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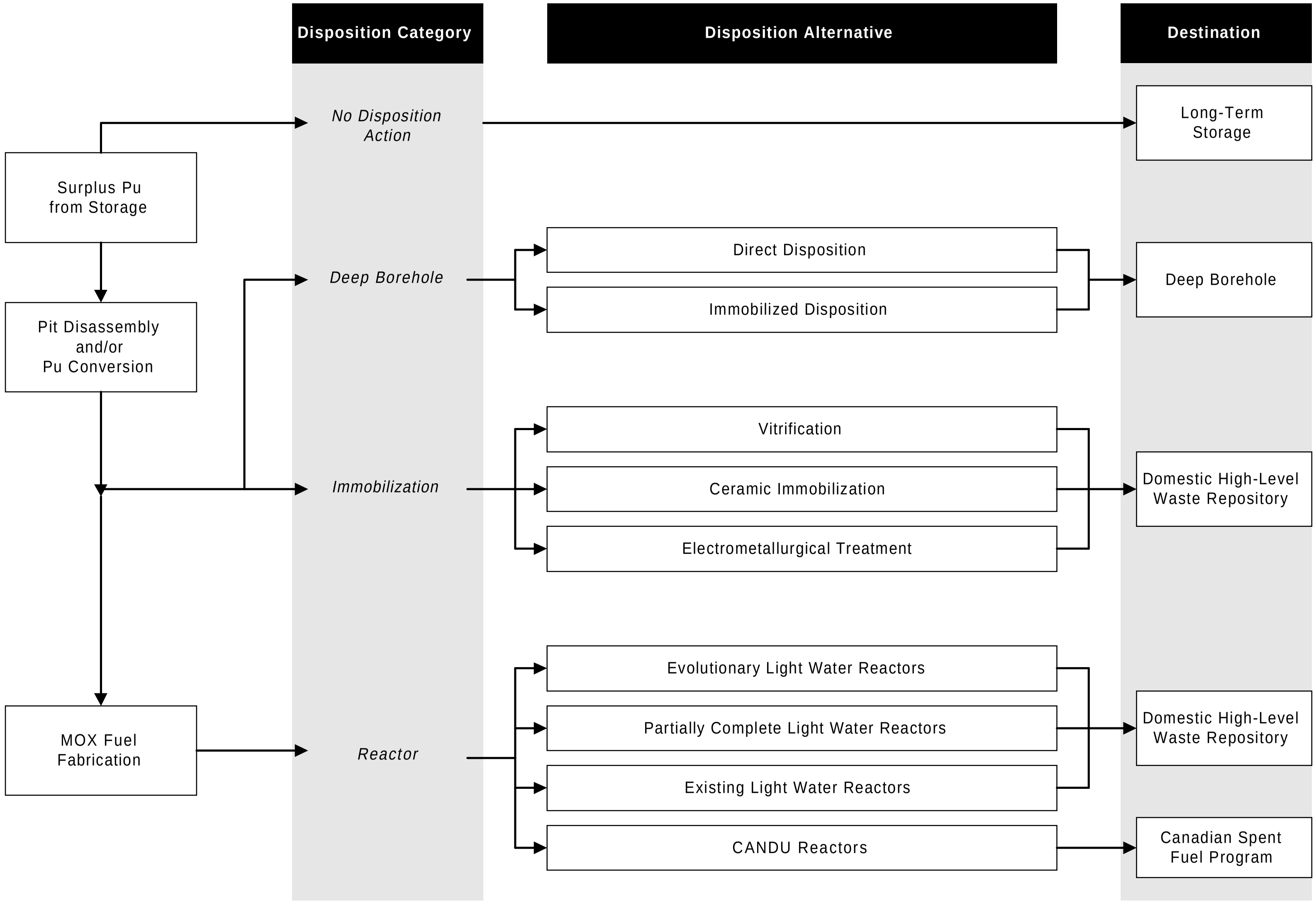
[1] President Clinton's March 1, 1995, Address to the Nixon for Peace and Freedom Policy Conference and the Department of Energy Openness Initiative, February 6, 1996.

[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.

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[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.

