A Report to Congress on Electrometallurgical Treatment Waste Forms

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A REPORT TO CONGRESS ON ELECTROMETALLURGICAL TREATMENT WASTE FORMS

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ACRONYMS

ANL	Argonne National Laboratory
ANL-W	Argonne National Laboratory-West
ASTM	American Society for Testing and Materials
DOE	Department of Energy
DOE-CH	Department of Energy's Chicago Operations Office
DOE-EM	Department of Energy's Office of Environmental Management
DOE-NE	Department of Energy's Office of Nuclear Energy, Science and Technology
DOE-RW	Department of Energy's Office of Civilian Radioactive Waste Management
DU	Depleted Uranium
EBR-II	Experimental Breeder Reactor-II
EIS	Environmental Impact Statement
EMT	Electrometallurgical Treatment
FCF	Fuel Conditioning Facility
FFTF	Fast Flux Test Facility
HEU	Highly Enriched Uranium
HLW	High Level Waste
INEEL	Idaho National Engineering and Environmental Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
LEU	Low Enriched Uranium
LLW	Low Level Waste
MTHM	Metric Tons of Heavy Metal
NEPA	National Environmental Policy Act
NPV	Net Present Value
ROD	Record of Decision
RSWF	Radioactive Scrap and Waste Facility
SNF	Spent Nuclear Fuel
TSPA	Total System Performance Assessment
TVA	Tennessee Valley Authority
WASRD	Waste Acceptance System Requirements Document
WIPP	Waste Isolation Pilot Plant

Executive Summary

Stored within the Department of Energy (DOE) complex are 60 metric tons heavy metal (MTHM) of sodium-bonded fuel that is unsuitable for direct disposal in a geologic repository. Various agreements between DOE and state governments require the disposition of all DOE spent fuel. Therefore, treatment of this fuel to produce waste forms that are suitable for disposal is required. Following completion of an environmental impact statement, DOE decided to process a portion of the fuel (25 MTHM) by electrometallurgical treatment. The fuel selected for processing is primarily from the Experimental Breeder Reactor-II (EBR-II) and Fast Flux Test Facility (FFTF). A decision on processing the remaining 35 MTHM of sodium-bonded spent fuel from the Fermi-1 plant was deferred for up to five years to allow time to assess the economic merits of electrometallurgical technology compared to other, less-mature technologies. Because the fuel that was held back is considerably less radioactive, it may be more amenable to alternative treatment techniques.

The processes involved in the application of electrometallurgical technology to spent nuclear fuel have been developed by Argonne National Laboratory (ANL), where they were demonstrated with a representative quantity of EBR-II fuel at the ANL-West (ANL-W) site in Idaho. A special committee of the National Research Council reviewed the demonstration results as well as the technical basis of these processes. The committee's report endorsed the technology and, in fact, recommended that DOE consider broadening the application to other types of spent fuel. Following the Record of Decision (ROD) in September 2000, electrometallurgical treatment operations were initiated at ANL-W.

In considering the fiscal year 2001 appropriation for Disposition of Spent Fuel Activities and the Disposition Technology Activities, the House Committee on Appropriations requested DOE to prepare a report that describes the waste forms that will be produced by treating the 25 MTHM of fuel. This report was to include a description of physical characteristics, disposition paths and total life cycle cost for all activities. These combined activities are called the "Spent Fuel Treatment Program" for convenience in this report.

The two high level waste forms are produced as an integral part of the separation of the fission products from the uranium. The bulk of the fission products and transuranic elements are incorporated into the ceramic waste form, which is a glass-bonded sodalite monolith. The metal waste form contains fuel claddings, the remainder of the fission products, and trace amounts of uranium. The processes to produce these waste forms have been demonstrated with both laboratory samples and materials taken from actual fuel treatment. Accepted test methods have shown that the performance of these waste forms in the repository will be at least as satisfactory as that of defense high-level waste glass—the nationally accepted standard for high level waste (HLW) performance. Currently, several different organizations within DOE are working together to assure that the necessary data and documentation for waste acceptance are available when a geologic repository is ready to receive waste shipments.

The sodium-bonded spent fuel includes fuel assemblies made of highly enriched uranium (HEU) as well as larger, more massive assemblies made of depleted uranium (DU). These different fuel types are treated independently, resulting in separate uranium byproducts with different characteristics. The recovered HEU is downblended to low enriched uranium (LEU). Both types of uranium byproducts are similar to other types of materials being stored in bulk quantity at ANL-W. While there are defined waste disposition paths for both uranium streams, process improvements are also being pursued to allow for potential use of the LEU in off-specification nuclear fuel. These improvements will be assessed over the next year prior to making a decision for the final disposition.

The total life cycle costs for the treatment operations and disposal costs have been developed for the approved technologies and proposed budget profiles. For the disposition of uranium, the most expensive options were chosen in order to provide a more conservative total program cost. At the assumed funding profiles, treatment would be completed in 2013 and all waste disposed by 2017. The total cost would be $633 million, including treatment operations, technology enhancements, uranium disposal, waste qualification, storage, packaging, and disposal. Accounting for escalation and discount factors provided by the Federal guidelines, the present value of that cost is $423 million.

1.0 Introduction

Within the DOE complex, there is a quantity of spent nuclear fuel containing elemental sodium that was used within the fuel elements to provide a thermal bond between the fuel matrix and the cladding. The sodium within the fuel matrix is highly reactive. Because of its presence, the fuel is unsuitable for direct disposal in a geologic repository and requires treatment [1].

Most of this fuel was generated during operation of EBR-II at Argonne National Laboratory-West (ANL-W) in Idaho and Fermi-1 in Michigan. Both were fast reactors using metallic fuel with stainless steel cladding and sodium coolant. Some sodium-bonded experimental fuel was also produced for testing in FFTF at Hanford. At ANL, a program has been established to condition these fuels for eventual disposal by a process called electrometallurgical treatment (EMT) [2]. This program is administered by DOE's Office of Nuclear Energy, Science and Technology (DOE-NE) with oversight by the Chicago Operations Office (DOE-CH). In House Report 106-693, accompanying H.R. 4733, the Energy and Water Development Appropriations Bill, 2001, the House Committee on Appropriations requested DOE to prepare this report on the disposition of the resulting waste streams and uranium from electrometallurgical treatment [3]. The language requesting the report is as follows:

> *In order to ensure that there is a clear and final disposition option for all the waste forms resulting from EMT and that no further treatment will be required, the Committee directs the Office of Civilian Radioactive Waste Management, the Office of Environmental Management, and the Office of Nuclear Energy to prepare a complete report on all waste forms generated through the use of EMT. This will include: ceramic waste forms (actinide elements and fission products in a glass-ceramic matrix), the metal waste forms (noble metal fission products in a fuel-cladding matrix), and the recovered uranium streams. The report should describe the volumes of waste generated, radioactivity content, waste forms created and lifecycle costs in annual increments of processing 25 MT of Experimental Breeder Reactor II fuel. The final disposition path for each waste form should be identified, along with applicable storage and disposal costs. This report is due to the House and Senate Committees on Appropriations by March 31, 2001.* H. R. Report No. 693, 106th Congress, 2nd Session, at 89-90 (2000).

DOE is responsible for the disposition of approximately 60 MTHM of sodium-bonded spent nuclear fuel. ANL has demonstrated the electrometallurgical treatment technology needed to prepare these fuel types for eventual disposal. During this demonstration, which was conducted between June 1996 and August 1999, 100 EBR-II driver and 13 EBR-II blanket assemblies were treated. Driver fuels were positioned in the central core of the reactor and provided the bulk of the power. They employed highly enriched uranium (greater than 20 percent enriched in the 235 isotope of uranium). Blanket fuel

was made with depleted uranium (approximately 0.2 percent ^{235}U), and surrounded the reactors. Plutonium was incidentally produced in the blanket fuel as a byproduct of neutron shielding. The fuel treated during the demonstration was a small (1 MTHM) but representative quantity of sodium-bonded fuel. The development of waste forms for stabilizing the fission products and transuranics was part of the demonstration. A committee of the National Research Council was established to review the progress and to evaluate the results. The final report noted the following:

> Finding: The Committee finds that ANL has met all of the criteria developed for judging the success of its electrometallurgical demonstration project.
>
> Finding: The Committee finds no technical barriers to the use of electrometallurgical technology to process the remainder of the EBR-II fuel. [4]

As required by the National Environmental Policy Act (NEPA), an Environmental Impact Statement (EIS) [5] was prepared to evaluate available and appropriate treatment options for DOE sodium-bonded fuel. In the final EIS, DOE identified electrometallurgical treatment as its Preferred Alternative for the treatment and management of all sodium-bonded fuel, except Fermi-1 blanket fuel. Because of the different physical characteristics of the Fermi-1 sodium-bonded blanket spent nuclear fuel (about 34 MTHM), DOE has decided to continue to store this material while alternative treatments are evaluated. Should no alternative prove more cost effective for this spent nuclear fuel, EMT of the Fermi-1 spent nuclear fuel remains a viable option. An EIS ROD to implement the preferred alternative was issued in September 2000, and production operations started later that month [6]. A summary of the ROD is provided in appendix A.

DOE established the Spent Fuel Treatment program at ANL to treat the 25 MTHM of EBR-II and FFTF fuel and recover the uranium for interim storage. The fission products and transuranic elements from this fuel and the previously treated demonstration fuel will be placed in waste forms suitable for geologic disposal. From EMT, two HLW forms are produced. They are called the ceramic waste and the metal waste.

