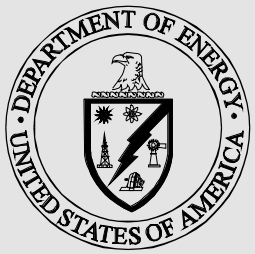
DOE/MD-0003 Rev. 1



Office of Fissile Materials Disposition

United States Department of Energy

Technical Summary Report For Surplus Weapons-Usable Plutonium Disposition

October 31, 1996

Rev. 1

FOREWORD

The *Technical Summary Report* presents the results of the Department of Energy's analyses of the alternatives for the disposition of surplus weapons-usable fissile plutonium. This report summarizes the alternatives that were considered and the results of the analyses of the technical, cost and schedule data to support the Record of Decision.

Additional information related to this document and the Fissile Materials Disposition Program can be found at the FMDP Internet site at:

"http://web.fie.com/htdoc/fed/doe/fsl/pub/menu/any/"

PREFACE

This report summarizes representative technical, cost, and schedule data for the reasonable alternatives being considered for the disposition of plutonium declared surplus to national security requirements in the *Storage and Disposition of Weapons-Usable Fissile Materials Draft Environmental Impact Statement* (Storage and Disposition PEIS). The original report (Revision 0) was issued on July 17, 1996 with a request for comments by August 31, 1996. A number of comments were received by the Department and the report revised in response to those comments. A companion report (*Summary Report for the Long-Term Storage of Weapons Usable Fissile Materials [Revision 0]*) was also issued in July 1996 to address technical, cost and schedule data on the long-term alternatives. It is also being revised in response to comments and will issued shortly.

The technical, cost and schedule data in this report will be considered in conjunction with the Storage and Disposition Final PEIS, and a nonproliferation study (*Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Materials Storage and Disposition Alternatives*) in making storage and disposition decisions. For this reason, it should be noted, that the Draft PEIS states disposition alternatives may be combined but does not specify the potential hybrids analyzed in this document.

Sidebars have been used to show where revisions of fact and data have been made to the original report, except for Chapter 6. This chapter is essentially all new material. Editorial changes were not marked.

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EXECUTIVE SUMMARY

ES.1 INTRODUCTION

The United States has declared 38.2 metric tons of weapons-grade plutonium surplus to national security needs.[1] Additional inventories of plutonium are expected to bring the total amount of plutonium that is surplus to approximately 50 metric tons.

To establish a framework for selecting plutonium disposition options which would achieve a high degree of proliferation resistance, the National Academy of Sciences (NAS) reviewed a number of options and concluded that the national objective should be to make the surplus "plutonium roughly as inaccessible for weapons use as the much larger and growing quantity of plutonium that exists in spent fuel from commercial reactors,"[2] a state the NAS defined as the *spent fuel standard*. The Department of Energy (DOE) has enhanced this statement to read:

> *DOE Spent Fuel Standard*
>
> A concept to make the plutonium as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in the spent fuel from commercial reactors.

The DOE enhancement makes explicit the concept of material attractiveness which was implicit in the NAS usage of the term. The spent fuel standard is not a specification-type standard. It encompasses a range of barriers which deter accessibility to and use of plutonium, including such barriers as a radiation field, dilution, inaccessible location, and size and weight. In the aggregate, these barriers achieve a degree of inaccessibility and a difficulty of extraction of the plutonium comparable to that of plutonium in "typical" commercial spent fuel. Once having achieved the spent fuel standard, the formerly weapons-usable plutonium is rendered no more attractive for use in nuclear weapons than the much larger and growing inventory of plutonium in commercial spent fuel.

Building on the NAS work, the DOE completed a *screening process* in March 1995[3] in which a large set of proposed, conceptual options for the disposition of plutonium were evaluated. The options that remained after the screening process were identified as

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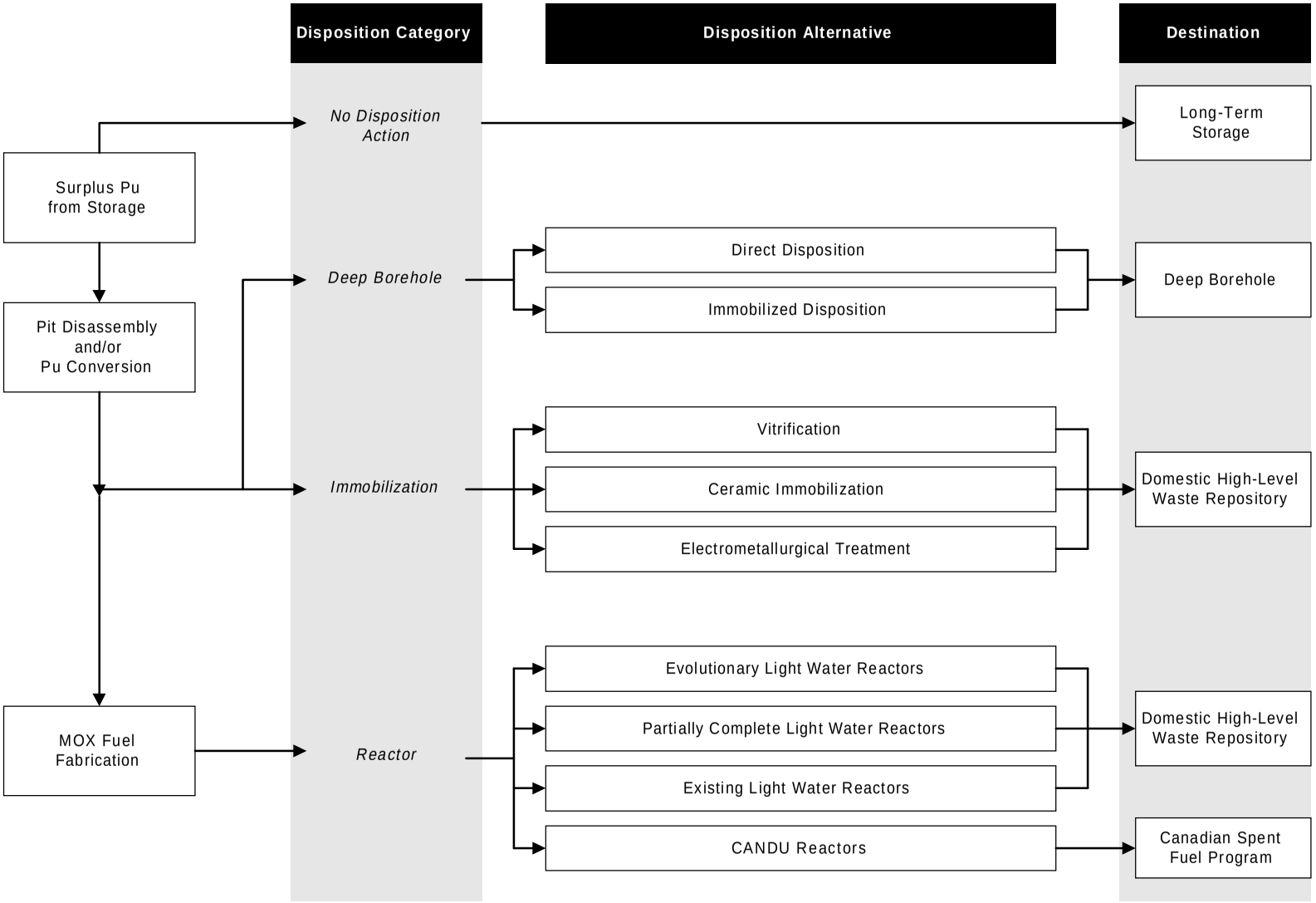
[1] President Clinton's March 1, 1995, Address to the Nixon for Peace and Freedom Policy Conference and the Department of Energy Openness Initiative, February 6, 1996.

[2] National Academy of Sciences, Committee on International Security and Arms Control, Management and Disposition of Excess Weapons Plutonium, National Academy Press, Washington, DC, 1994.

[3] U.S. Department of Energy, DOE/MD-0002, "Summary Report of The Screening Process, March 29, 1995. Referred to as "The Screening Report" in this document.

Figure ES-1. ***Surplus Plutonium Disposition Alternatives***



reasonable alternatives and have been analyzed for environmental impacts in the Draft Programmatic Environmental Impact Statement (PEIS)[4].

As shown in Figure ES-1, the reasonable alternatives fall into three categories or combinations of them: reactor, immobilization, and deep borehole (also known as direct geologic disposal) or combinations of them. In the *reactor alternatives*, plutonium is used as a fuel source for commercial reactors, resulting in the residual plutonium being incorporated in highly radioactive spent fuel assemblies. In the *immobilization alternatives*, the plutonium is fixed in various matrices in large canisters that also contain highly radioactive material. In the *deep borehole alternatives*, the plutonium is emplaced at depths of several kilometers. In all three categories of alternatives, barriers are created to make recovery and reuse of the plutonium difficult; however, the nature of the barriers to recovery and reuse vary with the category of alternatives. The definitions and understanding of how the reasonable alternatives might be implemented has matured since the screening process and since the Draft PEIS as additional engineering information has become available. The alternatives and variants discussed in this report are listed in Table ES-1 and described in detail in Chapter 2.

Table ES-1. ***Alternatives and Variants Analyzed in this Report***

Disposition Category	*Alternatives*	*Variants**
Reactor	Existing Light Water Reactors	1. Existing Light Water Reactors using Greenfield Facilities 2. Existing Light Water Reactors using Existing Facilities
	Partially Complete Light Water Reactors	None
	Evolutionary LWRs	None
	Canadian Deuterium Uranium Reactors (CANDU)	None
Immobilization	Vitrification	1. Greenfield Glass 2. Adjunct Melter 3. Can-in-Canister
	Ceramic	1. Greenfield Ceramic 2. Can-in-Canister
	Electrometallurgical Treatment	None
Deep Borehole	Direct Emplacement	None
	Immobilized Emplacement	None
Hybrid†	Existing Light Water Reactors with Immobilization Can-in-Canister	None
	CANDU Reactors with Immobilization Can-in-Canister	None

* For an alternative which has no variants, the terms "variant" and "alternative" are used synonymously.

† Hybrid alternatives combine two or more technologies for accomplishing plutonium disposition.

[4] U.S. Department of Energy, DOE/EIS-0229-D, "Storage and Disposition of Weapons-Usable Fissile Materials, Draft Programmatic Environmental Impact Statement," February 1996.

ES.2 TECHNICAL VIABILITY

ES.2.1 Technical Summary

Though each of the alternatives appears to be technically viable, each is currently at a different level of technical maturity. There is high confidence that the technologies are sufficiently mature to allow procurement and/or construction of facilities and equipment to meet plutonium disposition technical requirements and to begin disposition in about a decade.

ES.2.2 Common Technologies

Technologies common to most alternatives (safeguards and security, plutonium chemical and mechanical processing, existing infrastructure, licensing, transportation and packaging, and the high-level waste repository) generally are not significant discriminators among alternatives, but the following points apply:

- *High-level Waste Repository.* The CANDU reactor and deep borehole alternatives do not depend on a U.S. high-level waste repository and thus are unaffected by U.S. repository actions in contrast to the other reactor and the immobilization alternatives. While existing statutes permit consideration of MOX spent fuel for disposal in a high-level waste repository, immobilized disposition forms may require authorizing legislation, NRC rule-making, or other actions prior to such consideration.
  - The waste forms from the plutonium disposition immobilized alternatives have a higher actinide content than the immobilized high level waste form presently being considered for the high-level waste repository.
  - The MOX spent fuel from reactor irradiation for plutonium disposition is similar to low enriched uranium spent fuel already considered for the repository.
  - The spent fuel generated by the existing light water reactor alternatives would replace the equivalent low enriched uranium spent fuel that otherwise would have been generated.

- *Plutonium Processing.* Plutonium processing, which is the recovery of plutonium from surplus weapons components and surplus plutonium-bearing materials and conversion to forms (usually oxides) suitable for further disposition actions, is a significant fraction of the technical effort required to render the plutonium to the spent fuel standard. For some alternatives, the cost for plutonium processing is as great as all of the other operations combined; additionally, in many alternatives, the time required for the extraction and conversion processes limits the start of the plutonium disposition mission.

ES.2.3 Reactor Alternatives

Existing light water reactors can be readily converted to enable the use of MOX fuels. Many European light water reactors operate on MOX fuel cycles and at least three companies are actively involved in MOX fuel fabrication. Although some technical risks exist for the alternative, they are all amenable to engineering resolution.

The MOX fuel cores which are currently operating in Europe are partial cores. The cores analyzed in this report are full core MOX fuel cycles. Full core MOX fuel designs were selected to complete the disposition mission faster with fewer reactors. The full core MOX fuel designs can be implemented with or without integral depletable neutron absorbers, where the absorbers provide enhanced plutonium throughput capability but require an extensive fuel qualification demonstration program. For cores not using integral neutron absorbers, there is no substantial difference between partial versus full core MOX fuel cores for fabrication; the differences will reside in reactor performance since additional analyses will be required to confirm the adequacy of the new full core MOX fuel designs.

CANDU reactors appear to be capable of operating on MOX fuel cycles, but this has never been demonstrated on any industrial scale. Therefore, additional development is required to achieve the level of maturity for the CANDU reactors as exists for light water reactors.

The *partially complete* and *evolutionary light water reactor* alternatives are similar to the existing light water reactor alternative, except that the reactors need to be completed or built, respectively, and the core designs would differ somewhat. There is more technical risk for these alternatives, relative to the existing light water reactor alternative. The increased technical risks are due to two factors, namely: (1) the partially complete and evolutionary reactor alternatives core designs both require integral neutron absorbers—a novel MOX fuel technology not currently in use—to perform the mission with only two reactors; and (2) there are inherent uncertainties associated with completing or building reactor facilities. These reactors would generate additional spent fuel above that for existing light water reactors.

ES.2.4 Immobilization Alternatives

All of the immobilization alternatives will require qualification of the waste form for the high-level waste repository.

All *vitrification* alternatives require additional research and development prior to implementation of immobilization of weapons-usable plutonium. However, a growing experience base exists relating to the vitrification of high level waste. These existing technologies can be adapted to the plutonium disposition mission, though different equipment designs and glass formulations will generally be necessary.

The facility requirements for *ceramic* immobilization are generally similar to those for vitrification. Vitrification and ceramic immobilization alternatives are similar with regard to the technical maturity of incorporating plutonium in their respective matrices. Ceramic

immobilization offers the potential for superior plutonium confinement over geologic time frames.

The technical viability of the *electrometallurgical treatment* has been demonstrated for treatment of spent nuclear fuels, but has not yet been fully established for the plutonium disposition mission. The experimental data base for the alternative is limited, and critical questions on waste form performance are not yet resolved. This alternative is considered practical only if the underlying technology is developed.

ES.2.5 Deep Borehole Alternatives

The most significant uncertainties for the deep borehole alternatives relate to selecting and qualifying a site and to obtaining the requisite licensing approvals. These uncertainties can be resolved but will first require a mandate. The front-end feed processing operations for the deep borehole alternatives are much simpler than for other alternatives because no highly radioactive materials are processed, thus avoiding the need for remote handling operations. Emplacement technologies are comprised of largely low-technology operations which would be adaptations from existing hardware and processes used in industry, requiring only a system integration of the various components for this application. One of the chief safety advantages of the deep borehole alternatives is their ability to isolate plutonium from the biosphere on geologic time scales.

ES.2.6 Hybrid Alternatives

Two hybrid alternatives were considered as examples of how different technologies might be combined to effect disposition of all the nation's surplus plutonium. Since hybrids combine technology from different categories that were deemed technically viable, both hybrid alternatives are technical viable. The hybrid alternatives benefit by combining the strengths of two different technology approaches and thus provide robustness since they provide a dual path for implementing plutonium disposition.

ES.3 COST SUMMARY

The variants discussed in this report are based on pre-conceptual design information in most cases. As such, large uncertainties in the point estimates for cost and schedule estimates provided in this report apply. The key parameters that drive the uncertainties are identified explicitly in Chapters 4 and 5 for the cost and schedule estimates, respectively. These parameters include: *for all alternatives:* how will the alternatives develop and comply with regulatory and oversight requirements and how will front-end plutonium processing be configured (existing facility, co-located, or new facility); *for reactor alternatives*: how many and what kind of reactors will be used, what core management strategies are adopted, and what are the business arrangements for implementation; *for immobilization alternatives*: what are the material throughputs and facility schedules and how will waste form processing and qualification proceed; *for deep borehole alternatives*: how will site selection

and qualification be accomplished. Quantification of some key uncertainties is provided in Chapter 6.

Two figures of merit are important for summarizing cost impacts: investment costs and life cycle costs. These data are provided in Figures ES-2a and ES-2b for constant dollar (undiscounted) and discounted dollar costs, respectively.

Some of the important investment-related conclusions from this study are:

- Alternatives which utilize existing facilities for plutonium processing and immobilization or fuel fabrication are less expensive than building new facilities for the same functions.
- The investment costs for existing reactor alternatives tend to be about $1 billion;[5] completing or building new reactors increases the capital commitments by several billion dollars.
- The investment costs for using existing facilities for immobilization are less than or approximately $1 billion; building new facilities for immobilization increases the investment cost significantly.
- Hybrid alternatives require a small increment in investment over the existing reactor cases alone.
- Investment costs for the deep borehole alternatives are greater than $1 billion.

Some of the important life cycle cost conclusions are:

- The can-in-canister alternatives are the most attractive alternatives for immobilization based on cost considerations.
- While there is a credit for the low enriched uranium and natural uranium fuel displaced in existing light water reactors and CANDU reactors, the combined investment and operating costs for MOX fuel are higher than for commercial uranium fuels; thus, the cost of MOX fuel cannot compete economically with low enriched uranium fuel for light water reactors or natural uranium fuel for CANDU reactors.

[5] For convenience, text commentary is expressed in constant 1996 dollars unless otherwise noted.

Figure ES-2a. ***Investment and Operating Costs for Baseline Alternatives (constant $)***[1]

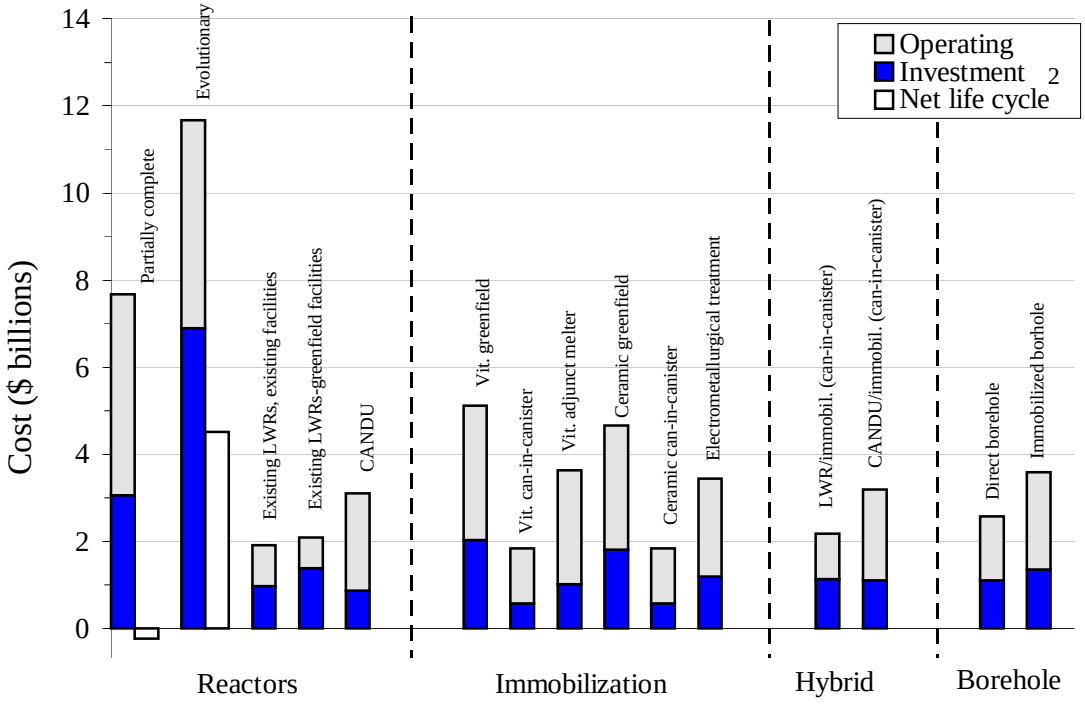
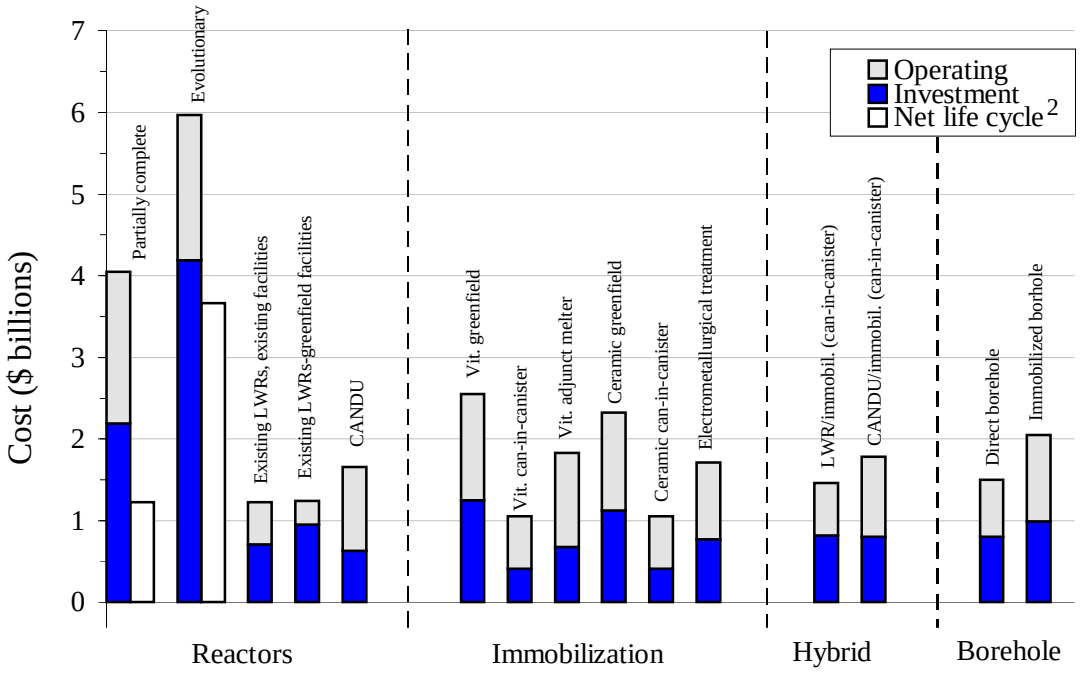


Figure ES-2b. ***Investment and Operating Costs for Baseline Alternatives (discounted $)*** [1]



[1] The costs are for base case estimates as defined in Chapter 4. Chapter 6 identifies a series of cost uncertainty factors and provides a quantitative estimate of them for many of the alternatives.

[2] For the net life cycle costs of the evolutionary and partially complete reactor alternatives, electricity is sold at $0.029/kWh with all revenues assumed here to accrue to the government. No acquisition cost or salvage value for the reactors are included. Alternative assumptions are considered in Chapter 6 .

- A large fraction of the life cycle cost for plutonium disposition is the extraction of plutonium from pits and other plutonium-bearing materials.
- The deep borehole alternatives are more expensive than the can-in-canister and existing light water reactor, existing facilities alternatives. The immobilized emplacement borehole alternative is especially expensive with a $1 billion premium over the direct emplacement alternative.
- The sensitivity to the assumed discount rate (here assumed to be 5% in real terms), while not trivial, is small in comparison to the inherent uncertainties in the cost estimates.

Among the reactor alternatives there are two that have the potential to realize revenues: namely, the partially complete and evolutionary light water reactors.

For the partially complete and evolutionary reactor alternatives, revenues will accrue to the owners. The gross amount of revenues are incorporated in the net life cycle costs in Figures ES-2a and ES-2b. The extent to which they might impact net plutonium disposition mission costs to the government are shown, assuming all revenues accrue to the government. Depending on the business arrangements, actual impact on overall cost may vary significantly, as discussed in Chapter 6.

Regarding evolutionary reactors, the Department in its Record of Decision on Tritium Production did not choose to construct new reactor(s) for tritium supply. Rather, the Department chose to pursue a strategy of evaluating (1) using existing commercial light water reactors and (2) construction of a linear accelerator.[6] Subsequently, the Department issued a request for expressions of interest for tritium production that also solicited interest regarding the future potential use of mixed oxide fuel from surplus weapons plutonium either coincident with or separate from tritium production.

Through the initial responses to the request for expressions of interest, the Department was able to determine that there appears to be sufficient commercial interest in use of existing light water reactors for plutonium disposition mission alone and/or in a joint mission of tritium production and plutonium disposition. The use of existing reactors would be subject to formal procurement procedures and business negotiations, including the fees, if any, which the utilities would charge for irradiation services.

ES.4 SCHEDULE SUMMARY

Table ES-2 summarizes the schedule information and as noted in ES.3, significant uncertainties also apply to the schedules for implementation. Chapter 6 discusses some of the key schedule uncertainty factors. Some of the key conclusions from this study are:

[6] DOE News Release, October 10, 1995.

- When using European MOX fuel fabrication capacity for LWR and CANDU reactors, ensuring an adequate supply of plutonium oxide is the rate-limiting step. For the other existing reactor variant and the partially complete reactor alternative, availability of MOX fuel is the rate-limiting step. For the evolutionary reactor alternative, the availability of a reactor is limiting.
- The can-in-canister variants can use available plutonium materials (oxides) and pilot immobilization equipment and begin pilot plant (1.25 MT/yr) operation in seven years.
- For the deep borehole alternatives, obtaining the siting approvals is the rate-limiting step. The time to start disposition for borehole alternatives is estimated to be ten years and the nominal disposition period is ten years. However, once in operation, the borehole alternatives offer the possibility of completing plutonium disposition very quickly, possibly in as few as three years after start-up.
- Hybrid alternatives have important schedule advantages in that the immobilization leg can be initiated in as little as seven years, operational flexibility is retained, and a back-up contingency capability is built in if one of the technologies were to fail or be delayed. The mission could also be shorter using both immobilization and reactor technologies than that of either of the technologies separately, if desired.

ES.5 SUMMARY OF ADVANTAGES AND DISADVANTAGES

Table ES-3 identifies some of the key technical, cost, and schedule advantages and disadvantages of the alternatives analyzed.

Table ES-2. *Disposition Schedule Summary*

	Time to start (yrs)[1]	*Time to complete (yrs)*[2]	*Remarks*
Reactor Alternatives[3]			
Existing LWRs, Existing Facilities	9	24	Reflects initial use of European MOX fuel fabrication plant until domestic facility is available. Unavailability of European MOX fuel fabrication and/or plutonium oxide for LUAs and initial reactor core loads can delay the disposition mission up to 4 years.
Existing LWRs, Greenfield Facilities	13	31	
CANDU	8–10	<24	CANDU fuel irradiation likely could begin earlier with European fuel fabrication, just like LWRs. Since CANDU MOX fuel fabrication is less certain than for LWRs, only half of the LWR schedule acceleration of 4 years is assumed to apply to the CANDU alternative. The earlier date shown here assumes a two-year schedule credit for European MOX fabrication.
Partially Complete LWRs	13	28	
Evolutionary LWRs	14	28	
Immobilization Alternatives			
Vitrification Can-in-Canister	7	18	
Vitrification Greenfield	12	21	
Vitrification Adjunct Melter	12	21	
Ceramic Can-in-Canister	7	18	
Ceramic Greenfield	12	21	
Electrometallurgical Treatment	13	22	
Deep Borehole Alternatives			
Immobilized Emplacement	10	20	The implementation time is assumed to be 10 years; it could be compressed to as little as 3 years
Direct Emplacement	10	20	The implementation time is assumed to be 10 years; it could be compressed to as little as 3 years
Hybrid Alternatives			
Existing LWRs with Vitrification Can-in-Canister	7	<25	The 7 years corresponds to the immobilization portion of the hybrid. The reactor portion starts up in 9 years.
CANDU with Vitrification Can-in-Canister	7	<22	The 7 years corresponds to the immobilization portion. The reactor portion will start in 8–10 years.

[1] Time is measured from authorization to proceed. Start-up time refers to the initiation of production-scale operations, which for can-in-canister variants is taken to be 1.25 MT/yr capacity versus full scale (5 MT/yr) capacity.

[2] Time to complete is the entire duration from authorization to proceed to completion of the disposition mission. The disposition mission is considered complete: for LWRs – after the first irradiation cycle for the last MOX bundles; for CANDUs – after the last bundle has completed its intended irradiation; for immobilization – when the last immobilized waste form is fabricated; and for deep borehole – when the last borehole is sealed.

[3] For reactor alternatives, this start of production-scale operations is defined to be the beginning of the irradiation cycle for the mission fuel. For existing LWRs, this is 2–3 years after irradiation of lead use assemblies. For partially complete and evolutionary reactors, the mission starts when the reactors go to full power with their MOX cores.

Table ES-3. ***Summary of Alternative Technical, Cost and Schedule Advantages and Disadvantages***

Alternative	*Advantages*	*Disadvantages*
Reactors		
Existing LWRs, Existing Facilities	• Proven technology • International technology base • Timely start-up • Cost effective • Large reactor base to draw upon	• Depends on successful negotiations with reactor owner(s) • If long delays accrue, limited availability of reactors • Need to qualify fuel form • Need for international transportation, security, and other agreements for the European fuel fabrication portion of the alternative.
CANDU Reactors	• Independent of U.S. high-level waste repository • Timely start-up • Adaptation of proven technology	• Depends on successful negotiations with reactor owner(s) • Less proven for MOX fuel use than existing LWRs • Need to develop and qualify fuel forms • More costly than existing LWRs • Need for international transportation, security, and other agreements, including for European fuel fabrication
Existing LWRs, Greenfield Facilities	• Does not impact or depend on other DOE missions	• Depends on successful negotiations with reactor owner(s) • Need to qualify the fuel form • Higher cost and longer time to start-up than existing LWRs, existing facilities • If long delays accrue, limited availability of reactors
Partially Complete LWRs	• Potential low life cycle costs	• Depends on successful negotiations with reactor owner(s) • High investment costs • Technical risk associated with reactor completion and fuel qualification • Limited set of reactors available
Evolutionary LWRs	• None, compared to existing reactor, existing facilities variant	• High investment and life cycle costs • Technical risk associated with reactor completion and fuel qualification • Technical and schedule risk with designing and building new facilities

Table ES-3. ***Summary of Alternative Technical, Cost, and Schedule Advantages and Disadvantages-Continued***

Alternative	*Advantages*	*Disadvantages*
Immobilization		
Vitrification Can-in-Canister	• Timely start-up • Cost effective • Most technically mature of vitrification variants	• Need to perform additional research and development to produce and qualify waste form
Vitrification Adjunct Melter	• Less dependent on DWPF operations than can-in-canister operations	• Less technically mature and requires more development than can-in-canister variant • Starts later than can-in-canister • Higher investment and life cycle costs than can-in-canister variant
Vitrification Greenfield	• Does not impact or depend on other DOE missions	• Less technically mature and requires more development than can-in-canister variant • Starts later than can-in-canister • Higher investment and life cycle costs than can-in-canister variant • Technical and schedule risk with designing and building new facilities
Ceramic Can-in-Canister	• Timely start-up • Cost effective • Most technically viable of ceramic variants • Potential for superior plutonium retention	• Need to perform additional research and development to produce and qualify waste form
Ceramic Greenfield	• Does not impact or depend on other DOE missions	• Less technically mature and requires more development than can-in-canister variant • Starts later than can-in-canister • Higher investment and life cycle costs than can-in-canister variant • Technical and schedule risk with designing and building new facilities
Electrometallurgical Treatment	• None, relative to other immobilization alternatives	• Technical viability for plutonium disposition not demonstrated • More uncertainty for long-term performance of waste form • Greater uncertainty for schedule start-up

Table ES-3. ***Summary of Alternative Technical, Cost, and Schedule Advantages and Disadvantages-Continued***

Alternative	*Advantages*	*Disadvantages*
Deep Borehole		
Immobilized Emplacement	• Results in geologic disposal • Superior plutonium isolation and criticality safety over direct emplacement • Independent of the high-level waste repository	• Regulatory approval regime is not defined • Life cycle costs high relative to direct emplacement • Difficulty in obtaining siting approval
Direct Emplacement	• Results in geologic disposal • Less expensive than immobilized emplacement • Independent of the high-level waste repository	• Regulatory approval regime is not defined • Life cycle costs are high relative to leading immobilization and reactor alternatives • More difficult to demonstrate sub-criticality over geologic time • Difficulty in obtaining siting approval
Hybrids		
Hybrids	• Couples the strengths of the immobilization and reactor alternatives • Timely start-up • Flexibility is provided – Better assurance of disposition start-up and accelerate mission completion – Technology backup in the event one technology is unavailable • Ability to optimize feed processing	• Increased costs compared to either technology separately • Problems associated with both alternatives considered separately (see reactor and immobilization commentary)

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

The United States has declared 38.2 metric tons of weapons-grade plutonium surplus to national security needs.[1] Additional inventories of plutonium are expected to bring the total amount of plutonium that is surplus to approximately 50 metric tons. The President has directed that placing the surplus weapons-usable plutonium in a form that provides a high degree of proliferation resistance[2] is a national policy.[3] In their joint declaration from the April 1996 Moscow Nuclear Safety Summit, the leaders of the seven largest industrial countries and the Russian Federation endorsed the need to render the surplus fissile materials (both highly enriched uranium and plutonium) in Russia and the United States to a high degree of proliferation resistance:

> [Surplus fissile material needs to be] safety managed and transformed into spent fuel or other forms equally unusable for nuclear weapons.[4]

To establish a framework for selecting plutonium disposition options which would achieve a high degree of proliferation resistance, the National Academy of Sciences (NAS) reviewed a number of options and concluded that the national objective should be to make the surplus weapons-grade "plutonium roughly as inaccessible for weapons use as the much larger and growing quantity of plutonium that exists in spent fuel from commercial reactors,"[5] a state it defined as the *spent fuel standard*. The Department of Energy (DOE) has enhanced this statement to read:

DOE Spent Fuel Standard
A concept to make the plutonium as unattractive and inaccessible for retrieval and weapons use as the residual plutonium in the spent fuel from commercial reactors.

[1] President Clinton's March 1, 1995, Address to the Nixon for Peace and Freedom Policy Conference and the Department of Energy Openness Initiative, February 6, 1996.

[2] Definitions of key terms are provided in Appendix B: Acronyms and Glossary.

[3] Press Release from the Office of the Press Secretary, The White House, "Nonproliferation and Export Control Policy," September 27, 1993.

[4] Joint Declaration from Moscow Nuclear Safety Summit, April 20, 1996.

[5] National Academy of Sciences, Committee on International Security and Arms Control, Management and Disposition of Excess Weapons Plutonium, National Academy Press, Washington, DC, 1994.

The DOE enhancement makes explicit the concept of material attractiveness, which was implicit in the NAS usage of the term. The spent fuel standard is not a specification-type standard. It encompasses a range of barriers which deter accessibility to and use of plutonium, including such barriers as a radiation field, dilution, inaccessible location, and size and weight. In the aggregate, these barriers achieve a degree of inaccessibility and a difficulty for extraction of plutonium comparable to that of plutonium in "typical" commercial spent fuel. Once having achieved the spent fuel standard, the formerly weapons-usable plutonium is rendered no more attractive for use in nuclear weapons than the much larger and growing inventory of plutonium in commercial spent fuel.

