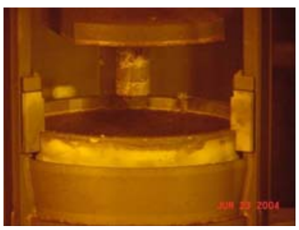

Idaho National Laboratory Preferred Disposition Plan for Sodium-Bonded Spent Nuclear Fuel

Prepared by

Idaho National Laboratory for
the Department of Energy

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Executive Summary

The Department of Energy (DOE) is responsible for storage, management and disposal of approximately 60 metric tons heavy metal (MTHM) of sodium-bonded spent nuclear fuel. This sodium-bonded fuel was produced as part of DOE's fast reactor development program. In the FY 2007 Performance Evaluation Measurement Plan (PEMP) for Idaho National Laboratory, the Department of Energy requested that INL investigate "More cost effective alternatives to current treatment methods of EBR-II and other sodium bearing fuel prior to ultimate disposal". This request was listed as a challenge measure. The following deliverables were requested:

- Prepare a recommendation for alternative methods for treatment and disposal of EBR-II sodium bonded fuels by January 31, 2007.
- The recommended alternative should include consideration of cost and schedule improvements, improvements in the end product and potential uses and or disposal alternatives.

This report provides the recommendation of INL for treatment of sodium-bonded fuel. The inventory of sodium-bonded spent fuel is stored in Idaho or planned for shipment to Idaho.

There are two types of sodium-bonded spent fuel: driver and blanket fuels. This fuel is from three different nuclear reactors: Experimental Breeder Reactor-II (EBR-II), Enrico Fermi Atomic Power Plant (Fermi-1), and Fast Flux Test Facility (FFTF). The initial inventory of fuel included 3.1 MTHM driver and 22.4 MTHM blanket fuels from EBR-II, 0.25 MTHM driver fuel from FFTF, and 34 MTHM blanket fuel from Fermi-1. There is also approximately 0.05 MTHM of oxide debris material embedded in sodium from fast reactor safety testing at Sandia National Laboratory (SNL). Approximately 3.3 MTHM of EBR-II fuel have been treated to date as part of pyroprocessing development, testing, and implementation.

Sodium-bonded spent nuclear fuel is generally considered not suitable for direct disposal in a geological repository due to the presence of elemental sodium. Since elemental sodium is known to violently react with water and produce a potentially explosive gas (hydrogen), the bond sodium component would be classified as a characteristic reactive waste. Treatment for this type of reactive waste is defined in RCRA regulations in 40CFR268.40, Treatment Standards for Hazardous Waste. At this time, the geologic repository does not plan on receiving Resource Conservation and Recovery Act (RCRA) hazardous waste. Disposal of this fuel would thus require deactivation or removal of sodium. Two different processes, pyroprocessing and sodium removal via the melt-drain-evaporate-carbonate (MEDEC) process, have been studied and demonstrated for sodium-bonded fuel.

Over the last decade, DOE has been developing and implementing pyroprocessing for treatment of sodium-bonded spent fuel. Concurrent with treatment operations, they have been performing R&D on the pyroprocess fuel cycle in support of AFCI. DOE has also been actively evaluating alternative disposal technologies since 1998. A National Research Council report evaluated the technical feasibility of alternative disposal options. An economic analysis and Environmental Impact Statement were prepared with a Record of Decision for a disposal path. Also, three reports to Congress discussed sodium-bonded spent fuel management.

In September 2000, a Program Implementation Plan was prepared by the Laboratory and approved by DOE-NE for treating the EBR-II and FFTF sodium-bonded spent fuel. Under this plan the fuel would be treated by FY2011 using pyroprocessing. Staffing for treatment operations would be gradually increased from 5 day per week and 8 hours per day to 7 days per week and 12 hours per day and eventually 24 hours per day. Treatment activities followed this plan through FY2002. In FY2003, treatment operations were combined with the Advanced Accelerator Applications Program to form the Advanced Fuel Cycle Initiative (AFCI). At that point, the focus of operations was directed to change from treatment to research and development on the pyrochemical fuel cycle. Under this program many advancements were made in the technology including initial demonstrations of group recovery of actinides at engineering-scale, laboratory-scale reduction of spent oxide fuel to metal, and of high dissolution of spent fuel electrochemically. EBR-II fuel was still treated, but mainly as needed to support fuel cycle development and demonstration. Concurrent with these operations, the MEDEC technology was assessed for treating the EBR-II blanket fuel. Under this time period funding for treatment of EBR-II and process testing decreased from $22.3M in FY2003 to $7.5M under continuing resolution in FY2007.

Based on this previous work, the recommendation of INL is to complete treatment of EBR-II fuel and treat FFTF fuel by pyroprocessing. Treatment of EBR-II blanket fuel by MEDEC is feasible, but does not offer any significant advantages. The plan put forward allows for fuel to be treated in a timely manner while also completing the demonstrations of the pyrochemical fuel cycle. Transuranics would be recovered for recycle instead of disposal. Treatment of driver fuel along with additional R&D would be completed in FY2014, and EBR-II blanket treatment would continue for an additional seven years. Final production of high-level waste would take an additional three years. The estimated total cost to completion for treatment of the EBR-II fuel, including R&D and waste disposal, is approximately $362.6 million in unescalated 2005 dollars. The cost for FFTF fuel receipt, storage, and treatment is an additional $50 million and is assumed to be provided by DOE-EM. INL would also propose that work go forward on eventual receipt and treatment of SNL material at INL using a combination of pyroprocessing and MEDEC technology. Presently SNL is funding a feasibility study and cost study for treatment of this material at INL. This study should be completed in late 2007. Funding for the ongoing study is being provided by SNL. Treatment funding would be assumed to be from NNSA.

Under this proposal, staffing for treatment would be gradually increased to support operations 7 days per week and 12 hours per day. In order to minimize costs in individual years, full staffing would not be increased to 24 hours per day. Funding in a typical year would be approximately $24M, approximately the same level as the program was funded at the time AFCI was formed and well below the initial implementation plan value of approximately $40M.

If a commitment is made to this treatment plan, options exist to provide additional cost sharing. For the next several years, treatment operations and R&D are integrated. After most of the R&D activities are completed, the option to transfer all treatment costs to DOE-EM would exist. Additionally, INL has examined the option to provide recovered uranium from driver fuel to the Highly Enriched Uranium Disposition Program Office for use as off-specification fuel for commercial light water reactors. There would be some additional costs to process the driver fuel to make it ready for this program, but those costs would potentially be funded under HDPO. At this point additional commitments on driver fuel to be treated and treatment rates are needed to go forward with this option.

Because of the limited irradiation history of the Fermi-1 blanket fuel, different disposal options may exist. DOE’s Office of Environmental Management (EM) is conducting an investigation into cost effective alternatives, including direct disposal and sodium removal via MEDEC. The direct disposal method would simply package the fuel into standard canisters that would be shipped to a permanent repository. The total cost has been roughly estimated at $100 million. While it does appear to be the cheaper option, direct disposal would need to be approved by the Environmental Protection Agency (EPA) because it would involve placing characteristic reactive wastes into a permanent waste repository. Based on experience in dealing with sodium-bonded spent fuel, making this case will be difficult. Assuming that direct disposal is not feasible, INL recommends the MEDEC process for treating the Fermi-1 blanket. The estimated cost for MEDEC processing and disposal of the Fermi-1 fuel is $160 million. INL does not have responsibility for the Fermi-1 blanket fuel.

TABLE OF CONTENTS

ACRONYMS AND ABBREVIATIONS

ABR	Advanced Burner Reactor
AFCI	Advanced Fuel Cycle Initiative
ANL	Argonne National Laboratory
DOE	Department of Energy
EBR-II	Experimental Breeder Reactor-II
EIS	Environmental Impact Statement
EM	Office of Environmental Management
EPA	Environmental Protection Agency
Fermi-1	Enrico Fermi Atomic Power Plant
FFTF	Fast Flux Test Facility
GNEP	Global Nuclear Energy Partnership
HDPO	Highly Enriched Uranium Disposition Program Office
INL	Idaho National Laboratory
INTEC	Idaho Nuclear Technology and Engineering Center
MEDEC	Melt Drain Evaporate Carbonate
MTHM	Metric Tons Heavy Metal
NE	Office of Nuclear Energy, Science, and Technology
NRC	National Research Council
PUREX	Plutonium and Uranium Recovery by Extraction
RSWF	Radioactive Scrap and Waste Facility
RCRA	Resource Conservation and Recovery Act
R&D	Research and Development
SNF	Spent Nuclear Fuel
SRS	Savannah River Site
TVA	Tennessee Valley Authority
UREX+	Uranium Extraction Plus

LIST OF FIGURES

LIST OF TABLES

1.0 Introduction

In the FY 2007 Performance Evaluation Measurement Plan (PEMP) for Idaho National Laboratory, the Department of Energy requested that INL investigate "More cost effective alternatives to current treatment methods of EBR-II and other sodium bearing fuel prior to ultimate disposal". This request was listed as a challenge measure. The following deliverables were requested:

- Prepare a recommendation for alternative methods for treatment and disposal of EBR-II sodium bonded fuels by January 31, 2007.
- The recommended alternative should include consideration of cost and schedule improvements, improvements in the end product and potential uses and or disposal alternatives.

This report provides the recommendation of INL for treatment of sodium-bonded fuel. The inventory of sodium-bonded spent fuel is stored in Idaho or planned for shipment to Idaho. Since DOE is committed to meeting its agreement with the State (Settlement and Consent order issued on October 17, 1995, in the actions of *Public Service Co. of Colorado v. Batt*, No. CV 91-0035-S-EJL [D. Id.] and *United States v. Batt*, No. CV 91-0054-EJL [D. Id]), the sodium-bonded spent fuel must leave Idaho by 2035. Sodium-bonded fuel includes the following: EBR-II driver fuel stored at both the Materials and Fuels Complex (MFC) at INL and the Idaho Nuclear Technology and Engineering Center (INTEC), EBR-II blanket fuel stored at MFC, Fast Flux Test Reactor (FFTF) fuel stored at Hanford, specialty material stored at Sandia National Laboratory (SNL), and the Fermi-1 blanket material stored at INTEC. The section that follows provides general information on these fuel types.

2.0 Sodium-Bonded Fuel Description

Typical commercial nuclear reactors use water as a coolant, and the fuel is made of oxide materials. DOE's fast nuclear reactor development program used liquid-sodium metal as a coolant. Metallic fuel could be used in these reactors. It allowed for efficient transfer of heat from fuel rods. The metallic fuel rod was encased in stainless steel cladding and bonded to the cladding with sodium. This cladding served to isolate the fuel and fission products from the reactor coolant. A schematic of a sodium-bonded fuel element is provided in Figure 1. Headspace above the sodium and fuel, known as the plenum, allowed for fission gases to accumulate. Sodium-cooled fast reactors and metallic fuels are both leading technologies being assessed for transmutation of wastes in the Global Nuclear Energy Partnership (GNEP).

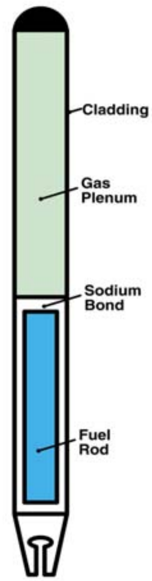

Figure 1. Sodium-Bonded EBR-II Driver Fuel Element

2.1 Sodium-Bonded Fuel Types and Characteristics

DOE's fast reactors used two fuel types: driver and blanket fuels. Each fuel type has different isotopic compositions that affect processing for final disposal. Driver fuel is highly enriched in the fissile uranium-235 isotope, which limits the quantity of spent fuel that can be processed at one time. Blanket fuel contains mostly non-fissile uranium-238. Some of this uranium-238 was converted to plutonium-239 during its time in the reactor, an important issue for fuel handling or treatment. The low fissile content of blanket fuel allows greater quantities to be processed at one time relative to driver fuel.

Another key difference between driver and blanket fuel is the interaction of bond sodium with the metallic fuel rods. Within the reactor, fissioning of uranium-235 in driver fuel produces fission products that cause the fuel rods to swell and develop porosity. The porosity allows sodium to become infused into the fuel rods. Separation of bond-sodium from driver fuel requires dissolution or melting of the fuel. Blanket fuel experienced little fissioning, so fuel swelling and porosity were significantly less. This lack of porosity keeps most sodium outside the blanket fuel rods, allowing either chemical or physical methods to be considered for sodium removal.

Sodium-bonded fuel should be stored in a dry, inert environment. The stainless steel cladding is known to gradually deteriorate when in contact with water, and exposed sodium will violently react with water. Experience at INL with sodium-bonded fuel stored in sealed metallic canisters in water storage basins resulted in some elements (Figure 2) reacting significantly with water to produce hydrogen gas [ref. 1]. Additionally, some driver fuel (Figure 3) that was kept in dry storage inside seal-welded containers at INL was found to have reacted with moisture in the internal atmosphere in the storage canisters. Hydrogen was evolved and accumulated in the storage canisters due to reaction of water with sodium. Such deterioration of cladding has not yet been seen with blanket fuel. Due to this reactive nature, all operations with sodium-bonded fuels are performed in an inert atmosphere.