Other secondary wastes are generated as part of these treatment operations. These wastes include low-level waste, transuranic waste, transuranic-mixed waste, and common sanitary wastes. The disposition of these waste streams was assessed as part of the EIS process. These streams will be treated and disposed of using standard existing practices. For completeness, the quantities of secondary wastes generated and the disposal means are provided in appendix B.

This report describes EMT, outlines the disposition plans for both the uranium and the two high-level wastes, and provides the life-cycle costs estimates for these operations.

2.0 Electrometallurgical Treatment

Electrometallurgical treatment is being employed to ready the EBR-II and FFTF sodium-bonded spent nuclear fuel for disposal. A description of these fuel types, including storage locations, is therefore provided along with the process description.

2.1 Description of Fuel Types and Quantities

DOE is responsible for managing the sodium-bonded spent nuclear fuel at the Idaho National Engineering and Environmental Laboratory (INEEL), ANL-W, and Hanford sites [1]. The fuels to be electrometallurgically treated can be grouped into four categories according to fuel designs, reactor type, and storage location:

- EBR-II drivers stored at ANL-W,
- EBR-II drivers stored at the Idaho Nuclear Technology and Engineering Center (INTEC),
- EBR-II blankets stored at ANL-W, and
- FFTF sodium-bonded metal fuel driver pins stored at Hanford.

Different fuel alloys, cladding materials, and geometrical configurations were used. The uranium enrichments ranged from depleted to 97 percent ^{235}U. Table 1 provides the breakdown of the approximately 25 MTHM into the four categories. The Fermi blanket (34 MTHM), which is not presently scheduled for treatment, is stored on the INEEL at INTEC.

Table 1. Sodium-Bonded Fuel for Planned Electrometallurgical Treatment

Fuel Type	EBR-II Driver at ANL-W *(kg HM)	EBR-II Driver at INTEC (kg HM)	EBR-II Blanket at ANL-W (kg HM)	FFTF Fuel at Hanford (kg HM)	Total Sodium-Bonded Fuel to be Treated (kg HM)
Driver Fuel	700	2000	0	250	2950
Blanket Fuel	0	0	21,800	0	21,800
Total	700	2000	21,800	250	24,750

* HM is heavy metal.

2.2 Electrometallurgical Process Description

The flowsheet for electrometallurgical treatment is depicted in figure 1. For EMT, the key processing step occurs in the electrorefiner where the bond sodium is neutralized and the uranium metal is separated from fission products and matrix materials. The operation of this equipment affects the characteristics of the uranium product and both the metal and ceramic waste forms.

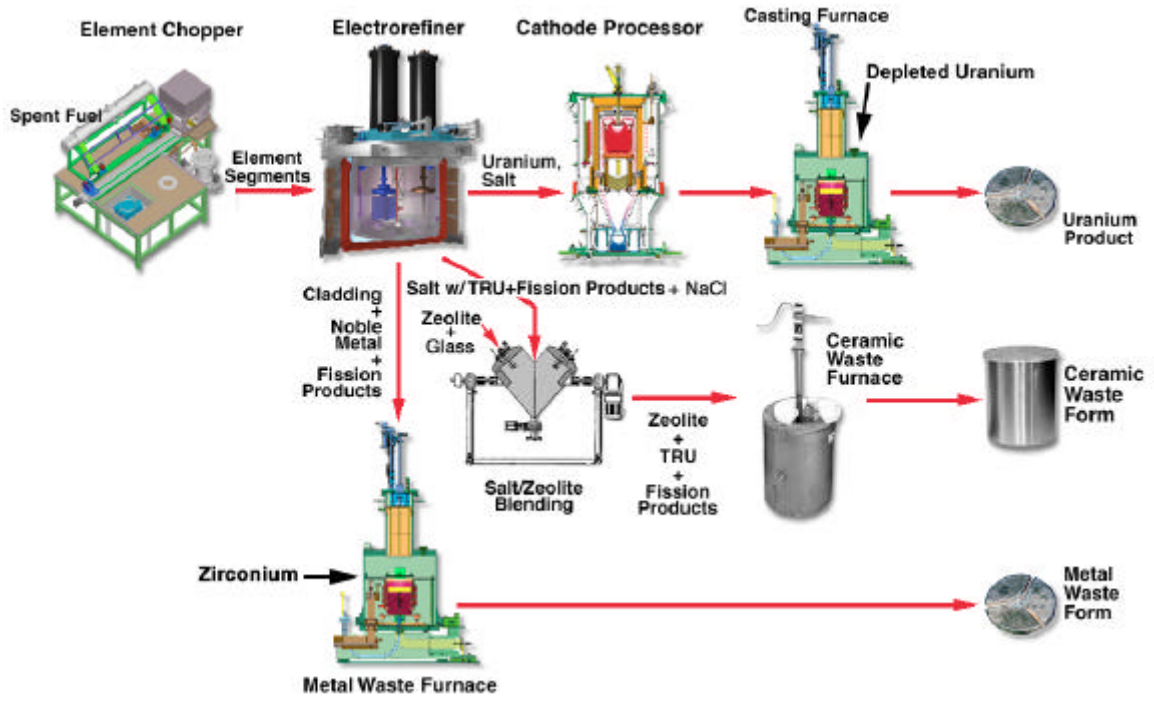

Figure 1. EBR-II Spent Fuel Treatment Flowsheet

The fuel treatment operations are performed in the Fuel Conditioning Facility (FCF) hot-cell complex at ANL-W. FCF shown in Figure 2 consists of two operating hot cells. Spent fuel is first transferred into a rectangular-shaped, air-filled hot cell where the fuel elements are separated from the fuel assembly hardware using the vertical assembly dismantler. Intact fuel elements are transferred into the adjacent, annular-shaped, argon-filled hot cell.

In the argon cell, fuel elements are first chopped into segments with an element chopper. These segments are then transferred to the electrorefiners in steel baskets (anode baskets).

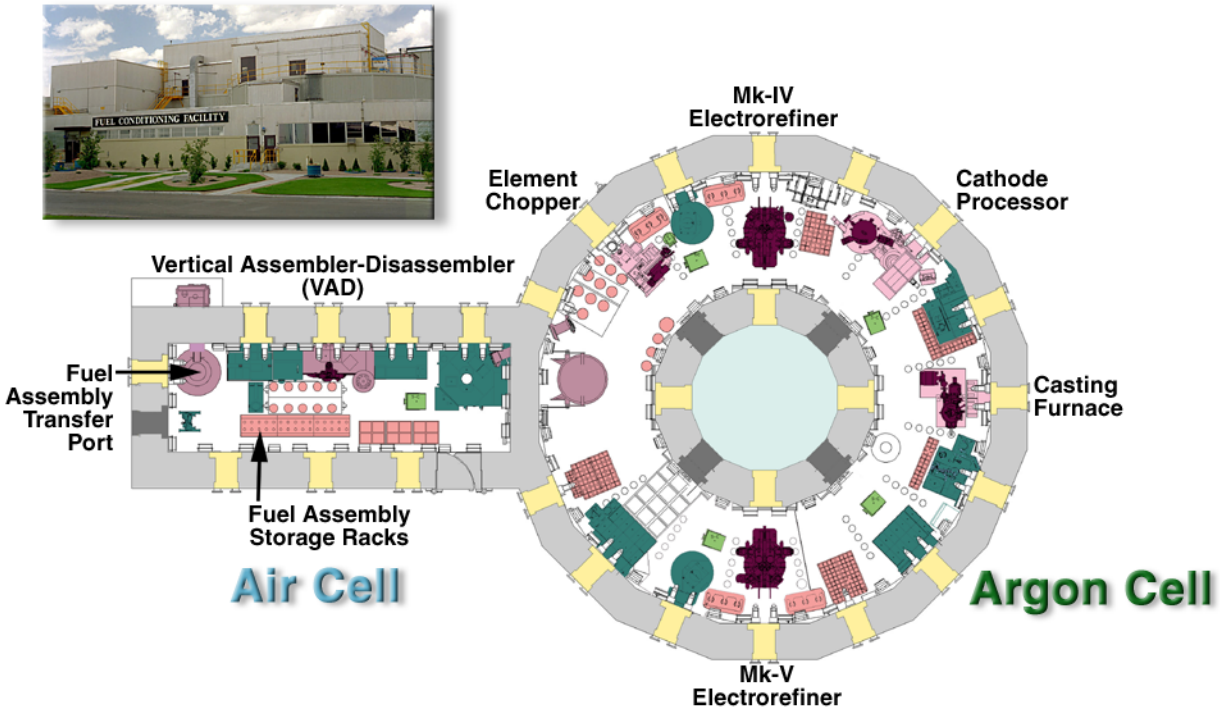

Figure 2. Fuel Conditioning Facility

Fuel treatment operations in the electrorefiners are based on a process that uses molten salts and liquid metals in an electrochemical operation. The molten salt medium is a solution of LiCl-KCl eutectic and dissolved actinide chlorides, such as UCl_3. Separate electrorefining and fuel chopping equipment is used for blanket and driver fuel.

In the electrorefiners, the spent fuel is electrotransported out of the anode baskets, and an equivalent amount of uranium is deposited on a cathode. The uranium is separated from the bulk of the fission products and transuranics. The transuranics and alkali, alkaline earth, rare earth, and halide fission products are primarily in the salt phase. The sodium is neutralized by forming nonhazardous NaCl. The elements that distribute into the salt phase are eventually disposed of in the ceramic waste.