The Interagency Working Group on Plutonium Disposition was tasked by the National Security Council with the comprehensive review of long-term options for plutonium disposition.[6] The DOE has the technical lead for this interagency study. Building on the NAS work, the DOE completed a *screening process* in March 1995[7] in which a large set of proposed, conceptual options for the disposition of plutonium were evaluated. The options that remained after the screening process were identified as reasonable alternatives and have been analyzed in the Draft Programmatic Environmental Impact Statement (PEIS)[8].

1.2 DOE TECHNICAL APPROACH

The plutonium disposition alternatives discussed in this report fall into one of three *categories o*r combinations of them: reactor, immobilization, or deep borehole. Each alternative was defined for analysis as the beginning-to-end set of operations (e.g., from surplus plutonium to geologic disposal) necessary to address all of the surplus weapons-usable plutonium. Several of the alternatives can be implemented in a variety of ways that have significant differences in technical, economic, and/or schedule performance. These different implementation approaches are referred to as "variants" in this report. Hybrid approaches that combine different categories of technologies were also analyzed.

As the agency responsible for the management of special nuclear materials, the DOE has the technical lead for the study of plutonium disposition. The DOE has pursued a series of actions designed to enhance the technical understanding of the alternatives and to provide for implementation. These include:

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[6] Press Release from the Office of the Press Secretary, The White House, "Nonproliferation and Export Control Policy," September 27, 1993.

[7] U.S. Department of Energy, DOE/MD-0002, "Summary Report of The Screening Process, March 29, 1995. Referred to as "The Screening Report" in this document.

[8] U.S. Department of Energy, DOE/EIS-0229-D, "Storage and Disposition of Weapons-Usable Fissile Materials, Draft Programmatic Environmental Impact Statement," February 1996.

1. Defining the alternatives in sufficient detail to permit technical assessments to be performed.
2. Analyzing the alternatives with respect to technical, cost, and schedule criteria.
3. Performing experimental and developmental work to enhance the knowledge base of plutonium disposition.
4. Performing joint studies and joint experimental work with Russian counterparts.

For the first two actions, the data for each of the categories of alternatives were generated by one of three *Alternative Teams* (one for each category) which were composed of personnel from the national laboratories, contractors, and DOE. These personnel provided the expertise to represent all the technologies necessary to implement an alternative from its inception to its completion. These Alternative Teams were responsible for defining and analyzing each alternative in sufficient detail to allow comparative assessments of the alternatives by DOE.

The Alternative Teams defined and developed the network of operations that could be utilized to accomplish the disposition of material at a much greater level of detail than that used for either the Screening Report or the NAS Report. The following information was assembled for each of the alternatives analyzed:[9]

- Block flow diagrams describing process steps for all operations.
- Lists of major equipment and facilities to accomplish functions.
- Mass balance and rate data for unit operations and facilities.
- Sketches of equipment layouts and plot plans.
- Reviews of regulatory and operational considerations for facilities.
- Estimates of facility sizes, personnel requirements, and facility infrastructure requirements.
- Identification of balance of plant requirements.

For the third action, the DOE has been actively engaged in experimental activities to advance the understanding of the technologies. These experimental activities include, but are not limited to:

- Development of a prototype process for extracting plutonium from weapons components.
- Fabricating fuel pellets using weapons-grade plutonium.
- Engineering-scale fabrication of ceramic waste forms with plutonium.

[9] Specific engineering data are presented in the Alternative Team Summary Reports (See References).

- Full-scale "cold" (i.e., without any radionuclides) demonstration of a glass immobilization concept.

The results of the fourth action is a joint U.S. and Russian published study covering the technologies of long-term storage, plutonium conversion and stabilization, geologic disposal, immobilization, water-cooled reactors and fast reactors, and the economic analysis and nonproliferation issues associated with these studies.

CHAPTER 2. DESCRIPTION OF TECHNOLOGY ALTERNATIVES

2.0 OVERVIEW OF PLUTONIUM DISPOSITION TECHNOLOGIES

This chapter provides a high level summary of more detailed Alternative Technical Summary Reports. Section 2.1 summarizes technologies that are common to most of the alternatives. Sections 2.2, 2.3, and 2.4 summarize the specific technologies for the reactor, immobilization, and borehole alternatives, respectively. Section 2.5 describes two hybrid alternatives which combine two disposition technologies in order to exploit advantages of each of them, as illustrative examples of how hybrids might be implemented.

Reactor technologies irradiate mixed plutonium oxide and uranium oxide (MOX) fuel in existing, partially complete or evolutionary[1] reactors to introduce a radiation barrier. The resulting spent fuel is similar to that generated by operating commercial reactors today and would be expected to be acceptable for disposal in a high-level waste repository in the U.S. or Canada, as applicable. Existing boiling water reactors (BWRs) and pressurized water reactors (PWRs), existing Canadian Natural Uranium Deuterium Oxide (CANDU) heavy water reactors, partially complete PWRs, and evolutionary PWR and BWR reactors are being evaluated for the disposition mission. Variations based upon the amount of plutonium irradiated per reactor year, facility ownership, and use of existing European, existing modified domestic, or new U.S. facilities for fabrication of MOX fuel assemblies have been examined and are discussed in this report.

Immobilization technologies are expected to achieve the spent fuel standard by mixing radioactive isotopes with plutonium in a glass, ceramic, or glass-bonded zeolite matrix and placing the material in a large canister. The size, weight, composition, and radiation barrier of the filled canister are intended to provide barriers to plutonium recovery comparable to that of spent fuel assemblies. New facilities for mixing the surplus plutonium and radioactive defense high-level waste or ^{137}Cs (Cesium) and immobilizing this mixture in a large canister either in a glass, ceramic, or glass-bonded zeolite matrix have been examined. Use of existing facilities and processes that are integrated with ongoing high-level waste processing operations at the Defense Waste Processing Facility (DWPF) have also been examined. In two approaches, plutonium disposition facilities produce small cans of immobilized plutonium either as a glass or ceramic matrix (without a radiation barrier) that are subsequently emplaced in standard DWPF canisters that are then filled with molten glass containing radioactive high-level wastes. In another approach, ^{137}Cs and plutonium are combined in a melter adjacent to the DWPF melter to immobilize the plutonium in a glass matrix which is then placed in a large canister. For the electrometallurgical treatment alternative, an electrometallurgical process to produce an immobilized glass-bonded zeolite

[1] As used in this report, all new light water reactors designs considered are deemed to be "evolutionary" designs. In parlance used elsewhere, some of the designs are referred to as "advanced" designs.

waste form containing a ^{137}Cs barrier is produced in modified facilities at Argonne National Laboratory-West (ANL-W). All of the canisters with immobilized plutonium and a radiation barrier would be sent to the high-level waste repository for geologic disposal.

The *deep borehole* alternatives, in contrast to the reactor and immobilization alternatives, do not introduce a radiation barrier to achieve the spent fuel standard. Instead a substantial geologic barrier to recovery of plutonium is introduced by emplacement of the surplus plutonium at depths of several kilometers in stable isolated rock formations, with various materials and devices to inhibit redrilling and recovery of the material. Two alternatives were evaluated: 1) direct emplacement of plutonium oxides and metals and 2) immobilization of the plutonium in a ceramic matrix prior to emplacement.

2.1 COMMON TECHNOLOGIES

2.1.1 Safeguards and Security

As proliferation resistance is the primary objective of the disposition program, significant analyses and design efforts have been undertaken in an attempt to achieve this goal. Alternatives have been designed to accommodate safeguards and security technologies that reduce the threat of theft of plutonium by unauthorized parties and the threat of recovery and reuse of plutonium after disposition. The alternatives included provisions for both domestic safeguards as well as international safeguards under IAEA requirements. A team of safeguards and security experts has been working with each Alternative Team to assure that proliferation risks and impacts have been considered consistently throughout the program.

2.1.2 Transportation and Packaging

For transportation of material over public roads and rail systems, special consideration has been given to packaging requirements and transportation options. In general, plutonium material forms prior to attaining high background levels of radiation will be shipped via roads in the DOE Safe, Secure Trailer (SST) System and via rail in special casks after irradiation. Packaging technology exists to accommodate all material forms. Although some additional containers may need to be qualified, the costs associated with transportation and packaging are not significant enough to distinguish among alternatives.

International transport is required for the CANDU alternative and for the portion of the existing LWR, existing facilities variant using European facilities. Modes of transport are available but will require international agreement and approval .

2.1.3 Front-End Processes

Plutonium surplus to national security needs which will be subject to disposition actions exists in a variety of forms, including "pits" from dismantled nuclear weapons, pure and impure metal and plutonium oxide, plutonium containing alloys, various chemical com-

pounds, and unirradiated reactor fuels. Most of this plutonium cannot be used directly as feed material for any of the three disposition categories; therefore, it must first be prepared and conditioned. Thus the objective of front-end processing is to put plutonium in the desired form so it can be used as feed for the various disposition alternatives.[2] Throughout this report, front-end processing and plutonium processing are used interchangeably to denote those operations required to prepare the plutonium for further disposition. Also, the PEIS analyzed pit disassembly and plutonium (or mixed feed) processing as two separate functions in separate facilities. In this report, although the pit disassembly and mixed feed processing are still separate functions, they occur in the same facility.

For purposes of alternative analyses, the following quantities of plutonium approximate the form and quantity of materials that are expected to be declared surplus.

Plutonium metals and oxides from weapon dismantlements and other high purity, weapons-grade oxides and metal	32.5 MT
Lower-purity or non-weapons grade metals and oxides, and various plutonium materials including fresh fuel forms, halides, and compounds	17.5 MT
TOTAL	50.0 MT

Feed Purity Requirements

MOX reactor fuels require a very pure plutonium oxide feed. The requirements are based on qualified fuel fabrication techniques, ASTM standards, or reactor vendor specifications. In general, the plutonium oxide must have a minimum plutonium content of 86 wt. %, with additional restrictions on specific impurities. The plutonium oxide produced by the pit conversion processing operations may meet MOX feed purity specifications or may require some additional processing. It is expected a simple thermal treatment step will be sufficient to ensure required feed purity; however, as a worse case, an aqueous chemical purification treatment may be required. Other sources of plutonium will require an aqueous chemical purification treatment.

The feed for the glass or ceramic immobilization alternatives can be pure and impure plutonium oxides (“dry” feed) or plutonium nitrate solutions (“wet” feed). This feed should be relatively free of halides. For the electrometallurgical treatment alternative, plutonium feeds can be metals, oxides, and chlorides.

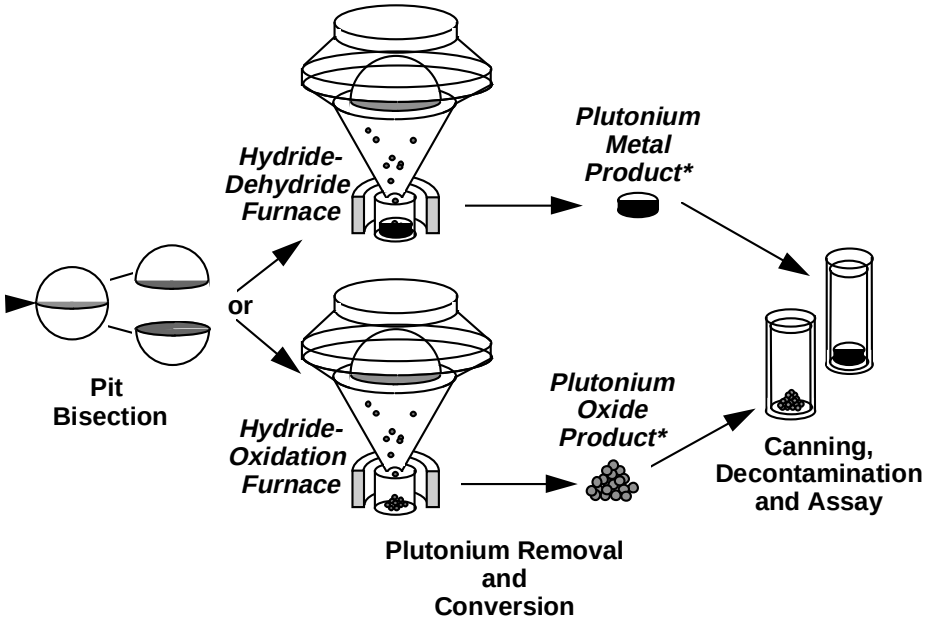
For deep borehole alternatives, plutonium may be emplaced into the borehole as metals or oxides directly in shipping product cans or immobilized in a ceramic prior to emplacement without any significant preprocessing. There are no major material feed purity requirements.

[2] Front-end processing includes all glovebox operations needed to prepare plutonium for disposition and only excludes a MOX fuel fabrication facility, reactors, hot cell operations for immobilization, and borehole site facilities.

Front-end processing may be grouped into two distinct sets of operations: pit conversion processing and mixed feed processing. Pit conversion processing involves recovery of plutonium in pits from dismantled nuclear weapons to prepare the plutonium as feed for disposition. Mixed feed processing prepares all of the other categories of plutonium (i.e., pure/impure metal, pure/impure oxide, etc.) as feed for subsequent disposition.

Figures 2-1 and 2-2a through 2-2d show the relationship between the currently existing plutonium forms and the front-end processing required to prepare the plutonium as feed for the three disposition categories.

Figure 2-1. ***Pit Conversion Process***



* The plutonium metal will be recast in a furnace and the plutonium oxide mixed to mask classified information.

Pit conversion processing removes plutonium from a pit by separating the pit into hemishells and subsequently removing the plutonium from the hemishells. The latter step is achieved by reacting the plutonium metal with hydrogen gas to form a solid chemical compound called plutonium hydride. The plutonium hydride is formed as small particles which are collected in a furnace crucible where they either can be chemically reacted with oxygen to form plutonium oxide (PuO_2) or can be transformed to pure metal by heating. The plutonium oxide is pure enough to be used as feed for the borehole and immobilization alternatives but may require an additional thermal processing step to be pure enough to be used as feed for fabricating MOX fuel pellets. Figure 2-1 is a summary of the major components of pit conversion processing operations.

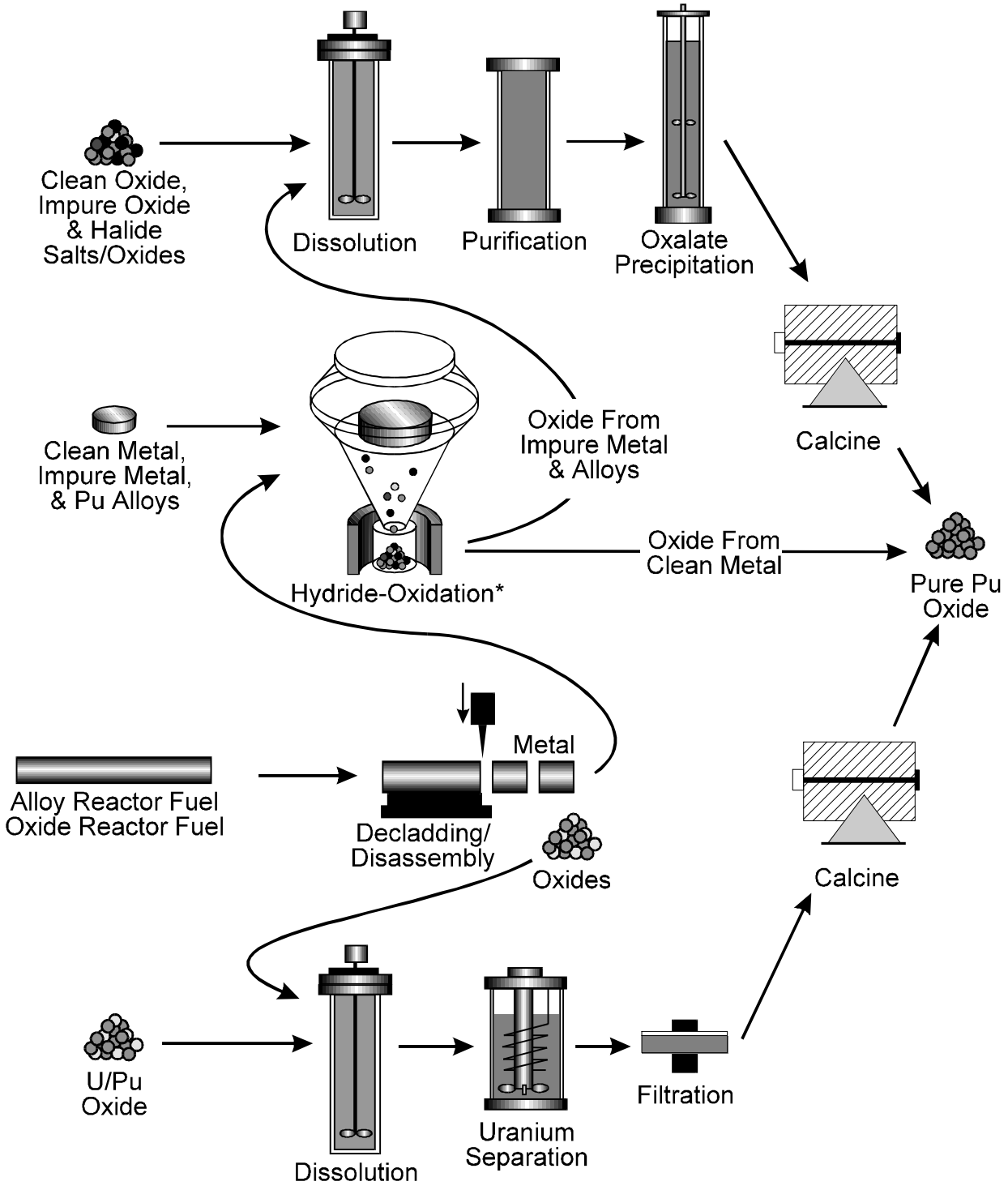
Mixed feed processing operations are more complicated than pit conversion processing because of the variety of surplus non-pit plutonium forms, because of differences in their impurities, and because of the different feed specifications required for the different disposi-

tion alternatives. For example, plutonium oxide used for MOX fuel must meet stringent purity specifications. Thus chemical purification operations must be performed to purify the non-pit plutonium for the reactor alternatives. Purification operations can be complex, requiring chemical reagents and generating wastes that require safe disposal. On the other hand, plutonium oxide or metal destined for either the immobilization alternatives or the deep borehole alternatives does not have to meet as stringent purity specifications and generally would not require purification. Figures 2-2a through 2-2d summarize and compare possible major components of mixed feed processing operations for the plutonium disposition alternatives. Clean non-pit metal, impure metals, and alloys could be converted to oxides using the same hydride/oxide process that is being developed for the pit conversion process, if desired. Resulting impure oxides may require subsequent purification, depending upon the alternative.

2.1.4 Existing Facilities

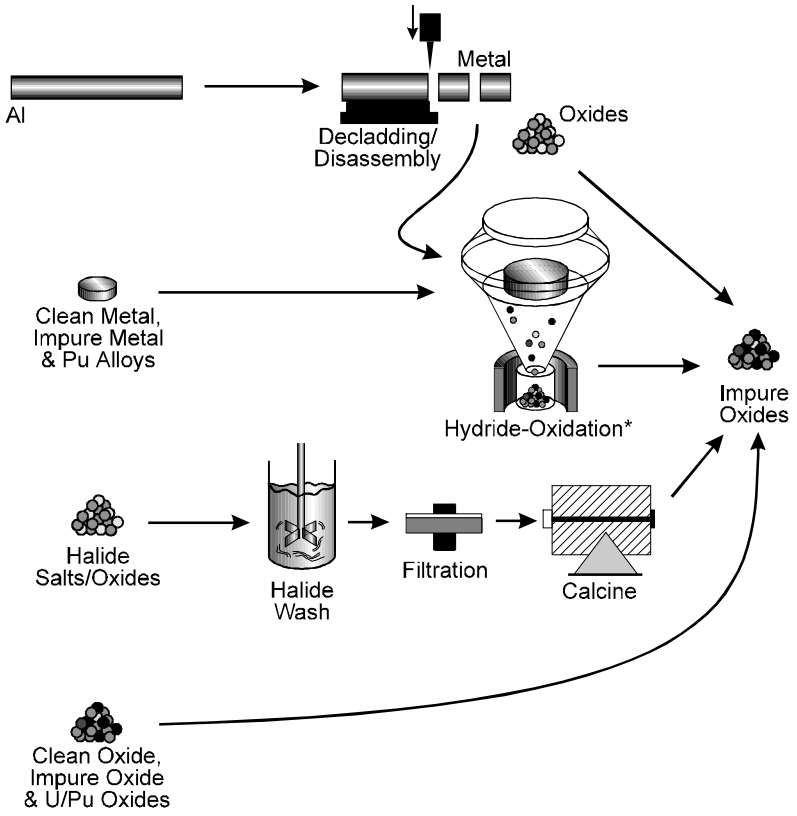
The PEIS analyzed new "greenfield" sites rather than any existing facilities to bound environmental impacts. Initial cost and schedule analyses were similarly applied to greenfield sites to evaluate worse-case scenarios. However, significant cost and schedule savings could potentially be realized through the use of existing sites or facilities due to operation of already existing site security infrastructures (e.g. existing perimeter access control systems, trained guard force), waste treatment operations, analytical chemistry facilities, sewers, waterlines, etc. In addition, obtaining regulatory approvals for the facility and its operation may be facilitated by existing site licenses or permits. National Environmental Policy Act (NEPA) coverage may already be in place at some sites, and some of these operations may already be bounded by limits contained in NEPA compliance documentation for the various sites. Cost and schedule savings could be partially or wholly offset by the need for upgrading these facilities to current codes and standards, the need for decontaminating these facilities for reuse, and the impact associated with force-fitting processes into existing buildings which could result in sub-optimum operations. A preliminary engineering assessment of existing facilities to accommodate plutonium processing has been performed which shows that large cost and schedule advantages can be realized by using the existing facilities. Notwithstanding, a more detailed engineering assessment would be required to confirm and qualify what cost and schedule advantages might accrue by using existing facilities over new facilities at sites with no plutonium handling infrastructure.

Figure 2-2a. ***Mixed Feed Processing (Reactors)***



* Same process and equipment in Pit Conversion Process could be used.
Note: The aqueous unit operations shown are an illustrative example of those which could be employed.

Figure 2-2b. ***Mixed Feed Processing (Immobilization & Immobilized Deep Borehole)***



* Same process and equipment in Pit Conversion Process could be used.

Figure 2-2c. ***Mixed Feed Processing (Direct Deep Borehole)***

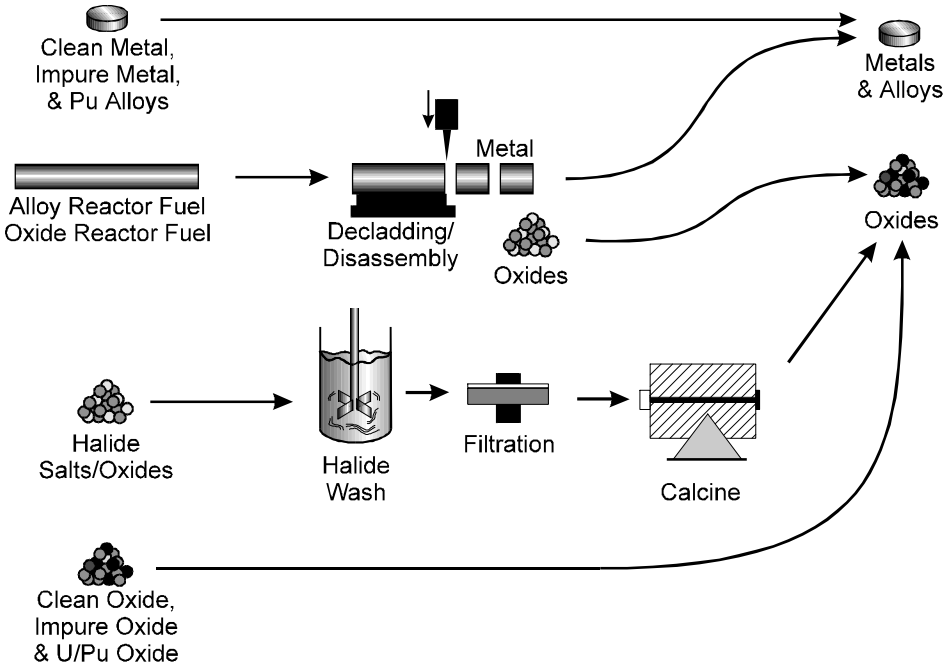
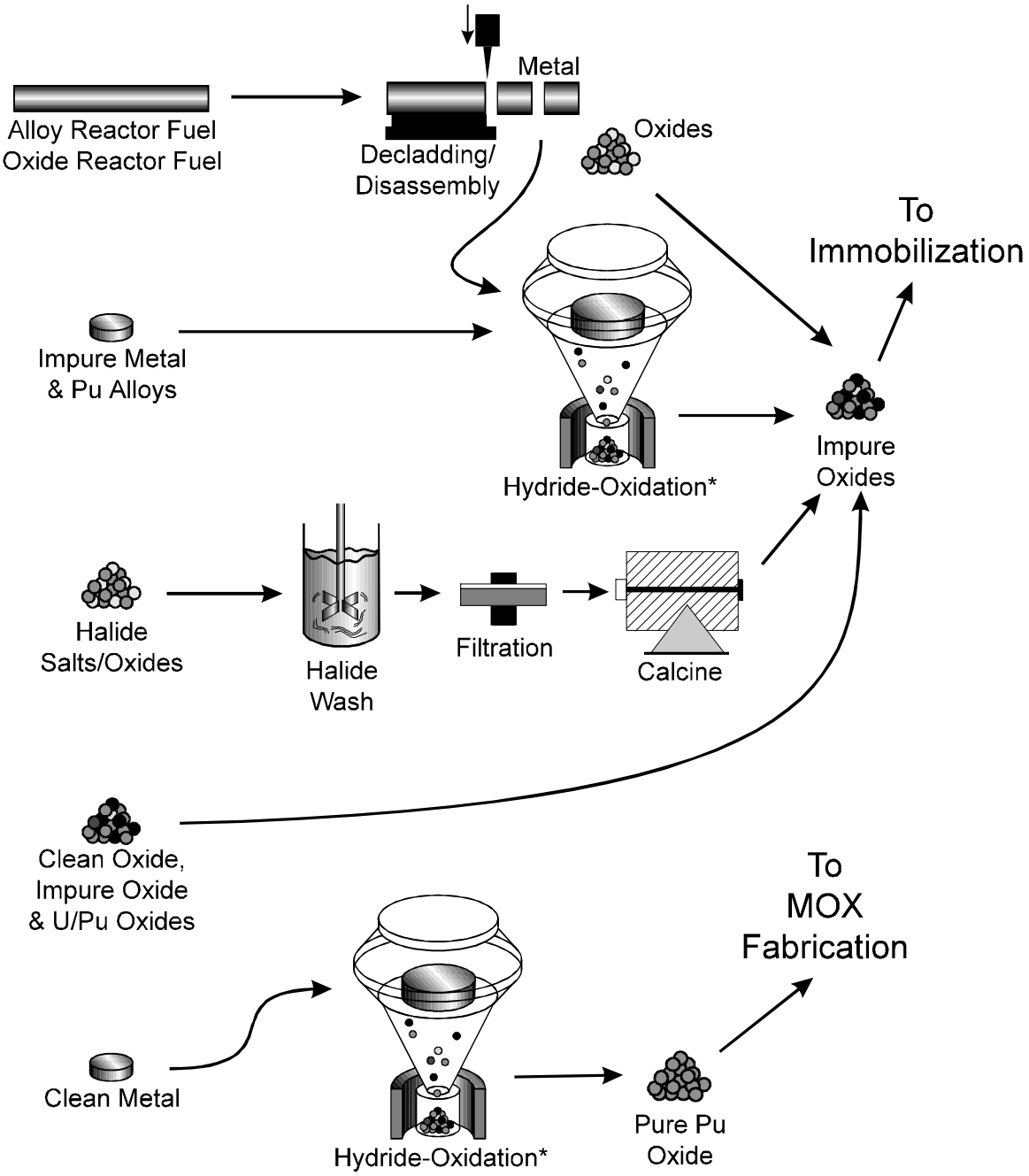


Figure 2-2d. ***Mixed Feed Processing (Hybrid)***



* Same process and equipment in Pit Conversion Process could be used.

The use of existing facilities and processing capabilities at the Idaho National Engineering Laboratory (INEL), Hanford, and the Savannah River Site (SRS) for front-end processing options were evaluated. All three sites are suitable for plutonium processing and could potentially accommodate front-end processing within existing buildings, though considerable facility modification, decontamination and equipment procurement would be required, depending on the building selected.

2.1.5 Oversight and Licensing

The alternatives were designed under the assumption that all facilities would have to be subject to an external (to DOE) authority such as the NRC or Defense Nuclear Facilities Safety Board (DNFSB).

2.1.6 High-Level Waste Repository

The spent fuel assemblies generated by the reactor alternatives and the waste canisters generated by the immobilization alternatives require placement in a high-level waste repository for geologic disposal of the plutonium. Though the disposition cost summaries include geologic emplacement for all alternatives, for the reactor and immobilization alternatives, geologic disposal is not included in the material disposition mission since it is unnecessary to achieve the spent fuel standard. Analyses have been conducted to evaluate the feasibility of introducing immobilized plutonium forms and MOX spent fuel into a high-level waste repository. This study assumed that a repository designed for commercial spent nuclear fuel and defense high-level waste will be operational in the U.S. and the plutonium forms from the disposition mission will meet the repository acceptance criteria. Because no repository has been licensed at this time, a comparative analysis between the performance of the plutonium forms against those expected for commercial spent nuclear fuel and defense high-level waste has been conducted. The analyses included regulatory/statutory and technical performance evaluations.

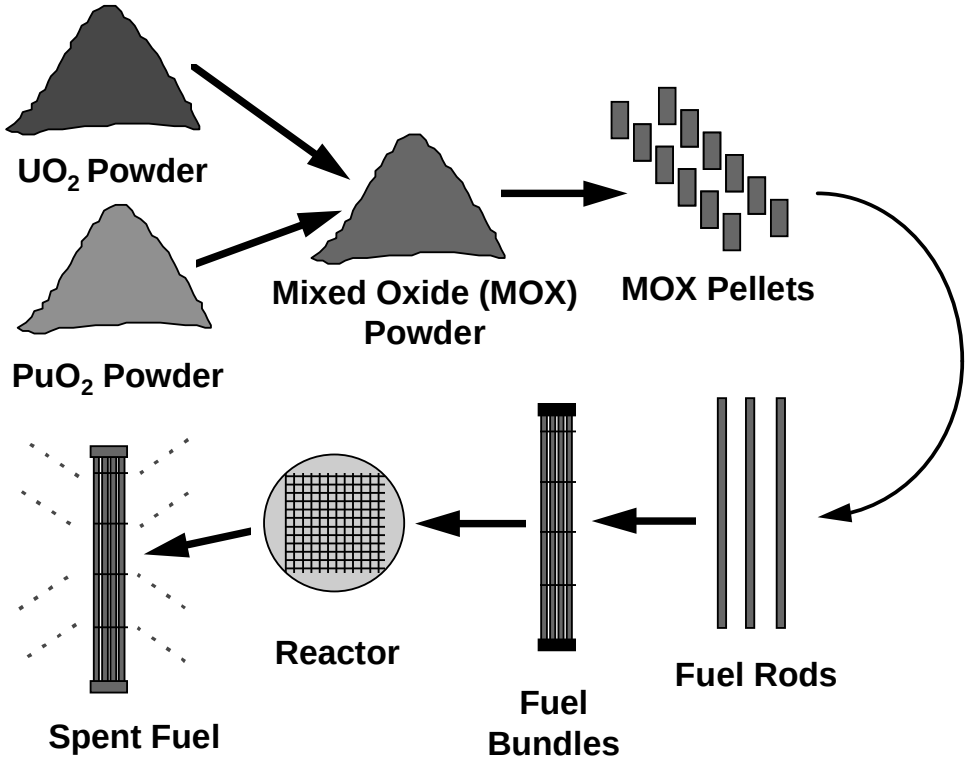
Spent fuel resulting from the use of MOX fuel in reactors falls within the definition of "spent nuclear fuel" as specified in Section 2(23) of the Nuclear Waste Policy Act (NWPA), as amended, and can therefore be considered for disposal in a high-level waste repository licensed pursuant to the NWPA. According to Section 2(12)A of the NWPA, the definition of high-level waste does not explicitly include the plutonium-loaded immobilized form. However, under Section 2(12)B of the NWPA, the NRC has the authority to classify this form as a high-level waste through rulemaking. Such rulemaking or clarification in authorizing legislation will be necessary before this form can be considered for disposal in an NWPA repository.

For all alternatives analyzed in this report (excluding the CANDU and deep borehole alternatives), the final geologic disposal of the forms will have to follow the licensing provisions of 10 CFR 60 and the applicable NEPA process. Licensing of the repositories for the CANDU and deep borehole alternatives will also be required. Licensing the repository for the CANDU spent fuel is under the purview of Canadian regulatory authorities. Licensing of the deep borehole as a repository will be accomplished pursuant to applicable regulations, once promulgated.

2.2 REACTOR ALTERNATIVES

A total of five reactor variants covering four alternatives are addressed in this section and depicted in Figure 2-3. The variants are defined in Table 2-1. Additionally, sensitivities to certain parameters are addressed in the technical, cost, and schedule sections, where important. These sensitivities include MOX plant ownership (U.S. government, new U.S. private, or existing European private), and the use of new versus modified facilities for plutonium processing and fuel fabrication.

Figure 2-3. ***Generic Reactor Alternative***



MOX fuel, as for any nuclear reactor fuel, must meet very exacting requirements for a number of parameters. These include plutonium content, impurity concentrations of various elements, feedstock morphology (oxide particulate size) which influences grain size of the MOX fuel pellet, physical size and shape of MOX fuel pellets, and uniformity of plutonium distribution throughout the pellet. A complex industrial facility, the MOX fuel fabrication plant is necessary to meet these requirements and verify the quality of the fuel pellets. Process steps in the MOX fuel facility will include preparatory milling of plutonium and uranium oxides, blending, pressing the "green" (unfired) pellets, sintering (baking at high temperature), grinding to final shape, physical inspection and assay, as well as loading into fuel rods, backfilling and welding the rods, and verifying physical characteristics of the completed rods.

Table 2-1. ***Reactor Category Variants***

Variant	*Plutonium Processing/ MOX Fabrication Facility*	*Number of Reactors*	*Integral Neutron Absorbers*
Existing LWRs existing facilities	Existing Facilities on DOE site with European fabrication of initial cores	5	No
Existing LWRs greenfield facilities	New Co-functional Plutonium Processing Facility and MOX Fabrication Plant	4	Yes
Partially complete LWRs	Existing Facilities on DOE site	2	Yes
Evolutionary LWRs	Existing Facilities on DOE site	2	Yes
CANDU	Existing Facilities on DOE site	2 for 5 years on reference fuel; then 4 reactors on advanced fuel (CANFLEX)	Not in MOX fuel elements

The number of possible technical and business arrangements for reactor deployment strategies is very large. This report summarizes five variants as illustrative examples of the deployment strategies. The interested reader may review the Reactor Alternative Summary Reports for more detailed explanations. Some of the important characteristics for the variants are presented in Table 2-2.

Many parameters need to be specified to properly characterize the possible reactor deployment approaches. These parameters are choices available to the designers and will depend upon which specific reactor types and ownership might be selected. Therefore, the variants are presented to represent a range of choices provided as a basis for analyses and comparison. These variants are illustrative only and do not reflect optimizations of any of the parameters. The choices available for different reactor deployment approaches can be assessed from the Table 2-3, which provides a range of parameters which need to be identified to characterize just the LWR alternatives. Obviously, exhaustive coverage of all combinations of parameters is impractical. To address key significant parameters, sensitivity analyses have been performed. The results of the sensitivity analyses are reported in the technical, cost, and schedule sections, where applicable.

