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.

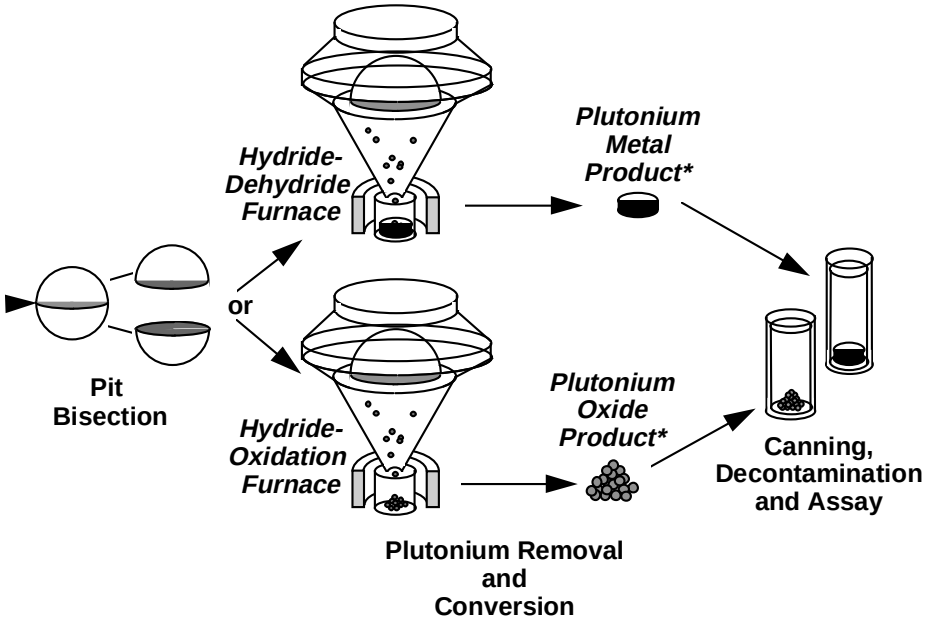
For deep borehole alternatives, plutonium may be emplaced into the borehole as metals or oxides directly in shipping product cans or immobilized in a ceramic prior to emplacement without any significant preprocessing. There are no major material feed purity requirements.

[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.

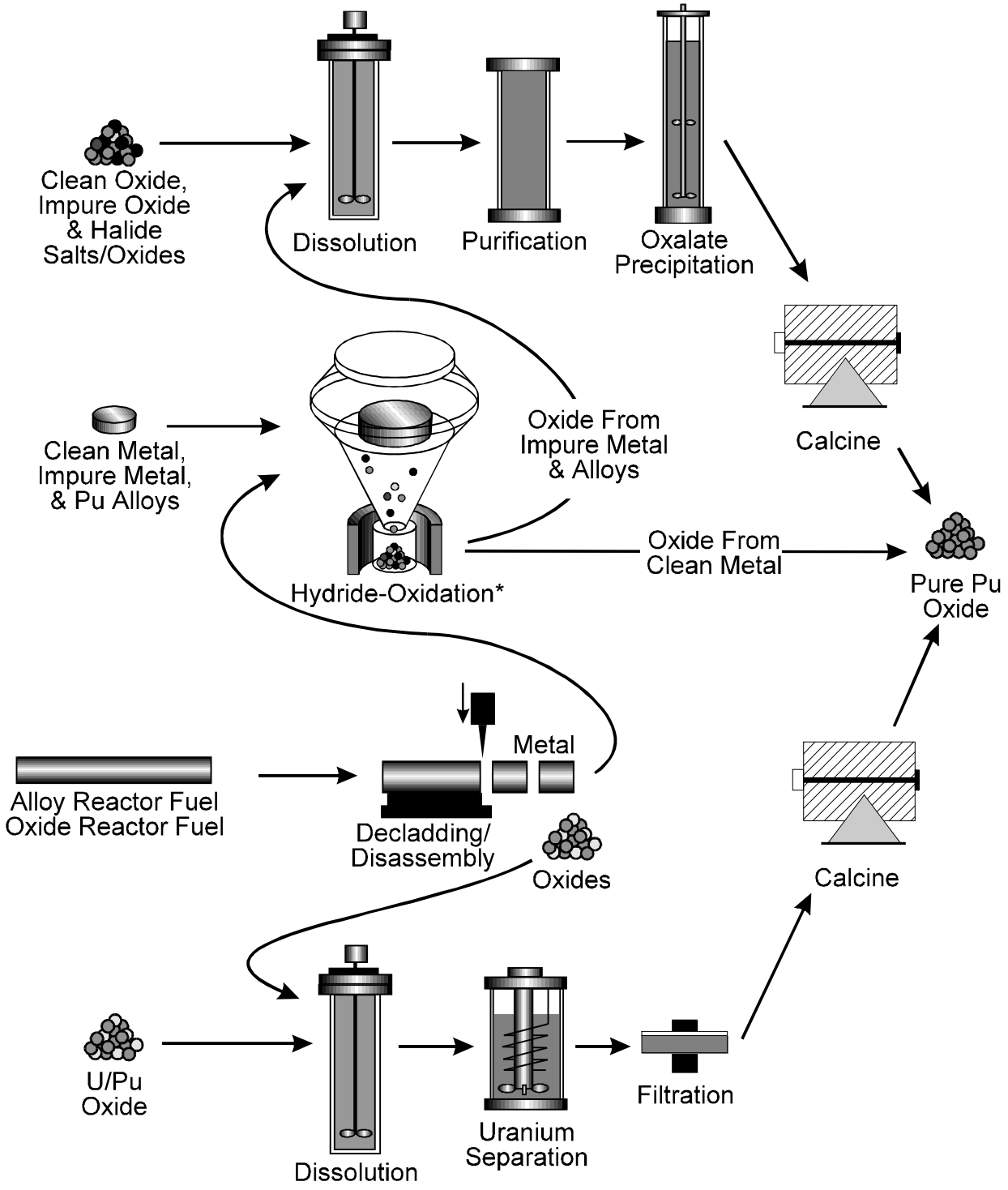
Mixed feed processing operations are more complicated than pit conversion processing because of the variety of surplus non-pit plutonium forms, because of differences in their impurities, and because of the different feed specifications required for the different disposi-