Most of the noble metal fission products and fuel alloy material are retained in the chopped cladding segments in the anode baskets. Some actinides are also retained in the fuel segments. The cladding hull segments and the retained fission products are eventually stabilized into the metal waste.

The cathode products from electrorefining operations are further processed to distill adhering salt and to consolidate this recovered uranium. These operations are performed in the cathode processor and casting furnace, respectively. Separate uranium products are produced from driver and blanket processing. As part of the driver fuel processing, the solid cathode contains highly enriched uranium. The recovered uranium metal is blended

with DU to produce a product that is less than 20 percent enriched. A DU ingot is produced from blanket processing. The low enriched uranium product and DU product are formed into ingots and placed in interim storage in canisters at ANL-W.

Fuel can be processed until either a sodium or plutonium limit is reached in the electrorefiner. As the NaCl concentration in the salt increases the melting point of the salt increases, its concentration must be limited. The plutonium limit is associated with electrorefiner criticality concerns. Once one of these limits is reached, enough salt will be removed and replaced with fresh salt so that additional fuel can be processed. The removed salt is stabilized for disposal in the ceramic waste form. The treatment schedules for driver and blanket fuel and the production of both HLW forms are provided in table 2. Production HLW operations do not start until fiscal year 2005, but they include stabilization of all wastes including those produced from earlier treatment operations. The assumptions required to meet these throughput rates are provided in detail in the Spent Fuel Treatment Program's Implementation Plan [2], but in general they require an established funding and staffing level and successful equipment upgrades.

Table 2. Annual Fuel Treated and HLW Produced

	FY 2000	FY 2001	FY 2002	FY 2003	FY 2004	FY 2005	FY 2006	FY 2007
Fuel Treated (kg-HM)	230	540	540	630	1100	1600	3210	3500
Metal Waste Produced (kg-waste)	0	0	0	0	0	120	250	920
Ceramic Waste Produced (kg-waste)	0	0	0	0	0	0	160	7700

	FY 2008	FY 2009	FY 2010	FY 2011	FY 2012	FY 2013	Total
Fuel Treated (kg-HM)	3500	3500	3500	2900			24750
Metal Waste Produced (kg-waste)	920	920	920	920	880		5850
Ceramic Waste Produced (kg-waste)	7700	7700	7700	7700	7700	4840	51200

Although the stabilization of the reactive component of the nuclear fuel is the primary reason for electrometallurgical treatment, an additional benefit is a reduction in the number of canisters that will be shipped to the repository when compared to direct disposal. Based on the data in the Sodium-Bonded Spent Nuclear Fuel Final EIS [5], EBR-II and FFTF sodium-bonded fuel would require 309 canisters for direct disposal, whereas the two electrometallurgical HLW forms will require 59 canisters. Even though the HLW masses are greater than the spent nuclear fuel masses, this decrease in numbers of canisters is due primarily to criticality safety limits that are imposed due to the high enrichments of the driver fuel and total mass for the blanket fuel.

3.0 Disposal of HLW Forms

The ceramic and the metal waste forms from electrometallurgical treatment are identified as HLW in the most recent DOE order governing radioactive waste management, DOE Order 435.1. Development of both waste forms has been ongoing at Argonne in Illinois since 1985 as part of both the Integral Fast Reactor program and the EBR-II Spent Fuel Demonstration Program. In arriving at these final waste forms, different waste formulations were examined and tested. These waste forms are uniquely capable of stabilizing fission product chlorides and metals while most other HLW forms stabilize oxides. The electrometallurgical demonstration included production and testing of irradiated and nonirradiated samples of both waste forms.

During the demonstration, the waste forms and the process were shown to produce acceptable waste forms for disposal in a geologic repository. In order to help ensure the acceptability of the waste forms, Argonne personnel have had increased interactions with DOE programs associated with the potential repository at the Yucca Mountain Site in Nevada, and waste form acceptance. Personnel supported the preparation of the draft Yucca Mountain Repository EIS. They responded to the data call and reviewed the document. Data for the EMT waste forms from treating 60 MTHM of sodium-bonded fuel, which includes the Fermi blankets, are included in appendix A of this draft EIS [7].

Argonne, in support of DOE-NE and DOE-CH, also participates in regular meetings with personnel of the National Spent Nuclear Fuel Program, the INEEL Spent Nuclear Fuel Program, and DOE HLW programs. These programs are operated as part of DOE's Office of Environmental Management (DOE-EM). The purpose of many of these meetings is to determine the activities necessary to prepare DOE-owned spent nuclear fuel and HLW for disposal in a geologic repository. Issues addressed include disposal requirements, data needs, interfaces for standardized canisters, material shipments, and quality assurance programs. Many of these meetings also include DOE Office of Civilian Radioactive Waste Management (DOE-RW) personnel.

Because a geologic repository will not be available before these HLWs are generated, they will be placed in interim storage in the Radioactive Scrap and Waste Facility (RSWF) at ANL-W, as shown in Figure 3. RSWF is a below-ground dry storage facility. It is presently used to store irradiated spent nuclear fuel and various remote-handled waste streams. It has ample storage locations for the anticipated HLW.

The HLW will be stored in RSWF in containers that are designed to fit into the DOE Standardized Canisters for DOE-owned spent nuclear fuel [8]. DOE also has the option to load directly into the Standardized Canister. The majority of the canisters will just contain only ceramic waste, since a greater volume of ceramic waste is produced. The reference plan is to co-load metal and ceramic waste in approximately 20 percent of the ANL-W canisters. The ability to segregate the metal waste is also an option. When a geologic repository is ready to start accepting waste, the canisters will be removed from RSWF and transported by cask to INTEC. Both INTEC and ANL-W are within INEEL.

A packaging and transfer facility for materials to the repository is in the design stages at INTEC. The ANL containers would be loaded directly into the DOE Standardized Canisters at this facility and shipped to the repository as depicted in Fig. 4. Transfer from the INTEC facility to the repository instead of directly from ANL-W is the reference plan since DOE's programs at INEEL are focused on rail shipments. There is no rail spur to the ANL-W site.

All of the HLW will be generated for disposal by the end of 2013, and canister quantities of wastes will have been generated by 2007. Therefore, repository shipments could occur as early as 2010 the initial waste receipt date for a potential repository. DOE's agreement with the State of Idaho is that all spent nuclear fuel be moved out of the state and all HLW must be ready to be moved out of the state by 2035.