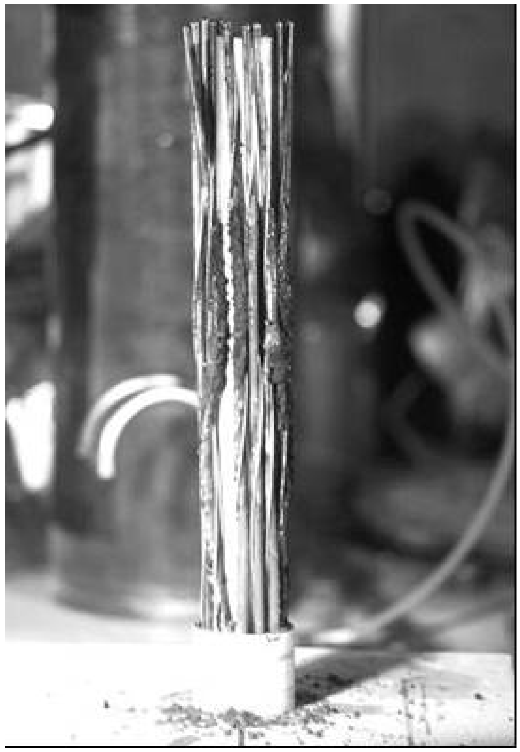

Figure 2. Fuel from Storage Canister that Leaked in Water Storage Basin

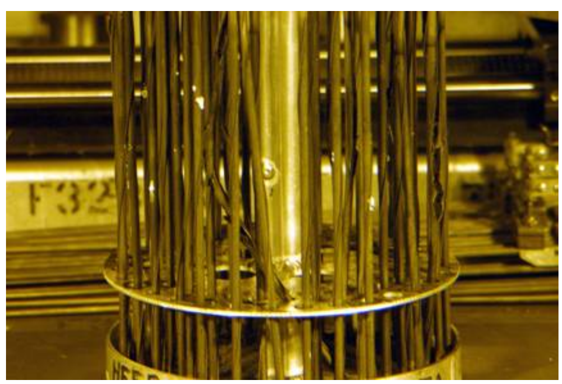

Figure 3. Fuel that Reacted with Moisture in Container Kept in Dry Storage

2.2 Spent Fuel Source and Quantities

Sodium-bonded fuel was principally used in three different reactors: EBR-II, Fermi-1, and FFTF. The quantity of fuel from each reactor is shown in Table 1.

EBR-II was a research and test reactor in Idaho used to demonstrate the engineering feasibility of a sodium-cooled, liquid metal fast reactor with a steam electric power plant and an integrated fuel cycle. Full operations began in November 1962 and continued until September 1994. During its operation, numerous fuel designs were tested, but sodium-bonded fuel was always used for both its driver and blanket fuel. The driver fuel was comprised of highly enriched uranium metal alloyed with either zirconium metal, a mixture of noble metals, or plutonium-zirconium metal. Fresh blanket fuel was pure depleted uranium metal, while spent blanket fuel contains about 1 wt% plutonium. Pyroprocessing is currently being used for treatment of EBR-II fuel.

Fermi-1 was a sodium-cooled fast reactor in Monroe Beach, Michigan. The reactor started operations in 1963 and operated until September 1972. This fast reactor used a metal driver fuel without a sodium bond and a sodium-bonded blanket fuel. This report discusses only the Fermi-1 blanket spent nuclear fuel, which was a depleted uranium-molybdenum alloy in a stainless steel cladding. Fermi-1 blanket elements are similar to EBR-II blanket elements with respect to enrichment but are physically larger and have very low neutron exposure in the reactor. Because of the low neutron exposure, the Fermi-1 blanket fuel contains only about 0.02% plutonium by weight, and less stringent safeguard and security requirements are needed relative to EBR-II blanket fuel. After the Fermi-1 reactor was permanently shut down, the blanket assemblies were placed into fourteen canisters and transported to DOE's Idaho Site in 1974 and 1975. The canisters were placed into an underground dry storage system.

FFTF, on the DOE Hanford Site near Richland, Washington, operated as part of DOE's fast reactor development program in the 1980s and tested various fuel types. A small quantity (0.25 MTHM) of experimental sodium-bonded driver fuel is currently stored at the Hanford site in Washington and will be transported to INL pursuant to the Record of Decision for the Programmatic Spent Nuclear Fuel EIS of 1995 [ref. 2]. The fuel is mostly either uranium-zirconium or uranium-plutonium-zirconium metal alloy. Most of this material was irradiated and has characteristics similar to EBR-II driver fuel.

DOE's sodium-bonded fuel inventory also includes a small quantity (0.05 MTHM) of uranium oxide fuel particulate dispersed in sodium metal. This material was used in passive cooling experiments at Sandia National Laboratory from 1977 to 1985.

Table 1. Summary of DOE Sodium-Bonded Spent Nuclear Fuel in Storage

Fuel Type	EBR-II Driver (MTHM)	EBR-II Blanket (MTHM)	FFTF Driver (MTHM)	Fermi-1 Blanket (MTHM)	Sandia Sodium Rubble Bed Materials (MTHM)	Total Sodium-Bonded Fuel (MTHM)
Initial Fuel June 1996	3.1	22.4	0.25	34.0	0.05	59.8
Fuel Treated as of December 2006	0.8	2.5	0	0	0	3.3
Remaining Untreated Fuel	2.3	19.9	0.25	34.0	0.05	56.5

3.0 Previous Studies

From 1996 to 1999, DOE performed a successful technology demonstration of pyroprocessing for treating sodium-bonded spent nuclear fuel. In 1998, DOE asked the National Research Council (NRC) to evaluate alternative technologies to pyroprocessing for treating sodium-bonded fuel. A Spring 1998 NRC Status Report stated all alternative technologies with the exception of the PUREX process are at an early stage of development and would require significant research and development (R&D) as well as "hot" demonstrations using spent nuclear fuel [ref. 3]. The report also stated that the over pack (i.e., direct disposal) alternative for sodium-bonded fuel did not require processing, but direct emplacement of sodium-bonded SNF was precluded by DOE policy concerning acceptance at Yucca Mountain of Resource Conservation Recovery Act (RCRA) hazardous waste. A report of the INEEL Spent Nuclear Fuel Task Team made the same conclusion on direct disposal [ref. 4]. The report concluded that sodium-bonded fuels are not suitable for repository disposal and therefore must be treated.

Following the pyroprocessing demonstration, DOE prepared the Environmental Impact Statement (EIS) for the Treatment and Management of Sodium-Bonded Spent Nuclear Fuel [ref. 5]. A separate cost evaluation of treatment technologies and a no-action alternative (direct disposal) was also prepared [ref. 6]. The evaluation concluded that costs for treatment options still under consideration were similar. The no-action alternative cost was lower than treatment options, but the report identified that two key technical uncertainties with direct disposal were absence of a clear disposal path and the effects of long-term storage of the spent fuel. The Record of Decision for the EIS stated that DOE would use pyroprocessing for all sodium-bonded fuel except that from the Fermi-1 reactor [ref. 7]. Because of different physical characteristics of the Fermi-1 sodium-bonded fuel, DOE decided to continue to store this material while alternative treatments were evaluated. In September 2000, a Program Implementation Plan was prepared by the Laboratory and approved by DOE-NE for treating EBR-II and FFTF sodium-bonded spent fuel. Implementation of pyroprocessing treatment of the EBR-II sodium-bonded spent fuel started in 2000.

In March 2001, three DOE offices (Office of Nuclear Energy, Science and Technology; Office of Civilian Radioactive Waste Management; and Office of Environmental Management) issued a report to Congress stating there is a clear and final disposition for all waste forms resulting from pyroprocessing and that no further treatment would be required [ref. 8]. In October 2003, DOE Office of Nuclear Energy, Science and Technology reported to Congress that pyroprocessing remains the preferred path for treating EBR-II fuel, but DOE would continue to evaluate alternatives that could provide significant cost savings [ref. 9]. In March 2006, DOE reported to Congress that pyroprocessing is still the preferred option for treatment of EBR-II fuel [ref. 10]. They noted that direct disposal was the preferred option for both FFTF fuel and Fermi-1, but since that time, DOE-EM has started funding INL to move forward on receipt and eventual treatment of FFTF fuel by pyroprocessing.

4.0 Disposal Options

Spent nuclear fuel, at the time of disposal, will be considered high-level waste and require disposal in a deep geologic repository. At this time, the geologic repository is not being licensed to receive Resource Conservation and Recovery Act (RCRA) hazardous waste. So when the fuel is packaged for final disposal, a hazardous waste determination will be required. For materials containing a potentially reactive component, as is the case for the fuel addressed in this report, RCRA regulations in 40 CFR 261.23 must be used to determine if they exhibit hazardous waste characteristics requiring treatment prior to disposal. The pertinent parts of these regulations define characteristic reactive waste as follows [ref. 11]:

> *A solid waste exhibits the characteristic of reactivity if a representative sample of the waste has any of the following properties:*
>
> *(1) It is normally unstable and readily undergoes violent change without detonating.*
> *(2) It reacts violently with water.*
> *(3) It forms potentially explosive mixtures with water.*

Since elemental sodium is known to violently react with water and produce a potentially explosive gas (hydrogen), the bond sodium component would be classified as a characteristic reactive waste. Treatment for this type of reactive waste is defined in RCRA regulations in 40CFR268.40, Treatment Standards for Hazardous Waste. These treatment standards state the following:

> *A prohibited waste (a waste that cannot be land disposed) identified in the table "Treatment Standards for Hazardous Wastes" may be land disposed only if it meets the requirements found in the table. For each waste, the table identifies one of three types of treatment standard requirements:" [ref. 11]*

From the table of treatment standards, water reactive waste requires deactivation to remove the hazardous characteristic of a waste. When rendered non-hazardous, this waste ceases to be restricted from land disposal due to the RCRA-defined hazardous characteristic of reactivity.

Based on these regulatory requirements, sodium-bonded fuel disposal options need to include either physical removal or chemical deactivation of the sodium. Based on fuel characteristics, driver fuel will require some type of chemical treatment because the elemental sodium has become infused into the fuel. For the blanket fuel, physical separation of the sodium or chemical processes may be considered. Pyroprocessing and sodium removal are the two approaches that have been studied in greatest detail. In addition, DOE has proposed that a new treatment standard may be established to allow direct disposal of some sodium-bonded fuel.

4.1 Pyroprocessing

Pyroprocessing (also known as electrometallurgical treatment) is a chemical process that converts bond sodium into sodium chloride (common table salt) while separating spent nuclear fuel into a uranium product and acceptable high-level waste forms. The pyroprocessing flowsheet (Figure 4) uses a high temperature electrolytic cell containing molten salts, lithium chloride/potassium chloride, and steel electrodes. One electrode contains chopped spent fuel, which is electrochemically dissolved in the molten salt when a voltage is applied to the system. Oxidation of metals from the fuel to chlorides in the salt occurs at the anode, resulting in the formation of sodium chloride, uranium chloride, and various fission product and transuranic chlorides. Simultaneously, uranium is deposited on a solid metal cathode immersed in the molten salt. This recovered uranium is stored for use as new fuel for reactors.

Treatment of EBR-II spent fuel by pyroprocessing is presently performed as part of AFCI. Two critical components of the proposed GNEP are recycling technologies that enhance proliferation resistance for more energy and less waste and Advanced Burner Reactors (ABR) that recycle nuclear fuel. Pyroprocessing is one such recycling technology that allows for reuse of nuclear fuel without separation of pure plutonium. The pyroprocessing fuel cycle and metal fuels like those used in EBR-II are leading candidates for fuel recycle in ABRs. Treatment of EBR-II fuel has allowed for R&D to support development and demonstration of the pyroprocess fuel cycle. Under AFCI, experiments are being performed to assess group recovery of actinides including transuranics, so they could be destroyed in an ABR. Pyroprocessing has distinct advantages with respect to criticality safety and resistance to radiation damage of process chemicals. Additionally, the technology was developed with the goal of recovering transuranic elements together as a group with all the actinide elements and some of the radioactive fission products. Such a product would still require operations in heavily shielded hot cells. R&D activities have also focused on complete dissolution of spent fuel to support recycle of all transuranics, options for treatment of oxide materials, and qualification and implementation of production processes for high-level wastes.

The technical viability of pyroprocessing for treatment of sodium-bonded fuel was demonstrated to the NRC. An April 2000 NRC report noted that the pyroprocessing demonstration met all success criteria [ref. 12]. More than 3.2 MTHM of EBR-II spent fuel have now been treated.