Note that all the reactor designs considered in this report are full core MOX fuel designs in an attempt to maximize the plutonium throughput. This is different from MOX-fueled cores used elsewhere in the world where partial core designs are deployed. In the partial core designs that operate today in Europe, typically 30% to 50% of the fuel assemblies contain MOX fuel with the balance being low enriched uranium fuel.

Table 2-2. ***Summary of Plutonium Throughput Characteristics for Reactor Variants***

Variant	Reactors	Pu Concentration %	Pu Throughput MT/yr	MOX (HM) Throughput[b] MT/yr	Burnup MWd/MTHM
			Avg[a]	Avg	
Existing LWR , Existing Facilities	5 PWRs	4.2	5.0	118.2	45,000 [g]
Existing LWR , Greenfield Facilities	4 BWRs	3.0	3.0	98.8	33,700 [g]
Partially Complete LWR	2 partially complete PWRs [c]	4.5	3.0	67.7	32,500
Evolutionary Large LWR	2 CE System 80+ [d]	6.8	3.5	52.2	42,400
CANDU	2 Bruce A CANDU reference fuel for 5 years, then 4 Bruce A CANFLEX [e]	2.2	2.9	136.1	9,700 [g]
		3.4 [f]	5.0	149.9	17,100 [g]

[a] The average throughput is the mass of plutonium loaded after the initial loading of the first reactor divided by the mission time.

[b] The heavy metal (HM) throughput is the plutonium throughput divided by the plutonium enrichment (expressed as a fraction).

[c] The partially complete reactor schedule is represented by the throughput for two CE System 80 reactors. The initial cores for this variant employ a 3.0% plutonium enrichment.

[d] The CE System 80+ reactors have a core design that can accommodate additional control assemblies and higher plutonium loading, relative to the CE System 80 reactors assumed for the partially complete reactor variant.

[e] Transition from CANDU or natural uranium to CANFLEX is continuous; i.e., there is no shutdown and initial core MOX loading.

[f] For CANDU and CANFLEX, the listed plutonium enrichment is the weighted average for the elements that contain plutonium.

[g] Existing LWR MOX fuel cycles mimic those for low enriched uranium cores. The CANDU fuel cycles take advantage of higher burn up capability of MOX fuel relative to natural uranium fuel, which has a typical burn up of less than 9,000 MWd/MTHM.

Table 2-3. *Deployment Approaches for LWRs*

Parameter	*Range of Possible Choices*	*Comments*
Plutonium Processing Facility	Greenfield, new facility at a DOE site, or an existing facility at an existing site	All three options could also be done either in conjunction with (co-functional, co-located facilities) or separate from a MOX fuel fabrication facility
Mixed Oxide Fuel Fabrication Facility	• Ownership - Privately-owned domestic, Government-owned domestic; existing European facilities. • Siting - Greenfield, new facility at a DOE site, an existing facility at an existing site, or existing European facilities.	Domestic production scale capacity could be developed in conjunction with or separate from a plutonium processing facility.
Type of Reactor	• PWRs and BWRs	Either PWRs or BWRs can be implemented with greenfield facilities or existing facilities and with or without integral neutron absorbers. The matching in this report is arbitrary. Any decisions will be made after ROD as a part of the business arrangements, if LWRs are chosen.
Number of Reactors	• Two is the minimum number for the evolutionary or partially complete alternatives. Three or four is the minimum for other alternatives. The maximum number of reactors is limited by the number of reactors available.	The PEIS examined the specific case of 4 LWRs. The environmental impacts do not depend on the number of reactors selected to any appreciable degree.
Core Design Approaches	• Full MOX core with neutron absorbers; full MOX core without neutron absorbers; partial MOX cores • Irradiation - From 25,000 - 50,000 MWd/MT HM (approximately) • Fuel Cycle length - 12, 18, and 24 months	

2.3 IMMOBILIZATION ALTERNATIVES

A total of six immobilization variants covering the three reasonable alternatives addressed in the PEIS are described in this section: vitrification, ceramic immobilization, and electrometallurgical treatment.

The following assumptions apply for the immobilization alternatives:

- The operational campaign of the immobilization facility will take no more that 10 years to complete.
- The nominal feed of plutonium to the facility is 50 metric tons. Nominal throughput is therefore 25 kg plutonium per day for 200 days of operation per year for ten years.
- Design for criticality safety will meet applicable DOE Orders and available NRC regulatory guides. Criticality is prevented by using batch mass control or equipment geometry as the preferred methods in the design. The use of appropriate neutron absorbers (e.g., gadolinium, samarium, or hafnium) has been assumed.
- The waste canister assumed for this study shall not exceed a 0.6 meter in diameter by 3.0 meter long cylindrical canister.
- The immobilized plutonium package will contain an added radiation field to increase proliferation resistance. The gamma radiation field will be greater than 100 R/hr at 1 meter from the package surface 30 years after initial fabrication.

The Immobilization Alternative team analyzed the variants described in Table 2-4 with a summary of the results shown in Table 2-5.

Table 2-4. *Immobilization Category Variants*

Variants	*Description*[1]
Vitrification Greenfield	• Combined plutonium processing and glass melter facility • A two step vitrification process • Plutonium immobilized in borosilicate glass with ^{137}Cs radiation barrier
Vitrification Can-in-Canister	• Existing facility on DOE site used for plutonium conversion and glass melter facility • Plutonium immobilized in glass in small cans; cans placed in DWPF canister with HLW as radiation barrier • Canister filling done at DWPF
Vitrification Adjunct Melter	• A two step vitrification process • Plutonium is first dissolved in glass frit in the plutonium processing plant in existing facility on a DOE site • New adjunct melter adjacent to DWPF as second stage melter • Final ^{137}Cs supernate from HLW at DWPF used as radiation source
Ceramic Greenfield	• Combined plutonium processing and ceramic immobilization facility • Plutonium immobilized in ceramic matrix with ^{137}Cs radiation barrier • Ceramic forms placed in canisters and backfilled with TiO_2
Ceramic Can-in-Canister	• Existing facility on DOE site used for plutonium conversion and ceramic immobilization facility • Plutonium immobilized in ceramic matrix in small cans; cans placed in DWPF canister with HLW as radiation barrier • Canister filling done at DWPF
Electrometallurgical Treatment	• Plutonium processing and immobilization performed at ANL-W using modified or new facilities • Immobilized form is in glass-bonded zeolite matrix with ^{137}Cs radiation barrier • Glass-bonded zeolite placed in canister and backfilled with appropriate filler

[1] Final formulation for plutonium-loaded immobilized forms is to be determined. All immobilized forms will be designed to be acceptable to the high-level waste repository.

Table 2-5. ***Summary of Characteristics of Immobilization Variants***

Alternative	Variant	Number of canisters to repository[1] Total/Incremental	Plutonium concentration in waste forms wt. %	Effective plutonium concentration in canister wt. %
Vitrification	New Greenfield Facility	600/600	5	5
Vitrification	Can-in-Canister	1000/200	10	3
Vitrification	Adjunct Melter	600/600	5	5
Ceramic	New Greenfield Facility	640/640	12	12
Ceramic	Can-in-Canister	1000/200	12	3
Electrometallurgical Treatment	None	960/960	5	5

[1] The total number of canisters is the total number of canisters containing surplus plutonium. The incremental number is the number of additional canisters required for plutonium disposition beyond requirements for ongoing DWPF operations. For can-in-canister variants, the incremental number of canisters results from small cans displacing approximately twenty percent of the volume inside the DWPF canisters already planned for the high-level waste program.

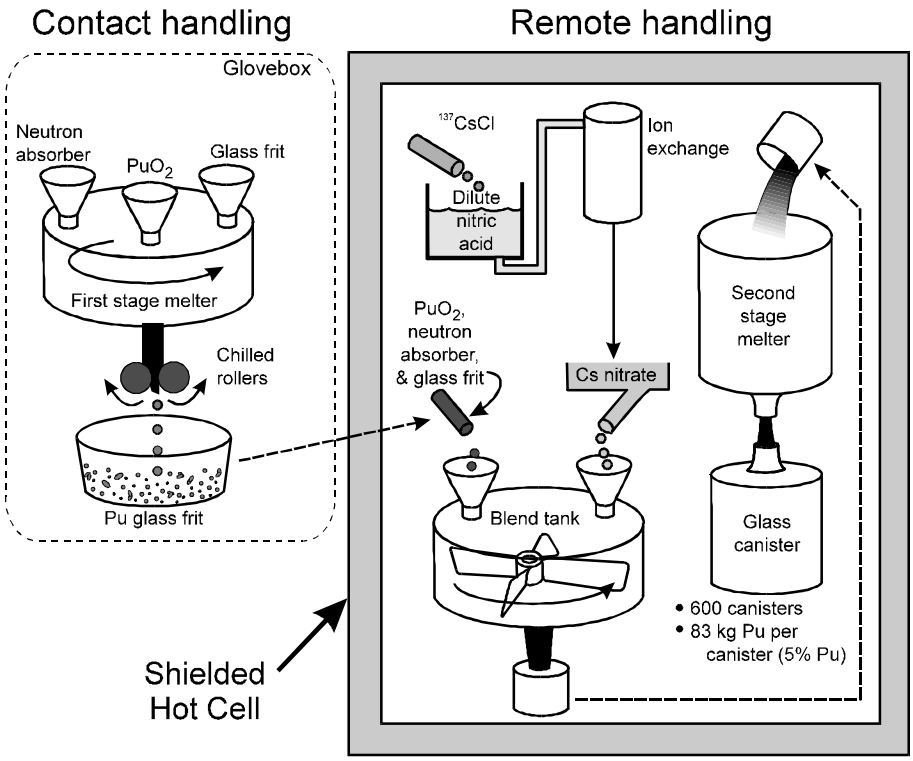
2.3.1 Vitrification Alternative

In several countries including the United States, radioactive high-level waste is being incorporated into molten glass in a process known as vitrification, producing highly radioactive glass "logs" to be stored for an interim period and then disposed. Vitrification has also been identified as a promising technology for the disposition of surplus weapons-usable plutonium, although such a process has not been demonstrated on an industrial scale. The immobilization technology considered here is to vitrify plutonium in borosilicate glass to produce a final waste form suitable for disposal in a high-level waste repository. Borosilicate glass has been chosen as the waste form for high-level waste in the western world because it combines high radioactive impurity solubility and high tolerance to high-level waste variability with excellent leach resistance and high thermal and radiation stability. Borosilicate glass can also be produced at temperatures 200^{o} C below more conventional glasses, thus minimizing volatility of fission products (e.g., ^{137}Cs) and dose to workers.

2.3.1.1 Vitrification Greenfield Variant

The Vitrification greenfield variant immobilizes plutonium through a two-step vitrification process in a borosilicate glass with ^{137}Cs uniformly distributed in the glass matrix to produce a radiation field in the final product ("internal radiation barrier"). The vitrification greenfield variant is shown conceptually in Figure 2-4.

Figure 2-4. ***Vitrification Greenfield Variant***



The plutonium feed materials to the vitrification facility will be plutonium oxide. This oxide is fed to a first stage melter which incorporates the plutonium in a borosilicate glass frit as shown on the left side of Figure 2-4. The first stage melter is located in the contact-handled portion of the facility. The frit will subsequently be blended with ^{137}Cs, with a neutron absorber, and with additional glass frit and fed to a second stage melter as shown on the right side of Figure 2-4. The ^{137}Cs is from 54 million curies of CsCl capsules at Hanford. The molten glass from the second stage melter containing the plutonium and the ^{137}Cs will be poured into a canister that will subsequently be welded closed, decontaminated, and stored onsite pending permanent disposal at a high-level waste repository.

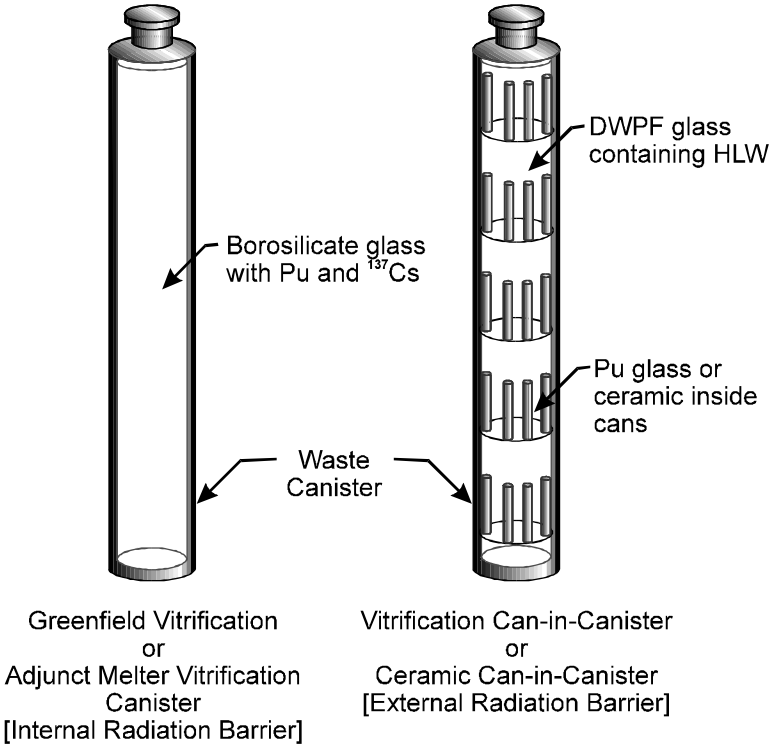
The plutonium loading in the borosilicate glass is a design parameter involving multiple tradeoffs that will be optimized based upon research, testing, and repository criticality analysis during later phases of the design. The final design loading selected will consider fission product availability as well as form quality, facility size, safety factors, and high-level waste acceptance criteria. For this early design phase, 5% (by weight) plutonium loading has been assumed. Lower plutonium loadings would increase the number of canisters going to a repository while higher loadings would reduce conservatism in safety assessments.

The facility is assumed to be constructed and operated on a generic site. After actual site selection, more specific site-related information will be evaluated.

2.3.1.2 Vitrification Can-in-Canister Variant

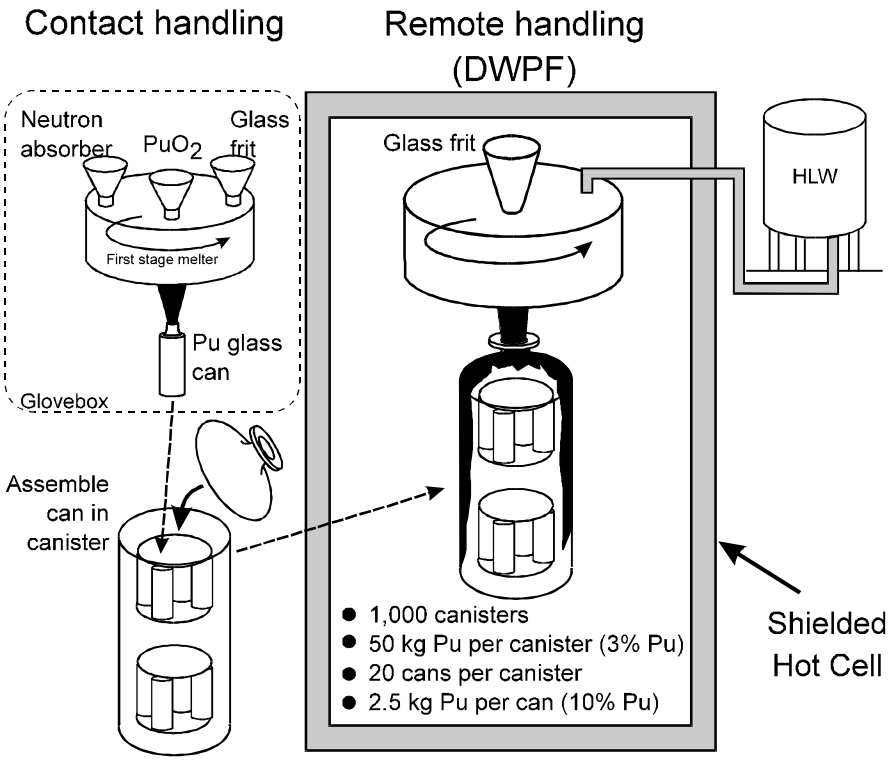
The Vitrification Can-in-Canister variant immobilizes plutonium in borosilicate glass in individual cans and utilizes high-level waste (HLW) glass produced at DWPF to provide an external radiation barrier for proliferation resistance. Molten plutonium glass is poured into small stainless-steel cans. The cans are then loaded onto a frame and placed inside an empty stainless-steel DWPF canister which had the top/neck removed. The canister is then assembled and transferred to the DWPF facility where molten HLW glass is poured around the small cans. After the filled canisters are decontaminated and welded closed, they will be stored onsite until they are sent for final disposal at a high-level waste repository. Figure 2-5 shows a comparison of the canisters. Figure 2-6 shows a schematic representation of the vitrification can-in-canister variant.

Figure 2-5. ***Canister Comparisons***



The plutonium loading in the borosilicate glass is a design parameter involving multiple tradeoffs that will be optimized based upon research, testing, and repository criticality analysis during later phases of the design. The selection of the final design loading will consider radionuclide availability as well as form quality, facility size, safety factors, and repository waste acceptance criteria. For this early design, a plutonium loading of 10% (by weight) within the small can has been assumed. There will be about 20 such cans per canister. This results in an average plutonium concentration of about 3% of the weight of the glass in the larger canister.

Figure 2-6. ***Vitrification Can-in-Canister Variant***

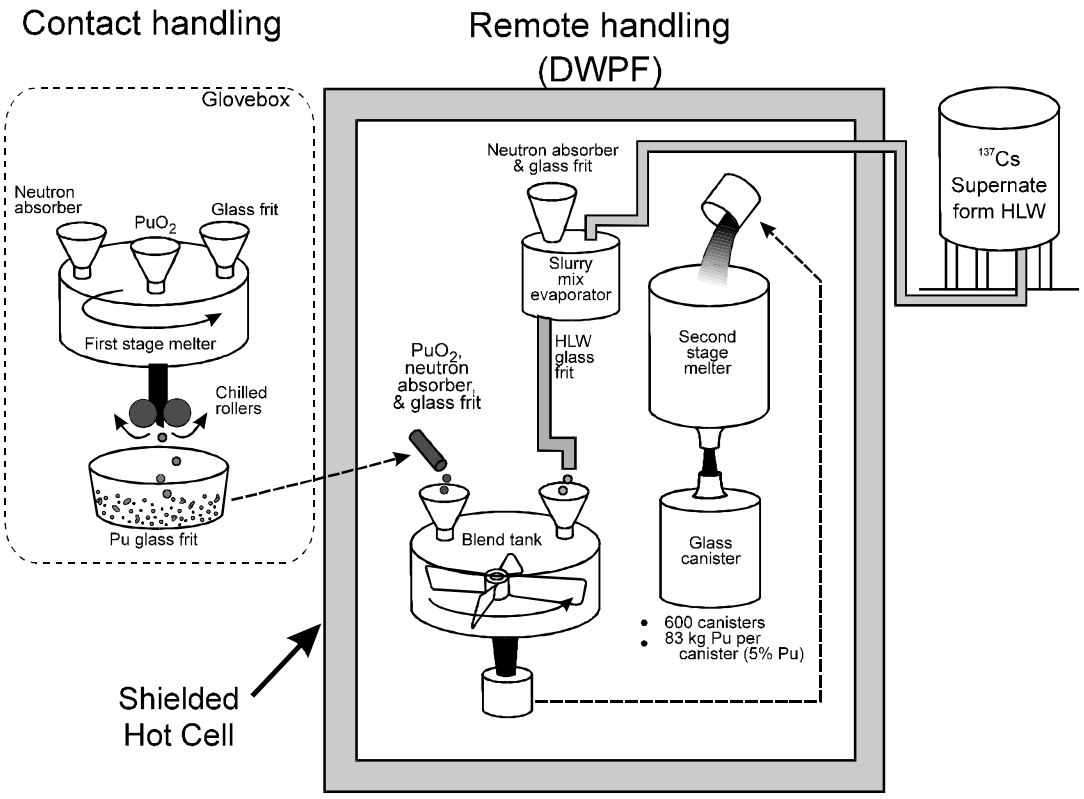


2.3.1.3 Vitrification Adjunct Melter Variant

The Vitrification-Adjunct Melter to DWPF variant is similar to the Vitrification greenfield variant, except this immobilization variant uses the existing facility at the SRS in conjunction with a new adjunct melter built next to DWPF. Figure 2-7 shows a schematic of the vitrification adjunct melter variant.

Plutonium oxide will be fed to vitrification equipment also located in existing facility on DOE site to produce glass frit containing plutonium. This glass frit will then be sent to the new Adjunct Melter facility adjacent to DWPF where it will be mixed with ^{137}Cs from the SRS tank farms, then melted in a second stage melter. The molten glass containing the plutonium and ^{137}Cs will be poured into 0.6 meter diameter x 3.0 meter high stainless steel canisters, which will subsequently be welded closed, decontaminated, and stored onsite until sent to final disposal at a high-level waste repository.

Figure 2-7. *Vitrification Adjunct Melter Variant*



2.3.2 Ceramic Alternative

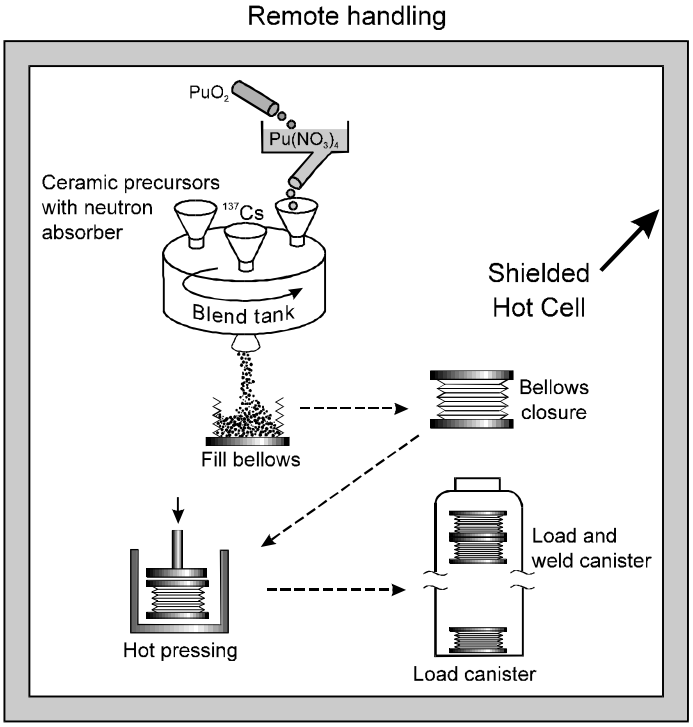
Since the late 1970s, various ceramic waste forms have been considered for immobilization of high-level waste; however, no industrial experience exists for high-level ceramic waste forms unlike borosilicate glass forms. The ceramic waste form is attractive for immobilization purposes because of its extremely low leachability, existence of natural mineral analogues that have demonstrated actinide immobilization over geologic time scales, and the high solid solubility of actinides in the ceramic resulting in a reasonable overall waste volume. Ceramic immobilization of simulated high-level waste in a Synthetic Rock (SYNROC) material has been demonstrated at full scale at the Australian Nuclear Science and Technology Organisation (ANSTO). Small scale samples have been made with greater than 10% plutonium. Although immobilization in ceramic has not replaced various existing and planned vitrification facilities for high-level waste, a considerable amount of research and development has been performed, particularly with higher mass plutonium isotopes and higher actinides procured from reactor recycled plutonium.

2.3.2.1 Ceramic Greenfield Variant

The Ceramic greenfield variant accepts plutonium oxide and, through a ceramic immobilization process, converts the plutonium into a form that can be disposed of in a high-level waste repository. Plutonium is immobilized in a titanate-based ceramic with ^{137}Cs

spiking to produce a radiation field that is uniformly distributed in the waste form. Figure 2-8 shows the greenfield ceramic variant.

Figure 2-8. ***Ceramic Greenfield Variant (dry feed)***



The plutonium feed materials to the ceramic fabrication facility will be plutonium oxide. The plutonium oxide is converted to plutonium nitrate and blended with ceramic precursors, neutron absorbers, and a cesium loaded titanate. The mixture is then calcined (heated), loaded into bellows, and hot pressed to produce a densified product. Twenty hot pressed bellows, 30 cm diameter, will be loaded into a canister, 36 cm diameter by 2.4 m long, with TiO_2 granules that are used as a packing material. The canisters are then stored onsite until they can be transferred to the high-level waste repository for disposal.

Additional assumptions for the variant are:

- The plutonium loading in the ceramic form is assumed to be 12% (by weight). This parameter is taken from demonstrated fabrication sizes (~33 kg using actinides), typical plutonium limits in glove box processing (~4 kg plutonium), and known plutonium loading data in ceramics (>12%). The final plutonium loading selected will consider form quality, facility size, safety factors, high-level waste repository acceptance criteria, and other considerations.

- The final ceramic product is contained in canisters and is stored onsite until it is transported to a high-level waste repository. Each product canister contains 20 compressed bellows with about 660 kg of ceramic, which includes approximately 80 kg of plutonium.

The ceramic product is assumed to be similar to Synroc-C which contains the mineral phases zirconolite ($CaZrTi_2O_7$), hollandite ($BaAl_2Ti_6O_{16}$), perovskite ($CaTiO_3$), and rutile (TiO_2). The actual phases selected will be the result of a research program, and it is assumed that the composition of the ceramic-forming chemicals (precursors) will not affect the processing equipment or sequence.

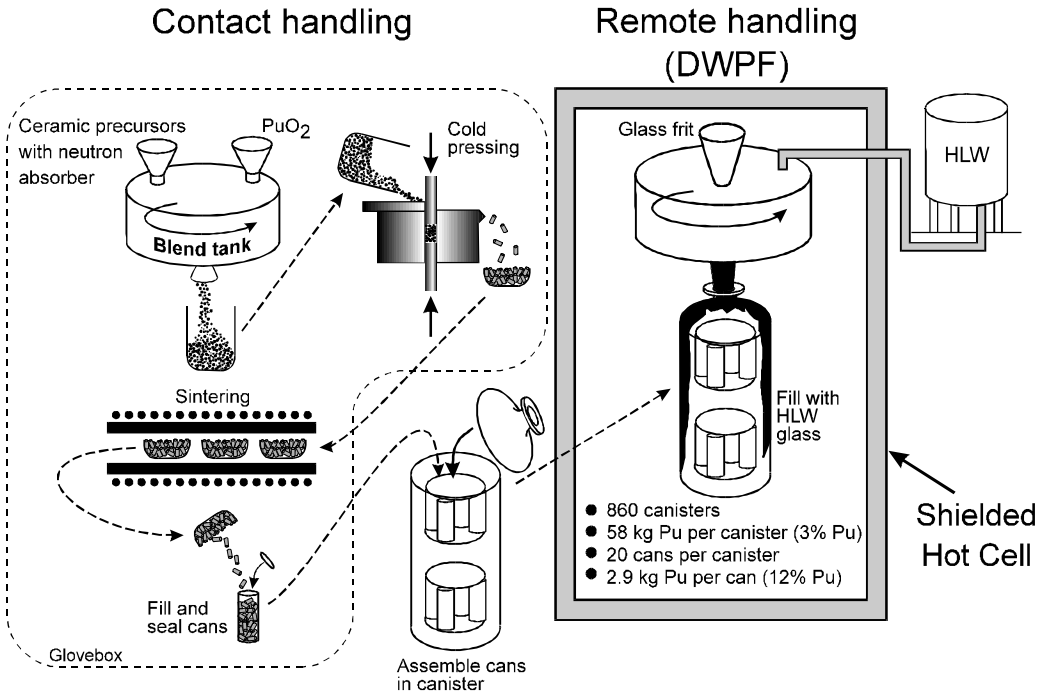
The facility is assumed to be constructed and operated on a generic site. After actual site selection, more specific site-related information will be required.

2.3.2.2 Ceramic Can-in-Canister Variant

This variant is analogous to the vitrification can-in-canister variant. The difference is that the plutonium that is inside the can is immobilized in a ceramic form, rather than a glass form. The ceramic product for this variant is formed using a cold press and sintering process, rather than the hot press process in the greenfield ceramic variant. Plutonium oxide is blended with ceramic precursors and neutron absorbers. This mixture is calcined, cold pressed and sintered to produce the densified product to be loaded into small cans. Figure 2-9 shows the ceramic can-in-canister variant.

Major advantages of the cold press and sinter option are increased throughput, simplicity, and proven production experience in the MOX fuel industry. An automated cold press can process 12.2 kg of plutonium an hour. Cold "pressing" is an option for the ceramic can-in-canister variant because the volatility of fission products (specifically ^{137}Cs) in the sintering process is not an issue.

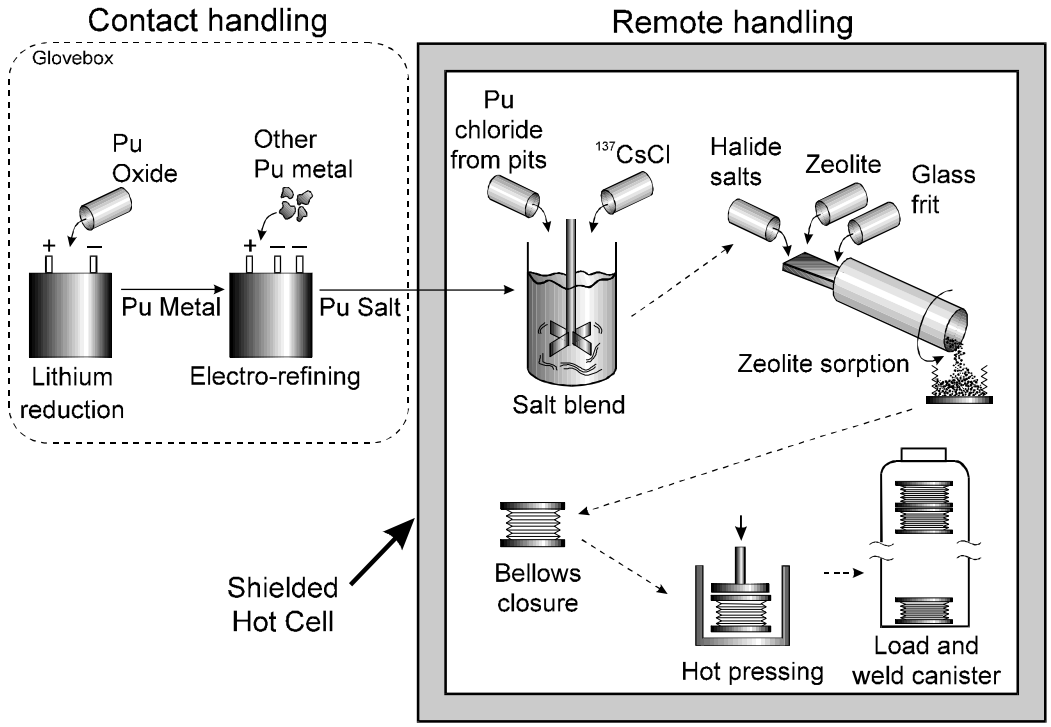
Figure 2-9. ***Ceramic Can-in-Canister Variant***



2.3.3 Electrometallurgical Treatment Alternative

In the Electrometallurgical Treatment Alternative, plutonium metal and oxide are converted to chlorides, dissolved in a molten salt solution, sorbed on zeolites, and then immobilized in a glass-bonded zeolite (GBZ) waste form. The immobilization operations will be integrated with operations in the ANL-West hot cells to treat DOE-owned spent fuels. The fission products from these fuels will contribute some radiation to the immobilization forms, but ^{137}Cs from the Hanford capsules will provide most of the radiation field to create a radiation barrier. Figure 2-10 shows the Electrometallurgical Treatment variant.

Figure 2-10. ***Electrometallurgical Treatment Alternative***



Feed to the immobilization operations will be plutonium metal, oxides, and chlorides. Oxide feeds will be converted to metals in a lithium reduction step and then sent, along with metal feeds, to an electrorefining cell. The electrorefiner converts plutonium metal to chloride using an anodic dissolution process. Metal from pits would be converted to chlorides directly in front-end processing using a hydride/chloride process; the ARIES process would have to be modified to accommodate the conversion to chloride. Plutonium chlorides from the electrorefiner and front-end processing are blended with salt to which CsCl is added to provide the radiation barrier. The blended salt is sorbed onto zeolite, and the zeolite is mixed with a suitable glass frit and hot pressed to make the monolithic mineral form (GBZ). The GBZ forms are loaded into canisters and stored onsite until they can be transferred to a high-level waste repository for disposal.

2.4 DEEP BOREHOLE ALTERNATIVES

Two alternatives are described in this section. Each can be defined as the entire sequence of processes and facilities necessary to convert stable stored weapons-usable plutonium forms into forms to be disposed ultimately in a government-owned deep borehole. The disposal form is not spiked with radioactive waste to provide a radiation barrier; the geologic barrier by itself provides a level of proliferation resistance.

In the deep borehole concept for geologic disposal of surplus fissile materials, the material will be emplaced in the lower part of one or more deep boreholes drilled in tectonically, hydrologically, thermally and geochemically stable rock formations. The borehole site facilities are presumed to be sited on non-DOE sites, unlike all other alternatives which are accomplished on DOE sites with greater or lesser amounts of infrastructure. Once the emplacement zone of the borehole is filled with materials, the "isolation zone" extending from the top of the emplacement zone to the ground surface is filled and sealed with appropriate materials. At emplacement depths, the groundwater is expected to be relatively stagnant, highly saline, hot (75-150^{O} C), and under high pressure. In deep boreholes there is a large barrier to transport posed by the isolation zone because of its low permeability and high sorptivity, the stability and low-solubility of the disposal form, and high salinity and the lack of driving forces for fluid flow. Thus the disposed material is expected to remain, for all practical purposes, permanently isolated from the biosphere.

The Deep Borehole Alternative team analyzed the alternatives in Table 2-6. Both borehole alternatives assume a disposition rate of five MT/year over a ten year operational period, although accelerated cases could allow emplacement in three years with simultaneous rather than sequential drilling of boreholes. The processing operations of the beginning-to-end direct and immobilized deep borehole alternatives are presented in Figures 2-11.