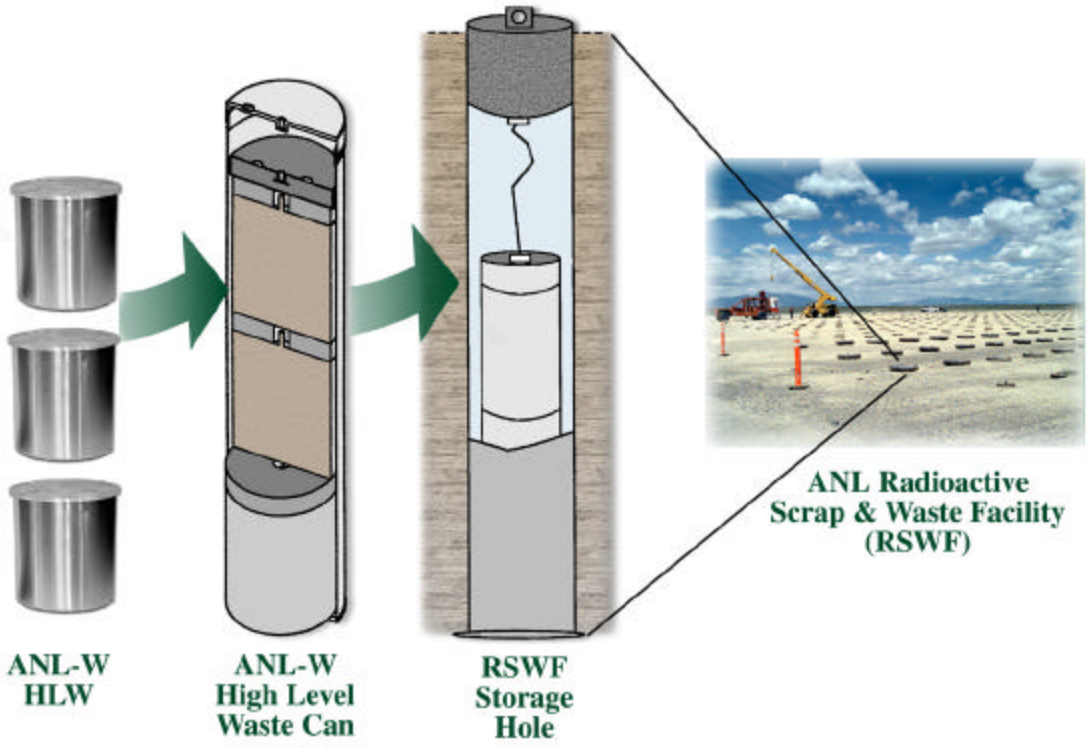

Figure 3. High Level Waste Packaged for Retrievable Interim Storage

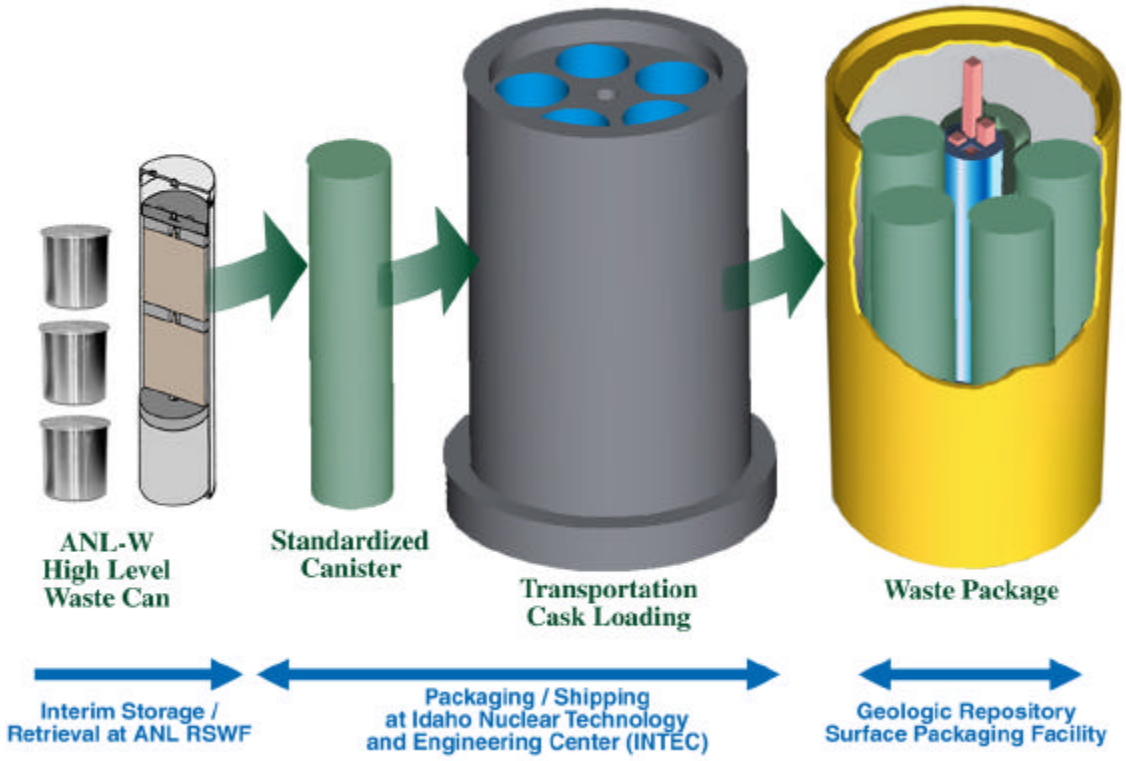

Figure 4. High Level Waste Shipment Coordinated with INEEL Spent Nuclear Fuel

3.1 Metal Waste Form Description

The metal waste form consists of metallic ingots that are used to stabilize the stainless steel cladding material, non-actinide fuel matrix materials, and noble metal fission products. Actinides that remain in the cladding hulls after dissolution are also present in the metal waste. Zirconium metal is added to produce a lower melting point alloy. Its presence also allows for the formation of a durable zirconium-iron intermetallic. The actinides in the metal waste are primarily in this phase and are, therefore, retained well in the waste matrix. The typical composition is stainless steel and 15 wt. percent zirconium.

The noble metal concentrations in the metal waste form are expected to be between 2 and 4 wt. percent when driver fuel is treated, depending on fuel burnup, and to be near 0.5 wt. percent when blankets are treated. The actinides will be present in the alloy in concentrations up to 10 wt. percent.

After the bulk of the fuel matrix is dissolved from the cladding material during electrorefining, the hulls are removed from the electrorefiners in anode baskets. These hulls are then processed in the metal-waste form furnace. In this furnace, the hulls are heated under vacuum to approximately 1100°C, where the salt vaporizes and transports to the condenser and is collected as an ingot. After completion of the distillation phase, the

crucible temperature will be increased, melting the cladding hulls and related fission products into a consolidated ingot. Cooled metal ingots will be removed from the crucible and stored in racks pending transfer to waste cans that will be placed in interim storage at RSWF. A typical metal waste form ingot will be between 30 and 40 kilograms (kg) and have a maximum diameter of 9.5 inches, and a thickness between 4 and 6 inches.

From the treatment of the 25 MTHM of sodium-bonded spent fuel, the total amount of metal waste generated is 5.85 MT or 3.8 m^3 of disposal volume. The composition of this waste form is provided in appendix C.

3.2 Ceramic Waste Form Description

The ceramic waste form is a glass-bonded sodalite produced from the thermal conversion of zeolite in a furnace. Zeolites are crystalline aluminosilicates of the alkali and alkaline earth elements. Their framework is a network of AlO_2 and SiO_2 tetrahedra linked by the sharing of oxygen atoms. The networks of tetrahedra in the zeolite form cages in which molecules are occluded. The alkali or alkaline earth ions, which provide charge balance, in this structure are subject to ion exchange. Both of these properties are taken advantage of with the ceramic waste form. Salt molecules are occluded within the zeolite structure, and fission products can be ion-exchanged. The specific zeolite being used as the base of the ceramic waste form is commercially available zeolite A, $Na_{12}[(AlO_2)_{12}(SiO_2)_{12}]$. When this material is processed at elevated temperatures, it converts to the mineral sodalite, $Na_6[(AlO_2)_6(SiO_2)_6]\bullet 2NaCl$. Figure 5 depicts the cage structure of zeolite A and sodalite. Zeolite is used as the starting material to facilitate the diffusion of salt into the crystal structure. The final ceramic waste mixture contains 75 wt. percent salt-loaded sodalite and 25 wt. percent glass. The glass is a commercially available borosilicate glass.

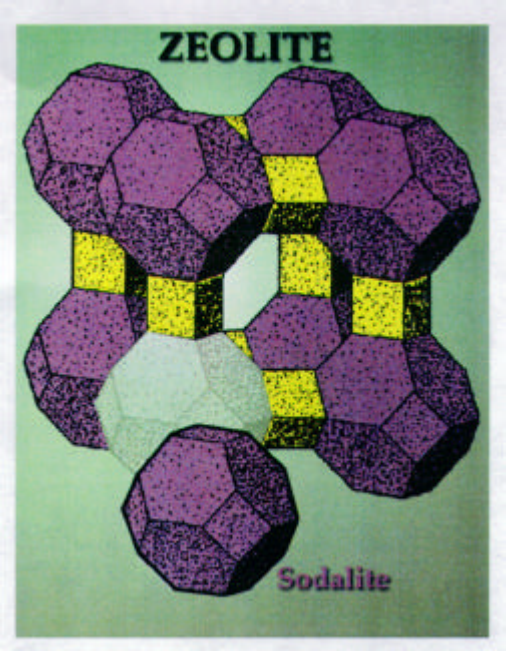

Figure 5. Zeolite A Pseudo Unit Cell and Sodalite Cage Structure

The salt that is removed from the electrorefiners will initially be ground to a relatively fine powder. The salt is next mixed at 500°C for approximately 15 hours with dried zeolite in a heated V-mixer. The zeolite is dried prior to transfer into the hot cells. In the V-mixer, the salt is occluded into the structure of the zeolite. This salt-loaded zeolite is then mixed with glass frit in a cold mixing operation in the same vessel. The glass-zeolite mixture is next transferred to a furnace where it is heated to 915°C to convert the powdered material into a monolithic waste form in a process called pressureless consolidation. In this process, the zeolite is converted to sodalite as well. This material will be placed in interim storage in the RSWF.

From the treatment of the 25 MTHM of sodium-bonded spent fuel, the total amount of ceramic waste generated is 51 MT or 33 m^3 of disposal volume. The compositional data for the ceramic waste form are provided in appendix D.

3.3 High-Level Waste Form Qualification

Acceptance of waste forms for disposal in a geologic repository will be based, in part, on their compliance with the requirements promulgated for waste acceptance in DOE's Waste Acceptance System Requirements Document (WASRD) [9]. In addition to the requirements in the WASRD, it is expected that disposal of the ceramic and metal waste forms will be required to have a performance standard on par with the other repository waste forms. In support of their qualification for disposal, tests, and analyses have been conducted to characterize the phase composition, microstructure, radionuclide distribution, and corrosion behaviors of the ceramic and metal waste forms. The testing programs were designed to determine corrosion mechanisms and support development of corrosion models following the approach summarized in the American Society for Testing and Materials (ASTM) standard C1174 [10].

The WASRD was issued by DOE to identify key interfaces between the waste form acceptance, transportation, storage, and disposal. It defines the technical requirements for accepting spent nuclear fuel (SNF) and HLW. Both the ceramic and metal waste forms must be shown to comply with these requirements by direct testing, analysis, and process control, as appropriate. Specific acceptance requirements for the ceramic and metal waste forms is anticipated to be added to future revisions of the WASRD, as was done for the Immobilized Plutonium Waste Form (WASRD REV 03, Section 4.2.3.1 M). These requirements include identification of the waste form, the method to monitor product consistency, and required compliance documentation.

Although compliance with most requirements in the WASRD will be demonstrated by specific measurements common to most waste forms, the method for monitoring product consistency is waste form-specific. The method for tracking the product consistency is selected based on the physical and chemical description of the waste form and the method of manufacture. The important consistency issues for the ceramic waste form are that the correct mixture of salt, zeolite, and glass binder was used and that the waste form was processed within established process limits. Tests have shown that the relative amounts

of these phases can be monitored by using the same test that is used for HLW glass, namely, the product consistency test (PCT) [11], to monitor the consistency of the ceramic waste form [12]. The PCT with a heterogeneous material, such as the ceramic waste form, can be conducted with the same precision as PCT with HLW glasses. Use of the same consistency test that is used for HLW glass for the ceramic waste form is technically reasonable, since the dissolution mechanisms for the individual sodalite and glass binder phases of the ceramic waste form are the same dissolution mechanism as for HLW glass. In fact, the dissolution model used for HLW glass is a modification of the model developed for aluminosilicate minerals [13], such as sodalite.