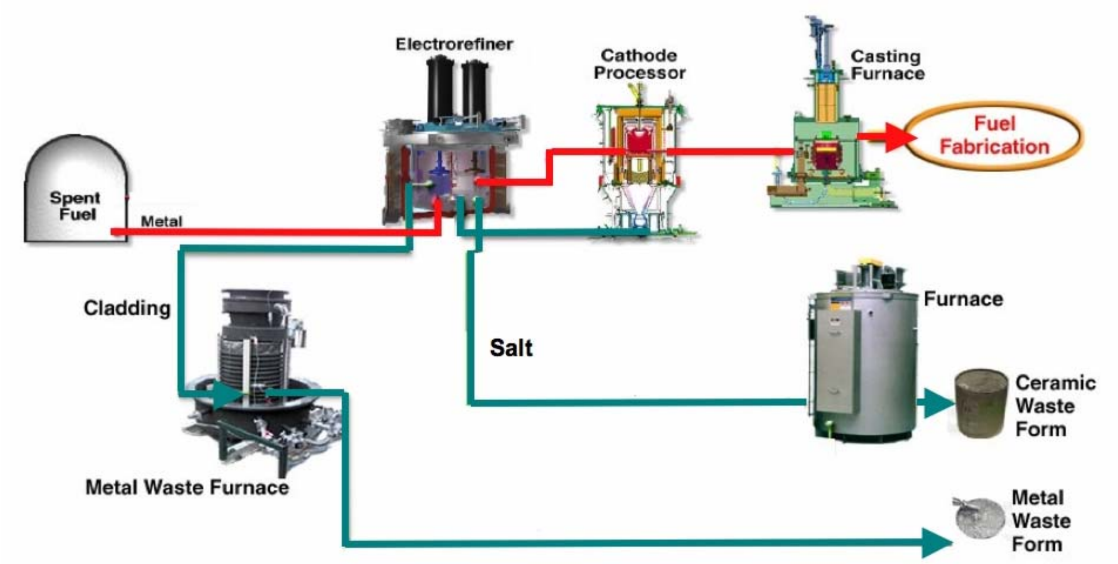

Figure 4. The Pyroprocessing Flowsheet

4.2 Sodium Removal and Deactivation

Two different processes, melt-drain-evaporate-carbonate (MEDEC) and fuel decladding and sodium removal through alcohol wash, have been used or tested for removal and deactivation of sodium from sodium-bonded fuel. These processes are only applicable to either Fermi-1 or EBR-II blanket fuels. For driver fuel, the sodium removal option would not be viable because elemental sodium has become infused into the fuel alloy. It cannot be completely removed without dissolving the fuel.

The melt-drain-evaporate-carbonate (MEDEC) technology was initially developed and tested in the 1980s to remove sodium from EBR-II fuel elements that had not been irradiated. The process uses a combination of heat and reduced pressure to melt and vaporize bond sodium, removing it from the metal fuel. The fuel elements are prepared by cutting off the ends. The elements are then heated to 650°C under reduced pressure (200 mTorr). After melting, the sodium evaporates and is condensed in a separate container. Once the sodium has been successfully removed, the cleaned fuel rods (Figure 5) can be packaged for direct disposal. The entire process is undertaken within an argon atmosphere to prevent reaction of sodium with oxygen or moisture in the atmosphere.

In FY2002, MEDEC tests were performed on unirradiated Fermi-1 fuel to verify process operating parameters and to support development of a cost estimate. In FY2003, additional MEDEC tests were run on an EBR-II blanket element that had been irradiated to a low burn-up similar to that experienced by the Fermi-1 blanket. The tests with irradiated fuel showed that the process was still viable. Radioactive cesium and trace amounts of plutonium were measured in the evaporated elemental sodium. This information was used to develop concepts and cost estimates for processing both Fermi-1 and EBR-II blanket. Fermi-1 blanket could be treated in a glovebox, but EBR-II blanket will need to be treated in a hot cell. The evaporated sodium must be converted into a final waste form. At DOE's Idaho site, a facility exists for performing sodium metal conversion to sodium carbonate; however, this facility has restrictive limits on acceptable plutonium levels and limited shielding for radioisotopes like cesium. This facility could be used for treatment of sodium from Fermi-1 blankets, but the presence of plutonium and cesium in the sodium from EBR-II blankets might preclude its use. Additional evaluations are needed to determine if this conversion method is feasible.

An alternative to MEDEC for sodium removal is the fuel decladding and sodium removal through alcohol wash process that was used successfully by Rocketdyne Corp (Canoga Park, CA) in the mid 1980s to remove sodium from 17 MTHM of spent EBR-II blanket fuel. In this process, fuel element cladding is cut to expose the fuel slugs, which are then soaked twice in an alcohol bath containing 20% water. The alcohol wash solution would be solidified as sodium carbonate and disposed of as low-level waste. This process has not been tested recently, and no life cycle cost estimates have been prepared for either Fermi-1 or EBR-II blanket fuel.

The recovered slugs from either sodium removal process would be either packaged for permanent disposal at the geologic repository or further processed by aqueous separations technologies like Uranium Extraction Plus (UREX+), a process being developed by DOE.

Figure 5. Fermi-1 Blanket Rod after Sodium Removal by MEDEC Process

4.3 Direct Disposal

For direct disposal, fuel assemblies are packaged into standard canisters and shipped to a permanent repository to be disposed as spent nuclear fuel. If additional containment is needed, the fuel could first be sealed in high-integrity cans and then packaged into standard canisters. This option is being considered for Fermi-1 blanket fuel. Direct disposal would need to be approved by the Environment Protection Agency (EPA) because it would involve placing characteristic reactive waste into a permanent waste repository.

4.4 Other Disposal Options

Aqueous technologies have been assessed for treatment of sodium-bonded fuel after removal of bond sodium. DOE's Savannah River Site (SRS) has the only operational facility for aqueous reprocessing. Historically, this facility processed highly-enriched-uranium aluminum-clad fuels and would require modifications or pretreatment of the sodium-bonded spent fuel. As mentioned is Section 4.2, decladding and alcohol wash were used in the 1980s to remove the cladding and sodium from EBR-II blankets. The resulting fuel slugs were processed at SRS in the low-enriched uranium canyon that is now closed.

Research on UREX+ has focused on treatment of commercial reactor oxide fuel, but this technology could be applied to treatment of sodium-bonded spent fuel after removal of bond sodium. Adequate details do not exist at this time to develop life cycle costs for treating sodium-bonded fuel using this technology.

Development of the other technologies such as melt and dilute, chloride volatility, fluoride volatility, and plasma arc processing are not currently funded by DOE for treating sodium-bonded fuel.

4.5 Disposal Options Summary

A summary of disposal options is provided in Table 2. The four main treatment options are pyroprocessing, sodium removal via MEDEC, sodium removal via alcohol wash, UREX+, and direct disposal. Pyroprocessing EBR-II fuel is ongoing at INL and could be applied to all type sodium-bonded fuel. The ROD for the EIS identified it as the preferred treatment for all sodium-bonded fuel except the Fermi-1 blanket. MEDEC and alcohol wash are both sodium removal technologies. They can be applied to both EBR-II and Fermi-1 blankets. Both technologies have been demonstrated with spent fuel. MEDEC tests were performed as recently as 2004. The alcohol wash process was performed in the 1980s. UREX+ has been demonstrated at laboratory-scale with commercial oxide spent fuel. It is a critical component of AFCI and the proposed GNEP. UREX+ tests with sodium-bonded spent fuel have not been performed, but metal fuel has been processed by other aqueous technologies after bond-sodium was removed.

Table 2. Feasibility of Processing Options by Fuel Type

Fuel Type	Pyroprocess	MEDEC	Alcohol Wash	UREX+	Direct disposal	Comments
EBR-II driver	on-going operations (preferred)	N/A	N/A	N/A	N/A	Sodium logged within the fuel matrix
FFTF driver	preferred option	N/A	N/A	N/A	N/A	Sodium logged within the fuel matrix
EBR-II blanket	on-going operations (preferred)	Demonstrated on engineering-scale non-irradiated fuel in 1980s. Lab-scale demonstrations in 2004.	Demonstrated on engineering scale in 1980s.	Feasible for transuranic recovery after sodium removal	N/A	Bulk of sodium separate from fuel matrix. High plutonium content due to long irradiation.
Fermi-1 blanket	feasible	preferred option	feasible	not useful due to low transuranic content	under evaluation	Bulk of sodium separate from fuel matrix. Low plutonium content due to short irradiation.
SNL Debris Bed	feasible after bulk sodium removal	feasible in conjunction with pyroprocessing	N/A	N/A	N/A	Material has a high sodium volume compared to fuel. Bulk sodium removal is preferred before additional treatment.

5.0 Research and Development Needs

Pyroprocessing of EBR-II spent fuel currently supports treatment goals for sodium-bonded spent fuel and research and development activities for GNEP. Transmutation of transuranics in ABRs is a critical component of this program, and pyroprocessing and metallic fuel are leading candidates for the ABR fuel cycle. Minimum quantities of fuels are needed to support research, development, and demonstration of the pyroprocessing fuel cycle. Key areas of focus include group actinide recovery (Figure 6), effect of transuranic concentrations in an electrorefiner, new materials for high temperature operations, performance of ternary (U-Pu-Zr) fuel separations, and engineering-scale waste operations.

For demonstrating group actinide recovery and assessing the effect of the transuranic concentration in the salt, process tests and experimental data are needed to optimize operations and confirm theoretical models. Additionally, engineering-scale transuranic recovery equipment needs to be tested so the recycle system for an ABR can be designed and materials can be recovered for advanced fuel fabrication. A minimum of 4 MTHM of additional EBR-II blanket would be needed for these operations. Salt from driver electrorefining operations can be used to provide data on fission product contamination in the recovered actinide product. Although sufficient fission product concentrations in electrorefiner salt exist from driver fuel processing to date, additional driver fuel processing will improve data quality.

In AFCI, high recovery efficiency of transuranics is an established criterion to support waste disposal options. Coatings of graphite crucibles are used in high temperature operations to prevent interaction between metal ingots and the crucibles. Application of these coatings is labor-intensive, and the coatings react with process material to form dross. Several promising candidate materials have been tested at laboratory scale, but further testing is needed at engineering scale with representative fission products. The successful scale-up of these materials will improve processing throughput, reduce costs, and minimize the need for handling secondary waste streams. This testing can be conducted simultaneously with treatment of at least 0.2 MTHM of EBR-II driver fuel.

An ABR utilizes fuel containing high concentrations of transuranics. Engineering-scale pyroprocessing operations have been limited to uranium-based fuel. The FFTF driver fuel includes approximately 10 kilograms of ternary fuel (U-Pu-Zr) that can be used to determine process conditions for future applications more closely related to an ABR.

For any separation process, the production of suitable high-level waste forms is a requirement. The viability of pyroprocessing-generated waste forms has been demonstrated using laboratory-scale samples. Scale-up of these processes has progressed (Figure 7) but still needs to be completed. R&D to support scale-up is essential, even if no additional fuel is processed. Waste materials that accumulated from treatment of 3.2 MTHM of EBR-II spent fuel need to be disposed in the planned repository.

Table 3 summarizes sodium-bonded fuel needs to support R&D for AFCI. An additional 0.2 MTHM of EBR-II driver fuel, 4 MTHM of EBR-II blanket fuel, and 0.01 MTHM of FFTF driver fuel are needed. No need has been identified for R&D activities with Fermi-1 fuel.

Table 3. Research and Development Needs by Fuel Type

Fuel Type	Quantity (MTHM)	Technology Needs
EBR-II driver	0.2	Develop advanced crucible materials for processing uranium product and metal waste.
FFTF driver	0.01	Obtain additional experimental data processing ternary (U-Pu-Zr) fuel elements.
EBR-II blanket	4	Obtain additional experimental data for electrorefining and group actinide recovery at different transuranic salt concentrations. Recover transuranic product for fast reactor fuel fabrication.
Fermi-1 blanket	0	None

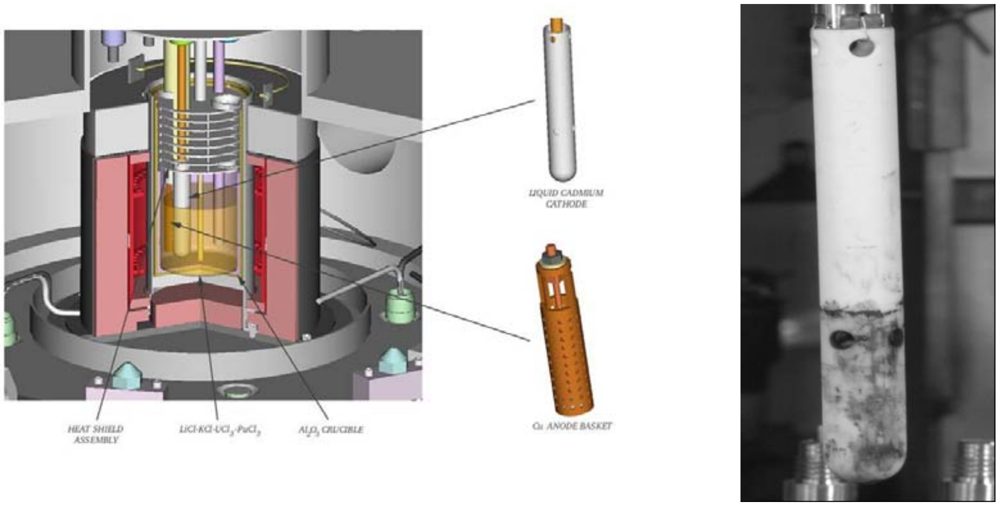

Figure 6. Laboratory-Scale Equipment for Group Actinide Recovery Experiments using Salt from Treatment of EBR-II Spent Fuel

Figure 7. Early Testing of the Prototype Metal Waste Furnace Used for Pyroprocessing

6.0 Life Cycle Costs

A number of studies have been commissioned by DOE to estimate life cycle costs for sodium-bonded spent fuel processing options. The focus of recent studies has been on pyroprocessing and sodium removal via MEDEC. Direct disposal, treatment via PUREX, and the melt and dilute process have not been considered recently, because of the cost study report that was issued in 1999 [ref 6]. In that report only direct disposal was appreciably cheaper than the other treatment alternatives, but direct disposal does not resolve classification of bond sodium as a characteristic reactive waste. Dilution was found to be very expensive—costing about $200 million more than other processing options. Cost differences between pyroprocessing and PUREX processing options were low and probably within the confidence band of the estimates. Thus, pyroprocessing and MEDEC are the two treatment options discussed further. In Section 6.1, a scenario involving minimum pyroprocessing is described. In Section 6.2, a scenario involving full implementation of pyroprocess is described. The costs described are the additional estimated cost to completion. Approximately $142 million have been spent on pyroprocessing implementation and treatment of EBR-II driver and blanket fuel through FY 2006. A number of other options have also been assessed. All these options are discussed in detail in the appendix.