2.4.1 Direct Emplacement Alternative

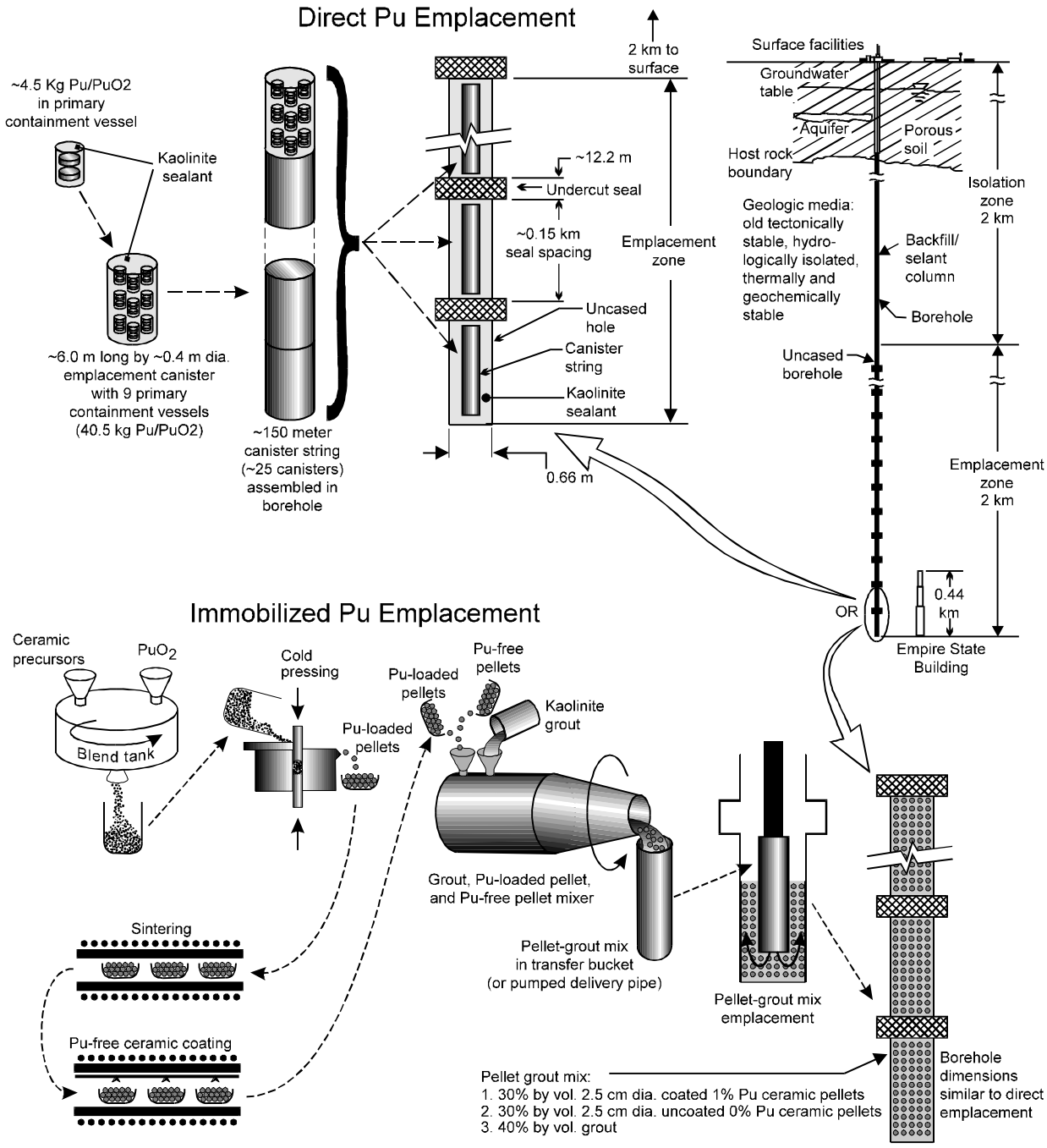
As shown in Figure 2-11, the direct emplacement alternative receives plutonium metal and oxide; and without further purification, this product is packed in metal product cans which are then sealed in primary containment vessels and delivered by SSTs to the deep borehole disposal facility. The product cans are placed in a container which holds plutonium product cans containing approximately 4.5 kg of plutonium with double containment. These transportation containers are directly encapsulated in large (0.4 meter diameter, 6.1 meter long) emplacement canisters with filler material mixture without reopening. Each emplacement canister contains 40.5 kg of plutonium. The emplacement canisters are then assembled into 152 meters long canister strings with 25 canisters per canister string. The canister strings are lowered into the emplacement zone of the boreholes (2 km deep) and are grouted in place with kaolinite clay. Finally, the isolation zone is sealed from the top of the emplacement zone to the surface with appropriate sealing materials.

Table 2-6. *Deep Borehole Alternatives*

Alternative	*Description*
Direct Emplacement	• Disposal form is plutonium metal or plutonium oxide • Emplaced at 2 km depth in four 4 km deep 0.66 to 0.91 meter diameter uncased boreholes • Emplaced in containment vessels (with void filling) within 0.4 meter diameter 6.1 meter long emplacement canisters • No radiation barrier
Immobilized Emplacement	• Disposal form is plutonium immobilized in SYNROC-like titanate ceramic pellet with thin plutonium-free coating • Ceramic pellets containing plutonium have 1% plutonium-loading • Plutonium pellets mixed with equal volume of plutonium-free ceramic pellets and kaolinite grout and emplaced directly without any canisters (mixing plutonium loaded and plutonium-free pellets creates an average plutonium loading of 0.5% by weight) • Emplaced at 2-4 km depth in four 4 km deep 0.66 to 0.91 meter diameter uncased boreholes • No radiation barrier

In the direct deep borehole alternative, the criticality safety of the plutonium-loaded product cans and the transportation containers during intra-site transportation, processing, emplacement, and post-emplacement performance will be ensured by spatial dispersal (i.e., spatial separation). The low solubility of the plutonium metal/plutonium oxide disposal forms and the very slow flow velocities expected at depth appear to provide sufficient resistance to mobilization by flowing groundwater. The heat generated by the plutonium is so small that the temperature rise due to alpha decay of the plutonium is negligible. The high salinity of the groundwater completely suppresses any buoyancy-related fluid flow due to temperature changes arising from both the heat generated by plutonium decay as well as due to geothermal heat. Estimates of fluid flow velocities due to water level fluctuations at the surface and earthquake generated fluid pressure fluctuations appear to be negligible as a result of the great distance from the surface, the low permeabilities of fractured rocks at depth, and stabilizing effect of the high salinity gradients.

Figure 2-11. ***Deep Borehole Alternatives***



2.4.2 Immobilized Emplacement Alternative

As shown in Figure 2-11, the immobilized emplacement alternative receives plutonium oxide from the front-end facility which is then transferred to the immobilization process of the front-end facility for forming plutonium-loaded ceramic pellets by a cold press and high temperature sintering process. The plutonium loading of the ceramic pellets is kept at the very low level of 1% by weight to assure criticality safety during processing and after emplacement. To provide a barrier to contamination during handling, the sintered ceramic pellets are subsequently coated with a thin impervious layer of ceramic that is free of plutonium. The ceramic material is a tailored, SYNROC-like titanate-based ceramic with the mineral phases zirconolite and perovskite as the primary constituents. The pellets will contain 98% ceramic and will be about approximately 4 g/cc in density. The ceramic pellets fabricated at the disassembly, conversion and immobilization facility are then transported by SSTs to the deep borehole disposal facility. At the emplacing facility, the plutonium-loaded ceramic pellets are uniformly mixed with an equal volume of plutonium-free ceramic pellets (to yield a pellet mixture with an average plutonium loading of 0.5% by weight) and 'grout' (i.e., kaolinite clay). This additional dilution of the plutonium-loaded pellets with plutonium-free pellets increases the criticality safety margin. The mix is then directly emplaced in the uncased emplacement zone of the borehole. No metal canisters, packaging materials, or borehole casings that could compromise the hydraulic sealing are left in the emplacement zone of the borehole, providing superior sealing compared to the direct emplacement alternative. Finally, as in the case of direct disposition, the isolation zone of the borehole is sealed from the top of the emplacement zone to the surface with appropriate materials.

The very low solubility and high thermodynamic stability of the ceramic disposition form is expected to provide superior long-term performance as compared to the direct emplacement form. The low solubility of the ceramic pellet disposal forms and the very slow flow velocities expected at depth indicate that many millions of years would be required to mobilize even one millionth of the emplaced plutonium.

2.5 HYBRID ALTERNATIVES

The alternatives described above dispose of all 50 MT of surplus plutonium using a single technology approach. Alternatives which use combinations of reactors, immobilization, and borehole approaches could be devised. Two of the more likely hybrid alternatives are presented here to indicate the potential impacts on technical, cost, and schedule. These two hybrids alternatives are the combination of immobilization can-in-canister with either existing LWRs or CANDU reactors. Both hybrids assume the use of modified existing facilities. Hybrid alternatives provide flexibility to the decision-making processes. Specifically, flexibility is retained in that a decision to utilize a hybrid approach preserves the option to go exclusively with either disposition technology at a later date and flexibility is retained in operations in that one technology is the back up for the other. Furthermore, a higher confidence of timely start-up of the disposition mission is achieved with the potential of a more rapid completion.

In the two cases considered, high-purity, weapons-grade plutonium from pits, metal, and oxides (approximately 32.5 MT) will be used as feed materials for the fabrication of MOX to be used in the reactors. The balance of the surplus plutonium (approximately 17.5 MT) will be used as feed materials for immobilization (either glass or ceramic) can-in-canister. For the LWR hybrid alternative, three existing LWRs without neutron absorbers are assumed. For the CANDU hybrid alternative, two CANDU reactors with reference fuel are assumed. The number of reactors deployed is limited by the capacity of the plutonium processing facility which provides materials for both the reactors and the immobilization plant. Although vitrification can-in-canister was costed in the hybrid, no distinction is made here regarding the selection of either a ceramic or vitrified can-in-canister approach since the cost and schedule differences between the two are small.

The hybrids considered here are illustrative, and others could be presented. No preference is intended by the cases chosen for discussion in this report. Moreover, cost and schedule improvements may be realized with further design optimization.

CHAPTER 3. TECHNICAL STATUS AND ASSESSMENT

Technologies analyzed in this section support alternatives judged to have a good chance of technical success. It is desirable to rely on technologies that have been proven for similar applications and have a high likelihood of success. The key factors relating to this section are:

- technical maturity
- technical risk
- research and engineering development needs
- condition, capacity, and reliability of infrastructure
- regulatory/licensing requirements

A particular difficulty is predicting how the regulatory process will proceed. This difficulty is exacerbated for some of the alternatives since no clear regulatory regime currently exists. Whereas the regulatory basis for reactors and fuel fabrication facilities is reasonably well documented, the basis for licensing an immobilization facility or a deep borehole, for example, has not been established. In all alternatives, the licensing arena represents a risk for experiencing protracted delays in the implementation actions which remains, at least in part, unpredictable.

3.1 COMMON TECHNOLOGIES

3.1.1 Safeguards and Security

A team of Safeguards and Security experts has been working with each Alternative Team to assure that proliferation risks and impacts have been considered consistently throughout the program. In addition, an independent technical evaluation team has been assembled to identify potential weaknesses in the proliferation resistance of disposition alternatives to theft, diversion, and/or retrieval and reuse of material. An unclassified summary report[1] of the team's conclusions was released in October, 1996.

3.1.2 Transportation and Packaging

In general, meeting the stored weapons standard requires transport of significant quantities of plutonium by safe, secure trailers (SSTs) in accordance with DOE Orders. It is likely that IAEA safeguards for these shipments can be accommodated without significant cost impact. Although there are no significant barriers to shipments by SST to Canada, agree-

[1] *Proliferation Vulnerability Red Team Report,* SAND97-8203-UC700, October 1996

ments for security and transfer of custody will need to be negotiated. Similarly, agreements for shipping materials to Europe will have to be negotiated.

Since there has been no need for certified containers before, NRC-certified containers for shipping immobilized plutonium forms designated for the high-level waste repository do not currently exist. A container is being designed and developed by the Westinghouse Savannah River Company as a primary container for defense high-level waste which has only trace quantities of plutonium. As this container is developed, it could be certified and used for other plutonium immobilized forms.

Transportation and associated packaging technologies required to support facility operations have been evaluated. Identification of surrogate facility locations, specifications of material forms, types of containers required, total number of shipments, modes of transportation, and total life cycle costs associated with transportation and packaging have been developed as a part of each alternative/variant analysis. Significant conclusions are:

- Based upon a review of DOT, DOE, and NRC regulatory requirements, all surplus weapons-usable plutonium feed materials are transportable, although it is impractical to ship liquids because of the very small permissible quantities based on 10 CFR 71 and 49 CFR 100-189 (limit is 20 curies, which is 30 to 40 grams of plutonium).

- It is likely that IAEA safeguards will not significantly impact the cost of shipping surplus fissile materials.

3.1.3 Front-End Processing

The Department has initiated a two-year project to demonstrate a pit disassembly and conversion system called the Advanced Recovery and Integrated Extraction System (ARIES). The project will demonstrate a full-scale integrated ARIES prototype with a throughput capacity of 250 to 500 pits per year (1 to 2 per 8-hour day). Depending on specific application, the throughput can be increased by the addition of specific modules or by replication of the entire system. The ARIES prototype will demonstrate the ARIES process and support the design of a production scale pit disassembly facility. The oxide from the ARIES test and demonstration phase will feed downstream disposition operations, including possible supply of plutonium oxide to European MOX fuel fabricators for an accelerated start-up of the existing reactor variants.

Components of the ARIES system have been developed and demonstrated in small scale applications, and the hydride-dehydride process is now in use at Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL) to remove plutonium from pits in support of other DOE programs. Plutonium oxide produced by the ARIES hydride-oxidation process was used to produce the first MOX fuel pellets made with plutonium from pits. This effort is part of the investigation of the suitability of weapons-grade MOX fuel for commercial reactors.

Most of the other chemical and physical processing steps to convert and stabilize plutonium materials to acceptable feed forms for any of the alternatives have been demonstrated within the DOE Complex, and no development efforts will be required that could be expected to delay implementation of any alternative.

3.1.4 Existing Facilities

A preliminary analysis was performed for front-end processing in Building 221F at the Savannah River Site (SRS). This building was selected as an illustrative example of potential cost savings and does not necessarily represent the optimum use of equipment and facility space nor serve to select Savannah River as the site for existing facilities for front-end processing. This analysis included both a system for pit conversion and processing for other types of plutonium feed for the disposition alternatives. This analysis indicated that both a cost savings and a shortening of the schedule for getting started could be realized over the greenfield approach through the use of Building 221F.

For the MOX fabrication facility, the Department briefly reviewed a number of existing facilities at Savannah River, INEL, Hanford, and the Nevada Test Site (NTS). All sites could accommodate MOX fuel fabrication though considerable facility modification and equipment procurement would be required. None of these facilities were originally intended for fuel fabrication except the Fuels and Materials Examination Facility (FMEF) at Hanford; however, this facility had installed systems and equipment for fabrication of specialized fuel for the Fast Flux Test Facility and for the Clinch River Breeder Reactor Plant. Extensive facility modifications would be required as the MOX fuel fabrication for LWRs or CANDU reactors involves work with a significantly different fuel form and throughput. A preliminary review of what could be eliminated from the greenfield approaches by using existing approaches indicated some potential cost and schedule savings could be realized over the greenfield approach through the use of an existing facility for MOX fuel fabrication. It was also learned that much of the cost and schedule advantage could be realized by utilizing the existing nuclear infrastructure at certain DOE sites for MOX fuel fabrication, even if a new facility were constructed.

An independent contractor reviewed a limited number of facilities within the DOE complex for potential licensability by the NRC as a MOX fuel fabrication facility. The review concluded that licensing the different facilities presented different degrees of difficulty. In some cases, the quality assurance records appear sufficient to demonstrate adequate design and construction while in at least one case, a post construction quality assurance program (e.g., analysis and tests) would be required.

3.1.5 Oversight and Licensing

A series of meetings were held in 1995 with the NRC staff to review oversight and licensing issues associated with the disposition alternatives and related common technologies. The results of these meetings were factored into the development of costs and schedules for each of these alternatives.

3.1.6 High-Level Waste Repository

Feasibility analyses were conducted to evaluate the potential for disposing plutonium waste forms in a high-level waste repository. The waste forms evaluated were: 1) spent fuels generated from existing LWRs, partially complete or evolutionary reactors operating with MOX fuel cores, 2) forms produced by immobilizing plutonium in glass or ceramic matrices, and 3) forms produced by the electrometallurgical treatment process. The analyses quantified impacts on an operating repository with a focus on logistics, thermal behavior of the waste forms in a repository environment, dose to the public at the accessible environment, and long-term criticality behavior of the wastes.

Repository analyses for the CANDU spent fuel have not been included in these discussions because the spent fuel from this option is expected to remain in Canada, where the reactor owners are responsible for disposal of their waste.

Logistics

For each alternative analyzed, the total number of additional waste packages that would be added to the approximately 12,000 packages currently envisioned for the first high-level waste repository is small enough that any changes in emplacement could be accommodated within the design ratings of such a repository. The number of additional waste packages ranges from as little as none for the existing LWR variants to as many as 488 waste packages for the spent fuel from the evolutionary reactors. This small change to the total handling of waste packages can be readily accommodated within the design ratings of the repository facilities. Assuming successful form qualification, it has been determined that the plutonium waste forms will be available to the repository for disposal within the time frame that the repository is currently planned to be operational.

Thermal Behavior

Thermal calculations for the waste package have shown that for the MOX spent fuels the peak cladding temperatures are well below the 350^{o} C required to meet the repository thermal goals (e.g., fuel cladding integrity, drift wall temperature, etc.). For the vitrified waste forms (Greenfield glass, adjunct melter, can-in-canister options) and the glass bonded zeolite (produced by the ET process) it has been shown that the peak temperatures are below the 400^{o} C glass transition temperature. Thermal analysis of the plutonium loaded ceramic waste packages (ceramic greenfield, and ceramic can-in-canister) shows a peak temperature around 200^{o} C. Ceramic, unlike glass, does not have a transition temperature because it is a crystalline material. The lowest melting point temperature for the oxides of this ceramic material is around 1800^{o} C. Therefore, the calculated peak temperatures are unlikely to affect the ceramic matrix.

Dose to the Public in the Accessible Environment

Total System Performance Assessments were conducted for each of the waste forms evaluated. Calculations at the accessible environment showed that the dose contribution from the

plutonium wastes are a factor of about two orders of magnitude less than the dose calculated for a repository with commercial spent nuclear fuel and defense high-level waste, exclusive of the forms envisioned for plutonium disposition.

Long-Term Criticality

Long-term criticality considerations fall into three broad categories: waste packages that retain their initial configuration with time (intact mode); waste packages and waste forms as they degrade with time (degraded mode); and fissile material transported away from the degraded waste forms and waste packages (external mode). Criticality calculations conducted to date for the plutonium waste forms have been for the intact mode. Degraded mode analyses are underway based on data being developed in the on-going research and development efforts. External mode evaluations will be addressed in concert with the commercial spent fuel and defense high-level waste program as part of the repository safety analysis.

MOX Spent Fuels

Criticality calculations for the MOX spent fuels followed the same methodology as is currently being used for the commercial spent fuel. No credit is taken for the residual integral neutron absorbers (e.g., gadolinium), and full burn-up credit is taken for the principal isotopics resulting from the nuclear reaction (principal isotope burn-up credit). The analysis of as-fabricated criticality assumed a waste package fully loaded with assemblies, flooded with water, and no additional neutron absorbers. For the BWR spent nuclear fuel from existing reactors using MOX fuel with integral neutron absorbers, the calculations show that the effective neutron multiplication factor, k_{eff}, values are lower than those obtained for the corresponding low-enriched uranium fuels. On the other hand, the PWR spent fuels from the partially complete and evolutionary reactors using MOX fuels contain a higher fissile content and require the use of criticality control technologies or reducing the number of assemblies per waste package to bring the k_{eff} values in compliance with NRC regulations. Calculations for the PWR spent fuel from existing reactors using MOX fuel without integral neutron absorbers have not been completed, but an inspection of the fissile content shows values that are comparable to those in low-enriched uranium spent fuels.

Immobilized Forms

The defense high-level waste currently planned for disposal in a high-level waste repository is a borosilicate glass waste. Because the defense high-level waste glass has no significant quantity of fissile material, no direct comparison with immobilized forms containing plutonium can be made. Therefore, the results of the long-term criticality calculations of the immobilized disposition forms were evaluated solely against the NRC requirements. In all cases only the intact form criticality was calculated, with neutron absorbers, like gadolinium, added to the immobilized form. In all cases, it was shown that the k_{eff} for both the dry and flooded conditions was well below the 0.95 specified by NRC. The waste forms included in these calculations are the greenfield glass, adjunct melter, can-in-canister glass,

the glass bonded zeolite, the ceramic greenfield, and the ceramic can-in-canister alternatives.

3.2 REACTOR ALTERNATIVES

Two components drive the degrees of technical risk for the reactor alternatives. The first component is fuel fabrication; the second is reactor operation. The technical risks associated with the alternatives are outlined below.

3.2.1 Existing Light Water Reactors

Although MOX fuel is not used in commercial reactors in the U.S., fabrication of MOX fuel for LWRs is an industrialized operation in Europe with at least three companies actively involved with the MOX fuel supply business. However, this experience involves the use of reactor-grade plutonium derived from previously irradiated fuel and is limited to partial MOX cores. As such, there are a number of technical uncertainties with the fabrication of MOX fuel from weapons-derived plutonium related to commercial MOX fuel usage:

1. Weapons-grade plutonium contains small amounts of gallium, a corrosive metal added as an alloying agent. The impact of gallium on the fuel fabrication process and the fabrication equipment is presently unknown. The potential impact will have to be determined or a process added to remove gallium from the MOX fuel feed. Aqueous processing is considered a backup process that could readily be used to remove the gallium, but this creates considerable radioactive aqueous waste and involves additional cost and complexity.

2. Reactor-grade plutonium used in Europe is generated through aqueous separation processes. Most of the weapons-derived plutonium is expected to be extracted via dry processes. The differences in the physical characteristics of the different sources of plutonium need to be assessed, since parameters such as particle size can be quite important in producing MOX fuel.

3. Some alternatives require MOX fuel with depletable integral neutron absorbers. There is no industrial experience with integral neutron absorbers in MOX fuel and a corresponding fuel fabrication process would have to be developed and qualified.

The use of MOX fuel in LWRs in the U.S. has its own risk, relative to operating experience with MOX fuel reactors in Europe. As with MOX fuel fabrication, there is extensive experience with the operation of reactors with MOX fuel. Existing reactors operating experience is based on partial MOX cores and would have to be reassessed for full MOX cores. Using full-core MOX fuel designs is innovative and is selected for the higher plutonium throughputs which can be achieved. The fuel fabrication of full-core MOX fuel designs is not significantly different from the fabrication of partial-core loads, assuming no integral depletable neutron absorbers are employed; however, reactor performance will need to be confirmed by additional analyses and will likely require lead test assemblies. The

impact of gallium, the higher fissile content of weapons-grade plutonium versus reactor-grade plutonium, and, depending on the variant selected, the impact of depletable integral neutron absorbers on in-reactor fuel performance would have to be characterized through a fuel qualification program. If the fuel qualification program were not successful because of the presence of gallium, aqueous processing of the feed would be required. If the fuel qualification program were not successful because of the presence of integral neutron absorbers, the reactor variant that does not use the integral neutron absorbers would be required. This would involve using more reactors for the mission. Confirmatory design analysis and a likely LUA irradiation would also be required, though such a confirmatory effort would be much less demanding than the integral neutron absorber variant.

In addition to the risks relating to the maturity of the technology, there are risks related to the availability of the infrastructure for fuel fabrication. European capacity for making MOX fuel is limited, so it is likely that a domestic MOX fuel capability will need to be developed by either using a new facility or modifying an existing facility. Some risks are present with actions which require designing, building, and licensing a plutonium facility in the United States. However, the design basis and regulatory requirements for a MOX fuel facility are well established. The risks relating to a new facility are partially offset by modifying existing facilities; however, modifications to existing structures represent their own risks because of the need to demonstrate conformance with modern regulatory requirements.

With sufficient delay in the program, it is possible the alternative could become non-viable due to the loss of the reactors as their licenses expire. The issue also applies to BWRs and PWRs but is less critical for PWRs because there are more PWRs, and they tend to be newer than BWRs. Section 5.2.2 addresses the availability of reactors in more detail.

A great many of the 110 commercial nuclear reactors licensed to operate in the U.S. can utilize MOX with few, if any, changes to the reactor design. Excluding reactors which are small (less than 750 MWe) and those with limited remaining life (licenses set to expire by 2015), approximately 60 or more reactors may be suitable for the mission. As few as three reactors are needed to complete the mission. Clearly, the capacity of the existing reactor infrastructure is adequate as long as there is no protracted delay in the mission. The risks present with the use of commercial reactors relate to obtaining an amendment of reactor licenses to utilize MOX fuel and negotiations between reactor owners and the U.S. government over use of the reactors for plutonium disposition.

There also may be issues related to packaging and shipping weapons-grade plutonium to Europe which would need to be resolved if European MOX fuel fabrication were selected for implementation.

3.2.2 CANDU Reactors

CANDU reactors have a number of technical viability risks similar to existing LWRs with respect to this mission. The similarities include: acceptance of MOX fuel with little or no reactor modification; operation with MOX fuel within an existing approved safety envelope;

common isotopics and gallium issues; and the need for negotiation of an agreement between the reactor owners and the respective governments. A number of characteristics imply simpler fabrication processes compared to LWR fuel fabrication processes: the small size of CANDU bundles, the absence of any need for integral neutron absorbers with plutonium, a fissile fuel content lower than LWR fuels, and low burnups. On the other hand, industrialization of CANDU MOX fuel has never been attempted and a fuel development and qualification program is required. Therefore, CANDU reactor technology, for the use of MOX, fuel is not as mature as that for LWRs. There also may be issues related to packaging and shipping weapons-grade plutonium to a separate, sovereign state which would need to be resolved.

The CANFLEX fuel form, which is currently being developed independently for natural uranium fuel designs for CANDU reactors, features a higher concentration of plutonium in the fuel than the reference MOX CANDU fuel form and requires a fuel qualification and demonstration phase that goes well beyond that required for adaptation of the existing reference CANDU MOX fuel. The MOX CANFLEX fuel design, although it has significant cost, schedule, and environmental advantages over the reference CANDU fuel design, represents a departure from the existing CANDU technology base and is therefore more developmental than the reference CANDU fuel.

3.2.3 Partially Complete Light Water Reactors

Partially complete LWRs share the same risks as the existing LWR existing facilities variant with the following additions: 1) integral neutron absorber MOX core strategies would be required and 2) the risks associated with the completion of the design, construction, and licensing of the reactors are present in addition to the existing LWR risks, and 3) there are only an limited number of partially complete reactors. Partially complete reactors require integral neutron absorbers since the enhanced plutonium throughput is required to complete disposition within approximately 25 years with two reactors.

3.2.4 Evolutionary Light Water Reactors

Evolutionary reactors involve more risk than the partially complete reactor variant since there are greater risks associated with designing, building, and licensing entirely new reactor facilities. The evolutionary reactor designs are novel and involve their own technical risk for qualification and procurement of equipment and satisfying regulatory reviews. For the same reason as with the partially complete reactors alternative, integral neutron absorbers are necessary for the evolutionary reactor alternative.

3.2.5 Actions to Address Technical Risk

All of the reactor alternatives pose some degree of technical risk to implement and the degree of risk varies with each alternative. The range of technical risk varies from adapting existing LWRs to new MOX fuel cycles, which is substantially a confirmatory effort, to building new LWRs with new fuel forms, which involves an extensive fuel qualification

program and extensive reactor construction. Activities are currently underway to mitigate the specific reactor alternative risks. These activities are as follows:

A. A series of fuel fabrication tests for LWR and CANDU fuels are being performed at LANL. These tests are being performed to address the fuel fabrication issues relating to morphology, powder particulate size, powder processing steps, processes to render plutonium powder from pits (dry versus wet processes), and gallium in the plutonium feed stream.

B. Irradiation tests of LWR fuel rods containing MOX fuel pellets are planned to confirm the adequacy of the fuel fabrication processes and to confirm the compatibility of LWR reactors with weapons-grade MOX fuel cycles.

C. Irradiation tests of CANDU fuel rods containing MOX fuel pellets are planned to confirm the adequacy of the fuel fabrication processes and the compatibility of the CANDU reactors with weapons-grade MOX fuel cycles. These irradiation tests will be performed in conjunction with tests of MOX fuel derived from Russian weapons-grade plutonium fabricated in Russia.

3.3 IMMOBILIZATION ALTERNATIVES

Despite an abundance of research and experience in immobilizing high-level waste, the plutonium immobilization alternatives still have a number of design questions to be resolved. Key technical uncertainties involve process equipment development and formulation of waste forms suitable for long-term performance in a high-level waste repository. Significant experience exists with some immobilized forms and a reliable body of experimental data is emerging. A summary of the technical risks relating to the immobilization alternatives is given below.

One important issue to be resolved for all immobilization alternatives is the need to establish a process for demonstrating acceptability of immobilized waste forms to a high-level waste repository. The immobilization alternatives differ from defense high-level waste with regard to the higher fissile loadings expected in the immobilized waste forms. A program will be required to demonstrate criticality prevention over long periods of emplacement. Preliminary results from consultations with the Office of Civilian Radioactive Waste Management indicate that all waste forms being analyzed are anticipated to be acceptable to a repository.

3.3.1 Vitrification Alternative

All of the vitrification variants will require research to understand and quantify a number of design considerations, including plutonium solubility and dissolution kinetics, selection of an optimum neutron absorber, solubility interactions of the neutron absorber and plutonium, impact of impurities on quality of waste form, and melter design for criticality control and compaction process. A development effort is in progress to design facilities and equipment for the mission. This effort can build upon the extensive data base of technologies for vitrification of high-level waste forms that exists both in the United States and overseas. Much

of that experience is limited to applications where actinide concentrations were very low (generally less than 0.1% by weight). However, an experience base for vitrification with higher concentrations of plutonium is beginning to emerge.

Conceptual designs of systems and components have been identified for the vitrification variants, and technologies have been demonstrated at laboratory scale. Crucible melts with plutonium nitrate feeds have successfully been dissolved in glass. For example, plutonium loading has been demonstrated at the laboratory scale at 11 wt % for Löffler glass (the proposed high-temperature glass form for the can-in-canister glass variant) and at 5% for the lower temperature alkali-tin-silicate (ATS) glass (the proposed glass for incorporating the cesium radiation barrier in the greenfield and adjunct melter variants). Key processing parameters requiring further development and demonstration are plutonium oxide (high and low fired) solubility in glass, uniform mixing in the melter, and processing time and temperatures for production-reliable operation of the melter at the required glass physical properties.

The can-in-canister variant appears the more viable since the glass containing the plutonium does not have to simultaneously incorporate the ^{137}Cs because the radiation source is the vitrified high-level waste outside the can. In addition, this approach allows use of the Defense Waste Processing Facility (DWPF) at Savannah River, eliminating the need for a new hot cell. The can-in-canister variant has been successfully demonstrated cold (i.e., without radionuclides) at the DWPF.

3.3.2 Ceramic Alternative

The ceramic variants are expected to provide superior confinement of plutonium over geologic time scales. This argument is supported by the existence of mineral forms found in nature ("natural analogs") that have demonstrated the immobilization of actinides for periods exceeding 100 million years. Ceramic waste forms have been under development for high-level waste for many years; however, the application of ceramic technology for the immobilization of plutonium is currently developmental. Key technical issues for plutonium immobilization include achieving simultaneous high densities, reacting plutonium from oxides to an incorporated phase, and attaining compatibility with expected impurities. Success in each of these areas depends on the ceramic mineral formulation, as well as the methodology selected for fabrication (including the technology for densifying the ceramic and whether the plutonium feed is dry oxide or a nitrate solution).

The two fabrication methods for ceramic immobilization being considered for this mission are generally well known: hot pressing in bellows and cold pressing and sintering. Hot pressing generally achieves higher densities and can retain ^{137}Cs added as a radiation barrier but accommodates a relatively lower throughput. Cold pressing and sintering is generally more cost effective due to a higher throughput and is suitable only for the can-in-canister approach because it will likely not retain ^{137}Cs at the high temperatures in the sintering furnace.

The can-in-canister variant appears the more viable since the ceramic containing the plutonium does not have to simultaneously incorporate the ^{137}Cs. In addition, this approach allows use of the Defense Waste Processing Facility (DWPF) at Savannah River with minimal interference on the ongoing high-level waste operation and eliminates the need for a new hot cell.

Hot pressed ceramic samples containing 10 to 100 grams of plutonium at a loading of 12% have been prepared which indicate that full-scale production is viable. Cold pressing and sintering has produced ceramic pellets with oxide powder loading of 12%. Full characterization of these samples have not yet been completed. The technology for cold-press and sinter is similar to that used for production of MOX fuel and is a mature production advantage for this waste form.

The baseline feed approach for producing hot press ceramics is the use of plutonium nitrate solution. This "wet" feed approach generally results in a more fully reacted plutonium ceramic product; however, it requires an off-gas system (thus larger capital equipment) and could result in greater volumes of secondary waste. A more desirable approach would be to use a "dry" plutonium oxide feed, which results in significantly reduced secondary waste but is more difficult to obtain completely reacted plutonium in the ceramic matrix and is less well demonstrated at the present. Additional developmental work to reduce technical uncertainties would be required to select the dry feed approach.

3.3.3 Electrometallurgical Treatment Alternative

The electrometallurgical treatment alternative requires further development to confirm its applicability as an immobilization option for plutonium disposition. Although the technical viability of several components of this alternative is well established for spent nuclear fuels, questions regarding the technical viability of this alternative for the plutonium disposition mission remain. Most of the technical risk associated with this alternative is due to a small experience base of several unit processes with pure plutonium. The lithium reduction step of the process has been demonstrated with uranium oxide and with mixed uranium and plutonium oxides but not with pure plutonium oxide or plutonium containing large quantities of inert material. The zeolite waste form has been demonstrated at a few gram scale (total mass) using plutonium-loaded chloride salt. The electrorefining process is currently being operated with irradiated Experimental Breeder Reactor-II fuel and blanket assemblies on a limited demonstration basis at ANL-W using some of the same facilities, equipment and processes that would apply to fissile materials disposition.

Regarding the qualification of the zeolite waste form for the high-level waste repository, a NAS National Research Council Report noted several concerns with the long-term performance of this waste form, including radioactive decay effects and chemical and thermal

stability.[2] The NAS recommended increased development program efforts to address these issues.

3.3.4 Actions to Address Technical Risk

The following activities are currently underway or will soon be initiated to mitigate specific implementation risks.

A. The glass can-in-canister approach was recently demonstrated at the DWPF. Small cans containing a high-temperature glass with a plutonium surrogate were loaded into two full-size DWPF canisters (one canister contained 8 cans and the other 20) which were subsequently filled with a surrogate high-level waste glass in DWPF as part of the cold startup qualification tests of that facility. Destructive and non-destructive analyses confirmed that the simulated high-level waste glass filled both canisters without creating significant void spaces, while preserving the integrity of the can and canister assembly. Additional information will be analyzed on the physical and chemical properties of both the simulated plutonium and high-level waste glasses. The results of these examinations will be used to quantify the operating parameters of the can-in-canister concept.

B. An effort is underway to develop and demonstrate prototypical systems for the production scale incorporation of plutonium in one of the glass and ceramic waste forms currently under investigation. The glass forms require the development of a suitable melter system which includes both suitable feeders and product load out systems. The ceramic forms require either (1) the development of a suitable feed preparation and cold pressing system coupled with an appropriate sintering heat cycle similar to that used to fabricate nuclear reactor fuel or (2) the development of a suitable feed preparation and hot pressing system. Each system must be operable within a glove box enclosure to provide for safe plutonium operations.

C. Current plans for electrometallurgical treatment alternative requires demonstration of the lithium reduction equipment to convert plutonium oxide to metal and for fabricating plutonium-spiked samples of glass-bonded zeolite for performance testing.

D. A continuing effort of research and development activities are being performed to address uncertainties associated with plutonium incorporation kinetics, plutonium and neutron absorber leach rates, neutron absorber selection, durability of waste forms, and other studies to identify potential show stoppers for implementation.

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[2] National Academy of Science, National Research Council, An Evaluation of the Electrometallurgical Approach for Treatment of Excess Weapons Plutonium, National Academy Press, Washington, DC, 1996.