The PCT and other partial dissolution tests are not appropriate consistency tests for the metal waste form because the component steel and intermetallic phases are sparingly soluble and because of difficulties in producing fine grained samples for testing. Several alternative methods for tracking product consistency are being investigated, including measurement of the overall composition and density, and characterization of the microstructure. A method to monitor product consistency will be selected based on properties of the metal waste form and key processing issues.

Acceptance of the ceramic and metal waste forms will also require that their performance is on par with the other repository waste forms . This can be done using the Total System Performance Assessment (TSPA) calculations. The anticipated approach for qualifying the ceramic and metal waste forms is to compare dissolution rates of the ceramic and metal waste forms with that calculated for HLW glass in TSPA. Tests have been conducted to determine the degradation behaviors of the ceramic and metal waste forms, to develop mechanistic corrosion models, and to measure parameter values. The predictions from the mechanistic models for ceramic and metal waste forms will be compared with the predictions of the HLW glass degradation model in the TSPA to determine if the TSPA glass model can be used to represent degradation of the ceramic waste form under anticipated disposal conditions. Preliminary comparisons with the HLW glass degradation model that has been proposed for use in the TSPA to be conducted for a potential repository at the Yucca Mountain Site in Nevada indicate that the HLW glass degradation model bounds the degradation rates of the ceramic and metal waste forms. Therefore, the HLW glass degradation rate may be used as an upper bound for the degradation of the ceramic and metal waste forms in TSPA calculations.

Although it is expected that these waste forms will be transported to a repository in DOE Standardized Canisters that are designed not to breach during a preclosure accident, preclosure characteristics of these waste forms, such as residual particulates and particulate generation due to impact loads, will be understood sufficiently either to determine that they are bounded by HLW glass or to provide the technical information necessary to perform beyond-design-basis-event dose consequence calculations.

4.0 Uranium

As noted earlier in table 1, 2,950 kg of driver fuel and 21,800 kg of blanket fuel are being treated as part of the Spent Fuel Treatment Program. Because of the differences in these two fuel types, primarily the enrichment differences, they are treated in separate equipment. Most of the EBR-II driver fuel is actually greater than 60 percent enriched. The batches sizes and throughput rates for the driver fuel are substantially smaller than for the blanket fuels due to criticality safety limits. These differences result in the fact that the treatment time for driver fuel is nearly the same as for the blanket fuel.

The products from driver and blanket treatment are also different. The driver product as it comes out of the electrorefiner is still HEU while the blanket product is still DU. In steps subsequent to electrorefining, the driver fuel is downblended with new DU to lower the enrichment to less than 20 percent in order to reduce the requirements, and hence the costs, for security. Once downblended, the recovered driver material is LEU. Therefore, these treatment operations result in two uranium streams, an LEU byproduct and a DU byproduct.

From the treatment of the 25 MTHM of EBR-II and FFTF sodium-bonded fuel, 11 MTHM of LEU product and 22 MTHM of DU product will be generated. The storage volumes for this material are 10 m^3 for the LEU and 26 m^3 for the DU.

4.1 LEU Byproduct Disposal Alternatives

Although the product is LEU, the original uranium in the spent fuel is HEU and is included in the national inventory of excess HEU. Its disposition is guided by the ROD for the Disposition of Surplus Highly Enriched Uranium Final Environmental Impact Statement [14], which states:

> "This implementation will involve gradually blending up to 85% of the surplus HEU to a U-235 enrichment level of approximately 4 percent for eventual sale and commercial use over time as reactor feed, and blending the remaining surplus HEU down to an enrichment level of about 0.9 percent for disposal as LLW."

One hundred driver assemblies were processed in the demonstration project. The database of these results has been used to assess the disposition options. Ingots of greater than 99.7 percent pure uranium have been produced under typical operating conditions. The balance of material is zirconium, the other alloy in the fuel material. In addition, a number of other elements appear in trace quantities at parts per million or parts per billion levels.

While the uranium is relatively pure from a chemical standpoint, the presence of even minute quantities of certain radioisotopes can have a significant effect. For example, plutonium is present in the ingot at some 10 parts per million, which is a consideration in all disposition options. Cesium (^{137}Cs) is present at a nominal 35 parts per billion, a

principal contributor to observed radiation levels ranging from 1 R/h to 300 R/h near the surface of the ingots. Process optimization has resulted in ingots consistently in the lower end of the range. In the Record of Decision for the Treatment and Management of Sodium-Bonded Spent Nuclear Fuel, DOE decided that the uranium separated from the spent fuel would be stored until a disposition is made through a separate NEPA review. The following options are being assessed as final disposition paths.

Low-Level Waste Option (LLW)

For HEU source material that is to be discarded as LLW, the ROD for the Disposition of Surplus Highly Enriched Uranium Final Environmental Impact Statement [15] states that the uranium will be downblended to 0.9 percent ^{235}U. For this option the LEU product from EMT would be downblended to 0.9 percent, and the resulting material disposed of in LLW disposal facilities at a DOE or commercial site For exemplary purposes the characteristics of the downblended material compared to the disposal criteria for the Hanford Site [16] are provided in appendix E.

Commercial Fuel Option

DOE is developing process changes that may allow the LEU to be used as fuel in the Tennessee Valley Authority (TVA) nuclear power plants. The research will continue for one year and the current plan will be reassessed based on the success of the research. In this option, the enriched uranium would be blended with natural uranium to reduce the enrichment to 4.8 percent ^{235}U. For unrestricted use as commercial fuel, this uranium source material would have to meet the American Society for Testing and Materials (ASTM) standards [15]. These standards impose tight limits on the uranium isotopic mix, chemical purity, and radioisotopes. Some commercial fuel has been manufactured from uranium that did not meet the ASTM standards. In particular, “off-spec” fuel has been manufactured for and irradiated in TVA nuclear power plants. The TVA specifications are more relaxed for a number of key isotopes and elements.

The composition of the ingots produced in the fuel treatment demonstration has been compared against both sets of specifications. The ^{236}U content is a factor of 5-6 higher than the ASTM specification but meets the TVA specification. This fact would make it unlikely that the LEU product could be used to make unrestricted use commercial fuel since the excessive fraction of ^{236}U cannot be removed by any further chemical processing. The ^{236}U content is characteristic of high burnup, highly enriched reactor fuel. The zirconium content is high by 10-15 percent for the TVA specification. The neptunium and plutonium contents are also high by at least a factor of 100. Based on the results obtained to date, some further processing or changes in processing conditions would be required before the LEU ingots could be used as source material for commercial fuel fabrication using the TVA specification.

4.2 DU Byproduct Disposal Options

There are fewer options for disposition of the DU byproduct that results from processing blanket fuel. The only reactor application for DU would be in systems with high core conversion ratios but advanced reactor development is not currently on the national agenda.

DOE plans to dispose of the DU byproduct of sodium-bonded blanket fuel treatment, as transuranic waste rather than LLW, due to the amount of plutonium contamination in the DU. The characteristics of the DU byproduct compared to the LLW disposal criteria are provided in appendix E. Further process improvements could reduce the plutonium contamination in DU ingots produced from EBR-II blanket fuel treatment, classifying it as LLW.

If the process improvements are not successful in reducing the plutonium contamination in the DU ingots, the material will be shipped to New Mexico for disposal at the Waste Isolation Pilot Plant (WIPP). The ingots could be shipped in a standard pipe component container [17]. Some amount of internal shielding would be required to reduce the external dose rate of the package to comply with contact handling requirements. Packaging the ingots at approximately 85 kg per container would require about 10 shipments to transport all the material to New Mexico from Idaho. A schematic of the pipe overpack system for WIPP shipments is shown in Fig. 6.

4.3 Uranium Storage Option

The uranium ingots produced from electrometallurgical treatment of spent nuclear fuel have been prepared for indefinite storage. Each product ingot is packaged in a carbon steel storage container that is backfilled with inert argon gas. Three or four of these product containers fit inside a carbon-steel inner canister with a carbon-steel shield plug at the top. The inner canister is placed inside an outer stainless steel canister, which is the unit placed into storage. This nested canister configuration is shown in Fig. 7. This storage design is similar to that used for the stabilization, packaging, and storage of plutonium-bearing materials, DOE Standard-3013, which provides criteria so that materials can be packaged and stored with minimal surveillance for up to 50 years.