6.1 Pyroprocessing for Driver and Sodium Removal for Blankets

One processing approach considered was pyroprocessing of driver fuel (EBR-II driver and FFTF driver) combined with sodium removal via MEDEC for blanket fuel (EBR-II blanket and Fermi-1 blanket). MEDEC for EBR-II blanket would be carried out in a shielded hot cell, and MEDEC for Fermi-1 blanket would be carried out in shielded gloveboxes. The additional cost to completion for this approach is estimated to be $680 million (not escalated or discounted). A breakdown of this cost by fuel type and activity (fuel processing or waste processing) is given in Table 4. MEDEC processing is categorized as Waste Processing for this table.

The costs for EBR-II driver treatment are based on an INL study prepared for AFCI in 2006. This report for this study is added as an appendix. The costs for FFTF driver treatment are based on an internal INL study from 2006 funded by DOE-EM. Numbers from that report have been adjusted to remove escalation factors. These studies assumed a single 12-hour shift seven days a week. For all pyroprocessing options, fuel treatment is performed in FCF, and waste processing is performed in HFEF.

Costs for MEDEC treatment of Fermi-1 blanket come from an internal report prepared by ANL for DOE-EM in 2003. Because of the low-irradiation history of this fuel, operations could be performed in a shielded glovebox. For this 2003 estimate, work was assumed to be performed in the TREAT building at MFC, but work could also be performed in other nuclear facilities. There is also an internal feasibility and cost study on MEDEC of EBR-II blanket that was completed by ANL in 2004. Because of the higher radiation fields associated with the EBR-II blanket, work would need to be performed in a hot cell. For this cost study, work was performed in HFEF. At the time that the study was performed, HFEF was not as committed for other programmatic missions. Conflicts will likely occur if these operations were eventually placed in HFEF.

Table 4. Breakdown of Estimated Costs to Complete Treatment for Pyroprocessing of Driver Fuel Combined with MEDEC Processing of Blanket Fuel.

	Fuel Processing Cost ($K)	**Waste Processing and Disposal Cost ($K)**	**Total Cost ($K)**
EBR-II driver	97,200	94,600	191,800
FFTF driver	35,500	6,700	42,200
EBR-II blanket	0	284,800	284,800
Fermi-1 blanket	0	160,900	160,900
Total	132,700	547,000	679,700

Treatment of driver fuel along with additional R&D would be completed in FY2014, and MEDEC treatment of EBR-II blanket and Fermi-1 blanket fuel would be initiated in FY2017 and be complete by FY2030. High-level waste disposal would begin in FY2026 and be complete by FY2035.

6.2 Pyroprocess for Driver and EBR-II Blanket, Sodium Removal for Fermi-1 Blanket

A second processing approach evaluated was pyroprocessing all sodium-bonded spent fuel except Fermi-1 blanket fuel. The Fermi-1 blanket would be treated by MEDEC. Included with this option is recovery of transuranics as part of pyroprocessing. The recovered transuranics may be used for fabricating ABR fuel. Recovery of transuranics also results in lower waste disposal costs because of process limits for transuranics in waste salts. Placing fewer transuranics in the waste forms results in less waste. In Table 5, cost estimates are given for scenarios in which all EBR-II and FFTF fuel is treated via pyroprocessing, while sodium is removed from Fermi-1 fuel via MEDEC. The pyroprocessing data were from 2006 INL internal studies previously mentioned that assumed a single shift operation seven days a week. Disposal costs have been estimated and combined with waste processing costs. The cost to completion is $566 million (not escalated or discounted).

Table 5. Breakdown of Life Cycle Costs to Complete Treatment for Pyroprocessing of EBR-II and FFTF Fuel Combined with Sodium Removal of Fermi-1 Fuel.

	Fuel Processing Cost ($K)	Waste Processing and Disposal Cost ($K)	Total Cost ($K)
EBR-II driver	97,200	94,600	191,800
FFTF driver	35,500	6,700	42,200
EBR-II blanket	76,200	94,600	170,800
Fermi-1 blanket	0	160,900	160,900
Total	208,900	356,800	565,700

Treatment of driver fuel along with additional R&D would be completed in FY2014, and EBR-II blanket treatment would continue for an additional seven years. Final production of high-level waste would take an additional three years.

7.0 Preferred Alternative

INL recommends that all remaining EBR-II fuel, driver and blanket, and FFTF fuel be treated by pyroprocessing. Under this plan and with adequate funding, treatment of the fuel would be accomplished well in advance of DOE's committed date to the State of Idaho, and R&D on the pyroprocessing fuel cycle in support of GNEP would be completed including demonstration and implementation of group recovery of actinides and production of high-level wastes for geological disposal. Under this plan, the bond sodium is converted into a non-reactive waste. The resulting waste forms would not be classified as RCRA hazardous waste. Transuranics to support ABR testing and recycling would be provided. DOE-EM has indicated that they are examining the option of direct disposal of Fermi-1 blanket. They are trying to determine if the fuel can be shown to be not a RCRA regulated material. Based on experience in dealing with sodium-bonded spent fuel, making this case will be difficult. Assuming that this path is not feasible, INL recommends the MEDEC process for treating Fermi-1 blanket. This overall recommended plan is that described in Section 6.2. This approach is $114 million less than the alternative treatment option described in Section 6.1.

The total costs provided up to this point have been total costs to DOE and have not distinguished between organizations within DOE. The total costs to completion for the recommended approach is $565,700k. These costs do not include $142,000k that has already been funded by DOE-NE for treatment of EBR-II fuel and associated R&D. The cost for the receipt, storage, and treatment of FFTF fuel is $50,000k. Since this fuel is owned by DOE-EM, this funding is assumed to be provided by DOE-EM. DOE-EM also owns the Fermi-1 blanket, and the cost for treatment of it by MEDEC is $160,900k.

The remaining costs for the EBR-II driver and blankets are $362,600k. All of the EBR-II blanket fuel is located at MFC. Most of the remaining EBR-II driver fuel is located at INTEC in water storage. INL would propose transfer of the driver at INTEC to MFC and placement into dry storage in the Radioactive Scrap and Waste Facility (RSWF). Dry storage is preferred for sodium-bonded fuel. INL would propose that DOE-NE continue in the near-term to fund treatment of EBR-II spent fuel including the INTEC driver, while R&D is performed concurrently in FCF and HFEF to support GNEP. INL would recommend though that DOE-EM fund the operations to transfer driver fuel from INTEC to RSWF. A recent engineering evaluation estimated the costs for transfer of this fuel at approximately $10M.

Treatment and R&D operations would be performed in parallel through FY2014. After that point, most of the operations would be largely focused on treatment. INL would propose transfer of treatment costs to DOE-EM at that point. Costs for treatment operations from FY2014 until completion are $265,800k. If this transfer were approved, the total additional costs to DOE-NE for treatment of EBR-II fuel and pyroprocessing R&D to support GNEP would be $139,000k.

Under previous studies dating back to the original EIS, the recovered uranium has been assumed to be a waste. The option has always existed to use HEU from EBR-II and FFTF fuel as feedstock for a fast reactor. The recovered product meets the requirements for fast reactor fuel, and under the Integral Fast Reactor Program it was to be used in remotely fabricated fuel for EBR-II. This material could be used as material for a start-up core for an advanced burner reactor, but most discussions to date have focused away from use of an HEU core. The option does exist for processing it further for use in commercial light water reactors. INL has been in ongoing discussions with the Highly Enriched Uranium Disposition Program Office (HDPO), AREVA, and Nuclear Fuels Services concerning options for purification of the uranium so that it could be included as off-specification material in commercial reactors like those operated by TVA. Based on these discussions, this option appears feasible. Some operations would need to be modified in FCF, but there are potential ways to include this material in HDPO. If this option were implemented, INL would pursue funding for incremental costs from HDPO. Based on the recent funding profile for treatment of EBR-II fuel and the uncertainty on transfer of the remaining driver fuel from INTEC to MFC, these studies cannot go much further. Funding for EBR-II Spent Fuel Treatment and associated pyroprocessing R&D has decreased from $22.3M in FY2003 to $7.5M in FY2007. Commitment on this additional source of material at INTEC and on a plan for treatment of the fuel is needed to establish a program with HDPO to provide additional off-spec HEU. If these plans were established, INL would propose use of internal program development funds to move forward on establishing this final disposition option for the HEU.

The final sodium containing material is the debris-bed material from SNL. Presently, SNL is funding a $1M feasibility study on the treatment of this material using a combination of pyroprocessing and MEDEC. This study should be completed in September 2007. They are also funding a cost study that will be completed in September 2007. In preparation for successfully completing both of these tasks, they are also moving forward with funding plans to receive the material as early as the end of FY2007. INL does not plan to move forward on receipt and treatment of this material until DOE-NE and NNSA reach agreement on funding for treatment of this material. The assumption is that NNSA will fund these operations as they have the work to date, but a firmer agreement is needed before receipt of the material at INL.

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Appendix

EBR-II and FFTF Spent Fuel Processing Options Report

EBR-II and FFTF Spent Fuel Processing Options Report

April 2006

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Executive Summary

The Department of Energy (DOE) is responsible for storage, management and disposal of approximately 60 metric tons heavy metal (MTHM) of sodium-bonded spent nuclear fuel. In the Energy and Water Development Appropriations Bill for FY2006, the Committee directed DOE to undertake a study to evaluate and propose a disposal solution for the entire sodium-bonded nuclear fuel inventory and consider what minimum amount of fuel is required for future experiments under the Advanced Fuel Cycle Initiative (AFCI). This report describes sodium-bonded fuel, previous studies, disposal technologies, research and development (R&D) needs, life cycle costs, and a preferred disposal path of irradiated fuel from the Experimental Breeder Reactor-II and Fast Flux Test Facility experimental reactors.

Sodium-bonded spent nuclear fuel is generally considered not suitable for direct disposal in a geological repository due to the presence of elemental sodium. Since elemental sodium is known to violently react with water and produce a potentially explosive gas (hydrogen), the bond sodium component would be classified as a characteristic reactive waste. At this time, the geologic repository does not plan on receiving Resource Conservation and Recovery Act (RCRA) hazardous waste and disposal of this fuel would thus require deactivation or removal of sodium. Two different processes have been recently studied and demonstrated for sodium-bonded fuel: pyroprocessing and sodium removal via the melt-drain-evaporate-carbonate (MEDEC) process.

Minimum R&D needs have also been examined to support AFCI and the proposed Global Nuclear Energy Partnership (GNEP). Two critical components of GNEP are recycling technologies that enhance proliferation resistance while producing more energy and less waste and Advanced Burner Reactors (ABR) that recycle nuclear fuel. Pyroprocessing is one such recycling technology that allows for recycle of nuclear fuel without separation of plutonium. The pyroprocessing fuel cycle and metal fuels like those used in EBR-II are leading candidates for fuel recycle in ABRs. To support further development of this technology, an additional 0.2 MTHM of EBR-II driver, 4 MTHM EBR-II blanket, and 0.01 MTHM FFTF driver fuel need to be processed. The R&D activities would be performed concurrently with treatment operations.

Considering cost and technology benefits, the preferred path forward is to treat the remaining EBR-II and FFTF fuel via pyroprocessing. Treatment of driver fuel along with additional near-term R&D would be completed in FY2014, and EBR-II blanket treatment would continue for an additional seven years. Final production of high-level waste would take an additional three years. The estimated total cost to complete, including R&D and waste disposal, is approximately $405 million in unescalated 2005 dollars. Of this total, $87.5 million is for final High Level Waste disposal in the geologic repository and is deferred until after 2030. The preferred option was selected because it provides actinides for advanced fuel research, is the lowest cost option, generates the least amount of High Level

Waste, and meets DOE's commitment to the State of Idaho. The operations will provide important research, development and demonstration information for Advance Fuel Cycle Facility design.