3.4 DEEP BOREHOLE ALTERNATIVES

While no deep borehole disposal facilities for plutonium disposition have ever been developed, many of the technologies needed for this alternative are quite mature; and the basic concept has been considered previously for waste disposal. The overall concept of deep borehole disposition has been considered in recent decades for disposal of both hazardous and radioactive wastes. This concept received significant investigation in the 1970s for disposal of high-level radioactive waste and spent nuclear reactor fuel. Similar studies have been conducted in other countries including Russia, Sweden, and Belgium.

Technical unknowns for deep borehole disposition center around underground conditions and post-closure performance and a regulatory environment against which performance objectives can be measured. It is believed that suitable rock formations can be found in a variety of areas, that they can be adequately characterized, and that the long term evolution of processes can be predicted to assure long term isolation and safety.

One distinguishing feature of the deep borehole alternatives is that it effects geologic disposal whereas, for the reactor and immobilization alternatives, the plutonium is converted to a waste form which must be disposed of in a high-level waste repository. In all cases, however, the disposition cost summaries budget for geologic disposal.

The immobilized deep borehole disposition alternative differs somewhat from the direct deep borehole disposition alternative in terms of technical unknowns. The extra cost of immobilizing the plutonium may be accepted in part to give added assurance of long term isolation safety and a simplified licensing safety argument. These factors result in this alternative having less technical uncertainty than the direct deep borehole disposition alternative.

The reasons for this increased confidence in the immobilized deep borehole disposition alternative with respect to long-term performance are:

1. *Reduced Post-Closure Contaminant Mobilization:* The ceramic pellet disposal form used in the immobilization alternative is the highest performing, most geologically compatible and thermodynamically stable disposal form available. The solubility and plutonium release rate from this disposal form is at least three to four orders of magnitude lower than those of other competing disposal forms including the plutonium metal or plutonium oxidedisposal forms of the direct disposal alternative.
2. *Increased Confidence in Emplacement Zone Sealing:* The degree of isolation of the disposed plutonium from the biosphere will depend not only on the geologic barrier posed by the geosphere but also on the nature of the transport mechanisms and the resistance to transport up the deep borehole past the deep borehole seals. It is necessary to seal properly not only the isolation zone in the upper half the deep borehole but also the emplacement zone in the bottom half of the deep borehole. The immobilized emplacement alternative reduces uncertainty in emplacement zone sealing by eliminating long, vertical canisters which could degrade into potential flowpaths.

3. *Increased Post-Closure Criticality Safety:* The plutonium loading in the ceramic pellet option has been kept to a very low 0.5% effective loading (for a 1:1 mix of 1% loaded pellets and plutonium-free pellets) to drive the criticality coefficient down to a value of 0.67 under the worst possible brine saturated conditions without any addition of integral neutron absorbers. This is far below the value of 0.95 specified for the safe storage of plutonium metal.

Siting guidelines and procedures is the largest area of uncertainty. Site suitability guidelines consistent with the mission and safety concept of deep borehole disposition will require development. Separated fissile material in significant quantities has never been considered for direct disposition before and a regulatory framework to address this deep borehole disposal does not currently exist. Therefore, regulatory uncertainty was identified as a risk that affects the viability of deep borehole disposition. However, preliminary discussions with licensing experts indicate that a licensing regime can be developed, given sufficient time and a mandate.

The equipment required to implement the deep borehole alternatives are adaptations of equipment designed and used for nuclear weapons testing, geological studies, and the petroleum and gas drilling industries. The equipment requirements with respect to environmental safety and quality are within current capability or are viable extrapolations from existing mechanical engineering designs. An integration and demonstration of the equipment will be required, and the systems engineering must be performed. Notwithstanding, the mechanical design is not expected to be a controlling technical risk for these alternatives.

3.4.1 Actions to Address Technical Risk

The potential for very long-term geochemical processes in the deep borehole environment to mobilize and redistribute fissile isotopes into critical configurations is a subject of current research and development activity. Preliminary research and development results indicate that there exist a number of characteristics of the deep borehole environment that provide a very strong safety argument against both post-closure criticality and post-closure contamination of the biosphere. The high safety margin arises from the great depth of burial, the high resistance to mobilization of the selected disposal forms, the properties of the subsurface rock and brines, the low-permeabilities of fractured rock at great depths, and the lack of driving forces for fluid flow at sites selected according to the site selection criteria developed for deep borehole disposition.

3.5 HYBRID ALTERNATIVES

Hybrid approaches, wherein different feed materials (pits versus impure plutonium, for example) go different routes, opens the possibility of utilizing existing facilities in different ways to achieve program objectives. As an example, a newly completed chemical recovery facility at Savannah River could be used as designed to directly support the immobilization portion of a hybrid alternative with relative little modification and expense. Other possible uses of present facilities are also possible and these approaches need to be further evaluated.

Likely benefits of a hybrid approach include:

- Hybrid approaches may provide better utilization of existing facilities and operations with fewer modifications and reduced expense.

- Hybrids may enhance early start capabilities since the start-up of any portion of the hybrid is a start of the U.S. plutonium disposition mission .

- Since parallel processing paths are being utilized, proper utilization of the hybrid approach could also result in earlier completion of disposition. As an example, the hybrid approach reduces the quantity of plutonium going through reactors by about 33%. This reduction in throughput could require either fewer reactors (same mission duration), or would result in an earlier finish using the same number of reactors as in the existing LWR variant.

- Hybrids provide insurance against technical or institutional hurdles which could arise for a single technology approach for disposition. If any significant roadblock is encountered in any one area of a hybrid, it would be possible to simply divert the feed material to the more viable technology. In the case of a single technology, such roadblocks would be more problematic.

- Hybrids minimize the purification and processing of the existing plutonium feed materials for disposition. Since such operations tend to produce quantities of transuranic and low level nuclear waste, utilization of a hybrid approach will likely reduce such waste over the case of stand alone reactor variants.

The downsides to the hybrid approaches include having two sets of processes and facilities to be designed and operated and also having both sets of technical issues to resolve.

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CHAPTER 4. COST SUMMARIES

Cost estimation methodology is described in Section 4.1. Costs for the reactor, immobilization, deep borehole, and hybrid alternatives are presented in Sections 4.2 through 4.5, respectively. Section 4.6 provides a summary and comparison of all alternative costs. Discussion of cost-related uncertainties is deferred to Chapter 6.

4.1 COST ESTIMATION METHODOLOGY

Cost estimates for each major facility in each alternative were generated using the 24 cost categories described in Appendix C. These 24 categories are aggregated into three higher-level cost categories: pre-operational, capital, and operating. Pre-operational costs include research and development, licensing, conceptual design, and startup costs. Capital costs include engineering, capital equipment, and construction costs. The capital cost represents the "line item" Congressional appropriation that would be required to fund the project. Pre-operational and capital costs would generally be incurred within the first ten years of the project and would require near-term Congressional funding. This near-term government funding requirement will be referred to as the *investment cost*[1]. Other life cycle costs, which will be referred to as *operating cost*, include staffing, maintenance, consumables, waste management, decontamination and decommissioning costs for performing the plutonium disposition mission. Operating costs that would be incurred independent of plutonium disposition activities, such as operation of the Defense Waste Processing Facility (DWPF) for the high-level waste mission or operation of existing reactors for power production, are not included.

Fuel displacement credits, which reflect the cost recovery that would be realized by displacement of uranium fuel by MOX fuel, are included in the estimates for existing reactors alternatives. Potential r*evenues* that might be realized by the partially complete and evolutionary reactors are estimated. Investment cost, operating cost, fuel displacement credits, and revenues are combined to yield a net *life cycle cost* for the alternative.

Life cycle costs are reported in terms of undiscounted constant dollars (1996$)[2] and discounted net present value. For discounted cost calculations, constant dollar cash flow streams are distributed over time, according to the schedules reported in Chapter 5, and discounted on an annual basis. Office of Management and Budget (OMB) Circular No. A-94 recommends using a real discount rate that has been adjusted to eliminate the effect of

[1] In government accounting parlance, pre-operational cost is referred to as "operating-funded costs" or OPC, capital cost is referred to as "total estimated cost" or TEC, and investment cost is referred to as "total project cost" (TPC). Note that the relationship OPC + TEC = TPC holds.

[2] Actual cash flows associated with future expenditures are reduced to account for inflation effects to yield equivalent expenditures in terms of 1996 dollars (1996$). For example, if inflation is 3% per year, an expenditure of $1.03 in 1997 would be equivalent to $1.00 measured in 1996$. Use of constant dollars simplifies cost estimation and accounting.

expected inflation to discount constant-dollar costs and benefits (including revenues). OMB issues annual revisions to the recommended rates for use during that year. In January 1995, OMB recommended a real discount rate (for 30 years) of 4.9%, but in January 1996 recommended a real discount rate (for 30 years) of 3.0%. The real discount rate can be approximated by subtracting expected inflation from the nominal interest rate. The published yields for long term treasury securities (maturing in the 2010 to 2020 timeframe) average greater than 7%. Subtracting OMB's forecast of expected inflation rate of about 2.7% results in real discount rates of approximately 4.5%. The Department, in its Technical Reference Report for Tritium Supply and Recycle, October 1995, used a real discount rate of 4.9%. Therefore, for this report in which the estimates have less precision, the discount rate represents a midpoint in the range of discount rates between 3 and 7 percent which have been utilized over recent years. The sensitivity of the results to the discount rate is discussed in Section 6.6.

Depending upon the alternative, costs were estimated for new facilities at DOE sites with no plutonium infrastructure (denoted as "greenfield" in this report), new facilities at DOE sites with plutonium-handling infrastructure or unused areas in existing buildings on such DOE sites (denoted as "existing facilities" in this report). Construction of facilities at greenfield sites would require development of site infrastructure such as health physics, analytical laboratories and waste handling. New facilities located at DOE sites with plutonium handling infrastructure would realize substantial cost savings associated with shared usage of such site infrastructure. Finally, maximum cost savings and schedule compression could be realized by modifying and using facilities, including buildings, at DOE sites with appropriate infrastructure. Use of modified facilities would reduce the costs of structures as well as heating, ventilation, and air conditioning, electrical, water, and other support systems. Cost estimates for usage of Building 221F and other facilities at Savannah River were developed in order to illustrate the level of savings that could be realized, but other DOE sites might be utilized. No recommendation regarding siting of facilities at Savannah River is implied by this example. A substantial portion of these savings could be realized by using the existing site infrastructure even if a new building is erected. MOX fuel fabrication costs were also calculated under private and government ownership arrangements. Finally, cost estimates for front-end facilities presume collocation of ARIES and non-pit processing equipment. If ARIES and non-pit processing equipment were not collocated, costs would be higher due to the duplication of some support infrastructure.

These preliminary cost estimates were generated based on pre-conceptual designs using various assumptions and approximations related to outcomes of research and development programs, licensing efforts, and negotiations with suppliers. Because designs are at the pre-conceptual level of definition, the estimates are subject to substantial uncertainty. Several of the more important sources of uncertainty have been identified in this chapter. Quantification of some of the key cost uncertainties is provided in Chapter 6.

4.2 REACTOR ALTERNATIVES COSTS

4.2.1 Assumptions

The financial structure of the reactor alternatives described in Chapter 2 tends to be more complex than the others. Key assumptions that are incorporated in their analysis are as follows:

1) Estimates of incentive fees, if any, that might be paid to utilities for MOX fuel irradiation services have not been included in reactor alternatives costs. Such fees are a part of business arrangements yet to be proposed and negotiated and may be in addition to the expected reimbursable costs that would be incurred by the utilities for MOX irradiation services. The magnitude of the fees, if any, represents a significant cost uncertainty which is discussed in Chapter 6.

2) Operating costs shown for all existing reactors are only the net additional costs for MOX fuel operations compared to operations with LEU or natural uranium fuel. For the partially complete and evolutionary reactors, operating costs incurred during uranium fuel operations are not included in the data reported here. The operating costs for the reactor alternatives include the operational costs for the front-end facility and the MOX fuel facility as well as any additional costs at the reactor site unique to plutonium disposition.

3) For the existing LWR and CANDU reactor alternatives, a credit is taken for the cost of the private utility's uranium fuel that the government-produced MOX fuel displaces.

4) Unless otherwise noted, government ownership of plutonium processing and MOX fuel fabrication facilities is assumed.

5) For all of the reactor variants analyzed in this Report, plutonium processing and MOX fuel fabrication equipment is placed in existing buildings at DOE sites with existing plutonium handling infrastructure, except for the existing reactor, Greenfield variant. The private MOX fuel facility approach, which is discussed in this Report, uses a new building on an existing DOE site with plutonium handling infrastructure.

6) Existing LWR and CANDU reactors are privately owned and operated, with revenues from electricity sales accruing to the utilities.

7) The cost for thermally processing plutonium from pits to remove gallium is included in the estimates for conservatism, even though the gallium removal operations are believed to be unnecessary.

8) High-level waste repository costs are included as part of the operating costs of the partially complete and evolutionary reactors ($0.001/kWh).

9) For the partially complete and evolutionary reactor alternatives, there are special financial assumptions which apply:

   - The revenue streams for these alternatives are priced at $ 0.029/kWh, a typical but conservative value for inflation-adjusted long-term electricity market price. (See Chapter 6 for alternative assumptions.)
   - No attempt to partition the revenue stream between the Government and private sector entities has been attempted since the split, if any, is subject to business arrangements yet to be proposed and negotiated (for partially complete reactor alternative only).
   - No salvage value is assigned to the reactors after they complete the plutonium disposition mission. The actual salvage value to be realized depends on a variety of unknown factors, especially the business arrangements yet to be proposed and negotiated. (See Chapter 6 for alternative assumptions.)
   - Only the costs and revenues for the reactors which relate to using MOX fuel are considered.

10) The cost for European fuel fabrication of LUAs and initial core loads for existing LWRs and CANDU reactors is $1500 per kilogram heavy metal. Use of European MOX fuel capacity is not included in the baseline cost estimate for CANDU reactors. The sensitivity to the European MOX fuel cost is explored in Section 6.2 for both LWRs and CANDU reactors.

4.2.2 Cost Analysis

Investment costs, undiscounted life cycle costs, and discounted life cycle costs of existing reactor alternatives are summarized in Figure 4-1, with supporting detail of costs by facility shown in Table 4-1.[3]

As indicated by the data, the existing LWR, existing facilities variant requires approximately $1 billion[4] in investment cost to design, license, and construct/modify plutonium processing (front-end) and MOX fuel fabrication facilities and to pay for modifications, licensing, and fuel test and qualifications for the privately-owned reactors. Of this investment cost $750 million is required for the plutonium processing and MOX fuel fabrication facilities at an existing site with existing plutonium handling infrastructure. Similar co-functional and co-

[3] The information derives from the Reactor Alternative Summary Reports. Differences between costs here and the Reactor Alternative Summery Reports, generally less that 2%, derive from a series of rounding errors and small differences in schedules (a few weeks over several years). These differences are not material to this Report. The Reactor Alternative Summery Reports cost basis also includes business-related cost items that are not included in the cost basis in this Report. These business-related costs are discussed in Chapter 6.

[4] All costs are undiscounted costs unless indicated otherwise.

located facilities at a greenfield site would cost $1050 million, or $300 million more. The CANDU MOX fuel fabrication facility investment cost is $40 million higher than that for the LWR MOX fuel facilities. This is due to the larger plant capacity needed to support higher heavy metal throughput for fabrication of the lower-enrichment CANDU fuel. However, the higher investment cost for the MOX fuel plant for the CANDU alternative relative to the existing LWR, existing facilities variant is more than offset by the lower investment costs required to convert CANDU reactors to MOX fuel cycles compared to the LWR transition. In general, the front-end plutonium processing facilities account for about one third of the investment cost in the existing LWR and CANDU variants. Relative to operating costs, the CANDU MOX fuel fabrication operating costs are higher than the costs of fabricating LWR MOX fuel, which can also be attributed to the greater heavy metal throughput associated with CANDU fuel.

Figure 4-1. ***Existing Reactor Alternatives Costs***

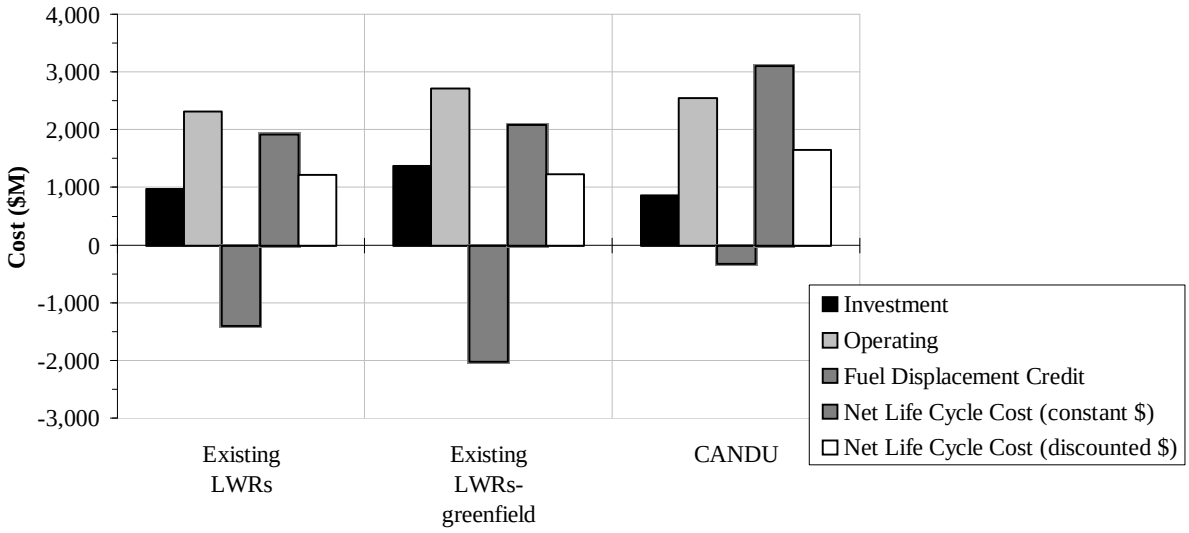


Table 4-1. ***Existing Reactor Alternatives Costs***

		Constant $ (millions)				*Discounted $ (millions)*			
Reactor Alternative	***Facility***	***Investment***	***Operating***	***Fuel Displacement Credit***	***Net Life Cycle Cost***	***Investment***	***Operating***	***Fuel Displacement Credit***	***Net Life Cycle Cost***
Existing LWRs, Existing Facilities	Front-end	340	1050	0	1390				
	MOX Fab	410	1130 [2]	-1390	150				
	Reactor	230	150	0	380				
	Total	**980**	**2330**	**-1390**	**1920**	**710**	**1230**	**-720**	**1220**
Existing LWRs, Greenfield Facilities[1]	Front-end	1050	2590	-2010	1630				
	Reactor	330	130	0	460				
	Total	**1380**	**2720**	**-2010**	**2090**	**950**	**1110**	**-820**	**1240**
CANDU	Front-end	320	1090	0	1410				
	MOX Fab	450	1430	-320	1560				
	Reactor	100	40	0	140				
	Total	**870**	**2560**	**-320**	**3110**	**630**	**1180**	**-150**	**1660**

[1] Because the greenfield front-end and MOX fuel fabrication facilities are collocated in the Existing Reactor, Greenfield variant, their costs are combined in the table.

[2] $240 M of this cost is for the fuel fabricated in Europe.

The uranium fuel displacement credit for the existing LWR, existing facilities variant (a five PWR case) is $1.4 billion, which is equivalent to the cost of LEU that is displaced by MOX fuel. The credits are $2 billion for the LWR, Greenfield facilities variant (a four BWR case), and $0.3 billion for the CANDU reactors. The credit is higher for the BWR case because these reactors use fuel with lower plutonium loading; hence, more uranium fuel assemblies are displaced by MOX fuel assemblies using the 50 MT of surplus plutonium. The lower CANDU MOX fuel credits reflect the lower cost of the natural uranium fuel used by the CANDU reactors. (The cost of natural uranium CANDU fuel is only $100 per kilogram of uranium, compared to approximately $1200 per kilogram of uranium for the low-enriched fuel used in LWRs. The cost figures in Table 4-1 reflect that the CANDU MOX fuel bundles replace natural uranium fuel bundles on an equivalent energy extraction basis, not on kilogram of heavy metal basis.) Note that the comparison of costs is the government's production cost of MOX fuel against the market price for LEU or natural uranium fuel; the latter cost includes capital cost recovery and return to the investors whereas the former does not include these costs.

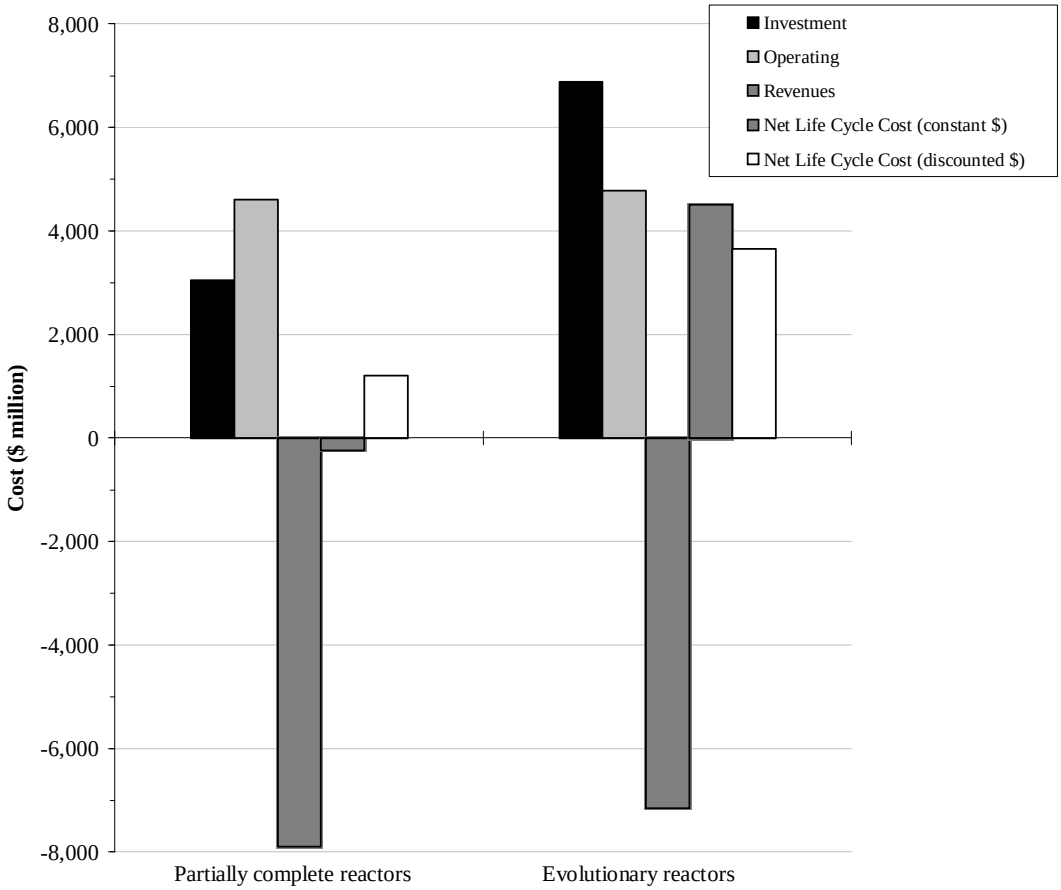
Government ownership of the MOX fuel fabrication facility saves the government approximately $600 million. This is due to the government's lower cost of capital relative to private financing, no interest during construction, and no need for a rate of return for private companies. Privately-financed facilities would have to recover the higher capital costs through higher MOX fuel charges to the utilities that use the fuel and, ultimately, to the government. In no case can MOX fuel complete economically with uranium fuel.

The partially complete and new evolutionary reactors require substantially greater investment and operating expenditures relative to the other reactor alternatives. Comparing Figure 4-1 and Figure 4-2, investment costs are $2 billion to almost $6 billion more than that for the existing reactors to cover the costs for completing or building the reactors. Operating costs, including the cost of operating the front-end facility, the MOX fuel fabrication facility, and the reactors, are approximately $3 billion more than existing reactor costs. Most of the difference derives from the reactor operational costs. For existing reactors, only the incremental costs associated with MOX fuel deployment above uranium fuel utilization accrue to the plutonium disposition mission. By contrast, the entire operating costs for the partially complete and evolutionary reactors accrue to the plutonium disposition mission since these reactors would not have operated had not the plutonium disposition mission required their use. Furthermore, no credit can be taken for uranium fuel displacement.

Table 4-2. ***Costs of Partially Complete and Evolutionary Reactors***

		Constant $ (millions)				*Discounted $ (millions)*			
Reactor Alternative	***Facility***	***Investment***	***Operating***	***Revenues***	***Net Life Cycle Cost***	***Investment***	***Operating***	***Revenues***	***Net Life Cycle Cost***
Partially Complete LWRs	Front-end	320	1090	0	1410				
	MOX Fab	350	1120	0	1470				
	Reactor	2380	2400	-7890	-3110				
	Total	**3050**	**4610**	**-7890**	**-230**	**2190**	**1860**	**-2830**	**1210**
Evolutionary LWRs	Front-end	320	1090	0	1410				
	MOX Fab	350	710	0	1060				
	Reactor	6210	2980	-7150	2040				
	Total	**6880**	**4780**	**-7150**	**4510**	**4190**	**1780**	**-2310**	**3660**

Figure 4-2. ***Costs of Partially Complete and Evolutionary Reactors***



4.2.3 Potential Revenues

For the partially complete and evolutionary reactor alternatives, revenues will accrue to the owners. The gross amount of revenues from the reactors are shown Table 4-2, as if they accrue to the government. However, the extent to which the revenues might impact net plutonium disposition mission costs to the government are not known since ultimately the share of the revenues due to the government for the partially complete alternative, if any, is not known.

Regarding evolutionary reactors, the Department in its Record of Decision on Tritium Production did not choose to construct new reactor(s) for tritium supply. Rather the Department chose to pursue a strategy of evaluating (1) using existing commercial light water reactors and (2) construction of a linear accelerator.[5] Subsequently, the Department

[5] DOE News Release, October 10, 1995.

issued a request for expressions of interest for tritium production that also solicited interest regarding the future potential use of mixed oxide fuel from surplus weapons plutonium either coincident with or separate from tritium production.

Through the initial responses to the request for expressions of interest, the Department was able to confirm that there appears to be sufficient commercial interest in use of existing or partially complete light water reactors for plutonium disposition mission alone and/or in a joint mission of tritium production and plutonium disposition. The use of existing reactors or partially complete would be subject to formal procurement procedures and business negotiations as well as resolution of licensing and other technical and policy issues.

In a Putnam, Hayes and Barlett final cost report on costs of tritium production, the authors used a range of revenues based upon a spectrum of assumptions concerning the unit sales price for electricity.[6] Using the data provided for the lowest case of forcasted revenues for the period of 2010 through 2020 in the southeast, electric sales price projections based upon $0.029/kWh were used to estimate revenues and are included in computing net life cycle costs shown in Figure 4-2.

If commercial interests should choose to complete partially complete reactors or build new reactors for commercial power generation and/or Government programs, such as the potential missions of tritium production and plutonium disposition, these reactors would, of course, be essentially the same as the larger pool of already licensed and operating commercial nuclear plants.

(Information previously here was moved to Chapter 6.)

4.3 IMMOBILIZATION ALTERNATIVES COSTS

4.3.1 Assumptions

Immobilization variants, described in detail in Chapter 2, incorporate the following economic assumptions:

1. The government owns all facilities.
2. Except where noted for greenfield alternatives, plutonium processing and immobilization equipment are in existing buildings at DOE sites with existing plutonium handing infrastructure. For the electrometallurgical treatment alternative, costs were based on co-located front-end processing at ANL-W, where some additional capacity would be required.

[6] Putnam, Hayes, and Bartlett, Inc., *DOE Tritium Production Options: PHB Final Report on Cost Analysis* (1 September 1995, text revisions 15 October 1995).

3. Immobilized material would be stored until it could be transferred to the federal high-level waste management system.
4. The fee for disposal of additional canisters resulting from plutonium disposition mission at a high-level waste repository is $500,000 per canister, consistent with expected cost for high-level waste canisters associated with the current DWPF program.

4.3.2 Cost Analysis

Investment, operating, undiscounted life cycle, and discounted life cycle costs of immobilization variants are summarized in Figure 4-3, with supporting detail of costs by facility shown in Table 4-3.

Figure 4-3. ***Immobilization Investment and Life Cycle Costs***

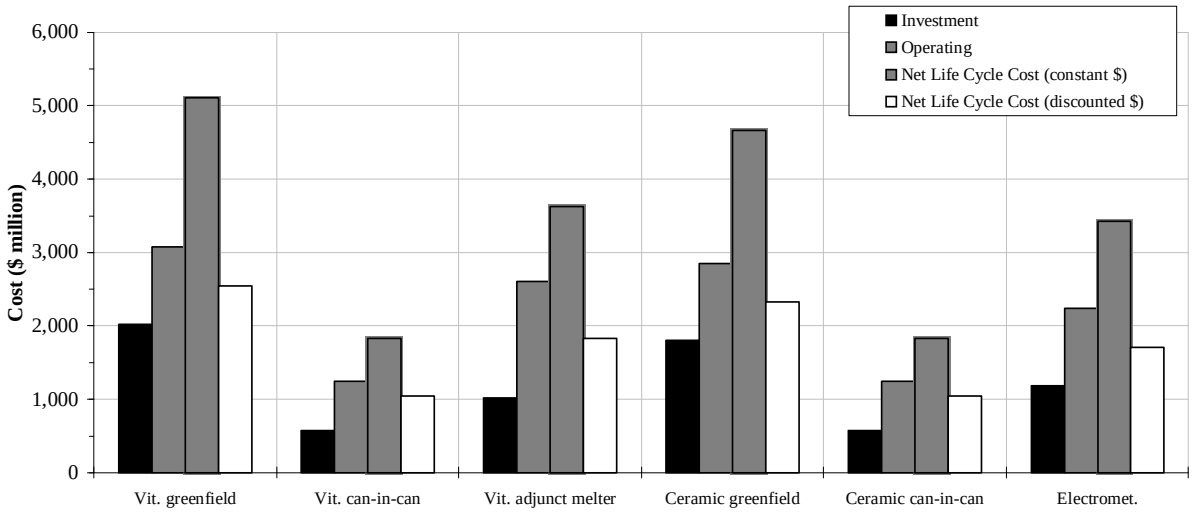


Table 4-3. *Immobilization Alternatives Costs*

		Constant $ (millions)			*Discounted $ (millions)*		
Immobilization Alternative	***Facility***	***Investment***	***Operating***	***Net Life Cycle Cost***	***Investment***	***Operating***	***Net Life Cycle Cost***
Vitrification Greenfield	Front-end	1000	980	1980			
	Immobilization	1030	1800	2830			
	Repository	0	300	300			
	Total	**2030**	**3080**	**5110**	**1250**	**1300**	**2550**
Vitrification Can-in-Canister	Front-end	360	980	1340			
	Immobilization	220	170	390			
	Repository	0	100	100			
	Total	**580**	**1250**	**1830**	**410**	**640**	**1050**
Vitrification Adjunct Melter	Front-end	340	980	1320			
	Immobilization	680	1330	2010			
	Repository	0	300	300			
	Total	**1020**	**2610**	**3630**	**680**	**1150**	**1830**
Ceramic Greenfield	Front-end	860	820	1680			
	Immobilization	950	1720	2670			
	Repository	0	320	320			
	Total	**1810**	**2860**	**4670**	**1120**	**1200**	**2330**
Ceramic Can-in-Canister	Front-end	360	980	1340			
	Immobilization	220	170	390			
	Repository	0	100	100			
	Total	**580**	**1250**	**1830**	**410**	**640**	**1050**
Electrometallurgical Treatment[1]	Front-end	730	890	1620			
	Immobilization	460	870	1330			
	Repository	0	480	480			
	Total	**1190**	**2240**	**3430**	**770**	**940**	**1710**

[1] Costs are based upon a stand-alone plutonium disposition mission. Cost sharing with DOE programs for the treatment of spent fuel has the potential to reduced costs by approximately $600 million.

Existing facilities and waste disposal operations provide the opportunity for significant cost savings for the plutonium disposition mission. As indicated by the data, the investment cost of the vitrification can-in-canister variant is approximately one fourth the greenfield vitrification variant investment cost. The cost ratio is about a factor of three for the ceramic greenfield versus the ceramic can-in-canister variant. Less dramatic investment savings can be realized using an adjunct melter strategy for vitrification, where costs are one half of the greenfield vitrification investment costs. Note that the front-end costs account for half of the investment costs for the two greenfield variants and well over half of the can-in-canister variants. The costs for the can-in-canister variants appear identical in the table; however, the variants were costed separately on their own bases.

The investment costs for the vitrification greenfield front-end facilities are approximately $150 million more than the ceramic greenfield front-end due to the inclusion of a first stage melter in the vitrification front-end facility. The investment cost of the electrometallurgical treatment variant is less than the cost of greenfield variants, but more than the cost of can-in-canister variants. The front-end facility for electrometallurgical treatment accounts for approximately two thirds of the investment costs. However, those costs could be reduced by performing some of the front-end process steps at other locations, thereby avoiding the need to add additional facility space necessary to co-locate all operations at ANL-W.

Operating costs range from $1.2 billion for the can-in-canister variants to over $3 billion for the vitrification greenfield variant. Use of DWPF reduces immobilization facility operating costs by a factor of ten relative to greenfield immobilization facilities for the vitrification and ceramic immobilization approaches. Use of DWPF facilities for the can-in-canister variants relative to the greenfield variants reduces overall operating costs by a factor of two. Repository costs refer to the canisters resulting from disposition operations. The electrometallurgical treatment alternative is assumed to process plutonium independent of a mission to treat spent nuclear fuel. If the plutonium disposition mission is conducted simultaneously with the operations to treat spent nuclear fuel, then approximately $600 million could be saved through the sharing of concurrent operating, storage, and waste disposal costs.

Life cycle costs of can-in-canister concepts are also significantly lower than for other immobilization variants. Discounted life cycle costs range from $1.0 billion for the can-in-canister variants to $2.6 billion for the vitrification greenfield variant.

(Information previously here was moved to Chapter 6.)

4.4 DEEP BOREHOLE ALTERNATIVES COSTS

4.4.1 Assumptions

Deep borehole alternatives, described in detail in Chapter 2, incorporate the following economic assumptions:

1) Government ownership of plutonium processing and borehole facilities is assumed.
2) Front-end and immobilization facilities are collocated at a government-owned site with plutonium processing infrastructure. Front-end processes are located in existing buildings where possible.
3) Borehole facilities are sited at a generic, non-DOE site.

4.4.2 Cost Analysis

Investment costs, operating costs, undiscounted life cycle costs, and discounted life cycle costs of borehole alternatives are summarized in Figure 4-4, with supporting detail of costs by facility shown in Table 4-4.