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

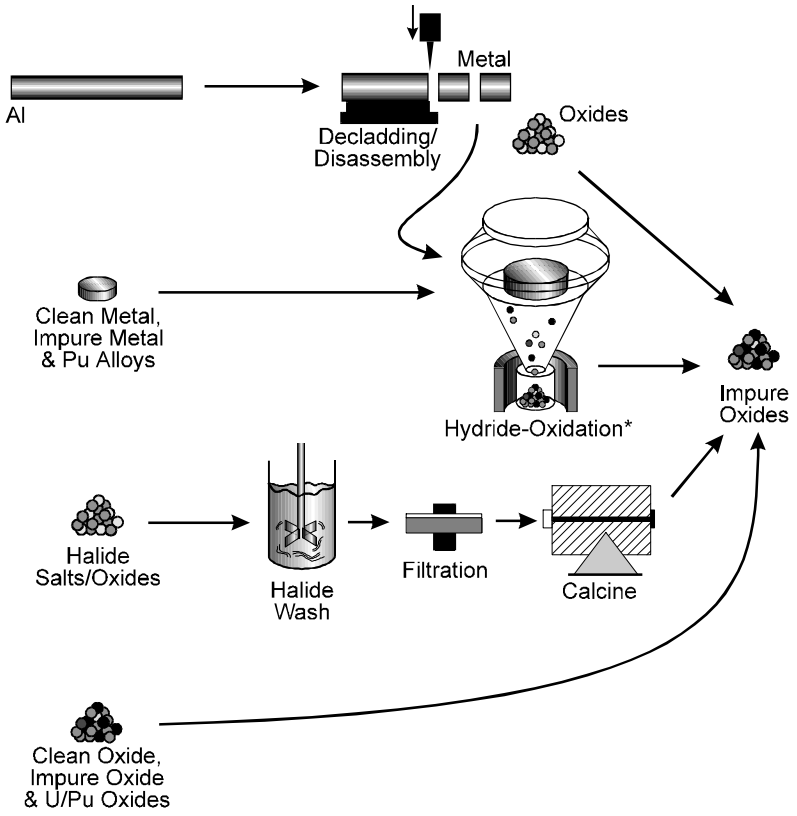
The PEIS analyzed new "greenfield" sites rather than any existing facilities to bound environmental impacts. Initial cost and schedule analyses were similarly applied to greenfield sites to evaluate worse-case scenarios. However, significant cost and schedule savings could potentially be realized through 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)***