Table of Contents

Page

List of Figures

List of Tables

List of Acronyms

ABR	Advanced Burner Reactor
ABTR	Advanced Burner Test Reactor
AFCI	Advanced Fuel Cycle Initiative
ANL	Argonne National Laboratory
CP	Cathode Processor
CTC	Cost to Completion
CWF	Ceramic Waste Form
DOE	Department of Energy
DU	Depleted Uranium
EBR-II	Experimental Breeder Reactor-II
EIS	Environmental Impact Statement
EM	Office of Environmental Management
EPA	Environmental Protection Agency
ER	Electrorefiner
FCF	Fuel Conditioning Facility at Idaho National Laboratory
Fermi-1	Enrico Fermi Atomic Power Plant
FFTF	Fast Flux Test Facility
FIFSC	Four-Inch Fuel Storage Canister
GNEP	Global Nuclear Energy Partnership
HEU	High Enrichment Uranium
HFDA	Hot Fuel Dissolution Apparatus
HFEF	Hot Fuel Examination Facility at Idaho National Laboratory
HLW	High Level Waste
HTER	High-Throughput Electrorefiner
ICP	Idaho Cleanup Project
INL	Idaho National Laboratory

INTEC	Idaho Nuclear Technology and Engineering Center
LCC	Liquid Cadmium Cathode
LEU	Low Enriched Uranium
MEDEC	Melt Drain Evaporate Carbonate
MFC	Materials and Fuels Complex at Idaho National Laboratory
MTHM	Metric Tons Heavy Metal
MWF	Metal Waste Form
NE	Office of Nuclear Energy
NRC	National Research Council
PUREX	Plutonium and Uranium Recovery by Extraction
RCRA	Resource Conservation and Recovery Act
R&D	Research and Development
RSWF	Radioactive Scrap and Waste Facility at Idaho National Laboratory
SNF	Spent Nuclear Fuel
SRS	Savannah River Site
TRU	Transuranic
UREX+	Uranium Extraction Plus

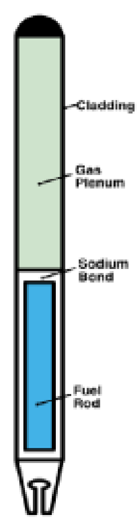
1. Introduction

The Department of Energy (DOE) is responsible for storage, management and disposal of approximately 60 metric tons heavy metal (MTHM) of sodium-bonded spent nuclear fuel. This sodium-bonded fuel was produced as part of DOE's fast reactor development program. In the Energy and Water Development Appropriations Bill for FY2006, the Committee directed DOE to undertake a study to evaluate and propose a disposal solution for the entire sodium-bonded nuclear fuel inventory and consider what minimum amount of fuel is required for future experiments under the Advanced Fuel Cycle Initiative (AFCI). In support of the Department of Energy's preparation of a "Report to Congress on the Preferred Disposal Pathway for Sodium-Bonded Spent Nuclear Fuel," Idaho National Laboratory (INL) has evaluated processing and disposal alternatives for treating the remaining Experimental Breeder Reactor-II (EBR-II) and Fast Flux Test Facility (FFTF) sodium-bonded spent fuel. This report describes sodium-bonded fuel, previous studies, disposal options, research and development (R&D) needs, life cycle costs, and a preferred disposal path. Detailed explanations of assumptions and technical risks have also been included to support revisiting this analysis at a later date if assumptions change.

2. Description of Sodium-Bonded Spent Nuclear Fuel

Typical commercial nuclear reactors use water as a coolant, and the fuel is made of oxide materials. DOE's fast nuclear reactor development program used liquid-sodium metal as a coolant. Metallic fuel could be used in these reactors. It allowed for efficient transfer of heat from fuel rods. The metallic fuel rod was encased in stainless steel cladding and bonded to the cladding with sodium. A schematic of a sodium-bonded fuel element is provided in Figure 1. Headspace above the sodium and fuel, known as the plenum, allowed for fission gases to accumulate. Sodium-cooled fast reactors and metallic fuels are both leading technologies being assessed for transmutation of wastes in AFCI and the proposed Global Nuclear Energy Partnership (GNEP).

Figure 1. Sodium-Bonded EBR-II Driver Fuel Element



2.1 Sodium-Bonded Fuel Types

DOE's fast reactors used two fuel types: driver and blanket fuels. Each fuel type has different isotopic compositions that affect processing for final disposal. Driver fuel is highly enriched in the fissile uranium-235 isotope, which limits the quantity of spent fuel that can be processed at one time. Blanket fuel contains mostly non-fissile uranium-238. Some of this uranium-238 was converted to plutonium-239 during its time in the reactor, an important issue for fuel handling or treatment. The low fissile content of blanket fuel allows greater quantities to be processed at one time relative to driver fuel.

Another key difference between driver and blanket fuel is the interaction of bond sodium with the metallic fuel rods. Within the reactor, fissioning of uranium-235 in driver fuel produces fission products that cause the fuel rods to swell and develop porosity. The porosity allows sodium to become infused into the fuel rods. Separation of bond-sodium from driver fuel requires dissolution or melting of the fuel. Blanket fuel experienced little fissioning, so fuel swelling and porosity are significantly less. This lack of porosity keeps most sodium outside the blanket fuel rods, allowing either chemical or physical methods to be considered for sodium removal.

2.2 Sodium-Bonded Fuel Sources

EBR-II was a research and test reactor in Idaho operated by Argonne National Laboratory (ANL) to demonstrate the engineering feasibility of a sodium-cooled, liquid metal fast reactor with a steam electric power plant and integrated fuel cycle. EBR-II went critical in November 1963 and operated until September 1994. During its operation, numerous fuel designs were tested, but sodium-bonded fuel was primarily used for both its driver and blanket fuel. The driver fuel was comprised of highly enriched uranium metal alloyed with either zirconium metal, a mixture of noble metals, or plutonium-zirconium metal. Fresh blanket fuel was pure depleted uranium (DU) metal, while spent blanket fuel contains about 1 wt% plutonium. All of the EBR-II blanket fuel and a portion of the driver fuel is at the INL Materials and Fuels Complex (MFC). There is 2 MTHM of the driver fuel at the Idaho Nuclear Technology and Engineering Center (INTEC) of the Idaho Cleanup Project (ICP).

Fermi-1 was a sodium-cooled fast reactor in Monroe Beach, Michigan. The reactor started operations in 1963 and operated until September 1972. This fast reactor used a metal driver fuel without a sodium bond and a sodium-bonded blanket fuel. The blanket fuel consisted of depleted U-Mo alloy in stainless steel cladding. Blanket elements are similar to EBR-II blanket elements with respect to enrichment but are physically larger and have very low neutron exposure in the reactor. Because of the low neutron exposure, the Fermi-1 blanket fuel contains only about 0.02% plutonium by weight, and less stringent safeguard and security requirements are needed relative to EBR-II blanket fuel. After the Fermi-1 reactor was permanently shut down, the blanket assemblies were placed into fourteen canisters and transported to DOE's Idaho Site in 1974 and 1975. The canisters were placed into an underground dry storage system.

The Fast Flux Test Facility (FFTF), on the DOE Hanford Site near Richland, Washington, operated as part of DOE's fast reactor development program in the 1980s and tested various fuel types. This reactor was primarily fueled with oxide fuel; however, a small quantity (0.25 MTHM) of experimental sodium-bonded driver fuel is currently stored at the Hanford site in Washington and will be transported to INL pursuant to the Record of Decision for the Programmatic Spent Nuclear Fuel Environmental Impact Statement (EIS) of 1995 [ref. 1]. The fuel is predominately either uranium-zirconium or uranium-plutonium-zirconium metal alloy. Most of this material was irradiated and has characteristics similar to EBR-II driver fuel.

DOE's sodium-bonded fuel inventory also includes a small quantity (0.05 MTHM) of uranium oxide fuel particulate dispersed in sodium metal. This material was used in passive cooling experiments at Sandia National Laboratory from 1977 to 1985.
The rest of this report only discusses the EBR-II and FFTF fuel.

2.3 Fuel Storage

Sodium-bonded fuel should be stored in a dry, inert environment. Stainless steel cladding that has been irradiated in fast reactors will deteriorate when in contact with water at a much shorter time scale than is assumed in a geologic repository. When that happens, exposed sodium will violently react with water.

$$Na + H_2O \rightarrow NaOH + \frac{1}{2}H_2$$

Water can also react with metallic U to make UO_2 and H_2.

$$U + 2H_2O \rightarrow UO_2 + 2H_2$$

With sufficient oxygen present, the hydrogen generated from either of these reactions can be explosive. Another consequence of having hydrogen present is that it can react with uranium metal to make unstable uranium hydride.

$$U + \frac{3}{2}H_2 \rightarrow UH_3$$

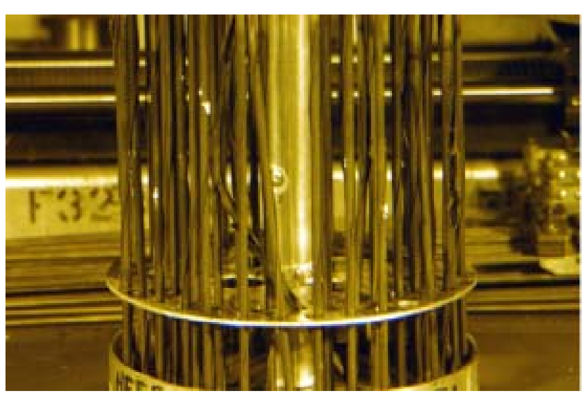
Uranium hydride reacts spontaneously in air to make uranium oxide and releases heat. Evidence of these reactions has been found in breeched EBR-II fuel in both wet storage at INTEC and dry storage at the Radioactive Scrap and Waste Facility (RSWF).

In the case of fuel stored at INTEC, the fuel elements were placed into 30.5-inch long stainless steel canisters. These canisters were designed to keep the fuel elements dry while they were placed in wet storage. However, some of the canister lids were inadequately tightened, resulting in the ingress of water. In a time period of less than 20 years, the cladding failed. The sodium and metallic fuel were exposed to water and reacted to form NaOH, H_2, and UO_2 [ref. 2]. It was speculated that the radiation field had weakened the driver fuel cladding and that stress corrosion cracking was the cause for the cladding failures. Figure 2 shows a photograph of some of the failed EBR-II driver fuel from the INTEC water storage basin.

Fuel failures have not been limited to cases where liquid water was in contact with cladding. Recently, it was discovered that some EBR-II driver fuel placed in supposedly dry storage at RSWF in seal-welded containers had also failed (see Figure 3) [ref. 3]. It is not known how moisture came in contact with the fuel elements, but the environment was less aggressive than that experienced in the INTEC water storage basin.

Figure 2 – Fuel from Storage Canister that Leaked in Water Storage Basin

Figure 3 – Fuel that Reacted with Moisture in Container Kept in Dry Storage



These events or occurrences demonstrate how the cladding does not provide an adequate barrier to prevent bond sodium from reacting with water.

3. Spent Fuel Treatment Technology

3.1 Motivation for Treatment

Spent nuclear fuel, at the time of disposal, will be considered high-level waste and require disposal in a deep geologic repository. At this time, the geologic repository is not being licensed to receive Resource Conservation and Recovery Act (RCRA) hazardous waste. So when the fuel is packaged for final disposal, a hazardous waste determination will be required. For materials containing a potentially reactive component, as is the case for the fuel addressed in this report, RCRA regulations in 40 CFR 261.23 must be used to determine if they exhibit hazardous waste characteristics requiring treatment prior to disposal. The pertinent parts of these regulations define characteristic reactive waste as follows [ref. 4]:

> *A solid waste exhibits the characteristic of reactivity if a representative sample of the waste has any of the following properties:*
>
> *(4) It is normally unstable and readily undergoes violent change without detonating.*
> *(5) It reacts violently with water.*
> *(6) It forms potentially explosive mixtures with water.*

Since elemental sodium is known to violently react with water and produce a potentially explosive gas (hydrogen), the bond sodium component would be classified as a characteristic reactive waste. Treatment for this type of reactive waste is defined in RCRA regulations in 40 CFR 268.40, Treatment Standards for Hazardous Waste. These treatment standards state the following:

> *A prohibited waste (a waste that cannot be land disposed) identified in the table "Treatment Standards for Hazardous Wastes" may be land disposed only if it meets the requirements found in the table. For each waste, the table identifies one of three types of treatment standard requirements:" [ref. 4]*

From the table of treatment standards, water reactive waste requires deactivation to remove the hazardous characteristic of a waste. When rendered non-hazardous, this waste ceases to be restricted from land disposal due to the RCRA-defined hazardous characteristic of reactivity.

Based on these regulatory requirements, sodium-bonded fuel disposal options need to include either physical removal or chemical deactivation of the sodium. Driver fuel will require some type of chemical treatment because the elemental sodium has become infused into the fuel. Physical separation of the sodium or chemical processes may be considered for blanket fuel. Pyroprocessing and sodium removal are the two technologies that have been studied in greatest detail.

3.2 Pyroprocessing Technology

Pyroprocessing (also known as electrometallurgical treatment) is a chemical process that converts bond sodium into sodium chloride (common table salt) while separating spent nuclear fuel into a uranium product and acceptable high-level waste forms. The separations process is called electrorefining. The vessel in which electrorefining is accomplished is called an electrorefiner (ER). It uses a high temperature electrolytic cell containing molten salts (i.e. lithium chloride/potassium chloride) and steel electrodes. One electrode contains chopped spent fuel, which is electrochemically dissolved in the molten salt when a voltage is applied to the system. Oxidation of metals (including sodium) from the fuel to chlorides in the salt readily occurs at the anode as the fuel matrix is dissolved, resulting in the formation of sodium chloride, uranium chloride, and various fission product and transuranic chlorides. Simultaneously, uranium is deposited on a solid metal cathode immersed in the molten salt. This uranium is recovered for use as new fuel for reactors.