Figure 4-4. ***Borehole Investment and Life Cycle Costs***

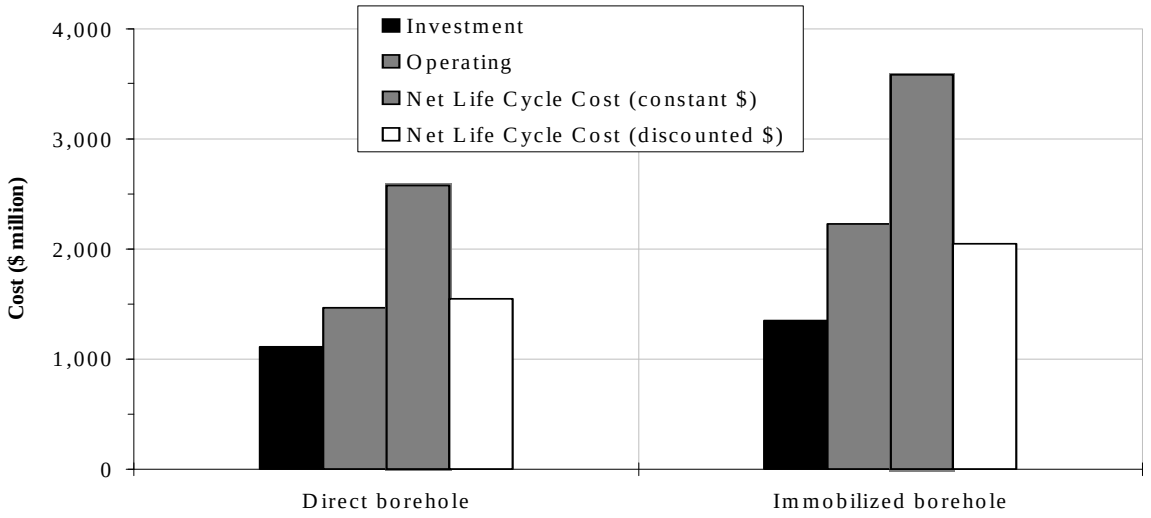


Table 4-4. ***Deep Borehole Alternatives Costs***

		Constant $ (millions)			*Discounted $ (millions)*		
Deep Borehole Alternative	***Facility***	***Investment***	***Operating***	***Net Life Cycle Cost***	***Investment***	***Operating***	***Net Life Cycle Cost***
Direct Emplacement	Front-end	240	800	1040			
	Borehole	870	670	1540			
	Total	**1110**	**1470**	**2580**	**800**	**700**	**1500**
Immobilized Emplacement	Front-end	580	1510	2090			
	Borehole	770	720	1490			
	Total	**1350**	**2230**	**3580**	**990**	**1060**	**2050**

As indicated by the data in the table and figure, the undiscounted life cycle cost of the direct emplacement borehole alternative is $1 billion less than immobilized borehole cost. In the Screening Report the borehole alternatives were considered to be a potentially desirable alternative because of presumed low cost to implement. The low cost was presumed because the borehole approaches typically involve low-technology processes and equipment that would be inexpensive compared to highly specialized MOX fuel fabrication equipment. It turns out the presumptions are incorrect. Two significant factors contribute. First, the borehole site facilities are generic, non-DOE sites, unlike all other alternatives which are accomplished on DOE sites with greater or lesser amounts of infrastructure. As such, large costs are required to develop the infrastructure to support the borehole facilities. Second, whereas the borehole processes are relatively low technology operations, they are processes which still must be performed in expensive Category I plutonium handling facilities.

The immobilized emplacement alternative is much more expensive than the direct emplacement alternative, owing to the large costs associated with the front-end processing, which is in turn due to the larger material throughput processed for the immobilized alternative

(approximately 500 MT per year). As indicated in Chapter 3, there is substantially more cost and schedule uncertainty in the direct emplacement alternative due to the difficulty anticipated in acquiring a license for direct emplacement of materials. The licensing analysis is anticipated to be greatly simplified by the use of immobilized forms for plutonium.

(Information previously here was moved to Chapter 6.)

4.5 HYBRID ALTERNATIVES COSTS

Costs for hybrid alternatives in which existing LWR or CANDU reactors effect disposition of approximately 32.5 MT of plutonium and immobilization facilities process the remaining 17.5 MT inventory are shown in Figure 4-5, with supporting detail included in Table 4-5.

Figure 4-5. ***Reactor/Immobilization Hybrids Investment and Life Cycle Costs***

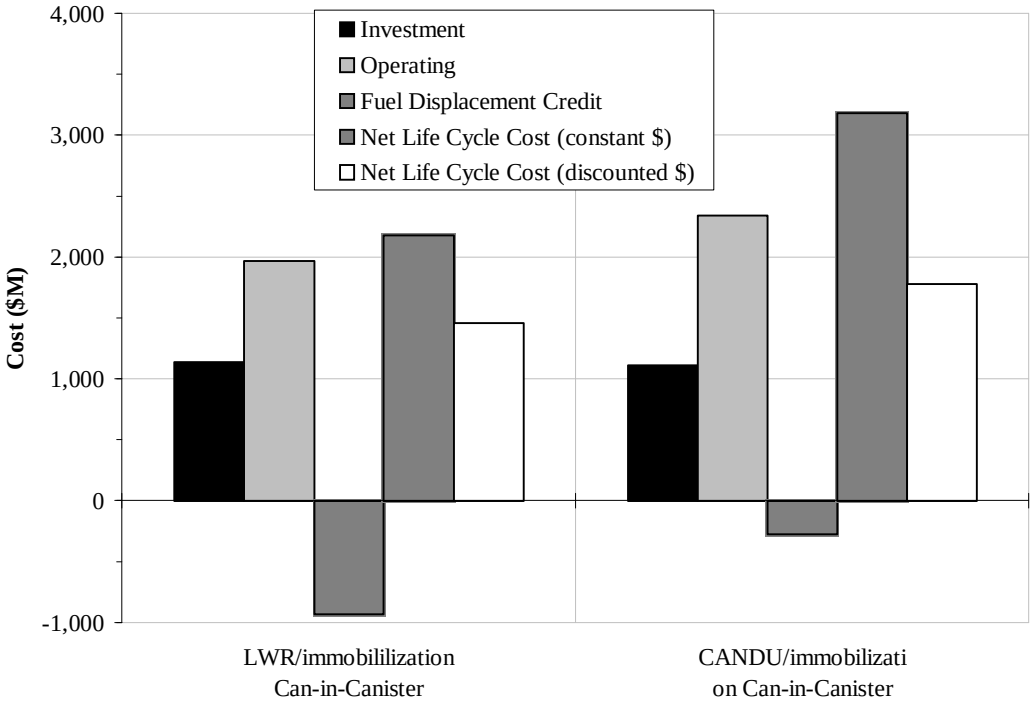


Table 4-5. ***Reactor/Immobilization Hybrid Alternatives Costs***

		Constant $ (millions)				*Discounted $ (millions)*			
Hybrid Alternative	***Facility***	***Investment***	***Operating***	***Fuel Displacement Credit***	***Net Life Cycle Cost***	***Investment***	***Operating***	***Fuel Displacement Credit***	***Net Life Cycle Cost***
Existing LWRs/	Front-end	360	970	0	1330				
Immobilization	MOX Fab	360	820 [1]	-930	250				
Can-in-Canister	Reactor	200	90	0	290				
(3 PWRs)	Immobilization	220	60	0	280				
	Repository	0	30	0	30				
	Total	**1140**	**1970**	**-930**	**2180**	**820**	**1120**	**-480**	**1460**
CANDU/	Front-end	340	980	0	1320				
Immobilization	MOX Fab	450	1240	-270	1420				
Can-in-Canister	Reactor	100	30	0	130				
	Immobilization	220	60	0	280				
	Repository	0	30	0	30				
	Total	**1110**	**2340**	**-270**	**3180**	**800**	**1120**	**-140**	**1780**

[1] $140 M of this cost is for the fuel fabricated in Europe.

The front-end facility costs are assumed to be similar to the costs for the can-in-canister alternatives. Because demands on the front-end facility are less than that for the can-in-canister alternative, the estimated costs for the hybrid alternatives are conservative in using the can-in-canister values.

The repository costs for disposal of immobilized waste forms is included in the immobilized operating costs. The repository cost for the spent fuel is a reactor-owner cost, not a cost to the government, and therefore is not included in the repository costs cited in Table 4-9.

In understanding the costs for the immobilization/reactor hybrids, the comparison to the stand-alone reactor alternatives costs is the most illuminating since approximately two-thirds of the plutonium goes the reactor route. In both the CANDU and LWR hybrid alternatives, the investment cost for the hybrid alternatives requires the investment costs for both the reactor and immobilization portions, not double-counting front-end costs for the two alternatives. This represents an approximately $200 million incremental investment for the hybrid alternatives. In the LWR hybrid, the net life cycle costs are approximately $100 million higher than the corresponding stand-alone LWR alternative mostly due to the lower MOX fuel credit. The net life cycle cost for the CANDU hybrid is approximately $70 million more than the stand-alone CANDU alternative. Note that, on an operational cost basis only for the fuel fabrication facility, the market value for LWR MOX fuel exceeds the operational cost for domestically-produced MOX fuel; however, this statement does not hold for CANDU fuel due to the low value of the displaced natural uranium fuel.

(Information previously here was moved to Chapter 6.)

4.6 OVERALL COMPARISON OF ALTERNATIVES COSTS

To facilitate comparisons among alternatives, undiscounted and discounted investment and operating and net life-cycle costs are summarized in Figure 4-6 and 4-7.

Figure 4-6. ***Investment and Operating Costs for Baseline Alternatives (constant $)***[1]

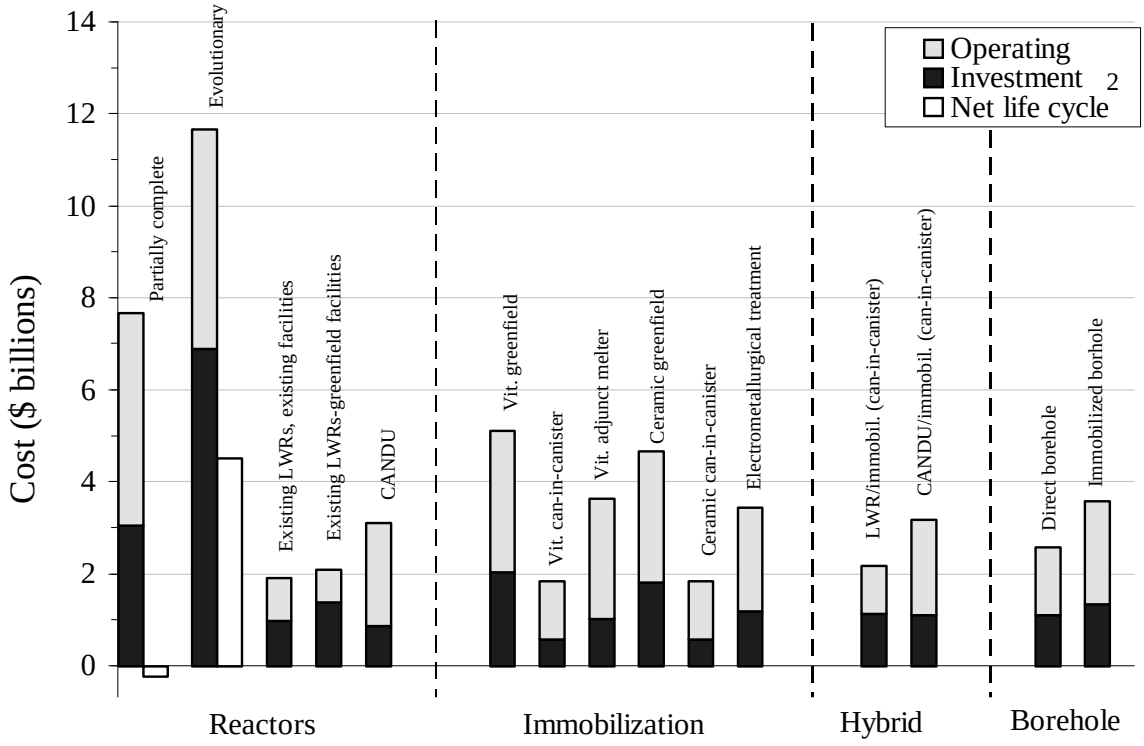
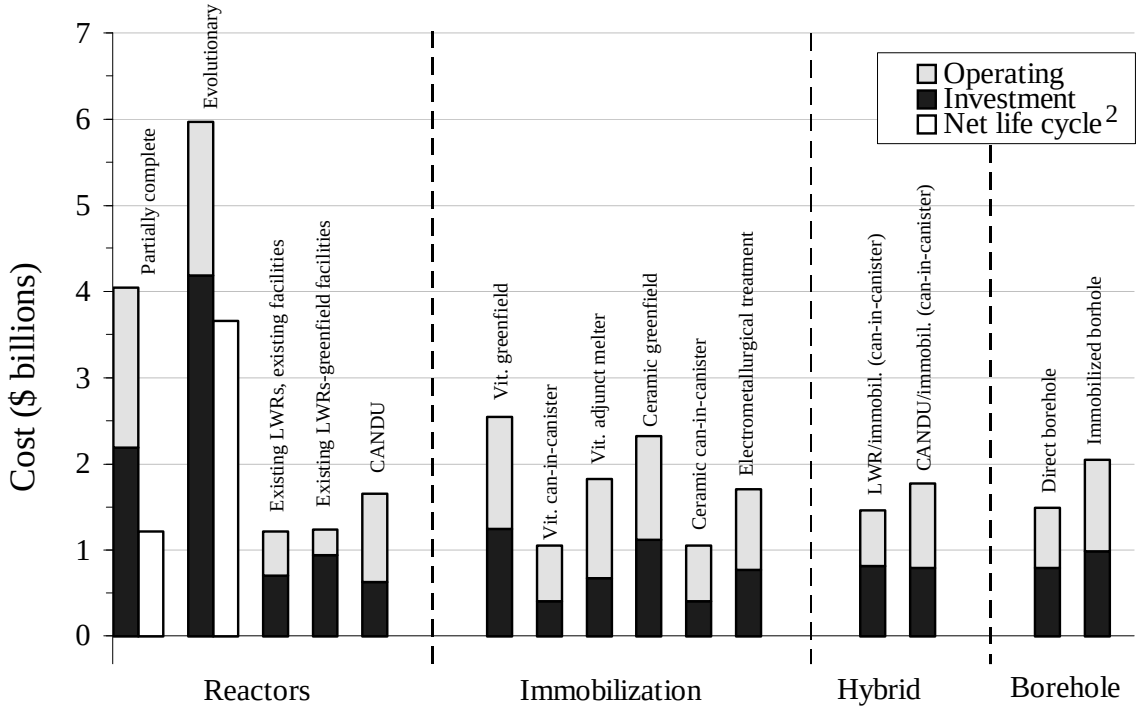


Figure 4-7. ***Investment and Operating Costs for Baseline Alternatives (discounted $)***[1]



[1] The costs are for base case estimates as defined in Chapter 4. Chapter 6 identifies a series of cost uncertainty factors and provides a quantitative estimate of them for many of the alternatives.

[2] For the net life cycle costs of the evolutionary and partially complete reactor alternatives, electricity is sold at $0.029/kWh with all revenues assumed here to accrue to the Government. No acquisition cost or salvage value for the reactors are included. Alternative assumptions are considered in Chapter 6.

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CHAPTER 5. SCHEDULE DATA SUMMARIES

The NAS labeled the lack of an existing international regime for surplus plutonium a "clear and present danger" and urged that actions should be initiated to effect the disposition of surplus plutonium without delay. Thus timeliness should be a primary determinant for the selection of approaches for plutonium disposition. Congress has urged the Department to demonstrate to the world its commitment to effect the disposition of surplus weapons-grade plutonium.[1] Based on Departmental focus on reducing exposure to the "present danger" and comments from interested parties, the Department has established its schedule requirements for initiating disposition (within 10 years) and completing disposition (within 25 years) after authorization.

Section 5.1 is a discussion of the schedule methodology. Sections 5.2 through 5.5 are discussions of the reactor, immobilization, borehole, and hybrid alternatives schedules, respectively. Section 5.6 is a tabular summary of schedule information. Some key uncertainties are discussed in Chapter 6.

5.1 SCHEDULE ESTIMATION METHODOLOGY

Schedules were generated by the Alternative Teams presuming a moderate national priority for plutonium disposition, as opposed to the very high national priority associated with the Manhattan Project or the Apollo Project. Furthermore, the Alternative Teams assumed no protracted delays such as those associated with the high-level waste repository program. The schedules presented here are neither inherently optimistic nor inherently pessimistic and include expert judgments of time required for technical activities such as research and development, engineering, design construction, licensing, and permitting. None of the schedules that are presented here have been optimized, and it is possible that schedule improvement could be realized as more details become available. Assuming one or more alternatives are selected at the Record of Decision, a dedicated effort will be applied to attempt to accelerate and optimize the schedules.

The Alternative Teams generated the schedules for their alternatives based on their assessment of all the key events that must occur to implement the alternatives. The basis for the schedules were established to be as consistent as possible, recognizing the inherent technology differences which exist among the alternatives. The overall approach for generating the schedules included:

- Identifying the necessary steps to implement the alternatives.
- Establishing the assumptions necessary to link the facilities and the events.
- Determining the critical schedule parameters.

[1] House Energy and Water Report accompanying the FY 1997 Appropriation Bill, HR-3816.

- Preparing nominal schedules.
- Identifying strategies which could be selected to accelerate schedules relative to the nominal cases.

In defining the schedule elements for a government project, one must be aware that there are a number of activities for federal projects that may not apply or are less important for a private sector project. These activities are reflected in the schedules provided in this report and include the following elements:

- Need for Congressional approval and funding authorization.
- Need for compliance with the National Environmental Policy Act.
- Special procurement and vendor selection rules and regulations.
- Need for external oversight of existing, non-licensed facilities. For the purposes of these analyses, DNFSB is assumed to provide oversight of existing DOE facilities.

As an example, for federal projects, the authority for the start of a project might occur later than the ROD. Given the urgency of the plutonium disposition mission, the authority to start the project is assumed to be coincident with the ROD.

The project activities considered by the Alternative Teams were analyzed by facility. These activities can be categorized generically as follows:

- Project definition and approval.
- Research, development, and demonstration.
- Siting, licensing, and permitting.
- Design, engineering, and procurement.
- Construction and/or facility modification.
- Operations, including pre-operational start-up activities.
- Decontamination and decommissioning.

For each alternative, two or more facilities are required for implementation. Consequently, completion and operation of each of the facilities must be properly sequenced to permit the facilities to operate as a system. The need for sequencing facilities appropriately is illustrated by the use of evolutionary light water reactors in conjunction with new facilities for plutonium processing and mixed oxide fuel fabrication. Clearly, the three facilities must be staged such that the operations in each facility are coordinated with operation of the other two.

The facilities analyzed include the following:

1. Plutonium processing (or front-end) facility, including extraction of plutonium from pits.
2. Fuel fabrication facility, for reactor options.
3. Reactors, immobilization plants, or borehole site facilities, as applicable.

5.2 REACTOR ALTERNATIVES SCHEDULES

5.2.1 Reactor Schedule Assumptions

Oversight and Licensing:

- For new fuel fabrication facilities, a five-year licensing duration is used. This duration is based on discussion with and input from the NRC.
- For existing LWRs, a three-year lead use assembly (LUA) license process is included prior to loading the LUA in the reactor. An 18-month reload license review period is included after the LUA has been irradiated; a review of the LUA performance is done during the second irradiation cycle. After this review is complete, the mission fuel may be loaded in the reactors during the next reload cycle. The LUAs and initial cores for the existing facilities variant would be fabricated in European facilities.
- For the evolutionary reactor alternative, a three-year licensing process is assumed before any site preparations may begin. The LUAs are irradiated for a two-year period with the initial LEU core load before starting to load mission fuel.
- A LUA from the American MOX fuel fabrication facility, when available, will be required for LWRs.
- For CANDU alternatives, no dedicated LUA test is required; rather, the fuel test and qualification processes achieve the objective of LUA demonstration.
- The baseline schedule for the CANDU alternative does not assume use of European MOX fuel fabrication capability. However, in the Schedule Summary Table (Table 5-1), a two-year acceleration in start-up is credited, based on the judgment that half the schedule acceleration achievable by the LWRs using European capability (4 years) should be achievable with CANDU reactors. Although the structural design of CANDU and LWR fuel assemblies are very different, the fabrication of the fuel pellets for the two reactor types, which is the distinguishing feature between MOX and uranium fuel fabrication, is similar.
- DNFSB review of the use of existing DOE facilities is assumed to be five years.

Plutonium Availability for Use of European Fuel Fabrication Schedules:

- For the existing LWR, existing facilities variant and the LWR hybrid alternative, the plutonium will be processed in a staged start. These variants require plutonium oxide feed before the ARIES production facility could provide it. For these variants, it is expected that the ARIES prototype, which is being developed to demonstrate the ARIES process and support design of the production facility, would also be used to disassemble some quantity of additional pits to provide a limited amount of feed to support MOX production in Europe.

MOX Fuel Fabrication:

- Whether the American MOX fuel fabrication facility is placed in a new building at a DOE site or placed in an existing building at a DOE site, the same schedule would be used in both situations.

Reactors:

- Existing reactors would be selected based on the remaining plant life under their current licenses such that sufficient life exists in the reactors to accommodate the plutonium disposition without any plant life extension actions[2].
- Finishing construction of the two partially complete reactors is staged so that the completion of the reactors corresponds to when MOX fuel from a domestic source would be available. Licensing is assumed to proceed in parallel with the reactor construction.

5.2.2 Reactor Alternatives Analysis

Generic Issues

There are key uncertainties in the schedule that are the same for all reactor alternatives. These key uncertainties include the following elements and are discussed qualitatively. A quantitative assessment of some of the key uncertainties is presented in Chapter 6.

Fuel qualification issues:

- The acceptability of the gallium in the plutonium oxide powder feed to the fuel fabrication processes needs to be demonstrated. It is expected that the gallium issue will have been addressed and resolved without impacting the schedule.

- For the alternatives using integral neutron absorbers, this novel approach will involve a significant fuel qualification program and its associated schedule uncertainty.

Availability of facilities:

- Modification and use of existing facilities for front-end processing and MOX fuel fabrication could potentially shorten the disposition schedule through the use of existing infrastructure, licenses and permits. However, there are also risks associated with modifying existing facilities that could offset these reductions in schedule,

[2] The existing LWR, greenfield facilities variant assumes four BWRs with a particular core management strategy as a basis. It happens that there are not four BWRs available to complete the mission before their licenses lapse (see Figure 5-2). This shortfall is not material to this report because the shortfall is only a couple of years and because this difference can be easily rectified by making minor changes to core designs and core management strategies (see Chapter 2).

such as the need to decontaminate some of these facilities for reuse and the impact associated with force-fitting processes into existing buildings, resulting in non-optimum operations. Also, some of the facilities that might be considered for plutonium processing operations are applicable to other Department missions, and use of them for the plutonium disposition mission could adversely impact those other Department missions.

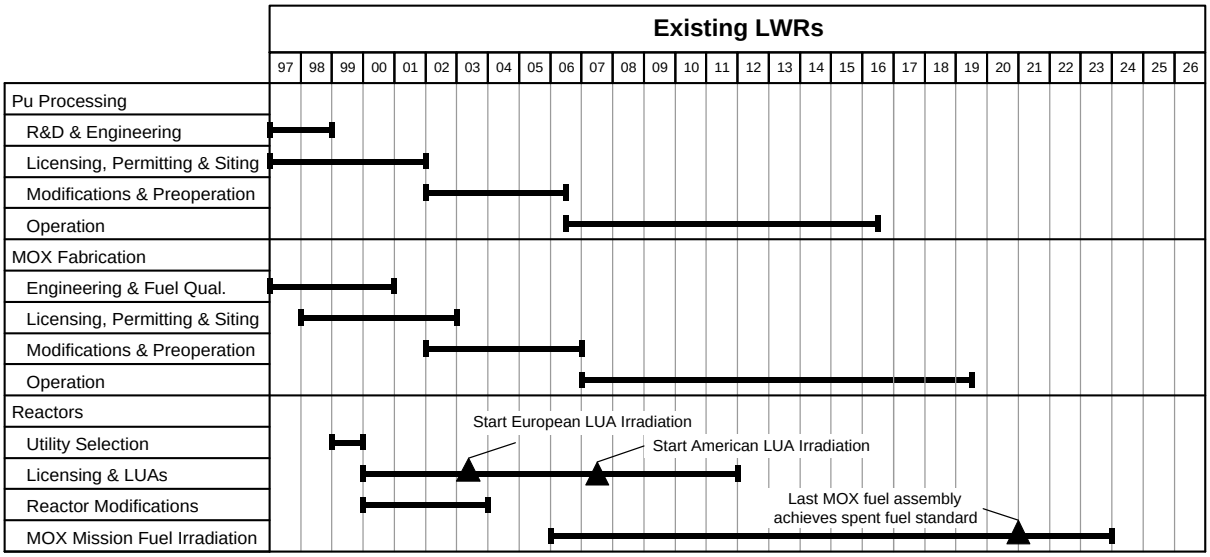
- New facilities involve a long series of actions for design, engineering, and construction, any of which can be delayed. The opportunities for delay include public policy changes or regulatory delays, as examples.

Existing LWRs

For the existing reactor alternatives, the opportunity exists to start the plutonium disposition mission earlier by using existing European MOX fuel fabrication capability. MOX fuel fabrication in Europe can be used to make LUAs and several core reloads as desired. To do so would require that high purity plutonium oxide be available. This oxide would be provided by the ARIES demonstration/prototype. The schedule advantage realized by using the ARIES-derived plutonium oxide in conjunction with European MOX fuel fabrication facilities is to accelerate the start-up of the plutonium disposition mission by approximately four and a half years for the existing LWR, existing facilities variant. The disadvantages for the strategy to accelerate reactor deployment, other than the cost increment, relate to requiring dedicated effort to extract plutonium from the ARIES demonstration/prototype in a production-like environment, the need to transport plutonium over international waters, and the need to negotiate terms and conditions associated with the use of foreign fuel fabrication.

Either BWRs or PWRs can be used for the mission. Two variants are considered to establish a range of possibilities for the existing LWRs. In the first variant (Figure 5-1) five PWRs use fuel with no integral neutron absorbers that is fabricated in European facilities for the first cores. Subsequent cores use fuel fabricated in modified domestic facilities. Plutonium processing is also accomplished in modified domestic facilities. In the second variant, four BWRs use MOX cores containing integral neutron absorbers and new domestic facilities are used for both plutonium processing and MOX fuel fabrication. As pointed out in Chapter 2, the selection of reactor types with the options of using integral neutron absorbers and European fuel fabrication capacity was arbitrary. Therefore, the advantages and disadvantages of variant 1 compared to variant 2 are the results of the construction of the variants and are not necessarily attributable to the difference in reactor type.

Figure 5-1. ***Existing LWR, Existing Facilities Schedule***



The schedule for the existing LWR, existing facilities variant is shown in Figure 5-1. The following observations are provided:

- Securing a fuel supply is on the critical path for reactor deployment. Note that the reactors are available to accept MOX fuel in 2004, well before the fuel can be delivered from a domestic MOX facility. Initial use of European fuel fabrication alleviates the schedule gap.

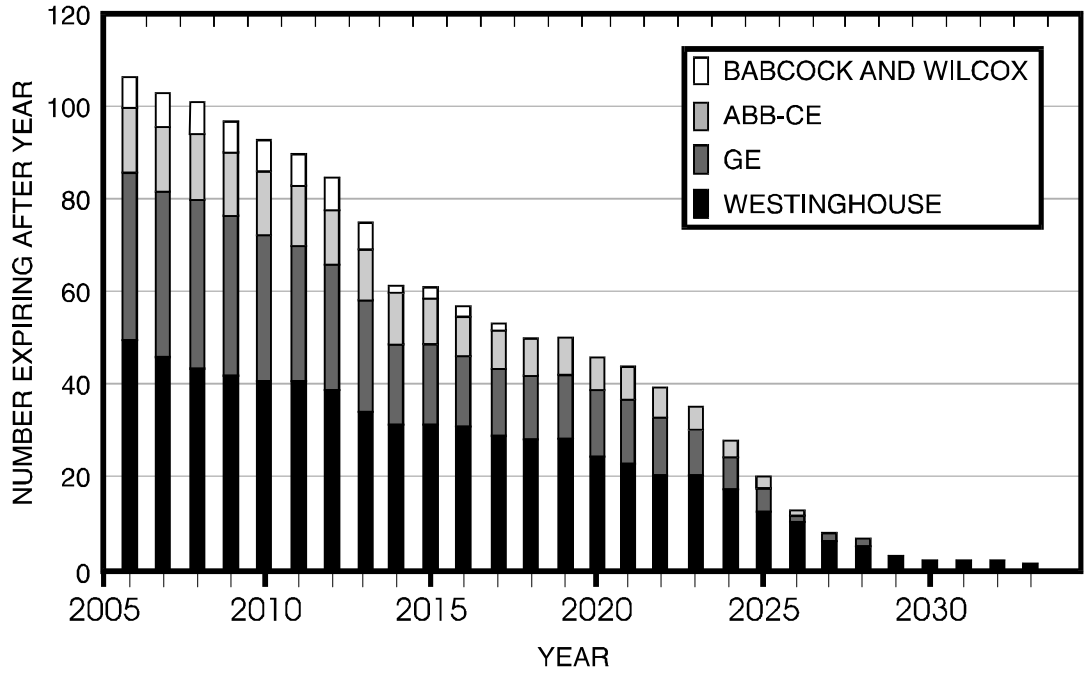
- The time to complete the campaign is a function of two variables, namely, which reactor design(s) is (are) selected and how many reactors are deployed for the mission. Everything else being equal, PWRs have a higher plutonium throughput than BWRs because PWRs generally do not have the same neutron utilization as BWRs. Likewise, all else being equal, full MOX core designs with integral neutron absorbers can achieve higher plutonium throughputs than partial core designs or full core designs without integral neutron absorbers because the integral neutron absorbers tend to counteract the positive reactivity effects of higher fissile loading. Higher plutonium throughputs yield shorter irradiation campaigns. Illustrative values for plutonium throughputs are provided in Chapter 2, Table 2-2.

- For LUAs, existing LWR options can begin irradiation of MOX fuel in approximately six years (for the European initial MOX fuel fabrication) to ten years without European fuel fabrication.

(Information moved to beginning of section.)

In the event that start-up of the campaign is significantly delayed, the viability of some of the existing LWR alternatives may become suspect as the number of licensed reactors begins to fall off after about 2015, as can be seen in Figure 5-2.

Figure 5-2. ***Existing Reactor Availability***



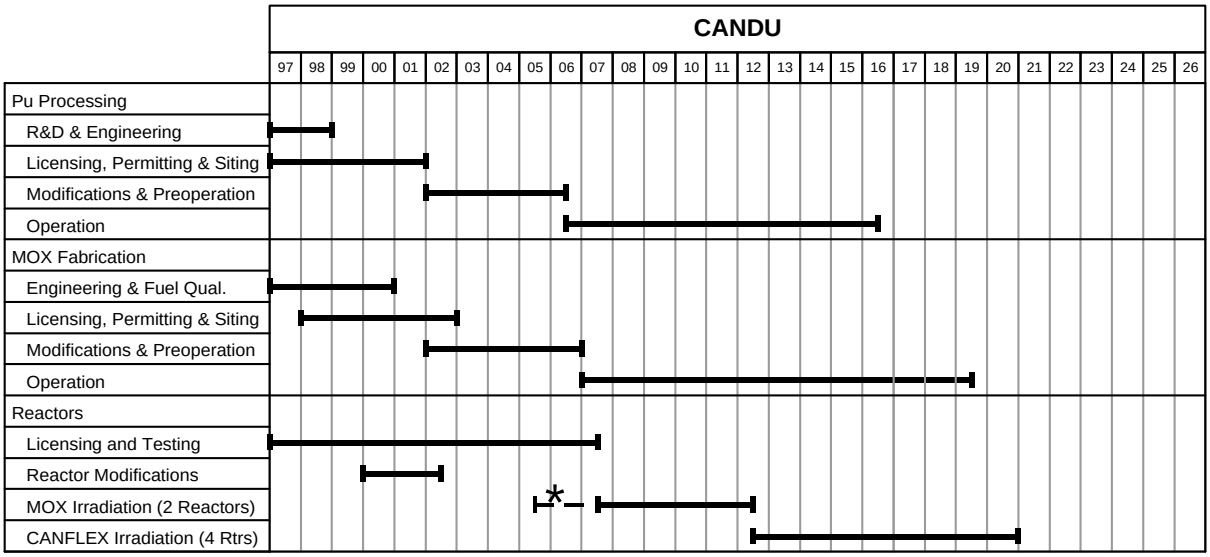
CANDU Reactors

The CANDU schedule shown in Figure 5-3 is similar to the schedule for the existing LWR, existing facilities variant schedule. The two variants have similar start times and critical paths, and both can be accelerated using modified facilities for plutonium processing and MOX fuel fabrication. Since CANDU fuel bundles are very short in length, it is easier to perform fuel qualification tests at full scale, and since CANDU reactors are refueled on-line, fuel performance testing is not delayed due to reactor outage scheduling. European fabrication of MOX fuel for CANDUs is possible, although no credit is given in the CANDU schedule baseline. The European data on MOX fuel for LWRs is not as applicable to CANDUs because of technical differences between the fuel types, including the pellet diameter, fissile content, and pellet surface finish. Therefore, a longer fuel qualification effort will be required for CANDU reactors than for LWRs. A smaller schedule credit of two years is given to the CANDU schedule using European fuel fabrication for start-up in Table 5-1.

The alternative uses the advanced CANFLEX fuel form when it is available, approximately five years after starting with low-plutonium-content reference fuel. An alternate approach is to start on the CANFLEX fuel form from the outset and further compress the mission schedule; however, this approach entails the higher schedule risk of putting the CANFLEX fuel qualification effort on the critical path.

In addition to the issues for existing reactors without integral neutron absorbers, the CANDU schedule risks include the efforts associated with fuel fabrication, design, and qualification, the issues relating to transportation and public, and institutional issues on both sides of the border.

Figure 5-3. *CANDU Schedule*



* Assumes European fuel fabrication

Partially Complete Reactors

While the reactors can be completed well in advance of the availability of MOX fuel, to defer costs, the completion of the reactors is staged such that the completion of the first of the two reactors is accomplished when fuel from the MOX fuel fabrication plant would be available. The first core load of the first reactor would be a low-enriched uranium (LEU) fuel with a MOX fuel LUA embedded within. This strategy is believed to be necessary to ensure that a LUA is tested in a prototypic core. The first reactor would transition to full core MOX fuel by replacing LEU assemblies at normal refuelings. The second reactor would be completed on a schedule to correspond to the end of the review of the LUA in the first reactor; the second reactor would begin operation with a full core MOX fuel load.

Partially complete reactors will require integral neutron absorbers. The reason that the partially complete reactor alternative is constrained to the use of integral neutron absorbers relates to the mission goal of completing the disposition mission in 25 years. Assuming two reactors for the mission, the plutonium throughput for cores without integral neutron absorbers is insufficient to meet the schedule constraint.

A major schedule risk exists for the partially complete alternative in that only a few partially complete reactors exist. Since only limited capacity exists, there is essentially no back-up if one of the two reactors becomes unavailable, in contrast with the existing LWR alternatives for which more plants exist. This risk is in addition to the schedule risks for completing the reactors and the risks for integral neutron absorbers.

Evolutionary LWRs

The evolutionary LWRs are the only reactors for which the availability of the reactors is critical to the start-up of the disposition mission. In all other cases, the fuel supply is the rate-limiting step. Additionally, the integral neutron absorber and reactor capacity arguments for the partially complete reactor alternative also apply here.

5.3 IMMOBILIZATION ALTERNATIVES SCHEDULES

5.3.1 Immobilization Schedule Assumptions

Each deployment schedule has been developed by combining the schedules for each of the individual facilities involved in the alternative. The estimated duration of individual activities are based on previous experience with starting plutonium processing facilities. These schedule estimates also assume that there are no major problems with funding, licensing, or technical implementation.

Licensing:

- For new immobilization facilities, a five-year duration is assumed based upon discussion with and input from the NRC. However, non-safety related construction is assumed to start about one year prior to the issue of a license.
- For existing DOE facilities, a five-year duration for DNFSB review is assumed.