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[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]

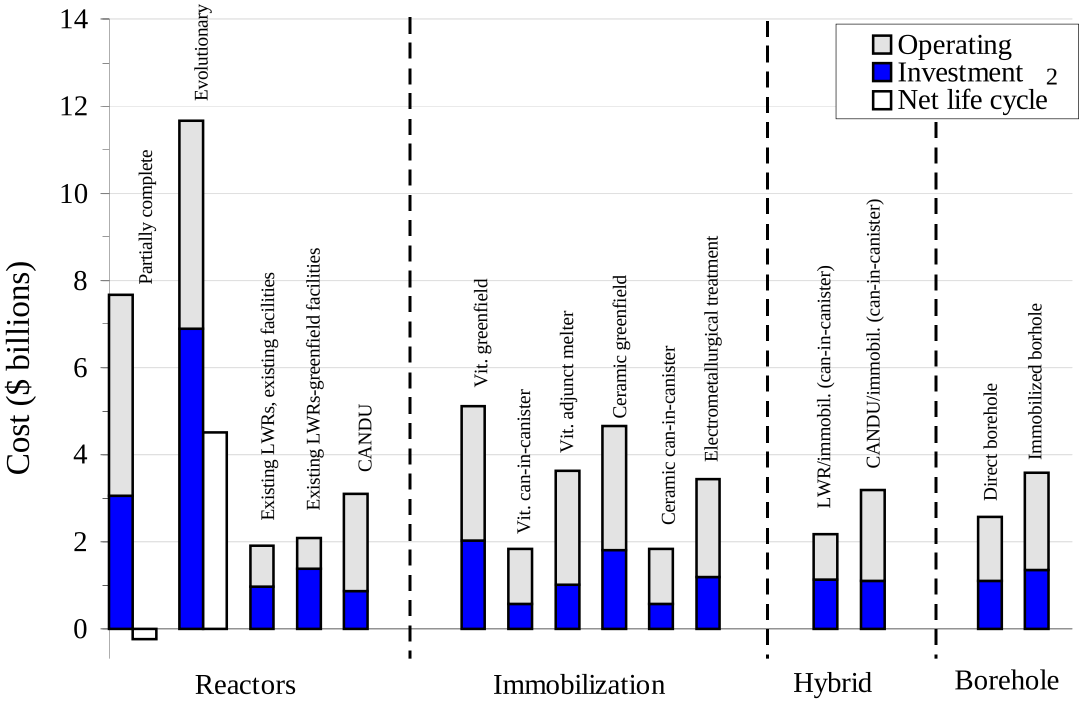
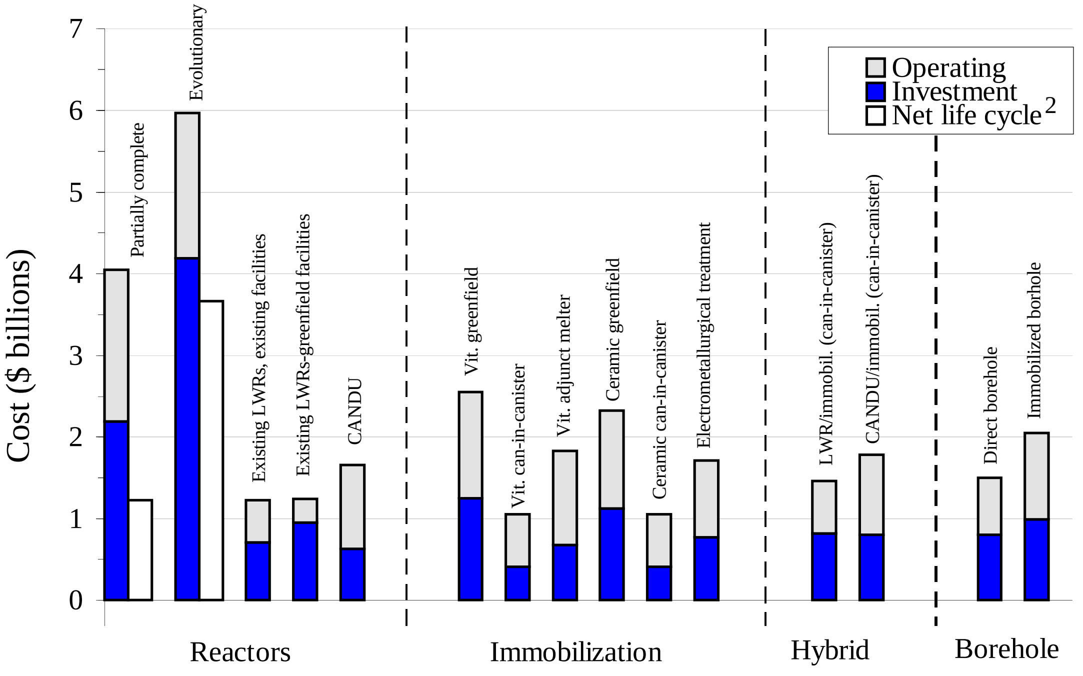


Figure ES-2b. ***Investment and Operating Costs for Baseline Alternatives (discounted $)*** [1]



[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:

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[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)