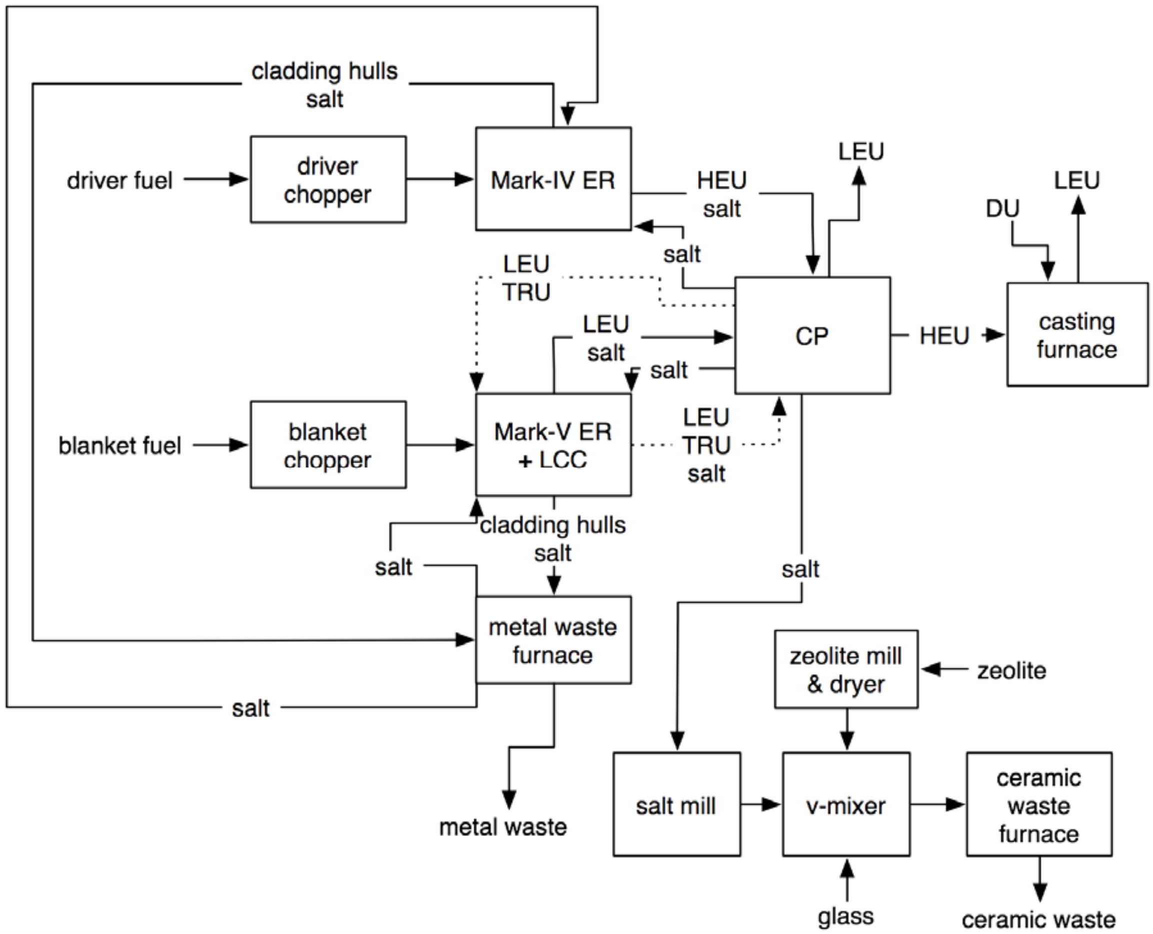
The current version of the pyrochemical process, which includes waste form production, is illustrated by the block flow diagram shown in Figure 4. Driver and blanket fuel is chopped into 6.4 to 12.8 mm segments respectively, loaded into anode baskets, and immersed in the molten LiCl-KCl electrolyte in either the Mark-IV or Mark-V electrorefiner (ER). The Mark-IV ER was the first hot cell design and is well suited for the throughput requirements for driver fuel. The Mark-V ER was the next generation electrorefiner, intended for higher fuel throughput as required for the blanket fuel. Pure uranium deposits are collected in both units when using a solid cathode, but transuranic elements can be co-deposited with uranium if a liquid-cadmium cathode is used. Thus, the product from the electrorefiner can be either uranium or group actinides. The cathode processor removes adhering salt and/or cadmium from the product via vacuum distillation.

Fission products accumulate in the ER salt, eventually making it necessary to remove salt for disposal of a ceramic high-level waste. The ceramic waste process consists of absorption of the salt first by dried zeolite-A followed by blending in glass frit and finally heating to over 900^{o}C to form a ceramic waste ingot. The ceramic waste form is comprised of sodalite regions interspersed in a glass matrix.

Cladding hulls and undissolved fission products and actinides are separated from salt in the metal waste furnace and melted into ingots of metal waste. Zirconium is added to the metal waste furnace feed to lower the melting point of the metal waste and produce a durable phase for fission products.

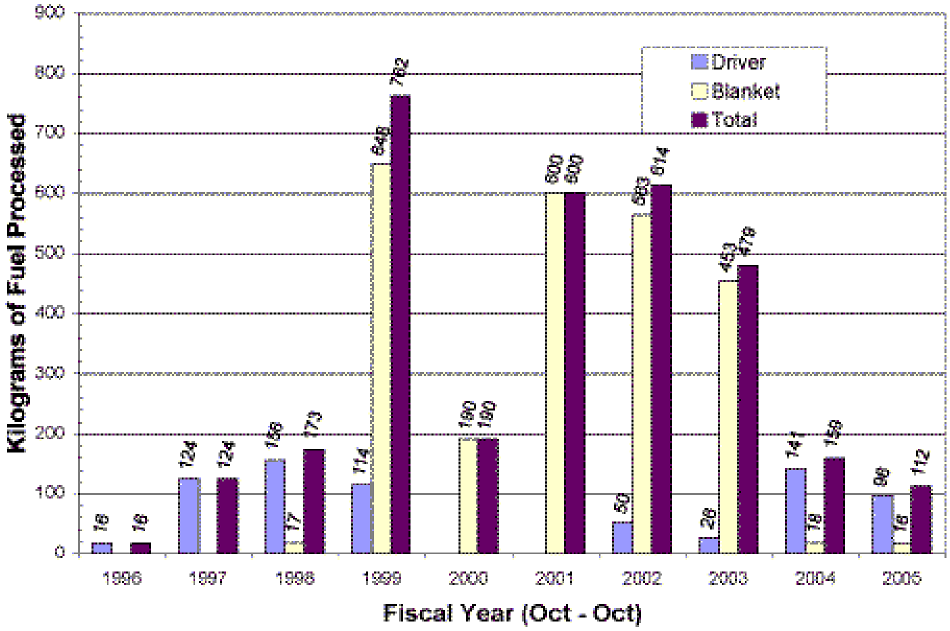
Note that this version of the process is what has been implemented to date and does not entirely reflect how the process should evolve in the future to accommodate the processing options discussed in this report. While the liquid cadmium cathode (LCC) functionality is included for group actinide removal, these actinides are currently recycled to the Mark-V electrorefiner instead of being used to fabricate new fast reactor fuel.

Figure 4. Current Flowsheet for Pyroprocessing of Spent EBR-II Fuel.



From 1996 through 1999, pyroprocessing of spent EBR-II fuel was successfully demonstrated with 1.1 MTHM of fuel processed (0.4 MTHM EBR-II driver and 0.7 MTHM blanket). An April 2000 National Research Council (NRC) report noted that the pyroprocessing demonstration met all the established success criteria [ref. 5]. Since the completion of the demonstration, additional fuel has been processed each year to both support completion of the fuel treatment and to provide valuable research data for process development. The amount of fuel processed in each year is shown in Figure 5. More than 3.2 MTHM of EBR-II spent fuel have now been treated. Quantities were largely limited by DOE funding levels and priorities. Following the completion of the demonstration in FY2000, staffing levels were decreased from 84 hours per week to 40 hours per week operations. Improved process equipment and process operating conditions have been implemented to increase the capabilities of the process.

Figure 5. Fuel Processed Each Year from FY-1996 through FY-2005.



The initial and remaining inventory of EBR-II and FFTF sodium-bonded spent fuel is summarized in Table 1. Two MTHM of the spent EBR-II driver fuel is currently stored at INTEC in wet storage. The driver fuel treated to date was spent EBR-II driver stored at MFC, but only 0.4 MTHM remains from this source. Other sodium-bonded spent fuel from the DOE complex, such as Fermi-1 blanket and sodium-bonded rubble material from Sandia National Laboratory, is not included in the table.

Table 1. Sodium-Bonded Metal Spent Fuel from EBR-II and FFTF

Fuel Type	EBR-II Driver (MTHM)	EBR-II Blanket (MTHM)	FFTF Driver (MTHM)	Total (MTHM)
Initial Fuel June 1996	3.1	22.4	0.25	25.75
Fuel Treated as of September 2005	0.7	2.5	0	3.2
Remaining Untreated Fuel	2.4	19.9	0.25	22.55

3.3 Sodium Removal and Deactivation

Two different processes, melt-drain-evaporate-carbonate (MEDEC) and fuel decladding with sodium removal through alcohol wash, have been used or tested for removal and deactivation of sodium from sodium-bonded fuel. These processes are only applicable to either Fermi-1 or EBR-II blanket fuels. For driver fuel, the sodium removal option would not be viable because elemental sodium has become infused into the fuel alloy. It cannot be completely removed without dissolving the fuel.

The MEDEC technology was initially developed and tested in the 1980s to remove sodium from EBR-II fuel elements that had not been irradiated. The process uses a combination of heat and reduced pressure to melt and vaporize bond sodium, removing it from the metal fuel. The fuel elements are prepared by cutting off the ends. The elements are then heated to 650°C under reduced pressure (200 mTorr). After melting, the sodium evaporates and is condensed in a separate container. Once the sodium has been successfully removed, the cleaned fuel rods (Figure 6) can be packaged for direct disposal. The entire process is undertaken within an argon atmosphere to prevent reaction of sodium with oxygen or moisture in the atmosphere.

In FY2002, MEDEC tests were performed on unirradiated Fermi-1 fuel to verify process operating parameters and to support development of a cost estimate. In FY2003, additional MEDEC tests were run on an EBR-II blanket element that had been irradiated to a low burn-up similar to that experienced by the Fermi-1 blanket. The tests with irradiated EBR-II blanket fuel showed that the process was effective at removing all of the detectable elemental sodium. However, radioactive cesium and trace amounts of plutonium were measured in the sodium that had been separated and collected. It is also important to note that the EBR-II blanket elements used for this test had relatively low burn-up compared to a majority of the blanket fuel. It is speculated that the cesium and plutonium contamination issue might be significant when processing higher burn-up elements, and even a low level of porosity from fission gas formation might affect the ability to remove all of the sodium. The Fermi-1 and EBR-II blanket elements that were tested had virtually no porosity.

The information from the aforementioned MEDEC experiments was used to develop concepts and cost estimates for processing both Fermi-1 and EBR-II blanket. Fermi-1 blanket could be treated in a glovebox, but EBR-II blanket would need to be treated in a hot cell. In all cases, the evaporated sodium must be converted into a final waste form. At DOE's Idaho site, a facility exists for performing sodium metal conversion to sodium carbonate. However, this facility has restrictive limits on acceptable plutonium levels and limited shielding for radioisotopes like cesium. This facility could be used for treatment of sodium from Fermi-1 blankets, but the presence of plutonium and cesium in the sodium from EBR-II blankets might preclude its use. Additional evaluations are needed to determine if this conversion method is feasible.

An alternative to MEDEC for sodium removal is the fuel decladding and sodium removal through alcohol wash process that was used successfully by Rocketdyne Corp (Canoga

Park, CA) in the mid 1980s to remove sodium from 17 MTHM of spent EBR-II blanket fuel. In this process, fuel element cladding was cut to expose the fuel slugs, which were then soaked twice in an alcohol bath containing 20% water. The alcohol wash solution was solidified as sodium carbonate and disposed of as low-level waste. This process has not been tested recently, and no life cycle cost estimates have been prepared for alcohol wash of either Fermi-1 or EBR-II blanket fuel.

The recovered slugs from either sodium removal process would be either packaged for permanent disposal at the geologic repository or further processed by aqueous separations technologies like Uranium Extraction Plus (UREX+), a technology being developed by DOE.

Figure 6. Fermi-1 Blanket Rod after Sodium Removal by MEDEC Process

3.4 Direct Disposal

For direct disposal, fuel assemblies are packaged into standard canisters and shipped to a permanent repository to be disposed as spent nuclear fuel. If additional containment is needed, the fuel could first be sealed in high-integrity cans and then packaged into standard canisters. This option is being considered for Fermi-1 blanket fuel. Direct disposal would need to be approved by the Environment Protection Agency (EPA) because it would involve placing characteristic reactive waste into a permanent waste repository.

3.5 Other Options

Aqueous technologies have been assessed for treatment of sodium-bonded fuel after removal of bond sodium. DOE's Savannah River Site (SRS) has the only operational facility for aqueous reprocessing in the United States. Historically, this facility processed aluminum-clad fuels and would require modifications or pretreatment of the sodium-bonded spent fuel. Decladding and alcohol wash were used in the 1980s to remove the cladding and sodium from EBR-II blankets, and the resulting fuel slugs were processed at SRS. Since this option would require front-end sodium removal and deactivation, the cost for this option would be greater than sodium removal and disposal.