Plutonium Availability for Start-up Schedules for Can-in-Canister Variants:

- The immobilization schedules assume that all front-end plutonium processing facilities would be constructed prior to start-up of the immobilization facilities, except for the start of the can-in-canister alternatives. However, the start-up of the facilities could be staged to support an accelerated start of the plutonium disposition mission. In a staged start, available stabilized oxides would be available prior to 2004. Use of these materials would allow immobilization of existing oxides for at least two years prior to the full-scale ARIES production.

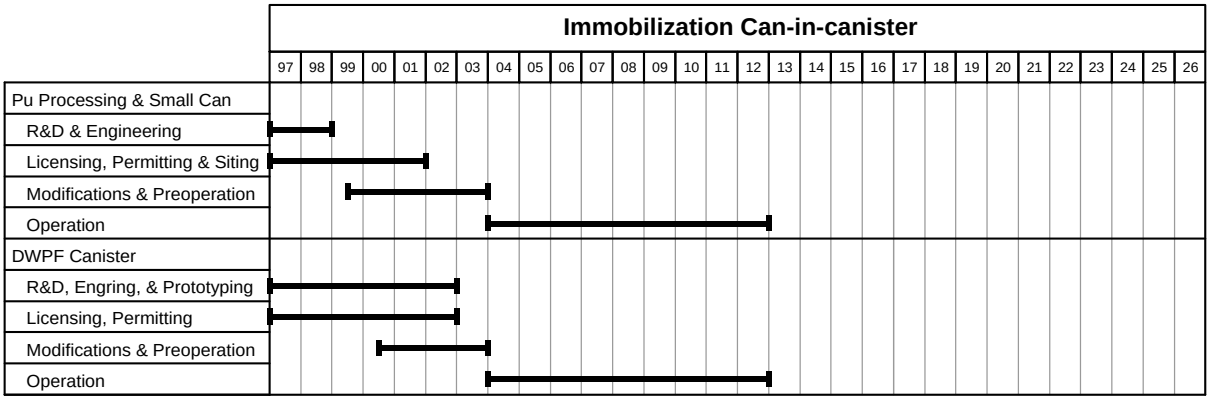
- The can-in-canister approaches are expected to start-up with plant operation at less than the full 5 MT/yr production rate for producing the small plutonium cans that are subsequently emplaced in the DWPF canisters. Doing this will require using oxide sources which are expected to be available in the next several years as a result of other Department missions. As much as three years advancement in the start-up schedule can be realized.

5.3.2 Immobilization Alternatives Analysis

Vitrification

The deployment schedules for variants of the vitrification alternative are strongly dependent upon whether existing facilities can be modified for the plutonium disposition mission. The greenfield variant uses new facilities, the can-in-canister variant uses modified facilities for both plutonium processing and immobilization functions, and the adjunct melter alternative represents an intermediate variant.

Figure 5-4. ***Vitrification Can-in-Canister Schedule ****



* Schedule for Ceramic Can-in-Canister would be similar

Each of these three variants also has two cases: 1) a dry plutonium oxide feed to the melters and 2) a wet plutonium nitrate solution feed to the melters. These two cases were considered to assure a viable process. The most rapid start-up would be for the dry feed case since virtually no processing is required for oxide feed materials which comprise about 1/3 of the potential non-pit feed material (about 6 MT). In this case, start-up is limited by the time needed to qualify the waste form and to install the immobilization equipment in existing plutonium facilities. The relatively small amount of feed processing capability needed for the balance of non-pit plutonium feed can be installed later after the early start-up. The schedule for the can-in-canister variant is shown in Figure 5-4, taking advantage of the minimal dry feed processing for start-up. For the vitrification variants, the following observations are provided:

- The schedule for the vitrification variants is driven by the selection, design, and installation of a suitable melter that can produce the vitrified product (while preventing any possibility of a criticality accident) that is acceptable to the high-level waste repository.

- The schedule assumes that existing facilities can be modified with minimal plutonium processing to house the melter to accelerate the mission approximately six years earlier than new facilities (late 2003 versus 2009).

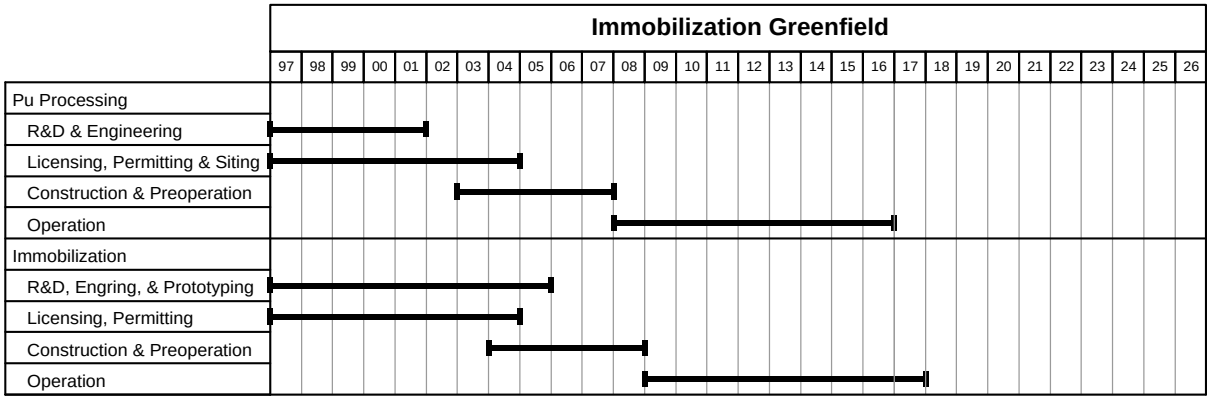
- Primary schedule drivers include the kinetics of the incorporating a plutonium in glass and the number of melters installed.

Key schedule uncertainties include determining the kinetics of incorporating a plutonium into a specific glass formulation and qualifying the vitrified product for inclusion into the high-level waste repository.

Ceramic Immobilization

There are two variants for ceramic immobilization: a new facility and a can-in-canister variant utilizing existing facilities at Savannah River. Each of these variants also has two cases: 1) a dry plutonium oxide feed to the ceramic immobilization process and 2) a wet plutonium nitrate solution feed to the ceramic immobilization process. For an accelerated start for the can-in-canister variant, the dry feed approach would not require feed processing for about 6 MT or approximately 1/3 of the potential non-pit feed material which is available. As in the can-in-canister vitrification variant, processing facilities would not be required to make use of the existing oxides, so the only time required would be for the installation of the immobilization system in an existing facility. Additional processing equipment could be installed at a later date for the balance of the non-pit plutonium feed after start-up.

Figure 5-5. ***Ceramic Greenfield Schedule***



The nominal schedule for the greenfield ceramic immobilization variant is presented in Figure 5-5. The following observations are provided:

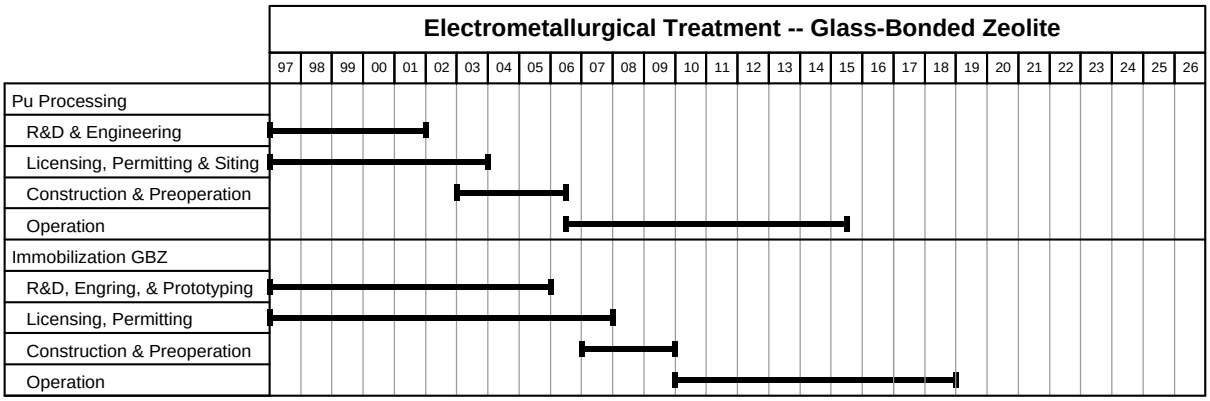
- The critical path for the ceramic immobilization variants is dominated by the selection of a formulation that can be demonstrated to be acceptable to the high-level waste repository.
- The time to complete the mission is a function of the ceramic process chosen (either hot pressing or cold-press and sinter) and the rate at which plutonium oxide can be supplied to the facility.

The key uncertainty in the schedule is qualifying the ceramic product for inclusion into the high-level waste repository.

Electrometallurgical Treatment

There is one variant for the electrometallurgical treatment which involves utilization of the ANL-W facilities. The nominal schedule for this variant is presented in Figure 5-6.

Figure 5-6. ***Electrometallurgical Treatment Schedule***



The following observations are provided:

- The critical path for this alternative is dominated by the selection of a formulation that can be demonstrated to be acceptable to the high-level waste repository and the demonstration of the lithium reduction of oxides-to-metal operations.

- This schedule is predicated on the underlying technology being selected and developed for the disposition of some DOE spent fuels.

The key uncertainty in the schedule is qualifying the glass-bonded zeolite product for inclusion into the high-level waste repository.

5.4 DEEP BOREHOLE ALTERNATIVES SCHEDULES

5.4.1 Deep Borehole Schedule Assumptions

Plutonium feed:

- Plutonium will be available as oxides or as metals, as required, from the plutonium processing facility to support emplacement.

Oversight, licensing and siting:

- The legislative and rulemaking framework can be established in about three years.
- Site selection, site characterization, NEPA compliance, and research and development can be accomplished within six years.

- Borehole licensing proceedings, which are critical path activities, can be accomplished in five years.
- DNFSB review of the use of existing DOE facilities is assumed to be five years.

Operations:

- A half-year cold operation phase precedes hot-operations at the borehole site. The operational emplacement phase takes ten years to complete in the reference alternatives.

Post-closure:

- Decontamination and decommissioning of borehole facilities and a license to close subsurface facilities will occur after the boreholes are sealed. Post-closure monitoring of the boreholes will likely be required. A two-year period is assigned to this function.

Plutonium Availability for Rapid Emplacement:

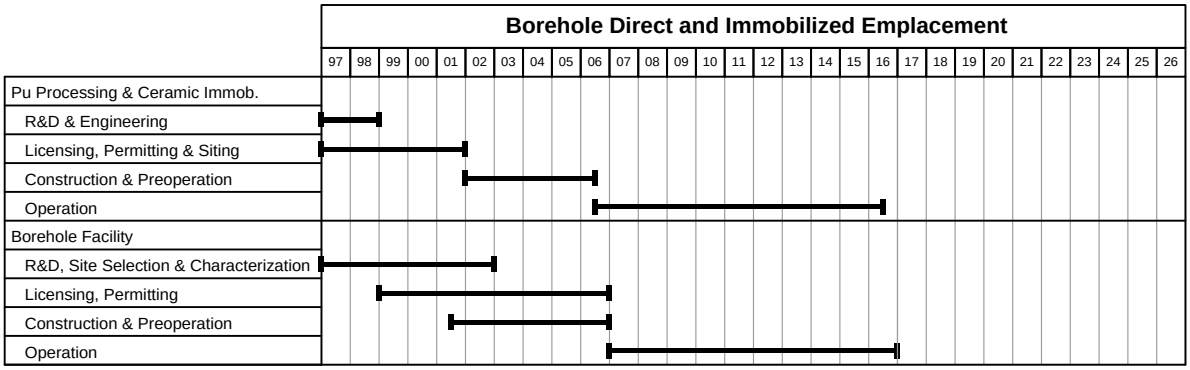
- Once sited and licensed, the critical path for emplacement is the supply of plutonium to the borehole facilities. Rapid emplacement of plutonium requires that extraction of plutonium from pits and other sources be accomplished on a schedule faster than otherwise demanded. It is assumed that plutonium processing will be accelerated if rapid emplacement is desired.

5.4.2 Deep Borehole Alternatives Schedules Analysis

Two significant functions drive the schedule for the deep borehole alternatives: namely, selecting and qualifying a site and obtaining the necessary licenses and permits.

Generally, plutonium processing and borehole facilities equipment and engineering do not appear to be critical path elements.

Figure 5-7. ***Direct and Immobilized Emplacement Deep Borehole Schedule***



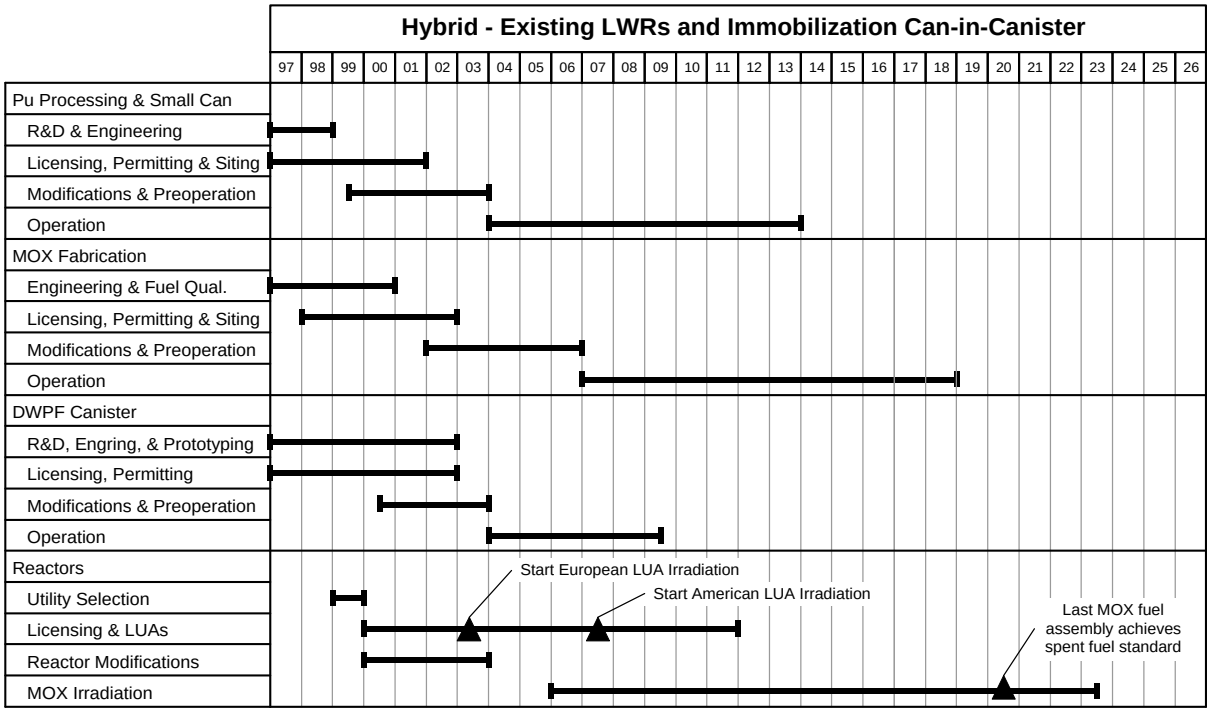
As shown in Figure 5-7, the 10-year duration includes a licensing schedule basis which was discussed with the NRC and appears to be obtainable. The time to emplace is a choice available to the designers.

For the deep borehole alternatives, acceleration of the schedule start-up is not likely since the critical path to start-up involves site selection and qualification. However, the emplacement time can be reduced to as little as three years, if desired, rather than the ten years discussed in the nominal schedule by accelerating the availability of plutonium and by drilling boreholes in parallel rather than series. The downside to the rapid emplacement involves two factors. First, the plutonium would need to be processed through the front-end processes at an advanced rate, which implies cost and technical risk. Second, this option may require performing significant plutonium processing earlier and at risk since resolution of the siting issues may not have been attained when the plutonium processing would be required.

5.5 HYBRID ALTERNATIVES SCHEDULES

The schedules for hybrids utilize existing facilities for plutonium processing where high purity weapons-grade plutonium is fed to a MOX fuel fabrication facility to be made into fuel for existing reactors and the balance diverted to can-in-canister immobilization facilities. A hybrid schedule is shown in Figure 5-8 for the LWR hybrid alternative using existing plutonium processing facilities, European MOX fuel fabrication capability, and early start of can-in-canister immobilization variant. The CANDU hybrid alternative schedule would be similar except that the reactor portion of the hybrid may not start as early with CANDUs as with LWRs.

Figure 5-8. ***Existing LWRs and Immobilization Can-in-Canister Schedule***



Many of the observations for the existing reactor and can-in-canister alternatives apply here. Some additional schedule considerations are:

- Both the reactor and immobilization portions of the hybrid can be started up using their respective accelerated deployment strategies, namely use of European fuel fabrication capability for reactors and use of existing oxides and pilot-plant operation for immobilization. This combination of the technologies provides a higher confidence in an accelerated start than either of them separately.
- Deployment of two technologies will provide increased flexibility and assurance of mission accomplishment should technical problems develop with one technology.
- Flexibility is retained in that a decision to utilize a hybrid approach preserves the option to go exclusively to reactors or exclusively to immobilization at a later date.

5.6 SCHEDULE DATA SUMMARY

Table 5-1 is a summary of the schedule data for the disposition alternatives.

Table 5-1. *Disposition Schedule Summary*

	Time to start (yrs)[1]	*Time to complete (yrs)* [2]	*Remarks*
Reactor Alternatives [3]			
Existing LWRs, Existing Facilities	9	24	Reflects initial use of European MOX fuel fabrication plant until domestic facility is available. Unavailability of European MOX fuel fabrication and/or plutonium oxide for LUAs and initial reactor core loads can delay the disposition mission up to 4 years.
Existing LWRs, Greenfield Facilities	13	31	
CANDU	8–10	<24	CANDU fuel irradiation likely could begin earlier with European fuel fabrication, just like LWRs. Since CANDU MOX fuel fabrication is less certain than for LWRs, only half of the LWR schedule acceleration of 4 years is assumed to apply to the CANDU alternative. The earlier date shown here assumes a two-year schedule credit for European MOX fabrication.
Partially complete LWRs	13	28	
Evolutionary LWRs	14	28	
Immobilization Alternatives			
Vitrification Can-in-Canister	7	18	
Vitrification Greenfield	12	21	
Vitrification Adjunct Melter	12	21	
Ceramic Can-in-Canister	7	18	
Ceramic Greenfield	12	21	
Electrometallurgical Treatment	13	22	
Deep Borehole Alternatives			
Immobilized Emplacement	10	20	The implementation time is assumed to be 10 years; it could be compressed to as little as 3 years
Direct Emplacement	10	20	The implementation time is assumed to be 10 years; it could be compressed to as little as 3 years
Hybrid Alternatives			
Existing LWRs with Vitrification Can-in-Canister	7	<25	The 7 years corresponds to the immobilization portion of the hybrid. The reactor portion starts up in 9 years.
CANDU with Vitrification Can-in-Canister	7	<22	The 7 years corresponds to the immobilization portion. The reactor portion will start in 8–10 years.

[1] Time is measured from authorization to proceed. Start-up time refers to the initiation of production-scale operations, which for can-in-canister variants is taken to be 1.25 MT/yr capacity versus full scale (5 MT/yr) capacity.

[2] Time to complete is the entire duration from authorization to proceed to completion of the disposition mission. The disposition mission is considered complete: for LWRs – after the first irradiation cycle for the last MOX bundles; for CANDUs – after the last bundle has completed its intended irradiation; for immobilization – when the last immobilized waste form is fabricated; and for deep borehole – when the last borehole is sealed.

[3] For reactor alternatives, this start of production-scale operations is defined to be the beginning of the irradiation cycle for the mission fuel. For existing LWRs, this is 2–3 years after irradiation of lead use assemblies. For partially complete and evolutionary reactors, the mission starts when the reactors go to full power with their MOX cores.

CHAPTER 6. COST AND SCHEDULE UNCERTAINTIES

This chapter provides information to support assessment of the some of the key uncertainties in the cost and schedule estimates provided in Chapters 4 and 5. Section 6.1 is an introduction to the chapter. Sections 6.2-6.5 detail some of the cost and schedule uncertainties for the various technologies. Section 6.6 provides a quantitative assessment of the sensitivities of the cost estimates to presumed discount rates.

6.1 INTRODUCTION

The uncertainty factors that are cited in this chapter generally map to technical, economic, or schedule issues that are amenable to engineering analysis. It is this set of issues that is addressed in this Report. However, these factors are not necessarily the most important factors that can influence the actual costs and schedules for the alternatives. Some examples of factors which are beyond the scope of this Report but which can nevertheless have significant impacts on schedules (and by extension, cost) include:

International Considerations – The rate of implementation of any alternative will be dependent on negotiations and agreements with the Russian Federation regarding reductions to its stockpiles of surplus weapons-usable plutonium. No such agreements have been negotiated, and considerations of terms and conditions that might be in such agreements would be presumptuous and speculative. In any event, international agreements could result in a regime which drives the plutonium disposition schedule more quickly or more slowly than estimated in Chapter 5.

Assignment of National Priority – The level of resolve in the United States over the next several Congresses and Presidential administrations, as influenced by the timeline of negotiations with Russia, will dictate how rapidly or how slowly plutonium disposition will be completed.

Institutional or Programmatic Issues – All large projects are vulnerable to extensive programmatic delays. As stated in Chapter 5, federal projects can be even more vulnerable to programmatic delays than private sector projects. The causes of programmatic delays can include changes in policy, laws, or regulations, legal challenges, delays in Congressional funding authorization, public opposition and intervention by third parties, as examples

Each of the values assigned to the factors driving the cost and schedule uncertainties are reasonable estimates for planning purposes. The values, however, are not necessarily bounding as less likely scenarios could be postulated that result in outcomes more extreme than those presented here. The values assigned to the factors were estimated in isolation from one another in that each factor was considered to be the only factor involved in assessing a cost or schedule impact. The factors could interact in complex ways; however,

insufficient information exists for assessing the impacts of factors operating simultaneously. Therefore, aggregation of uncertainties is not presented.

In the information provided in the following sections, cost impacts are reported in millions of constant 1996 dollars and generally are rounded to the nearest $100 million above the baseline estimates in Chapter 4. The schedule impacts are generally reported in years. The order of the uncertainty factors is arbitrary and does not imply a likelihood or consequence ranking.

6.2 REACTOR ALTERNATIVES

6.2.1 Existing LWRs

In general, LWR MOX fuel technology is well developed and currently operational in Europe. Some technical risks remain for reactor deployment, such as the impact of gallium on fuel fabrication and fuel performance, as outlined in Chapter 3. However, the magnitude of the potential cost and schedule impacts associated with the resolution of the reactor-specific technical issues is small compared to the potential impacts relating to the acquisition of MOX fuel fabrication and irradiation services. One overriding uncertainty that could have significant impact on the use of existing LWRs is the evolving deregulation of the electricity markets. However, impacts related to deregulation have not been assessed.

Table 6-1 identifies some critical factors which could have significant impacts on the cost and schedule estimates in Chapters 4 and 5 for the existing LWR alternative. The bases for the factors are discussed in the accompanying text.

Factor 1:

Utilities will accrue some risk to their investments for transitioning to MOX fuel cycles and likely will require compensation for assuming the risk. In the economic model used in Chapter 4, all of the incremental costs for using MOX fuel rather than uranium fuel are assumed to be paid by the Government and the value of the displaced uranium fuel is credited to the Government. Compensation from the Government to the reactor owners is treated as “irradiation service fees.” This model simplifies the actual business transactions between the reactor owners and the Government for purposes of analysis by separating actual cost incurred from any fees.

The actual business transactions would result from negotiations with selected reactor owners subsequent to a competitive procurement process. In this process, the reactor owners, perhaps in concert with other companies, would propose terms and conditions for providing irradiation services to the Government. The price structures that a reactor owner might use to base its proposal could depend on any number of factors, such as the company’s own financial status, the projected long-term costs for uranium fuels, exposure to financial and technical risks, local electric power market conditions, ability to enhance shareholder value, and assessments of prospective competitors for the disposition mission.

In any event, the net cost to the Government, reflected in this Report as a "fee," will ultimately be embedded in a framework of an integrated business arrangement yet to be proposed or negotiated.

Estimates for expected LWR irradiation service fees are provided in the Existing LWR Reactor Alternative Summary Report. The estimate in the Reports varies with particulars, but the estimates for the aggregated fee tends to center around $500 million. Note that even if no fee is paid, the reactor owners could receive the benefit of long-term price stability of their fuel supply, which is a tangible economic benefit to the utilities but a cost-free item to the Government.

Table 6-1. ***Approximate Cost and Schedule Impacts for Existing LWRs***

[The order of the factors is arbitrary, and the likelihood of each factor is unknown.]

Factor	*Source of Variation*	*Adjustment or Impact*	*Cost ($M)*	*Schedule (yr)*
1	Fee for irradiation services	Pay utilities a negotiated price for services	up to 500	none
2	Reactor modifications cause dedicated 1 month delay to convert to MOX fuel cycles; incremental replacement power needed	1200 MW of replacement power required for 30 days at each of 5 reactors and at a cost of $29/MWh	+100	+1 month
3	Variation in market price for LEU fuel	Price of LEU fuel rises to $1500 or falls to $1000 per kg heavy metal	-400 to +200	none
4	High level waste repository incurs additional cost for MOX fuel, relative to LEU fuel	The 1 mill per kWh fee is doubled with incremental cost charged to the Government	+200	none
5	Inability to use European fuel fabrication capability	Use a domestic MOX facility exclusively	-100	+4
6	Adverse variation in front end process parameters (including gallium removal) relative to baseline design	Front end operating costs increase by 10% and more extensive use of aqueous processing	+200	0 to +2
7	Modification and construction costs higher than estimated	Cost escalation of front end, MOX fuel fabrication, and reactor plants by 50%	+500	+2

Factor 2:

Although modifications to reactors are expected to be able to be accomplished in a manner that does not impact the implementation of MOX fuel cycles beyond what is already included in the cost estimates, an incremental dedicated one-month shutdown period for each of the five reactors in the existing LWR, existing facilities variant is postulated and characterized here. The Government would be liable for the cost of replacement power during the extended outage.

Factor 3:

The price that an LWR utility pays for its LEU fuel depends on many factors, but the price depends mainly on the cost of uranium ore and enrichment services. The market price for many of the fuels delivered to utilities today varies from about $1000-1500 per kilogram heavy metal (kgHM). The fuel credit in Chapter 4 was calculated using reference market prices for PWR and BWR fuels as $1193 and $1214 per kgHM, respectively. The cost impacts associated with the change in fuel price correspond to the existing LWR, existing facilities variant over the range indicated.

Factor 4:

The fee for disposal of spent LWR fuel is specified in the Nuclear Waste Policy Act as 1 mill per kilowatt-hour. Though not expected, there may be some incremental costs to the repository to enable it to accept the MOX-derived spent fuels that result from plutonium disposition. An additional 1 mill per kilowatt-hour is assigned to cover any incremental repository costs.

Factor 5:

Not using European facilities for initial fuel assemblies results in a 4 year time delay in the existing LWR, existing facilities variant as discussed in Chapter 5. The overall cost for using only American-fabricated fuel is less than the European case since the operating cost for producing fuel domestically in a government-owned, existing facility is less than the cost of buying it at market prices (approximately $800 vs. $1500 per kgHM) as well as minor savings in safeguards and transportation costs. See Table 7.2 in Volume I of the Reactor Alternatives Summary Report for details.

Factor 6:

Material and labor requirements for front end operations may be higher than anticipated. For example, a 10% increase in operating costs would correspond to $100 million. It is assumed that this level of increase in activity could be accommodated without an increase in the schedule. Additionally, if the ARIES process proves to be incapable of generating plutonium powder to meet morphology or gallium concentration criteria, aqueous processing will be required. The cost penalty in converting to aqueous processing will be the sunk cost in ARIES development (assumed to be $50 million) and the cost of establishing an aqueous processing line with the capability to process the entire 50 MT inventory.

This second cost is assumed to be $50 million more than the capital cost of the ARIES process in the baseline design. The operating costs for ARIES and aqueous processing are assumed to be comparable, so that no net increase in operating cost would be realized. Finally, the assumed schedule delay of 2 years stems from the delay in determining the acceptability of ARIES-derived powder for use in reactor fuel.

Factor 7:

Licensing, design, and construction costs may be higher than anticipated. A 50% cost overrun would correspond to $500 million. A 50% variation from the baseline cost would represent the approximate fidelity of the estimate and is a reasonable basis for planning purposes for considering cost overruns. The 50% value also corresponds to the value for cost overruns used with partially complete and evolutionary reactors, as discussed below. A two year schedule delay is also assumed.

6.2.2 CANDU Reactors

Many of the uncertainty factors for existing LWRs also apply to the CANDU alternative, but the impacts would differ. Table 6-2 identifies some critical factors which could have significant impacts on the CANDU reactor cost and schedule estimates. The factors are discussed in the accompanying text.

Factor 1:

See the corresponding discussion under factor 1 in the LWR subsection. Note, though, that the premium associated with fuel price stability for LWR fuel would be less important to the CANDU reactor owner since the CANDU fuel costs are so much lower.

Factor 2:

Although modifications to CANDU reactors are expected to be able to be accomplished in a manner that does not impact the implementation of MOX fuel cycles beyond what is already included in the cost estimates, an additional dedicated one-month shutdown period for each of the four CANDU reactors is characterized here.

Factor 3:

The CANDU MOX fuel fabrication cost estimates are predicated on LWR MOX experience. Owing to their smaller size and other characteristics, CANDU MOX fuel bundle costs may be overestimated by the LWR-derived experience. The values presented in Table 6-1 correspond to different cost estimates prepared by the reactor vendor (AECL) and LANL, respectively. (See Table 2.22 of Volume 2 of the Reactor Alternative Team Summary Report.)

Table 6-2. ***Approximate Cost and Schedule Impacts for CANDU Reactors***

[The order of the factors is arbitrary, and the likelihood of each factor is unknown.]

Factor	*Source of Variation*	*Adjustment or Impact*	*Cost ($M)*	*Schedule (yr)*
1	Fee for irradiation services	Pay utility a negotiated price for services	up to +500	none
2	Reactor modifications cause dedicated 1 month delay to convert to MOX fuel cycles; additional replacement power needed	769 MW of replacement power required for 30 days at each of 4 reactors and at a cost of $29/MWh	+100	+1 month
3	CANDU fuel fabrication costs	Owing to simpler fuel design, CANDU MOX fuel may be less expensive than LEU MOX fuel per kg heavy metal	-700 to -200	none
4	European CANDU MOX fuel fabrication capability	Use European MOX fuel fabrication to facilitate rapid start of CANDU reactors	+200	-2
5	Adverse variation in front end process parameters (including gallium removal) relative to baseline design	Front end operating costs increase by 10% and more extensive use of aqueous processing	+200	0 to +2
6	Modification and construction costs higher than estimated	Cost escalation of front end, MOX, and reactor plants by 50%	+400	+2

Factor 4:

The CANDU cost and schedule data in Chapters 4 and 5 do not assume European fuel fabrication of CANDU MOX fuel. Although the structural designs of CANDU and LWR fuel assemblies are very different, the fabrication of the fuel pellets for the two reactor types, which is the distinguishing feature between uranium and MOX fuel fabrication, is similar. Therefore, it is assumed that half of the LWR four-year schedule compression realized by European LWR MOX fuel fabrication would be realized by European CANDU MOX fuel fabrication. The two year increment implies an approximately $200 million penalty, assuming the CANDU alternative uses 136 MT/yr at a $700 per kgHM premium to purchase the fuel versus producing it (see Table 2-2 and Factor 5 in Section 6.2.1).

Factor 5:

See Factor 6 in Section 6.2.1.

Factor 6:

Licensing, design, and construction costs may be higher than anticipated. A 50% cost overrun would correspond to $400M. A two year schedule delay is also assumed.

6.2.3 Partially Complete and Evolutionary LWRs

The acquisition cost of the partially complete reactors is a major unknown. The actual acquisition price would depend on the business arrangements between the Government and the reactors' owner(s). The terms and conditions in the business arrangements would include factors such as the rights to the power produced, negotiated price of electricity, salvage value of the reactors after the mission is completed, the completion costs for the reactors, and the reactor owners' rights to the equity in their assets. The actual acquisition price would likely be small and perhaps be zero but remains an indeterminate quantity, absent applicable business terms and conditions. Other significant sources of uncertainty for partially complete and evolutionary reactors include the potential for construction cost overruns, the salvage value of the reactors after mission completion, and the market price for electricity. Potential cost and schedule impacts for these factors are shown in Table 6-3 and discussed in the accompanying text.

Factor 1:

The scenario employed here envisions cost overruns for front end, MOX fuel fabrication, and reactor facilities assumed to be as high as 50%. There are historical cases where nuclear facilities have overrun their cost bases by more than 50%. Many of these cases were subject to high cost of capital (not a factor here where costs are reported in constant dollars and costs are paid as accrued) or to institutional issues (beyond the scope of the report). The two year delay was assumed.

Factor 2:

At the end of the plutonium disposition mission, the partially complete and evolutionary reactors will have approximately 25 years remaining on their operating licenses and would be turned over to the private sector. The present value of this operating profit to the private sector, discounted at a private sector real discount rate of 9%, is approximately $2.5 billion when the plutonium disposition mission ends. Taking a 20% discount off its economic value to estimate its market price provides an estimate of $2000 million that DOE could potentially receive in that year from the private sector. The present value of this payment, discounted at the government's discount rate of 5%, is approximately $640 million in 1996.

Table 6-3. ***Approximate Cost and Schedule Impacts for Partially Complete and Evolutionary Reactors***

[The order of the factors is arbitrary, and the likelihood of each factor is unknown.]

Factor	*Source of Variation*	*Adjustment or Impact*	*Cost ($M)*	*Schedule (yr)*
1	Front end and reactor construction costs are higher than estimated	Cost escalation by 50% for partially complete (pc) and evolutionary (ev) reactor alternatives	+1500 pc +3400 ev	+2 +2
2	Salvage value of reactors received at end of Pu disposition mission	Reactors are sold at a projected market prices	-2000	none
3	Market price of electricity varies from baseline forecast	Price of electricity varies from baseline ($29/MWh) to $41/MWh	-3000	none
4	High level waste repository incurs additional cost for MOX fuel, relative to LEU fuel	The 1 mill per kWh fee is doubled	+ 300	none
5	Adverse variation in front end process parameters (including gallium removal) relative to baseline design	Front end operating costs increase by 10% and more extensive use of aqueous processing	+200	none

Factor 3:

The government would receive revenues from the sale of electricity incidental to the plutonium disposition mission. The baseline cost estimates cited in Chapter 4 assume that the electricity can be sold at a prevailing market price of $29/MWh. A recent report on tritium production by Putman, Hayes, and Bartlett cites a high market price of $41/MWh [PHB 1995]. If the high electricity price were realized, the government would receive approximately $3 billion more revenue as shown in Table 6.2.

Factor 4:

See the related discussion in Section 6.2.1.

Factor 5:

See the related discussion in Section 6.2.1. Note that there is no schedule delay, since availability of plutonium powder is not on the critical path for the alternatives in Table 6-3.

6.3 IMMOBILIZATION ALTERNATIVES

An overriding uncertainty for the immobilization variants pertains to the acceptability of the material form of immobilized plutonium to the repository. Until it is licensed, the nature of material forms that will be acceptable to the high level waste repository is an open question. The risk of a final destination also applies to reactor variants but the issue is less important because the repository is being designed to accommodate spent fuels with characteristics similar to MOX-derived spent fuel.