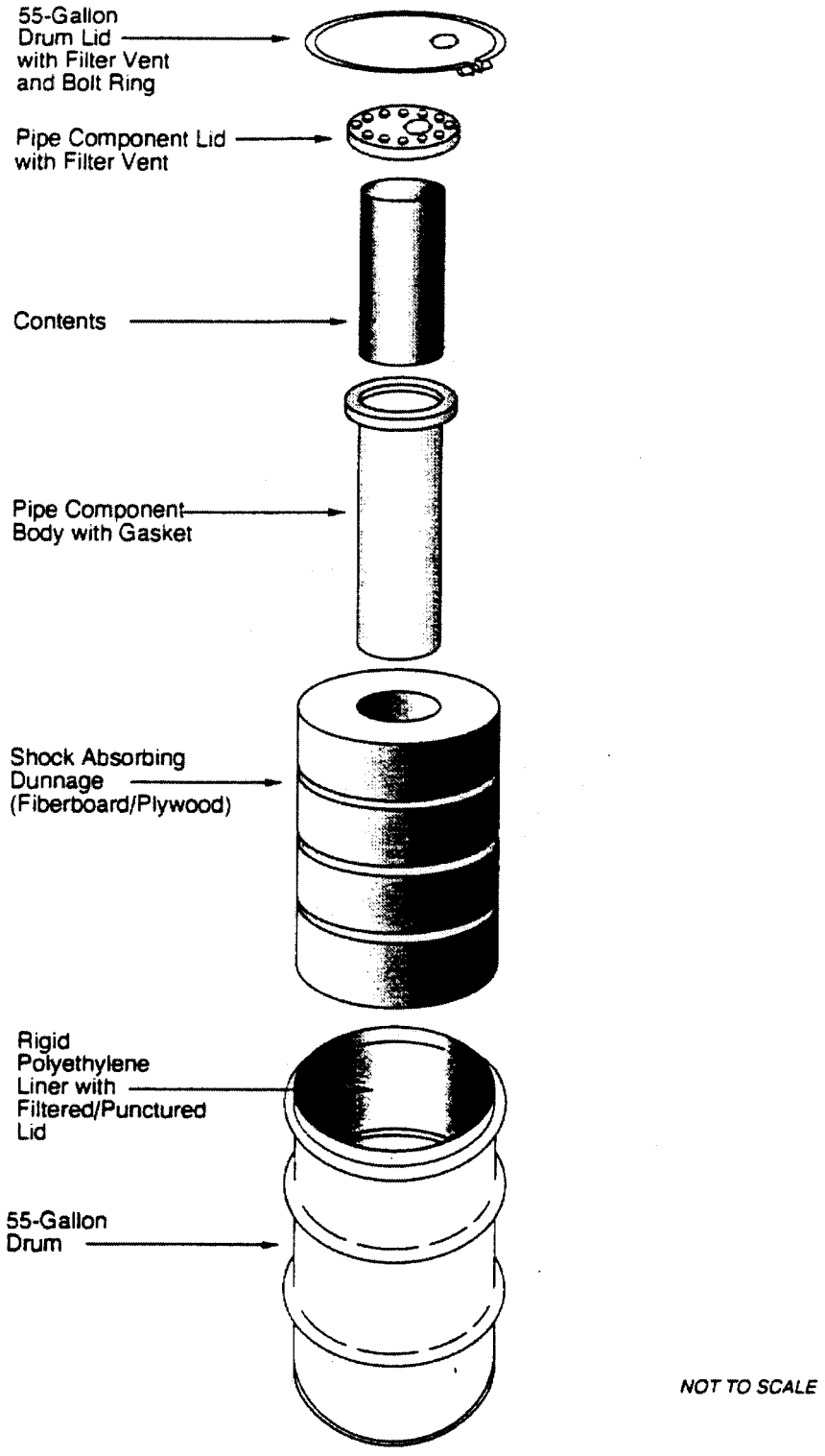

Figure 6. Schematic of Pipe Overpack System

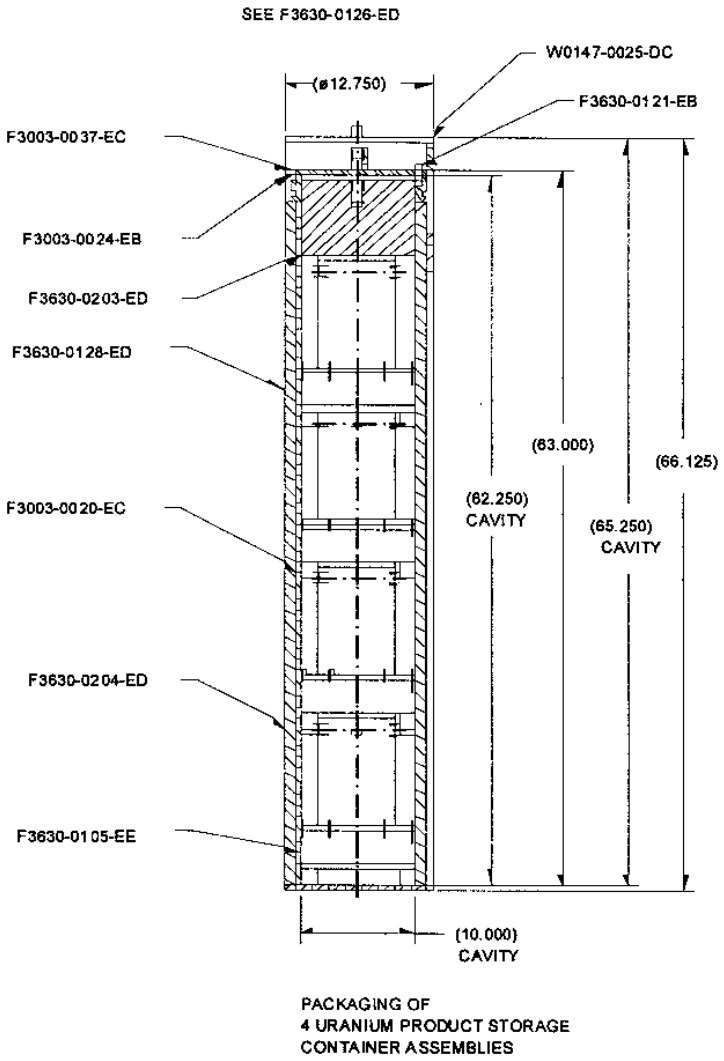

Figure 7. Outer Canister with Inner Canister Containing Four Product Storage Containers

After an outer canister is completely filled, it is transferred to ANL-W Building 792 which is shown in Figure 8. This building is located within a security area that is off limits to most Argonne personnel. This building, used to store materials and equipment for the Zero Power Physics Reactor, is normally unoccupied. The storage containers are placed within an open top, 6-inch thick steel box in a criticality safe configuration.

Figure 8. Building 792 Used to Store the Uranium Product Ingots

4.4 Uranium Byproduct Disposition Summary

Once placed in storage, the effort associated with maintaining the material is minimal. A health physics technician surveys the building on a weekly schedule, which takes about 15 minutes per visit. A continuous air monitor operates at all times. Weekly maintenance checks are required for this monitor. Because the material is less than 20 percent enriched, no additional security costs are incurred. In total, less than 1 hour of effort per week is needed to meet all DOE requirements for safe, secure storage of the LEU product material.

There are defined options for the disposition of the uranium byproduct. The worse-case scenarios from a cost perspective are that the LEU product will need to be downblended to 0.9 percent enriched uranium and disposed of as LLW, and the DU will be disposed of as transuranic waste. In the costing section that follows, these options have been assumed in order to provide a bounding case for the life-cycle cost for the program. Limited work is ongoing within the Spent Fuel Treatment Program to determine if changes can be made in process conditions that would further expand the disposition options for the uranium streams but also not limit the processing rates needed for production operations. Specifically, options for producing a higher purity uranium product are being tested and may be employed if they result in lower life-cycle costs. These options will be assessed over the next year, and a decision for the final disposition will be made.

5.0 Disposition Life-Cycle Costs

One purpose of this report is to provide the total life-cycle cost for treatment and disposal of the sodium-bonded spent nuclear fuel. These costs include all treatment costs, including those to downblend and dispose of the uranium byproducts, and the costs to dispose of the waste streams. In keeping with DOE guidelines for preparing life cycle cost estimates, these costs will be presented as net present values (NPV) including escalation and discounting. The rates of escalation and discounting for this estimate were 2.8 percent and 4.9 percent, respectively. These same values were also used as part of an independent cost study that was prepared to support the EIS for sodium-bonded fuel [18]. The discounting rate was based on guidance from the Office of Management and Budget [19].

5.1 Treatment Costs

In developing the implementation plan for this program, the costs for treatment operations were determined and documented [2]. They were not developed as NPV costs in that they did not include discounting. This cost includes all treatment costs for the fuel and activities to produce and qualify the two HLWs for disposal. Storage costs for the duration of the project are included, but final disposal costs for the uranium byproduct and two HLW forms are not. Those costs are presented in later sections. From this budget information, the NPV of the cost including escalation and discounting was determined. The NPV of the cost for the activities covered in the program's implementation plan are $372 million.

5.2 Costs to Down Blend LEU

An NPV cost estimate was made for the option to downblend the LEU uranium product to 0.9 percent and dispose of it as LLW. In preparing this estimate, it was assumed that these operations would be performed at ANL-W after the treatment operations were completed. The cost estimate includes engineering costs to modify equipment for these operations, the operating costs, and transportation and disposal costs. The NPV of the cost for downblending and disposing of the LEU product as LLW is $12 million.

5.3 Storage Costs

Storage costs during treatment operations are included as part of the overall operating costs. If material is left at ANL-W for time beyond that required for treatment, some incidental storage costs would be incurred. For the uranium byproduct streams, no additional storage costs are assumed. There should be no impediments to shipping these materials off site for disposal as the final disposition forms are generated. Production of the HLW will be completed by 2013. If the ANL-W wastes are not able to be shipped to a repository for disposal at that time, they can remain in storage at RSWF. As long as other materials are still in storage at RSWF, the incremental cost to leaving these materials in storage is marginal.