Research on UREX+ has focused on treatment of commercial reactor oxide fuel, but this technology could be applied to treatment of sodium-bonded spent fuel after removal of bond sodium. Adequate details, however, do not exist at this time to develop life cycle costs for treating sodium-bonded fuel using this technology. DOE will continue to assess progress in this area to determine if significant cost savings can be achieved for sodium-bonded fuel.

Development of the other technologies such as melt and dilute, chloride volatility, fluoride volatility, and plasma arc processing are not currently funded by DOE for treating sodium-bonded fuel.

A summary of disposal options is provided in Table 2. The five main treatment options are pyroprocessing, sodium removal via MEDEC, sodium removal via alcohol wash, UREX+, and direct disposal. Pyroprocessing EBR-II fuel is ongoing at INL and could be applied to all types of sodium-bonded fuel. The record of decision for the EIS identified it as the preferred treatment for all sodium-bonded fuel except the Fermi-1 blanket. MEDEC and alcohol wash can be applied to both EBR-II and Fermi-1 blankets. Both technologies have been demonstrated with spent fuel. MEDEC tests were performed as recently as 2004, while the alcohol wash process has not been performed since the 1980s. UREX+ has been demonstrated recently at laboratory scale with commercial oxide spent fuel. UREX+ tests with sodium-bonded spent fuel have not been performed, but metal fuel has been processed by other aqueous technologies after bond-sodium was removed.

Table 2. Feasibility of Processing Options by Fuel Type

Fuel Type	Pyroprocess	MEDEC	Alcohol Wash	UREX+	Direct Disposal	Comments
EBR-II driver	on-going operations (preferred)	N/A	N/A	N/A	N/A	Sodium infused within the fuel matrix
FFTF driver	preferred option	N/A	N/A	N/A	N/A	Sodium infused within the fuel matrix
EBR-II blanket	on-going operations (preferred)	Demonstrated on engineering-scale non-irradiated fuel in 1980s. Lab-scale demonstrations in 2004.	Demonstrated on engineering scale in 1980s.	Feasible for transuranic recovery after sodium removal	N/A	Bulk of sodium separate from fuel matrix. High plutonium content due to long irradiation.
Fermi-1 blanket	feasible	preferred option	feasible	not useful due to low transuranic content	under evaluation	Bulk of sodium separate from fuel matrix. Low plutonium content due to short irradiation.

4. Minimum Research and Development Needs

In addition to meeting AFCI fuel treatment goals, continued pyroprocessing of both EBR-II driver and blanket fuel supports research needs for the Global Nuclear Energy Partnership (GNEP). GNEP is focused on transmutation of transuranics in Advanced

Burner Reactors (ABRs). Pyroprocessing of metal fuel is considered to be a leading technology for the ABR fuel cycle. For pyroprocessing to be implemented cost-effectively at the needed scale for GNEP, a number of critical R&D areas need to be emphasized:

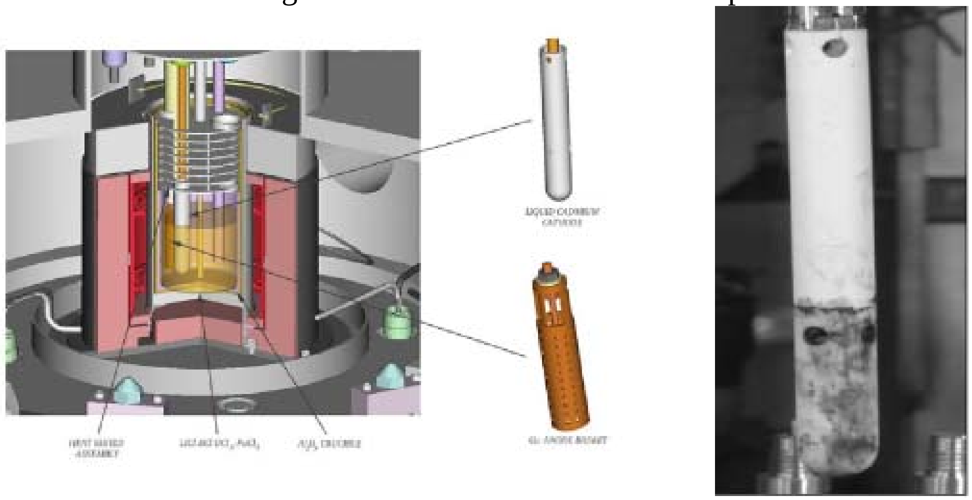
- Group actinide recovery
- Electrorefining using high transuranic (TRU)-content salt
- Advanced materials for pyroprocessing
- Electrorefining of ternary (U-Pu-Zr) fuel
- Engineering-scale waste processing

For demonstrating *group actinide recovery* and assessing the effect of the transuranic concentration in the salt, process tests and experimental data are needed to optimize operations and confirm theoretical models. The Hot Fuel Dissolution Apparatus (HFDA) has been used for these types of experiments at a small scale in the past and is ideally suited for further experimentation in the area (see Figure 7). Additionally, engineering-scale transuranic recovery equipment needs to be further tested so the recycle system for an ABR can be designed and materials can be recovered for advanced fuel fabrication. It is estimated that a minimum of 4 MTHM of additional EBR-II blanket would be needed for these operations. This is based on raising the Pu inventory in the Mark-V ER to the calculated limit of 50 kg. However, treating this quantity of blanket fuel will only raise the fission product concentration slightly due to the small amount of fission that occurred in the blanket. Data on group actinide recovery at various fission product concentrations needs to be well understood because it is a key limit in advanced fuel design. Since the Mark-IV electrorefiner processes primarily driver fuel that contains more fission products, the Mark-IV ER salt has a higher concentration of lanthanides than the Mark-V. Therefore, small quantities of Mark-IV ER salt could be transferred to the Mark-V ER to increase the fission product concentration. This controlled addition of salts will facilitate acquiring group actinide recovery data with representative levels of both Pu and fission products in the salt.

Coatings are applied to the graphite crucibles are used in high temperature operations to prevent interaction between metal ingots and the crucibles. Application of these coatings is labor intensive and the coatings react with process material to form dross. Several promising candidate advanced materials to replace the coated graphite have been tested at laboratory scale, but further testing is needed at engineering-scale with representative fission products. The successful scale-up of these materials will improve processing throughput, reduce costs, and minimize the need for handling secondary waste streams. This testing can be conducted simultaneously with treatment of at least 0.2 MTHM of EBR-II driver fuel.

An ABR would utilize fuel containing high concentrations of transuranics, while engineering-scale pyroprocessing operations have been limited to uranium-based fuel. Experiments involving treatment of ternary fuel (U-Pu-Zr) would provide data for some of the proposed ABR fuels. Approximately 10 kg of ternary fuel are part of the FFTF driver fuel inventory, which would provide sufficient material for these experiments.

Figure 7 – Laboratory-Scale Equipment for Group Actinide Recovery Experiments using Salt from Treatment of EBR-II Spent Fuel



For any separations process, the production of suitable high-level waste forms is a requirement. Pyroprocessing results in two high level waste forms—ceramic waste and metal waste. A photograph of the metal waste furnace to be installed in the Hot Fuel Examination Facility (HFEF) is shown in Figure 8. The viability of both types of waste forms has been demonstrated using laboratory-scale samples, and scale-up of these processes has progressed. But further development in the area of scale-up still needs to be completed. The metal waste furnace is close to being qualified for operation, but ceramic waste process qualification has not begun, additional equipment and laboratory-scale tests still need to be performed before qualification can begin. Work in this area needs to be completed, even if no additional fuel is processed via pyroprocessing, since approximately 1100 kg of fission product and actinide contaminated salt has accumulated to date from driver and blanket processing. Note that this salt is physically split between the electrorefiners and the unprocessed cladding hulls. The unprocessed cladding hull mass, not including salt, is approximately 750 kg. With the metal waste furnace close to being qualified, the following research and minimum production tasks are the focus for waste processing.

- Complete lab-scale testing to support ceramic waste process parameter selection
- Complete qualification of the ceramic waste process
- Process at least 1100 kg of fission product
- and actinide contaminated salt in the ceramic waste process
- Process at least 750 kg of cladding hulls in the metal waste furnace

Table 3 summarizes sodium-bonded fuel needs to support R&D for AFCI. An additional 0.2 MTHM of EBR-II driver fuel, 4 MTHM of EBR-II blanket fuel, and 0.01 MTHM of FFTF driver fuel are needed. Note that this does not include the ceramic waste and metal waste production activities.

Figure 8 – Early Testing of the Prototype Metal Waste Furnace Used for Pyroprocessing

Table 3 – Research and Development Needs by Fuel Type

Fuel Type	Quantity (MTHM)	Technology Needs
EBR-II driver	0.2	Develop advanced crucible materials for processing uranium product and metal waste.
FFTF driver	0.01	Obtain additional experimental data processing ternary (U-Pu-Zr) fuel elements.
EBR-II blanket	4	Obtain additional experimental data for electrorefining and group actinide recovery at different transuranic salt concentrations. Recover group actinide product for fast reactor fuel fabrication.

5. Processing and Disposal Options

Previous Work
From 1996 to 1999, DOE performed a successful technology demonstration of pyroprocessing for treating sodium-bonded spent nuclear fuel. In 1998, DOE asked the National Research Council (NRC) to evaluate alternative technologies to pyroprocessing for treating sodium-bonded fuel. A Spring 1998 NRC Status Report stated all alternative technologies, with the exception of plutonium and uranium recovery by extraction (PUREX), are at an early stage of development and would require significant research and development (R&D) as well as “hot” demonstrations using spent nuclear fuel [ref. 6].

The report also stated that the over pack (i.e., direct disposal) alternative for sodium-bonded fuel did not require processing, but direct emplacement of sodium-bonded apent nuclear fuel (SNF) was precluded by DOE policy concerning acceptance at Yucca Mountain of RCRA hazardous waste. A report of the Idaho National Engineering and Environmental Laboratory Spent Nuclear Fuel Task Team made the same conclusion on direct disposal [ref. 7]. The report concluded that sodium-bonded fuels are not suitable for repository disposal and therefore must be treated.

Following the pyroprocessing demonstration, DOE prepared the Environmental Impact Statement (EIS) for the Treatment and Management of Sodium-Bonded Spent Nuclear Fuel [ref. 8]. Six processing options were evaluated in that EIS, and each was found to have comparable environmental impact. Pyroprocessing of all sodium-bonded fuel except for Fermi-1 blanket was identified as the preferred alternative by DOE. A separate cost evaluation of treatment technologies and a no-action alternative (direct disposal) was also prepared [ref. 9]. The evaluation concluded that costs for treatment options still under consideration were similar. The no-action alternative cost was lower than treatment options, but the report identified two key technical uncertainties with direct disposal, absence of a clear disposal path without treatment and the effects of long-term storage of the spent fuel. The Record of Decision for the EIS stated that DOE would use pyroprocessing for all sodium-bonded fuel except that from the Fermi-1 reactor [ref. 10]. Because of different physical characteristics of the Fermi-1 sodium-bonded fuel, DOE decided to continue to store this material while alternative treatments were evaluated. Implementation of pyroprocessing treatment of the EBR-II sodium-bonded spent fuel started in 2000.

In March 2001, three DOE offices (Office of Nuclear Energy, Office of Civilian Radioactive Waste Management, and Office of Environmental Management) issued a report to Congress stating there is a clear and final disposition for all waste forms resulting from pyroprocessing and that no further treatment would be required beyond the metal and ceramic waste processing depicted in Figure 4 [ref. 11]. In October 2003, DOE Office of Nuclear Energy reported to Congress that pyroprocessing remains the preferred path for treating EBR-II fuel, but DOE would continue to evaluate alternatives that could provide significant cost savings [ref. 12].

Options for Completion of Treatment Project

Based on previous studies and recent experimental data, processing options have been identified to minimize life cycle costs while maximizing experimental data that support the successful development of pyroprocessing for fast reactor fuel. In addition to treating fuel via either electrorefining or MEDEC (blanket only), each option includes the installation and operation of the ceramic and metal waste processing equipment. This is essential, because 1100 kg of electrorefiner salt and 750 kg of cladding hulls and fuel hardware already exist and require conversion to their final high level waste (HLW) forms. Specifically, the options that have been evaluated are listed below [ref. 13].

1. *Minimum Fuel Option*: EBR-II driver and FFTF fuel would be processed using existing pyroprocessing equipment with emphasis on experiments to improve on-

line monitoring and improved uranium recovery. EBR-II blanket fuel would be processed by sodium removal by MEDEC and packaged for disposal. Two variations for the recovered high enriched uranium (HEU) from the electrorefined driver fuel were evaluated:

   A. HEU blended to low enriched uranium (LEU) in ingot form for interim storage
   B. HEU processed into a form and purity that can be used by commercial fuel fabricators.