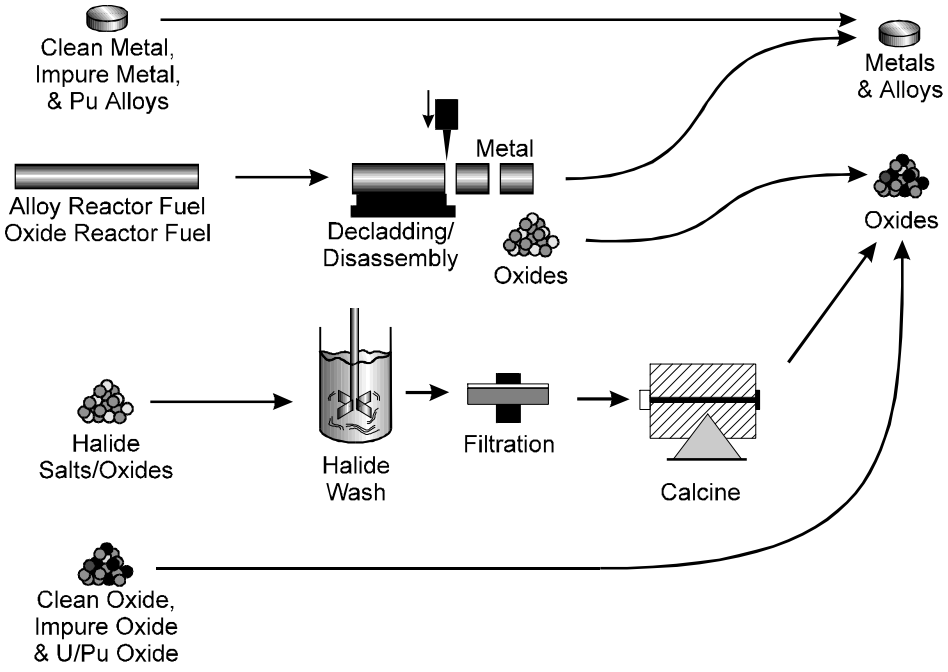
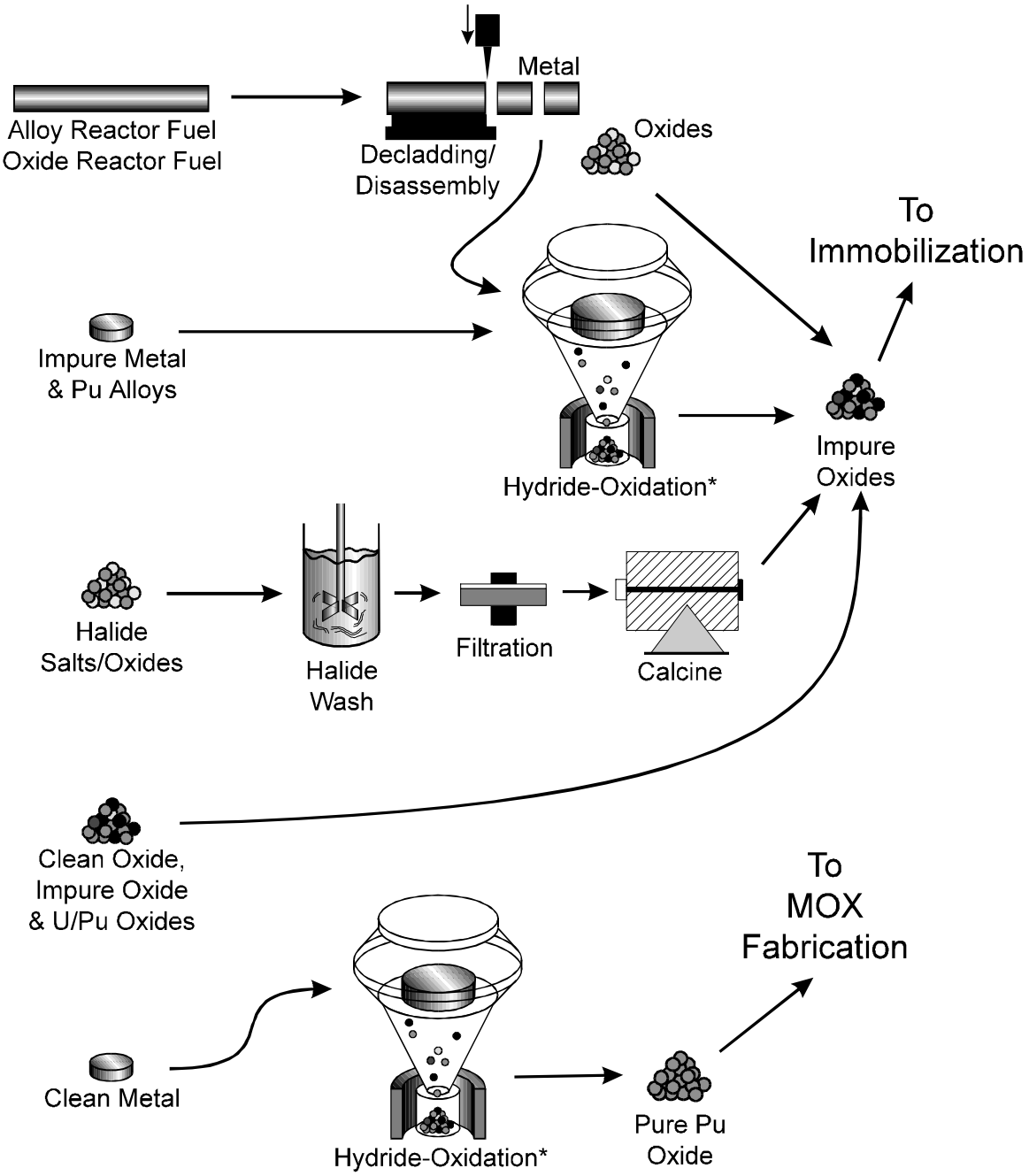