5.4 Fuel and HLW Packaging Costs

Additional costs will be incurred from operations at INTEC. A portion of the EBR-II driver fuel is presently stored at INTEC and will need to be packaged and transported to ANL-W. The planned path for transporting the final HLW products to the proposed repository is to have the HLW canisters packaged at INTEC and transported by rail from that facility. Cost estimates for these operations were obtained as part of preparation of the cost study that supported the EIS [18]. The NPV cost of these operations is $16 million.

5.5 Disposal Costs

The disposal costs for the HLW generated from electrometallurgical treatment were estimated earlier as part of the independent cost study assessing the alternatives for treatment of sodium-bonded fuel during the preparation of the EIS [18]. The cost for disposing a canister of HLW in a geologic repository was estimated to be $475,000. Fifty nine canisters of HLW will be generated from EMT; therefore the disposal cost will be $28 million. For the cost study, this value was assumed to be paid in 2015. Under this assumption, the NPV is $21 million.

The costs to dispose of the LEU uranium from driver fuel processing is already included in the NPV costs for downblending this material to 0.9 percent ^{235}U. Under the worse case scenario from a cost perspective, the DU from blanket fuel treatment will need to be disposed of as transuranic wastes. In estimating this cost, the packaging design noted in section 4.2.2 was assumed. With this packaging plan, 264-55 gallons drums of waste would be produced. From the earlier noted cost study, the estimated cost for disposal at WIPP including transportation cost is $17,500 per shipment, and each shipment can contain 6 m^3 of contact-handled waste. At this rate, the NPV disposal cost for the DU byproduct is $123,000.

From the cost study, the disposal of the incidental LLW and transuranic waste from treatment operations was estimated to be less than $1 million each. The NPV of this $2 million is $1.5 million if paid at the end of operations in FY 2013.

5.6 Total Life-Cycle Costs

To summarize, the net present value for the treatment costs for the sodium-bonded spent nuclear fuel is $372 million. This value also includes the costs to qualify the HLW for disposal. The NPV of the cost to downblend the recovered driver uranium from 19 percent enrichment to 0.9 percent and to dispose of it as LLW is $12 million. The cost to dispose of the DU material from blanket fuel is $123,000. The NPV of costs incurred at INTEC for packaging is $16 million. The NPV of the HLW disposal cost is $21 million. The NPV disposal costs for the remaining incidental transuranic waste and LLW is $1.5 million. Therefore the total life-cycle costs for treating the sodium-bonded spent nuclear fuel covered under the existing program is $423 million. Appendix F provides the NPV of these costs on an annual basis. Additionally, costs not including discounting are provided.

6.0 Summary

After the successful demonstration of electrometallurgical treatment, completion of a favorable review of the technology by the National Research Council and completion of a NEPA review, the Spent Fuel Treatment Program was established by DOE-NE at ANL to treat 25 MTHM of EBR-II and FFTF sodium-bonded spent nuclear fuel. At the request of the House Committee on Appropriations, this report has been prepared to outline the waste streams from the operations and the life-cycle costs for the program. A summary of the disposition paths and waste quantities is provided in Table 3. The two process waste streams, the ceramic and metal waste forms, are high-level wastes that will be disposed of in a geologic repository. The qualification of these materials for disposal is progressing. The secondary wastes will be disposed of using standard existing practices. Two uranium byproducts, one LEU and the other DU, also result from these operations. Defined options exist for the disposal of these byproducts. The most costly disposal option for the LEU is to blend the uranium to 0.9 percent ^{235}U and dispose of it as LLW. The most costly option for DU disposal is as transuranic waste. The total life-cycle cost for this program, $423 million, was developed assuming those disposition options.

Table 3. Disposition Paths for EMT Wastes and Uranium

High-Level Wastes	**Waste Volumes (m^3)**	**Waste Mass (MT)**	**Final Disposition Path**
Metal Waste Form	3.8	5.85	Geological disposal in a HLW repository
Ceramic Waste Form	33	51	Geological disposal in a HLW repository
Secondary Wastes			
Low-Level Wastes	300	62	Radioactive Waste Management Complex (RWMC)
Transuranic Wastes	5	2.3	Waste Isolation Pilot Plant (WIPP)
Mixed-Transuranic Wastes	15	8.2	WIPP/RWMC/ Commercial Facility
Sanitary Wastes	2,150	750	INEEL Landfill
Uranium	**Disposal Volume* (m^3)**	**Mass (MT)**	**Final Disposition Option****
Low-enriched uranium from driver treatment	162	280	Downblended and disposed as LLW
Depleted uranium from blanket treatment	55	22	Dispose as transuranic waste at WIPP

* These volumes include all packaging material for disposal of the uranium. They are not the same as the storage volumes noted elsewhere in the report.

** Process improvements are being pursued to allow for the potential use of the uranium as off-specification nuclear fuel.

7.0 References

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2. *Spent Fuel Treatment Implementation Plan,* Argonne National Laboratory, Document Number F0000-0061-ES-00 (October 2000).

3. H. R. Report No. 693, 106th Congressional, 2nd Session, at 89-90 (2000).

4. *Electrometallurgical Techniques for DOE Spent Fuel Treatment: Final Report*, National Research Council, National Academy Press, Washington, DC (2000).

5. U. S. Department of Energy, "Final Environmental Impact Statement for the Treatment and Management of Sodium Bonded Spent Nuclear Fuel," DOE/EIS-0306 (July 2000).

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13. B. Grambow, "A General Rate Equation for Nuclear Waste Glass Corrosion," Material Research Society Symposium Proceedings, 44, 15-24 (1985).

14. ASTM C 776, Standard Specification for Sintered Uranium Dioxide Pellets, American Society for Testing and Materials. See also ASTM C788, ASTM C 753, ASTM C776, ASTM C 1348 AND ASTM C 1334.

15. "Record of Decision for the Disposition of Surplus Highly Enriched Uranium Final Environmental Impact Statement," Federal Register, Vol. 61, No. 151/40619 (August 5, 1996).

16. "Hanford Site Solid Waste Acceptance Criteria," HNF-EP-0063, Rev. 6 (August 2000).

17. Safety Analysis Report for the TRUPACT-II Shipping Package, Rev. 17, Westinghouse Electric Corporation, Waste Isolation Division (January 1999).

18. "Cost Study of Alternatives Presented in the Draft Environmental Impact Statement for the Treatment and Management of Sodium-bonded Spent Nuclear Fuel" (August 1999).

19. "Discount Rates for Cost Effectiveness, Lease Purchase, and Related Analysis," Office of Economic Policy, Washington, DC (January 1999).

Appendix A - ROD for the Treatment and Management of Sodium-Bonded Spent Nuclear Fuel

Record of Decision for the Treatment and Management of Sodium-Bonded Spent Nuclear Fuel

AGENCY: Department of Energy (DOE)

ACTION: Record of Decision (ROD)

SUMMARY: DOE has issued a Final Environmental Impact Statement for the Treatment and Management of Sodium-Bonded Spent Nuclear Fuel (final EIS) (Notice of Availability, 65 FR 47987, August 4, 2000) (DOE/EIS-0306, July 2000). After careful consideration of public comments on the draft EIS and programmatic, environmental, nonproliferation, and cost issues, DOE has decided to implement the preferred alternative identified in the final EIS. That is, DOE has decided to electrometallurgically treat the EBR-II spent nuclear fuel (about 25 metric tons of heavy metal) and miscellaneous small lots of sodium-bonded spent nuclear fuel. The fuel will be treated at ANL-W. Because of the different physical characteristics of the Fermi-1 sodium-bonded blanket spent nuclear fuel (about 34 metric tons of heavy metal), DOE has decided to continue to store this material while alternative treatments are evaluated. Should no alternative prove more cost effective for this spent nuclear fuel, EMT of the Fermi-1 spent nuclear fuel remains a key option.

ADDRESSES:
The final EIS and this ROD are available on the NEPA home page at http://www.tis.eh.doe.gov/nepa or on the Office of Nuclear Energy, Science and Technology home page at http://nuclear.gov. You may request copies of the final EIS and this ROD by calling the toll-free number 1-877-450-6904, by faxing requests to 1-877-621-8288, via electronic mail to sodium.fuel.eis@hq.doe.gov, or via mail to: Susan Lesica, Document Manager, Office of Nuclear Energy, Science and Technology, NE-40, U.S. Department of Energy, 19901 Germantown Road, Germantown, Maryland 20874. NOTE: Phone numbers are no longer operable.

Appendix B – Secondary Waste Streams From Electrometallurgical Treatment

The treatment of the sodium-bonded fuel would generate secondary wastes from normal support operations and deactivation wastes following the conclusion of operations. Secondary wastes would include operational wastes such as failed equipment, rags, packaging materials, and other miscellaneous items. All of these materials would be categorized according to existing DOE orders and ANL-W waste management procedures.

The waste quantities provided here were derived from the data provided from the Preferred Alternative or Alternative 1 in the EIS [5]. The values have been adjusted to remove the impact of Fermi blanket treatment. Table B.1 provides the values directly from the EIS and the adjusted values expected from the treatment of just the EBR-II and FFTF sodium-bonded spent nuclear fuel.