The estimated uncertainties presented in Table 6-4 relate to the can-in-canister variants since these are the best characterized at this time.

Factor 1:

If R&D efforts fail to demonstrate baseline plutonium loadings, lower plutonium loading would be required. Halving the plutonium loading could be due to either a need to reduce the fissile content of the material form for the high level waste repository or due to an inability to demonstrate satisfactory dissolution and immobilization of plutonium in the host matrix during production. Doubling plant capacity would increase capital costs by $40 million (for additional melters) and operating costs by $160 million. Finally, $100 million additional repository costs would be incurred for the additional canisters. The total cost increment is approximately $300 million.

A schedule delay would likely correspond to the cost escalation. However, no estimate is provided due a lack of basis for estimation.

Factor 2:

If immobilized waste form qualification issues arise, the program might experience additional research, development, and licensing expenses as well as delays in implementation. It is assumed that additional research, development, and licensing expenditures of $100 million would be experienced. The corrective actions would be on the critical path so that a schedule delay of 2 years is assumed. Note that this corresponds to approximately doubling the current baseline waste form qualification cost estimate of $115million.

Factor 3:

Factor 3 refers to a postulated 3 year delay in DWPF operations that prevents placement of cans in canisters and filling them with high level waste. The plutonium-loaded cans would be produced on schedule and stored. Additional storage costs would be approximately $20 million.

Table 6-4. ***Approximate Cost and Schedule Impacts for Immobilization***

[The order of the factors is arbitrary, and the likelihood of each factor is unknown.]

Factor	*Source of Variation*	*Adjustment or Impact*	*Cost ($M)*	*Schedule (yr)*
1	Plutonium loading is too high; plutonium concentration drops in half	Double plant capacity to accommodate additional throughput, more logs to repository	+300	not estimated
2	Additional analyses and experiments required for form qualification	Additional costs and schedule delay	+100	+2
3	DWPF operations delay causes delay in plutonium disposition mission	Requires storage of Pu-loaded cans for 3 years	+20	+3
4	Plutonium disposition mission causes unanticipated impacts on DWPF operations	Additional facilities, hardware, and procedures must be applied to other DWPF operations	+30	none
5	Adverse variation in front end process parameters relative to baseline design	Front end operating costs increase by 10%	+100	none
6	Reduction in glass or ceramic formation times	50% reduction in cycle time, reduced melter or sintering furnace capacity and operating costs	-100	none
7	Modification and construction costs higher than estimated	Cost escalation of front end and immobilization plants by 50%	+300	+2
8	Assigned unit cost for canister disposal too low	The estimated unit cost for canister disposal is doubled	+100	none
9	Baseline can-in-canister design found unacceptable from nonproliferation perspective	Redesign can-in-canister to address nonproliferation concerns	+10	none

Factor 4:

The baseline design assumes that the plutonium disposition mission will have some impacts on DWPF operations. The cost of these impacts is included in the cost estimates in Chapters 4 and 5. For example, the baseline design includes security upgrades and facilities such as vaults, a local PIDAS fence, DWPF upgrades, and storage building upgrades. In addition,

the design includes the addition of 25 full time operators at DWPF and 55 full time security personnel. A 50% contingency on these costs corresponds to approximately $30 million

Factor 5:

As indicated in the discussion of the reactor alternatives, variation in front end process parameters may lead to a 10% increase in operating costs, or $100 million. Note that the reactor-specific morphology and gallium contamination impacts do not apply to the immobilization alternatives.

Factor 6:

Recent experimental results indicate that melting or sintering cycle times could be 1/2 of those assumed in the baseline designs. Capital and operating costs would be reduced by $25 million and $75 million, respectively.

Factor 7:

As indicated in the reactor discussion, a 50% cost overrun relative to estimates based upon preconceptual designs is considered.

Factor 8:

The cost estimated in the baseline cost estimate for canister disposal corresponds to the assigned cost for disposal of the existing DWPF canisters. The actual cost for DWPF canisters is indeterminate at present and it is not clear that plutonium-loaded canisters will be charged at the same rate. A factor of two increase in the cost for waste disposal is judged to envelop a wide range of possible outcomes in the actual costs for canisters.

Factor 9:

The current can-in-canister design may be deemed unacceptable from a safeguards and security perspective by the U. S. Government, the Russian Federation, or the international safeguards community. However, a recent report on the proliferation vulnerability of the plutonium disposition alternatives supports the position that can-in-canister system design modifications can likely mitigate proliferation vulnerabilities[1]. For example, different can materials may be needed to prevent separation of the plutonium-loaded cans from the surrounding glass matrix or smaller cans may have to be used to more closely approximate a homogeneous mixture of plutonium and other radioactive material. It is unlikely that mechanical or materials redesign costs would exceed $10 million. No schedule impact is anticipated.

[1] Proliferation Vulnerability Red Team Report, SAND97-8203-UC-700, October 1996.

6.4 BOREHOLE ALTERNATIVES

In general, licensing and siting are key uncertainties for the borehole alternatives. These uncertainties are judged to override all of the technical uncertainties associated with the borehole alternatives. Whereas some aspects associated with licensing and siting are factors that can be analyzed by engineering methods, the most important ones are not amenable to engineering analysis. Thus, assignment of risk to explicit uncertainty factors has not been attempted.

6.5 HYBRID ALTERNATIVES

A reactor/immobilization hybrid approach offers some significant possibilities for mitigating the impacts of the cost and schedule uncertainties cited in previous subsections, as well as the opportunity to adjust to major post-ROD policy changes that might preclude the deployment of one of the two technologies in the hybrid. As an example, if irradiation fees required by utilities were determined to be excessively large, the reactor technology could be dropped at that time and all the material directed to scaled-up immobilization facilities. Conversely, if the immobilization research and development does not progress as expected, the immobilization technology could be dropped and all the material then directed to the scaled-up MOX fuel fabrication and reactor facilities. Thus, the hybrid alternatives provide additional flexibilityat the expense of a relatively small increment in investment costs.

Table 6-5. ***Approximate Cost and Schedule Impacts for Reactor/Immobilization Hybrids***

[The order of the factors is arbitrary, and the likelihood of each factor is unknown.]

Factor	*Source of Variation*	*Adjustment or Impact*	*Cost ($M)*	*Schedule (yr)*
1	Unacceptable costs or technical difficulties with reactor or immobilization technologies	Implement only one of the two technologies in the hybrid	-100	not estimated
2	Fee for irradiation services	Pay utilities a negotiated price for services	up to +300	none
3	Plutonium loading is too high; plutonium concentration drops in half	Increase vitrification plant capacity and/or operate plant longer	+100	none

Factor 1:

If unacceptable cost or technical issues for MOX fuel are encountered[2] prior to construction, the immobilization facilities can be scaled-up to process 50 MT of plutonium, rather

[2] This assumes the LWR hybrid; the CANDU hybrid would be similar.

than the 17 MT feed stream assumed in the baseline hybrid example. Two types of costs would be incurred: the reactor alternative licensing and R&D costs and the costs of immobilization facilities to accommodate all 50 MT of plutonium. The first cost is approximately $250 million and the second cost is $1830 million. Hence, the total cost is $2080, which is $100 million less than the cost of the LWR/immobilization hybrid. Note that this cost reduction is realized rather than the large cost overruns that would be experienced if the 50 MT reactor alternative had been selected rather than the hybrid alternative.

Similarly, if unacceptable cost or technical issues for can-in-canister immobilization are encountered prior to construction, the MOX fuel fabrication and reactor facilities can be scaled-up to process 50 MT of plutonium, rather than the 33 MT feed stream assumed in the baseline hybrid example. The can-in-canister immobilization alternative licensing and R&D costs are approximately $120 million and the 50 MT MOX fuel fabrication and reactor facilities costs are $1920 million. Hence, the total cost is $2040, which is $140 million less than the cost of the LWR/immobilization hybrid.

Note that, coincidentally, the net savings in either event is about $100 million. These savings could be partially or wholly offset by the other uncertainties identified in Tables 6-1, 6-2, and 6-4, which would still apply as appropriate.

Factors 2-3:

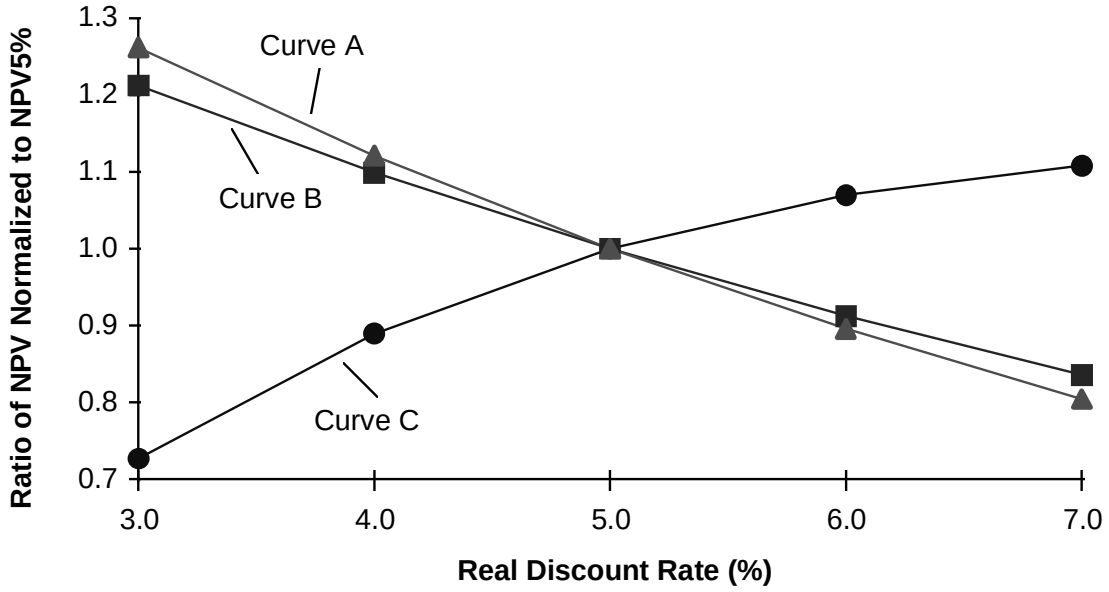
The last factors shown in Table 6-5 are representative of many other factors from Tables 6-1, 6-2, and 6-4 and demonstrate that individual cost and schedule impacts are less for most uncertainty factors in a hybrid approach. Because each of the two technologies of the hybrid would process a lower amount of material than its stand-alone counterpart, the magnitude of the impacts tend to be proportionally reduced.

6.6 SENSITIVITY TO DISCOUNT RATES

Discounted cost analyses are necessary to properly reflect the cost of capital over time which is generally assessed by applying an appropriate discount rate to determine the present value of future costs and benefits. However, since the cost of capital can never be determined *a priori*, it is important to understand how sensitive the cost estimates are to variations in the discount rate. Figure 6-1 depicts the sensitivity of the discounted cost as the discount rate varies from 3 to 7 % per year. The data are reported as the ratio of the net present value at a given discount rate to the discount rate base case of 5 % for the particular variant to normalize data to the base case analyses. The three variants selected have been chosen to represent the three type of cash flow profiles for the suite of alternatives:

Curve	***Variant***	***Cash Flow Profile***
A	Can-in-canister	All costs; no electric power revenues; no uranium fuel displacement credits
B	Existing LWRs, existing facilities	Credits but no revenues
C	Partially complete reactors	Revenues but no credits

Figure 6-1. ***Discount Rate Sensitivity***



From Figure 6-1, the following observations are offered:

1. The behavior of Curve A closely mirrors that of Curve B. This could be expected as the net cash flow profiles for the underlying variants are very similar. Importantly, the sensitivity to a 1% change in the discount rate is only 10% to 15% from the base case, which is small compared to the uncertainties in the cost estimates.

2. Curve B is slightly less sensitive than Curve A to the discount rate variations due to the small effect of the fuel credits, which tend to make cash flows in out-years nearer to zero than they would otherwise be. (Zero net cash flow in any year is unaffected by discount rate fluctuations.)
3. The trend for Curves A and B is that the normalized discounted cost increases with decreasing discount rate, as would be expected.
4. The behavior of Curve C is unlike that for Curves A and B. Note that the net present cost increases with increasing discount rate. This is readily explained by recognizing that the revenues for the alternative tend to accrue later in time than costs, thus making the present value of out-year revenues smaller as the discount rate increases.

The following illustrates the use of these sensitivity curves:

Assume an alternative without any revenues and a base case life cycle cost of $2000 million. If one wanted to know what the approximate life cycle cost would be at a 4% discount rate, the ratio of about 1.1 would be selected from Figure 6-1. Multiplying 1.1 times the base discounted life cycle cost yields a life cycle cost discounted at 4% of approximately $2200 million.

Discounted cost analyses can be misinterpreted to imply that the mission ought to be deferred in order to lower present value cost to the Government. Deferral of costs does, of course, reduce the net present cost to the Government. However, deferral of the plutonium disposition mission is also realized, a deferral which might pose an immeasurable threat/cost to US and international security. Conceptually, one must consider a trade off between the benefits of completing the mission earlier verses the additional costs incurred in doing so.

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CHAPTER 7. SUMMARY AND CONCLUSIONS

7.1 TECHNICAL CONCLUSIONS

7.1.1 General

Though each of the alternatives appears to be technically viable, each is currently at a different level of technical maturity. All alternatives will require some research and development, but there is high confidence that the technologies can support program requirements.

7.1.2 Common Technologies

- Proliferation vulnerability issues were addressed in an unclassified report (SAND97-8203-UC-700) released in October, 1996.

- Transportation and packaging technical issues appear to be readily resolvable. Furthermore, transportation issues do not appear to be significant discriminators between alternatives except for those alternatives involving transport of materials to other nations. In these alternatives, the transportation issues are mostly institutional and represent a higher degree of risk.

- The non-pit front-end process technologies are generally well developed and do not represent a significant technical risk to accomplishing the plutonium disposition mission. The pit processing technologies are being demonstrated presently, and they are expected to be available to support programmatic needs.

- With varying degrees of difficulty, all alternatives are expected to be able to satisfy oversight and regulatory requirements.

- LWR MOX spent fuel is similar to commercial uranium-based spent fuel to be sent to the high-level waste repository. Some prospective PWR MOX spent fuel may require some waste package modification (e.g., fewer assemblies per waste package) to accommodate the higher fissile content relative to commercial low enriched uranium-based spent fuel. Ceramic and vitrified waste forms also appear to be potential candidates for disposal in the high-level waste repository, though research and development will be required to obtain the necessary information for repository acceptance. In addition, authorizing legislation, NRC rule-making, or other actions may be required before placing immobilized plutonium in a high-level waste repository. While the glass-bonded zeolite waste form is less mature than the other immobilized forms, repository analyses to date identify no disqualifiers.

7.1.3 Reactor Alternatives

Existing LWRs

- MOX fabrication is a well-developed industrial technology currently operating in three countries.

- Cores involving integral neutron absorbers will require a significantly greater developmental effort to qualify the fuel form than the cores that do not involve integral neutron absorbers.

- The acceptability of small quantities of gallium in the fuel will need to be demonstrated or the gallium will need to be removed from the plutonium before fuel is fabricated.

- The licensing bases for the reactors and a MOX fuel facility are established.

- Modified facilities for both plutonium processing and fuel fabrication are viable approaches for the LWR cases (as well as for the CANDU cases).

- Sufficient reactor capacity exists, unless significant and unexpected delays occur in the mission. If such significant delays do occur, the availability of reactors with sufficient lifetimes remaining in their licenses is in question, particularly for BWRs.

- Foreign fuel fabrication facilities could be used to make some fuel early in the campaign, especially for lead use (or test) assemblies and a few subsequent partial core reloads. However, it is unlikely that sufficient fuel fabrication capacity will be available in Europe for the entire 50 MT mission. For this reason, a need for a domestic fuel fabrication facility is envisioned.

- Pressurized water reactors (PWRs), other things being equal, offer higher plutonium throughput per reactor year than boiling water reactors (BWRs).

CANDU Reactors

- The CANDU alternatives are similar in many respects to the existing LWR cases that do not use integral neutron absorbers. However, a qualified MOX fuel form for CANDU reactors does not exist and no industrial experience using CANDU MOX fuel is available, making the CANDU reactors less mature than LWR reactors for the plutonium mission.

- The CANFLEX fuel form, which involves a higher plutonium concentration in the fuel, is more attractive for the plutonium disposition mission because of its enhanced

ability to achieve higher plutonium throughputs. This advantage is partly offset by the need for a more extensive fuel development effort.

- Transportation across the border represents an institutional challenge to the CANDU alternatives. However, the transportation and packaging technologies to support the CANDU mission are well demonstrated and are technically viable.

Partially Complete LWRs

In most technical aspects the partially complete alternatives resemble the existing LWR cases. The important differences are: (1) because only two reactors are assumed to be available, the cores for the partially complete reactor alternative would have integral neutron absorbers, increasing the technical risk, relative to the existing LWR variants, which do not require integral neutron absorbers; (2) the reactors would need to be completed and the license application approved, both technical risks, relative to operating LWRs; (3) the partially complete reactors would generate spent fuel that otherwise would not have been generated, unlike the operating LWR alternatives where MOX spent fuel merely substitutes for LEU spent fuel.

Evolutionary LWRs

The conclusions that pertain to partially complete reactors would also apply to the evolutionary reactor cases. In addition, the technical risks for the evolutionary reactors are greater than the risks for the partially complete reactors given the latter's relative progress in licensing and construction. Furthermore, the evolutionary reactors themselves involve new reactor technologies that have not yet been deployed in the U.S., increasing the technical risk relative to partially completed reactors.

7.1.4 Immobilization Alternatives

Vitrification

- Experiments have been conducted to confirm that glass can immobilize significant concentrations of plutonium (> 5% for adjunct melter and greenfield variants and >10% for the can-in-canister variant).

- A significant data base exists relating to the vitrification of high level waste. The existing technologies can be adapted to the plutonium disposition mission, though different equipment designs and glass formulations will generally be necessary.

- In the can-in-canister and adjunct melter variants, using Savannah River facilities for the front-end processes as well for the vitrification processes provides substantial benefits.

- In terms of technical viability, it is judged that the can-in-canister variant is the most viable, the greenfield glass variant the least, and the adjunct melter variant intermediate. The can-in-canister approach is favored because it allows the

separation of loading the plutonium into the small cans (glove box operations) and the mixing of the glass with the ^{137}Cs or high-level waste (hot cell operation).

Ceramic Immobilization

- Ceramic technologies have comparable maturity to the vitrification alternatives. In the case of cold press and sinter, production would utilize mature MOX fuel fabrication technology.

- An experience data base exists for ceramic immobilization; in particular, confirmatory experiments have demonstrated ceramic immobilization with plutonium loadings greater than 12%.

- Ceramic forms are expected to provide superior plutonium retention and better resistance to radiation damage over long periods of time relative to other alternatives.

- The can-in-canister variant is judged to be more viable than the greenfield variant for the same reasons as the vitrification can-in-canister variant is more viable than the greenfield glass variant.

Electrometallurgical Treatment

- The technical maturity of this alternative for the plutonium disposition mission is less than the other immobilization alternatives. The experimental data base for the alternative is limited and critical questions pertaining to waste form performance remain unresolved.

- Less is known about the long-term performance of the glass bonded zeolite waste form than glass and ceramic waste forms.

- The electrometallurgical treatment alternative is sited at ANL-W where some of the necessary infrastructure exists; however, additional capabilities would need to be added for front-end treatment of pits.

7.1.5 Deep Borehole Alternatives

- The mechanical equipment and processes for the borehole alternative would be adaptations of existing hardware and processes, requiring only system integration of the various components for this application (and not a dedicated component development effort).

- The ceramic immobilized form offers enhanced nonproliferation benefits for isolation and other technical advantages relative to direct emplacement.

- The most significant uncertainties relate to selecting and qualifying a site. These uncertainties can be resolved but require a mandate.

- Borehole alternatives place the least demands on front-end processing of the suite of disposition alternatives.

- This approach exceeds the spent fuel standard and approximates the fissile content of natural uranium. The deep borehole alternatives are the only disposition approaches which attain geologic disposal in concert with meeting the spent fuel standard.

- The borehole alternatives offer the potential for enhanced safety performance as the plutonium can be isolated from the biosphere over geologic time scales.

7.1.6 Hybrid Alternatives

Two alternatives which combine technologies were considered as illustrative examples of hybrid alternatives, using existing LWR or CANDU reactors in conjunction with a can-in-canister approach. The important conclusions are as follows:

- The hybrid alternatives are viable alternatives, since the LWRs and CANDU reactors are both viable candidate approaches for the reactor component, and the vitrification and ceramic can-in-canister approaches are viable candidates for the immobilized component.

- Hybrids provide insurance against technical or institutional hurdles which could arise for a single technology approach for disposition. If any significant roadblock is encountered in any one area of a hybrid, it would be possible to simply divert the feed material to the more viable technology. In the case of a single technology, such roadblocks would be more problematic.

7.2 COST CONCLUSIONS

7.2.1 Investment Costs

The following discussion is in constant dollars unless otherwise stated.

- A significant fraction of the investment cost for an alternative/variant is related to the front-end facilities for the extraction of the plutonium from pits and other plutonium-bearing materials and for other functions which are common to all alternatives.

- Alternatives which utilize existing facilities for plutonium processing, immobilization, or fuel fabrication are preferable to building new facilities for the same function to realize significant investment cost savings.

- The investment costs for existing reactor variants tends to be about $1 billion; completing or building new reactors increases the capital commitments by several billion dollars.

- The investment cost for the immobilization alternatives ranges from approximately $0.6 billion for the can-in-canister variants to approximately $2 billion for new greenfield variants.

- Hybrid alternatives require approximately $200 million additional investment over the reactor stand alone alternatives.

- Large uncertainties in the cost estimates exist, relating to both engineering and institutional factors.

7.2.2 Life Cycle Costs

The following discussion is in constant dollars unless otherwise indicated.

- Like investment costs, the ranges of life cycle costs overlap for the three categories of alternatives; and as with investment costs, utilization of existing facilities is more attractive than building new facilities for the same functions.

- The net operating costs for the partially complete and evolutionary LWR variants depend on specific financial negotiations and are difficult to estimate.

- In no case could MOX fuel compete favorably with LEU fuel (natural uranium fuel for CANDU reactors) on a total cost basis

- The life cycle costs for hybrid alternatives are similar to the stand-alone reactor alternatives. For the LWR hybrid alternative, the cost is $260 million higher that the stand-alone reactor alternative; for the CANDU hybrid alternative cost is only $70 million higher.

- The immobilized borehole alternative life cycle cost is $1 billion greater than that for the direct emplacement alternative

- The sensitivity to the assumed discount rate, while not trivial, is relatively modest. In particular, a change in the discount rate by as much as 1% from the base case value (5% per year) changes net present worth only about 10% to 15%.

- Large uncertainties in the cost estimates exist, relating to both engineering and institutional factors.

7.3 SCHEDULE

- Significant schedule uncertainties exist, relating to both engineering and institutional factors.

- Opportunities for compressing or expanding schedules exist as only limited schedule optimizations have been performed.

7.3.1 Reactor Alternatives

- Except for using European MOX fuel fabrication facilities, the rate limiting step for existing and partially complete reactor alternatives is providing fuel to the reactors. This step is paced by the ability to make fuel at a MOX fuel plant and the ability to provide a supply of plutonium oxide to the MOX fuel plant.

- The time to attain production scale operation in existing LWRs and CANDU reactors is about 8–10 years from authorization, using European MOX facilities and specific feed streams for plutonium oxide.

- The time to complete the disposition mission is a function of the number of reactors committed to the mission, among other factors. For the variants considered in this report, the time to complete varies from about 24 to 31 years.

7.3.2 Immobilization Alternatives

- The rate limiting steps for the immobilization alternatives involve completing process development and demonstration and qualifying the waste form.

- The time to start the disposition mission ranges from 7 to 13 years after authorization.

- The operating campaign for the immobilization alternatives at full-scale operation was selected to be 10 years; it is possible to compress or expand the operating schedule by several years, if desired, by resizing the immobilization facility designs selected for analysis in this study. The overall mission duration is expected to be about 18 to 24 years.

7.3.3 Deep Borehole Alternatives

- The two related functions that drive the schedule for the deep borehole alternatives are selecting and qualifying a site and obtaining the necessary licenses and permits.

- The time to start-up is expected to be 10 years.

- The operating duration of the mission was established as 10 years, although completing all burial operations at the borehole site in 3 years is possible.

Therefore, the overall mission duration is estimated to be 20 years with accelerated emplacement reducing the duration by about 7 years.

7.3.4 Hybrid Alternatives

In general, the schedule data that apply to the component technologies apply to the hybrid alternatives as well. Some particular points apply:

- No schedule penalty accrues to using hybrid approaches. In fact, confidence in an early start-up and an earlier completion can both be improved, relative to their nominal schedules.

- Hybrid alternatives provide an inherent back-up technology approach to enhance confidence in attaining schedule goals.

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APPENDIX A: PROGRAMMATIC AND GENERAL DESIGN ASSUMPTIONS

The alternatives were defined under the following common set of requirements and assumptions.

General Assumptions

- The analyzed inventory of surplus plutonium is approximately 50 MT.
- Alternatives were designed to address the entire inventory. This does not mean necessarily that all material will ultimately channel through the same set of operations, but only that any alternatives had to provide a disposition path for all surplus material.
- Disposition of the plutonium will begin within approximately 10 years and be completed within approximately 25 years after the ROD. Authorization for initiation of the disposition mission coincides with the Record of Decision.
- Proliferation resistance equivalent to the spent fuel standard is the goal for the final form and/or location of the plutonium.
- All necessary operations to implement a disposition alternative, (e.g., transportation, licensing, safeguards and security, inspections, and packaging operations) from the inception of the program until disposition to the spent fuel standard must be included. Additionally, the impacts associated with ultimate disposition must be assessed.
- Adequate funding will be available, when required, to support the design and construction of the chosen disposition alternatives.

General Design Criteria - Licensing/Regulatory

- Facilities will comply with applicable Federal, state, and local laws and regulations, and DOE orders.
- All operations which are conducted in new facilities or in a privately-owned facility within the U.S. will be licensed by the NRC. Foreign fuel fabrication facilities will be licensed and regulated as per the cognizant nation's laws.
- Schedules presume legislation is available to support implementation of the alternatives. In all cases, some legislation will be required to enable a disposition alternative to be implemented.

General Design Criteria - Safeguards and Security

- While pending disposition to the spent fuel standard, the plutonium must meet *the Stored Weapons Standard*, as the term was coined by the NAS, and as specified in DOE orders and guides.

- All operations involving surplus plutonium will be performed under International Atomic Energy Agency (IAEA) safeguards, except those involved with classified parts, shapes, and information.

General Design Criteria - Waste Management

- A high-level waste repository will be available to accept spent fuel and immobilized forms.

- The Waste Isolation Pilot Project (WIPP) will be available to accept small amounts of TRU wastes generated in the plutonium processing operations.

- The impacts associated with geologic disposal, repository or deep borehole, must be assessed.

- Waste minimization and pollution control principles consistent with DOE policy will be applied in the design considerations of each technology.

APPENDIX B: ACRONYMS AND GLOSSARY

The following acronyms are used in this report.

ALWR	advanced light water reactor
ANL	Argonne National Laboratory
ANL-W	Argonne National Laboratory-West, near Idaho Falls, ID
ANRCP	Amarillo National Resource Center for Plutonium
ARIES	Advanced Recovery and Integrated Extraction System
BNL	Brookhaven National Laboratory
BWR	boiling water reactor
CANDU	Canadian Deuterium-Uranium Reactor
CANFLEX	advanced fuel for the CANDU reactors
CFR	Code of Federal Regulations
D&D	Decontamination and Decommissioning
DNFSB	Defense Nuclear Facilities Safety Board
DOE/MD	U.S. Department of Energy, Office of Fissile Materials Disposition
DPEIS	Draft Programmatic Environmental Impact Statement
DWPF	Defense Waste Processing Facility
EIS	Environmental Impact Statement
EPA	U.S. Environmental Protection Agency
ES&H	environment, safety, and health
FDI	Fluor Daniel, Inc.
FFTF	Fast Flux Test Facility
FMDP	Fissile Materials Disposition Program
FMEF	Fuel and Materials Examination Facility — Hanford site
FY	fiscal year
Go/Co	government-owned/contractor-operated
GMODS	Glass Material and Dissolution System
HEU	highly enriched uranium
HLW	radioactive high-level waste
HYDOX	Hydride/dehydride/oxidation
IAEA	International Atomic Energy Agency
INEL	Idaho National Engineering Laboratory
LANL	Los Alamos National Laboratory
LEU	low-enriched uranium
LLNL	Lawrence Livermore National Laboratory
LWR	light water reactor
M&O	Management and Operating Contractor
MC&A	Materials Control and Accounting
MGDS	Mined Geologic Disposal System
MOX	mixed plutonium and uranium oxide as in mixed oxide fuel
NAS	National Academy of Sciences
NEPA	National Environmental Policy Act
NRC	U.S. Nuclear Regulatory Commission

OMB	Office of Management and Budget
OPC	operating-funded costs
ORNL	Oak Ridge National Laboratory
PEIS	Programmatic Environmental Impact Statement
PWR	pressurized water reactor
R&D	research and development
ROD	Record of Decision
S&S	safeguards and security
SER	safety evaluation report
SNL	Sandia National Laboratories
SNM	special nuclear material
SRS	Savannah River Site
SST	Safe Secure Trailer
TEC	total estimated cost
TPC	total project cost
TRU	Transuranic (Radioactive) as in TRU waste
WIPP	Waste Isolation Pilot Plant
WSRC	Westinghouse Savannah River Company
Y-12	Y-12 Plant

The following list of terms includes those that have particular meaning to this document or have a specific meaning different from their conventional, lay usage.

Term	*Definition*
Actinide	A chemical element with atomic number between 89 (actinium) and 103 (lawrencium) located in the seventh period of the periodic table. These elements exhibit chemical properties similar to the first element of the series, actinium, due to their similar electronic structure. The actinide chemical elements also are unstable and exhibit radioactive decay. Uranium, thorium, and plutonium are other examples of actinide chemical elements.
Alternative	An alternative is defined as a beginning-to-end network of operations which collectively result in the transition of the inventory of surplus plutonium to forms (for reactor and immobilization approaches) or locations (for the deep borehole approaches) which attain a high level of proliferation resistance. For the reactor and immobilization alternatives, impacts associated with emplacement in a high-level waste repository are included in the discussion of these alternatives for completeness. Some of the alternatives can be incorporated through a variety of deployment strategies. These strategies are referred to as variants in this report.
Alternative Team	Alternative Teams were composed of cognizant engineers and scientists from the national laboratories, contractors and DOE who collectively provide the expertise to represent all the technologies necessary to implement an alternative from its inception to its completion.
Category	Three categories of alternatives are considered in this report, reactors, immobilization and deep borehole alternatives.
Disposition	The disposition of plutonium is achieved when the plutonium-bearing material attains a high degree of proliferation resistance such as meeting the spent fuel standard. Geologic disposal of plutonium is achieved when it is geologically emplaced. For the reactor and immobilization alternatives, DOE will implement disposition of the plutonium to the spent fuel standard, while geologic disposal might take place many years later. For the deep borehole alternatives, geologic disposal is achieved in concert with meeting the spent fuel standard.

Term	*Definition*
Greenfield	Greenfield facility is one located at an existing DOE site which has limited plutonium handling infrastructure, such as PANTEX or the Nevada Test Site. An "existing" site is one which has extensive plutonium handling infrastructure, such as the Savannah River Site. Greenfield siting is assumed bounding for most cost, schedule and environmental analysis.
Hybrid Alternatives	Hybrid alternatives combine two or more technologies for accomplishing plutonium disposition.
Integral Neutron Absorbers	A material (such as hafnium, gadolinium, or erbium) intentionally added into a reactor fuel to absorb neutrons in the reactor. These neutron absorbers are used by nuclear reactor designers to improve the performance of a core.
Lead Use Assemblies	A lead use assembly is a nuclear fuel assembly which is inserted in a reactor core to confirm its performance. Destructive testing of the assemblies after irradiation would not generally be performed. Performance tests which require destructive evaluation after irradiation are referred to as lead test assemblies.
Pit	The core element of a nuclear weapon's "primary" or fission component. Pits are made of plutonium-239 and are surrounded by some type of casing.
Proliferation Resistance	This term conceptualizes the characteristics that are deterrents to theft, diversion, or retrieval of fissile material for use in weapons. Its characteristics relate to the form of the material (chemical and physical), its location (a measure of the degree of accessibility), and applied safeguards and security provisions (which depend on institutional controls). Occasionally, the term "proliferation resistance" is used in the more narrow sense to refer to the first two characteristics only since it is the goal of DOE to achieve a high degree of proliferation resistance that relies minimally on institutional controls. The spent fuel standard is a benchmark for proliferation resistance for plutonium.
Screening	The process of eliminating options for disposition of plutonium from further consideration through use of technical information.

Term	*Definition*
Spent Fuel Standard	The Spent Fuel Standard, a term coined by the NAS and modified by the DOE, means that alternatives for the disposition of plutonium should seek to make this plutonium roughly as inaccessible and unattractive for weapons use as the much larger and growing stock of plutonium in civilian spent fuel.
Stored Weapon Standard	The Stored Weapons Standard invokes the high standards of security and accounting applied to the storage of intact nuclear weapons. Therefore, applying the stored weapons standard means those high standards will, to the extent practical, be maintained for these materials throughout dismantlement, storage, and disposition.
Variant	See alternative definition.
Weapons-grade	Weapons-grade plutonium is plutonium with less than 7% plutonium-240 content. Weapons-grade can be in a variety of chemical or physical forms.
Zeolite	Inorganic aluminum silicate mineral.

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APPENDIX C: COST CATEGORIES

Cost estimates were generated for each facility in terms of the 24 categories shown in Table C-1.

Table C-1. ***Cost Categories for Facilities***

	PREOPERATIONAL "UP-FRONT" COSTS (OPC)
1	Research and development
2	NEPA, licensing, permitting
3	Conceptual design
4	Quality assurance, site qualification, safeguards and security plan
5	Post construction start-up
6	Risk contingency (a fixed % of Cats 1-5 determined by estimator)
	CAPITAL "UP-FRONT" COSTS (TEC)
7	Title I, II, III engineering, design, & inspection
8a	Capital Equipment
8b	Direct & indirect construction/modification
9	Construction management
10	Initial spares (technology dependent)
11	Allowance for indeterminates (AFI) (a % of Cats 7-10 determined by estimator)
12	Risk contingency (varies with alternative; reflects technology/schedule risk not in Cat. 11)
	OPERATING COSTS
13	Operations & maintenance staffing
14	Consumables including utilities and privately produced reactor fuel
15	Major capital replacements or upgrades (fixed % of capital per year determined by estimator)
16	Waste handling and disposal (spent fuel, HLW, TRU, mixed, and LLW)
17	Oversight - DNFSB or NRC
18	Management and operations contractor fees (2% of cats 13-17) (Gov't owned facility only)
19	Payments-in-lieu-of-taxes to local communities (PILT) 1% of 13-17 (Gov't owned facility only)
20	Decontamination and decommissioning (fixed % of facility capital cost determined by estimator)
21	Revenues (if applicable, i.e. sales of MOX fuel, electricity, or reactor facility)
22	Government fees to private-owned facilities
23	Transportation of plutonium forms to facility and wastes out of facility
24	Storage of plutonium at existing 94-1 site facility (to be determined) (Not considered in this report, assumed to be DOE/EM cost)