in consequences or probabilities between the various alternatives. All of the alternatives in this study have acceptable risks or they would not be included in the alternatives evaluation.

2. On-site safety:
   - Containment
   - Worker safety
   - Fire safety
   - As low as reasonable achievable (ALARA).

D.1.6 Scalability

1. Are the facilities flexible to accept changing program requirements?
2. What are the major limitations to the flexibility of the facility?
   - Equipment
   - Facility floor space
   - Transportation
   - Staff.
3. Is there flexibility among the facilities to allow for significant changes in production or processing?
4. Would there be any security considerations for SNM if the production were scaled up?
5. Are there waste processing limits if the production were scaled up?

D.1.7 If the alternative consists of system element(s), is its ability to function within a system evaluated according to the above criteria?

1. Transportation: Logistics of transportation, transportation safety is included in off-site safety?
2. Coordination of product / process?
3. If facility is dual use, what are risks of cross contamination?