Table B.1 Secondary Waste Quantities from Electrometallurgical Treatment

Secondary Process Wastes	EIS Waste Volumes (m^3)	Spent Fuel Treatment Program Waste Volume (m^3)	Spent Fuel Treatment Program Waste Mass (kg)	Disposal Location
LLW	706	300	62,000	Radioactive Waste Management Complex (RWMC)
Transuranic Wastes	12.5	5	2300	Waste Isolation Pilot Plant (WIPP)
Mixed-Transuranic Wastes	35.3	15	8200	WIPP/RWMC/ Commercial Facility
Sanitary Wastes	4,960	2150	750,000	INEEL Landfill

Appendix C - Metal Waste Form Composition

The data provided in table C.1 are the average composition of the metal waste form from electrometallurgical treatment of the EBR-II and FFTF sodium-bonded spent nuclear fuel. The radioisotopes shown are the repository relevant ones. The bulk of the metal waste mass is stainless steel. It also contains 15 percent zirconium. This waste can be disposed of in less than six of the DOE standardized canisters.

Metal waste mass: 5.85 MT

Table C.1 Metal Waste Composition

Radioisotope	Total Ci	Ci/Canister
C-14	2.59E+00	4.32E-01
Ni-59	1.12E+01	1.86E+00
Ni-63	3.36E+02	5.59E+01
Se-79	6.56E+00	1.09E+00
Zr-93	1.58E+01	2.63E+00
Nb-93m	2.71E+01	4.51E+00
Nb-94	2.28E+00	3.80E-01
Tc-99	1.14E+02	1.90E+01
Pd-107	3.45E-01	5.74E-02
Sn-126	5.98E+00	9.96E-01
Pb-210	1.11E-06	1.85E-07
Ac-227	3.44E-04	5.73E-05
U-232	1.75E-03	2.92E-04
U-233	1.25E-04	2.08E-05
U-234	8.36E-01	1.39E-01
U-235	7.01E-04	1.17E-04
U-236	5.22E-02	8.69E-03
U-238	1.18E-01	1.96E-02
Np-237	1.31E-02	2.19E-03
Pu-238	8.80E+00	1.47E+00
Pu-239	2.47E+02	4.11E+01
Pu-240	2.00E+01	3.33E+00
Pu-241	1.29E+01	2.15E+00
Pu-242	1.02E-03	1.70E-04
Am-241	6.53E+00	1.09E+00
Am-242m	5.85E-02	9.75E-03
Am-243	8.72E-04	1.45E-04
Cm-244	7.06E-03	1.18E-03
Cm-245	3.29E-07	5.49E-08
Cm-246	3.14E-09	5.24E-10

Appendix D – Ceramic Waste Form Composition

The data provided in table D.1 are the average composition of the ceramic waste form from electrometallurgical treatment of the EBR-II and FFTF sodium-bonded spent nuclear fuel. The radioisotopes shown are the repository relevant ones. The bulk of the ceramic waste mass is zeolite. It also contains 25 percent glass. This waste can be disposed of in 53 of the DOE standardized canisters.

Ceramic waste mass: 51.0 MT

Table D.1 Ceramic Waste Composition

Radioisotope	Total Ci	Ci/Canister
Cl-36	4.57E-14	8.63E-16
Sr-90	5.46E+05	1.03E+04
I-129	2.46E-01	4.64E-03
Cs-135	1.26E+01	2.38E-01
Cs-137	6.34E+05	1.20E+04
Sm-151	1.77E+04	3.35E+02
Ra-226	1.04E-05	1.97E-07
Ra-228	1.15E-09	2.18E-11
Th-229	1.11E-05	2.09E-07
Th-230	4.79E-03	9.04E-05
Th-232	2.31E-09	4.36E-11
Pa-231	1.43E-02	2.70E-04
U-232	2.59E-03	4.88E-05
U-233	2.05E-04	3.86E-06
U-234	1.22E+00	2.30E-02
U-235	1.17E-03	2.21E-05
U-236	8.55E-02	1.61E-03
U-238	5.15E-02	9.72E-04
Np-237	8.62E-01	1.63E-02
Pu-238	5.77E+02	1.09E+01
Pu-239	1.62E+04	3.06E+02
Pu-240	1.31E+03	2.48E+01
Pu-241	8.45E+02	1.59E+01
Pu-242	6.70E-02	1.26E-03
Am-241	4.29E+02	8.09E+00
Am-242m	3.21E+05	6.05E+03
Am-243	5.73E-02	1.08E-03
Cm-244	4.64E-01	8.76E-03
Cm-245	2.17E-05	4.09E-07
Cm-246	2.06E-07	3.90E-09

Appendix E – Uranium Byproduct Composition

Table E.1 Critical Isotopes in the Uranium Byproduct and the LLW Disposal Criteria.

Element	Typical Downblended LEU Material		Typical DU Material*		Hanford Cat III LLW Limits,** Ci/m^3 [16]
	Activity, Ci/g Waste	Activity, Ci/m^3	Activity, Ci/g Waste	Activity, Ci/m^3	
Be10	1.23E-16	2.16E-10	0	0	2.40E+02
Sr90	1.53E-05	2.69E+01	0	0	5.40E+04
Zr93	1.40E-09	2.47E-03	2.98E-08	5.27E-02	5.40E+02
Cs137	3.50E-07	6.17E-01	6.66E-07	1.18E+00	1.20E+04
U234	4.98E-07	8.79E-01	0	0	1.90E+00
U235	1.53E-08	2.70E-02	5.32E-09	9.40E-03	5.00E-01
U236	1.50E-08	2.65E-02	0	0	2.00E+00
Np237	1.93E-10	3.41E-04	3.34E-10	5.91E-04	1.50E-01
Pu238	8.32E-09	1.47E-02	6.84E-08	1.21E-01	2.40E+01
U238	1.05E-08	1.85E-02	1.35E-15	2.38E-09	1.20E+00
Pu239	1.39E-08	2.46E-02	3.22E-06	5.68E+00	4.20E-01
Pu240	5.48E-10	9.68E-04	2.09E-07	3.69E-01	4.30E-01
Pu241	2.38E-09	4.20E-03	2.15E-06	3.81E+00	2.50E+01
Pu242	4.78E-16	8.43E-10	1.01E-12	1.77E-06	4.30E-01
Pu244	1.12E-24	1.97E-18	1.37E-22	2.42E-16	1.30E-01
TRU Activity, nCi/g	2.54E+01		5.65E+03		1.00E+02

* The present data for the DU material indicates that it will exceed the TRU limits for LLW and will therefore need to be disposed of as TRU waste in WIPP.

** The Hanford limits are provided as an example of disposal criteria for LLW.

Appendix F – Annual Costs

Table F.1 Net Present Value Costs

NPV Costs	FY 00	FY 01	FY 02	FY 03	FY 04	FY 05	FY 06	FY 07	FY 08	FY 09
Annual EMT Operating Costs	31,190	23,466	30,378	33,463	32,428	31,859	31,247	29,878	28,238	26,092
Annual Costs for LEU Downblending for LLW Disposal	0	0	0	0	0	0	0	0	0	0
Fuel and HLW Packaging Costs	0	0	0	518	1,725	1,094	1,364	1,528	2,339	1,742
HLW Disposal Costs	0	0	0	0	0	0	0	0	0	0
TRU and LLW Disposal	0	0	0	0	0	0	0	0	0	0
DU Disposal as TRU	0	0	0	0	0	0	0	0	0	0
Total	31,190	23,466	30,378	33,981	34,153	32,953	32,611	31,406	30,577	27,834

NPV Costs	FY 10	FY 11	FY 12	FY 13	FY 14	FY 15	FY 16	FY 17		Total
Annual EMT Operating Costs	22,594	22,142	21,699	6,906	0	0	0	0		371,580
Annual Costs for LEU Downblending for LLW Disposal	0	0	0	2,284	2,524	2,473	2,424	2,451		12,156
Fuel and HLW Packaging Costs	0	0	0	0	0	5,822	0	0		16,132
HLW Disposal Costs	0	0	0	0	0	21,000	0	0		21,000
TRU and LLW Disposal	0	0	0	1,538	0	0	0	0		1,538
DU Disposal as TRU	0	0	0	123	0	0	0	0		123
Total	22,594	22,142	21,169	10,851	2,524	29,295	2,424	2,451		422,529

Table F.2 Annual Costs Without Discounting

NPV Costs	FY 00	FY 01	FY 02	FY 03	FY 04	FY 05	FY 06	FY 07	FY 08	FY 09
Annual EMT Operating Costs	31,190	24,903	34,213	39,996	41,132	42,886	44,638	45,296	45,432	44,550
Annual Costs for LEU Downblending for LLW Disposal	0	0	0	0	0	0	0	0	0	0
Fuel and HLW Packaging Costs	0	0	0	598	2,088	1,389	1,818	2,135	3,430	2,680
HLW Disposal Costs	0	0	0	0	0	0	0	0	0	0
TRU and LLW Disposal	0	0	0	0	0	0	0	0	0	0
DU Disposal as TRU	0	0	0	0	0	0	0	0	0	0
Total	31,190	24,903	34,213	40,594	43,220	44,275	46,456	47,431	48,862	47,230

NPV Costs	FY 10	FY 11	FY 12	FY 13	FY 14	FY 15	FY 16	FY 17		Total
Annual EMT Operating Costs	40,940	42,578	44,281	14,958	0	0	0	0		536,993
Annual Costs for LEU Downblending for LLW Disposal	0	0	0	4,254	4,931	5,069	5,211	5,527		24,992
Fuel and HLW Packaging Costs	0	0	0	0	0	11,932	0	0		26,070
HLW Disposal Costs	0	0	0	0	0	42,000	0	0		42,000
TRU and LLW Disposal	0	0	0	2,864	0	0	0	0		2,864
DU Disposal as TRU	0	0	0	229	0	0	0	0		229
Total	40,940	42,578	44,281	22,305	4,931	59,001	5,211	5,527		633,148