Figure 2-2d. ***Mixed Feed Processing (Hybrid)***



* 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.

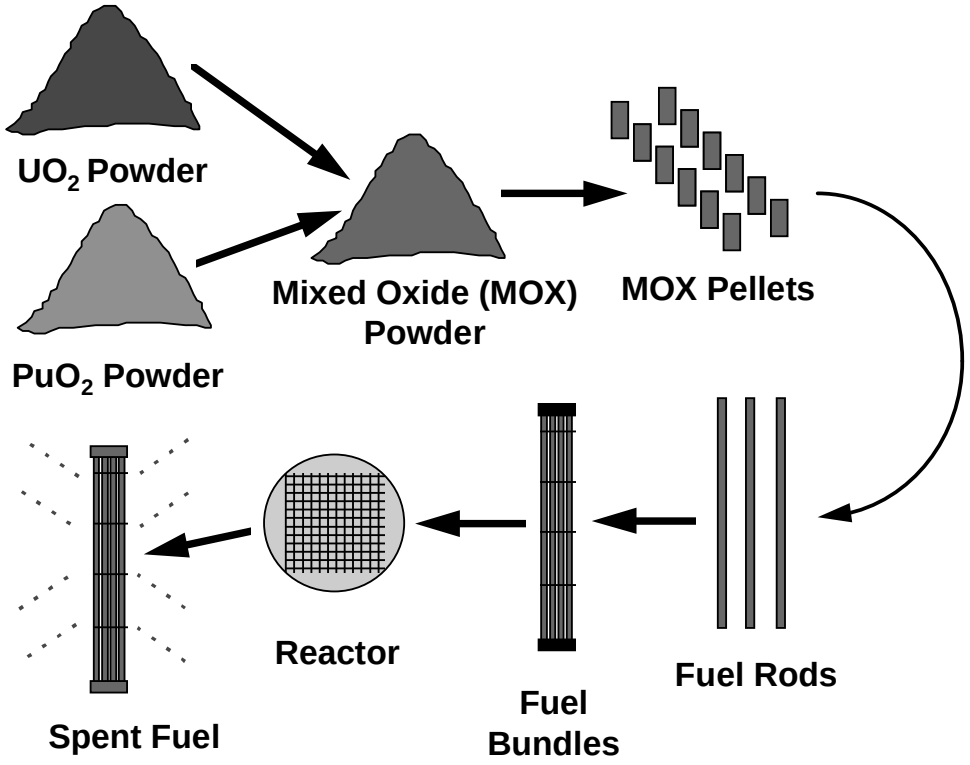
Spent fuel resulting from the use of MOX fuel in reactors falls within the definition of "spent nuclear fuel" as specified in Section 2(23) of the Nuclear Waste Policy Act (NWPA), as amended, and can therefore be considered for disposal in a high-level waste repository licensed pursuant to the NWPA. 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	