2. *Group Actinide Extraction Option*: EBR-II driver fuel, FFTF fuel, and EBR-II blanket fuel would be processed using upgraded existing pyroprocessing equipment. This option would initially concentrate on driver processing but would include engineering-scale group actinide recovery experiments to support advanced equipment design efforts and recovery of transuranics for advanced fast reactor fuel development. Upon the completion of processing driver fuel, facility criticality safety rules would be revised and existing equipment upgrades would be implemented to accommodate increased blanket fuel throughput. During the blanket processing, experiments would be performed to demonstrate the process of group actinide extraction from a molten salt containing significant fission products. In addition, new process monitoring that improves proliferation resistance would be tested. Two variations of this option have been evaluated:
   A. Group actinide recovery experiments would be conducted. The recovered actinides would be returned to the electrorefiner and eventually processed for HLW disposal.
   B. Actinides would be recovered for experimental fuels that can be fabricated as part of the AFCI fuels program.
3. *High-Throughput Demonstration Option*: EBR-II driver and FFTF fuel would be processed using upgraded existing equipment followed by processing blanket fuel with the "next generation" high-throughput electrorefiner and cathode processing equipment based on AFCI experimental results. This option would also include the group actinide recovery and process monitoring for proliferation resistance demonstrations.

For each processing option, two different staffing levels were considered:

- Personnel would be available on the standard INL work schedule (currently 80 hours in nine days of operations every two weeks; herein called the "40-hr staffing level").
- Operations and support staff would be increased to support 12-hour workdays and seven days per week operations with minimum support for backshift operations (herein called the "84-hr staffing level").

6. Cost and Schedule Estimate Summary for Processing and Disposal Options

The costs and schedules were based on our operating experience with sodium-bonded fuel both in our pyroprocessing operations and the development work that has been done on the MEDEC process. For each of the scenarios, throughput rates were established for the treatment, ceramic waste, and metal waste operations. In addition, specific equipment requirements and high level waste disposal quantities were identified with costs developed for the individual items. The technical basis section describes the methods for establishing throughputs and equipment needs. For the operating cost estimates, the staffing levels were based on the historical operating experience in our hot cells and include facility staff, necessary support personnel and materials and supplies for the projected operations and maintenance. The research and development costs were also based on our experience in developing the present equipment. The total costs are dominated by labor costs because the majority of the equipment is already installed.

6.1 Technical Basis

Fuel Treatment. Two types of fuel processing were considered—electrorefining and MEDEC. MEDEC would only be used for Options 1A and 1B to treat the remaining EBR-II blanket. The throughput for the MEDEC process was estimated to be 1420 kg/year based on an analysis performed in FY2004 [ref. 14]. For pyroprocessing, the driver treatment rate was assumed to be up to 140 kg/year for the 40-hr staffing level and up to 360 kg/year for the 84-hr staffing level. The 140 kg/year rate is an improvement over the current rate of 108 kg/year, largely attributed to improvements in the cathode processor batch size, in process crucibles used in the cathode processor and casting furnace, and a small increase in project staffing level. The blanket treatment rate was assumed to be up to 1000 kg/yr for the Mark-V at a 40-hr staffing level and 2500 kg/yr for the Mark-V at an 84-hr staffing level. When using a high-throughput ER and cathode processor, the rates were estimated to be 2000 kg/yr for 40-hr staffing and 5000 kg/yr for 84-hr staffing. With 40 hours per week operations, the maximum amount of blanket material processed during a year to date is 600 kg. To increase the blanket treatment rate to 1000 kg/year, an in-cell equipment handling station would need to be added and the previously mentioned improvements to process crucibles for the cathode processor would be needed.

Ceramic Waste. The following elements in the fuel were assumed to accumulate in the salt as chlorides: Na, Rb, Sr, Y, Cs, Ba, La, Ce, Pr, Nd, Pm, Sm, Eu, Gd, Np, Pu, and Am. Uranium chloride also exists in the salt but was assumed kept at a constant mass (25 kg) via controlled addition of the oxidant. For Options 2B and 3, it was assumed that the transuranics were periodically removed from the Mark-V ER using a liquid cadmium cathode (LCC) to make fast reactor fuel. However, this was only done to the extent needed to prevent hitting the Pu-limit (50 kg) for the Mark-V ER. While 135 kg transuranics from the blanket would be collected for fast reactor fuel fabrication, 115 kg of transuranics would be allowed to go into the ceramic waste. This amount of transuranics do not need to go into the ceramic waste, but that was the assumption for the calculations made for this report.

In order to calculate the ceramic waste generated each year, the total amount of salt available for processing was calculated as a function of cumulative fuel treated. Salt was only considered available for disposal if (1) the electrorefiner was finished with its mission or (2) salt had been removed from the electrorefiner to prevent it from exceeding the liquid volume limit for the vessel. A discrete event model was created as a tool to estimate processing rates. In the model, several processing operations were linked until either all of the driver or all of the blanket was processed. The different processing operations were electrorefining, salt removal, salt replacement, salt dilution, and group actinide recovery.

What drove the logic behind each step was to try to get the salt volume to the limit (Mark-IV = 415 liters, Mark-V = 449 liters) as fast as possible without exceeding the nominal NaCl limit (mole fraction of 0.3) and without exceeding the total plutonium inventory limit (12 kg for the Mark-IV and 50 kg for the Mark-V). In each case, the model calculated an increasing volume of salt kept outside of the ER. This salt was considered eligible for disposal in the ceramic waste process.

Table 4 shows Option 2A produces much more blanket-derived salt waste (i.e., 2.8 MT) than the other options because the entire inventory of EBR-II blanket is being treated in the Mark-V without removing any transuranics for fuel fabrication. Plutonium concentration, rather than NaCl, becomes the limiting factor in Mark-V ER operations. A relatively high rate of both LiCl-KCl dilution and removal of salt from the Mark-V ER are needed. In Option 2B, only 450 kg of LiCl-KCl needs to be added to the Mark-V ER, while in Option 2A that total is nearly three times larger at 1300 kg.

Table 4. Total Salt Generation from Fuel Treatment

Option	**Fuel Type**	**Total salt (MT)**
1A	Driver	1.0
1A	Blanket	0.7
1B	Driver	1.0
1B	Blanket	0.7
2A	Driver	1.0
2A	Blanket	2.8
2B	Driver	1.0
2B	Blanket	1.7
3	Driver	1.0
3	Blanket	1.7

Based on scale-up research and development needs, installation of the ceramic waste processing equipment is planned for FY2011, and processing could start in FY2012 at 50% the maximum rate (maximum ~ 380 kg salt—one ceramic waste form per month). The rate of waste salt removal from the ER limits the rate of ceramic waste form (CWF) processing. Since an entire ER full of salt is available after the last year of treatment, it is necessary that the ceramic waste process run 2 to 3 years after fuel processing is complete. In most options, the ceramic waste processing rate was low for several years and then ramped up to the maximum or near-maximum level in the last few years. Ceramic waste processing rates were based on 8 kg of salt per 100 kg of salt-loaded zeolite and glass v-mixer batch. Four v-mixer batches were required to load each ceramic waste furnace batch. The ceramic waste form is assumed to be a total of 400 kg, containing 8 wt% salt.

Metal Waste. The metal waste amount for each fuel type was calculated by summing B, C, N, Al, Si, P, S, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Ge, As, Se, Zr, Nb, Mo, Tc, Ru, Rh, Pd, Ag, Cd, In, Sn, Sb, Te, Ta, and W. Extra zirconium was added to bring the zirconium fraction up to 15 wt% in each case. Total metal waste amounts for each fuel are given in Table 5. While the total metal waste from all of the fuel sums to 6.0 MT, it should be noted that Options 1A and 1B would involve generating only 3.1 MT of metal waste because cladding hulls from the unprocessed EBR-II blanket would be carried along with the fuel after MEDEC treatment and not be separated into the metal waste stream.

Table 5. Metal Waste Quantities by Fuel Type

Fuel Type	Mass of Metal Waste (kg)
EBR-II driver	944
INTEC-driver	1545
FFTF	237
EBR-II blanket	3273

The batch size for the metal waste furnace was 60 kg (metal), which is what the typical ingot mass has been during process development in the prototype metal waste furnace. Yearly totals of 50 to 500 kg of metal waste were processed as fuel was treated to avoid waste accumulation and to recycle the salt. For each option, the yearly throughput rates for the metal waste furnace were chosen with the following guidelines:

- Metal waste processing should be complete in the same year as electrorefining.
- The cumulative metal waste treated by any year had to be less than or equal to the amount of metal waste produced to that point in time.
- A 500-kg annual throughput was used as the maximum, so staffing levels would be minimized.
- Processing rates were not allowed to fluctuate up and down from year to year. They were either constant or increased with time, consistent with the operating facility becoming more proficient with the process.
- The first year's throughput was never more than half of the maximum annual throughput.

Equipment. Support operations to keep equipment running and support minor upgrades for the entire process have been included in the cost estimates. In some cases, new equipment has also been included. Specifically in support of processing ceramic waste, costs were included for out-of-cell equipment to qualify the ceramic waste process as well as upgrades of in-cell HFEF equipment and installation of new in-cell equipment. New out-of-cell equipment includes a v-mixer, salt handling glove box, and salt roller mill. In-cell equipment includes a new production ceramic waste furnace and upgrades to the ceramic waste support station, v-mixer, and grinder/classifier. In support of processing metal waste, costs were included for installation of the metal waste furnace, support table, and condensate sampling furnace in-cell (HFEF). In support of high-throughput electrorefining (Option 3), costs were included for development, design, fabrication, and installation of both a new high-throughput electrorefiner and a new high-throughput cathode processor in the Fuel Conditioning Facility (FCF). The cumulative cost of these engineering development activities is estimated to be $69.9M, spanning over 8 years. This number was estimated based on the actual costs for developing and implementing the present electrorefiners and the costs that were incurred to remove and dispose of a first generation driver element chopper. It includes the cost of removing an existing electrorefiner to make room for the high-throughput electrorefiner (HTER) but does not include final decommissioning costs. The investment to develop a higher-throughput electrorefiner and cathode processor may not prove cost effective just for treating the relatively small fuel masses involved in this project, but such an investment probably would prove economical for larger scale future spent fuel treatment activities as might be seen as a result of the proposed GNEP.

In support of MEDEC (Options 1A and 1B), costs were included for development, design, fabrication, and installation of an in-cell furnace for performing the necessary sodium distillation [ref. 14]. In support of fuel receipt, equipment costs were included for equipment in HFEF to receive, unload, inspect and store both INTEC and FFTF fuel. However, the costs were not included for packaging and shipping the fuel from its present location at either INTEC or FFTF. These equipment costs are listed as part of receipt and store cost for operations.

Disposal. Disposal costs for all five basic options were based on final waste volume and numbers of canisters that would be required to package, transport and dispose of that volume of waste at Yucca Mountain. With regard to MEDEC disposal costs, the two options that included MEDEC processing of EBR-II blanket fuel (i.e., Options 1A and 1B) identically required 77 canisters [ref. 14]. That 2004 estimate determined a total cost to retrieve, package, qualify waste, purchase 77 canisters, load/certify the waste in those 77 canisters (including INTEC costs), transport those packages to Yucca Mountain (including payment of Yucca Mountain disposal fees) of $1.22M for each of the 77 canisters without contingency. Assumptions underlying the cited reference were re-evaluated in January 2006 and considered accurate. A 40% contingency was applied to this task bringing the January 2006 estimated cost per canister to $1.7M including the canister itself, loading, qualification, certification, shipping, disposal fee, and a 40% contingency. The estimated total disposal cost attributable to 77 canisters of MEDEC-derived waste is $131.3M. With regard to metal and ceramic waste disposal, all five options include metal and ceramic waste production and disposal at Yucca Mountain. The January 2006 cost per canister is estimated to cost $1.75M including the canister itself, loading, seal certification, shipping, disposal fee and a 40% contingency. Options 1A and 1B (which utilized MEDEC treatment of EBR-II blanket fuel) each produced 31 canisters of metal and ceramic waste. The estimated total disposal cost attributable to 31 canisters of metal and ceramic waste in Options 1A and 1B is $54.2M. Option 2A produced 80 canisters of metal and ceramic waste. The estimated total disposal cost attributable to 80 canisters of metal and ceramic waste in Scenario 2A is $140M. Options

2B and 3 each produced 50 canisters of metal and ceramic waste. With total disposal cost of $87.5M.

Table 6 summarizes numbers of canisters and total disposal costs for the five cases. MEDEC-based treatment of EBR-II spent fuel incurs an additional $98M disposal cost compared to the Group Actinide Extraction Option in which transuranics are recovered for experimental fuels fabrication as part of the AFCI Program (Option 2B).

Table 6. Quantity of Waste Canisters

Scenario	MEDEC Canisters	MWF & CWF Canisters	Total Canisters	Total Cost ($M)
1A	77	31	108	186
1B	77	31	108	186
2A		80	80	140
2B		50	50	88
3		50	50	88

6.2 Cost and Schedule Estimates

The cost-to-date for processing EBR-II spent fuel is approximately $142M. This includes R&D costs for fuel and waste treatment, equipment development, and operations costs for treating EBR-II driver and blanket fuel. Table 7 summarizes the estimated cost-to-completion (CTC) for each of the five processing options at two different staffing levels, largely based on the technical basis given in Section 6.1 and the technical risks listed in the appendix. Additionally, contingencies were estimated based on activity type and uniformly applied to labor, materials and supplies within that activity across all five options and two operations work schedules. The levels varied from 10 to 40%, based on the estimated level of technical risk. Examples of high-risk (40% contingency) activities are MEDEC and HTER equipment development. Examples of low-risk activities are ceramic waste process researcher support and fuel processing in FCF. No escalation or discounting was applied to the annual cost estimations.

Table 7. Cost to Completion and Processing Completion Dates for Processing Options

Option	Staffing (hrs/wk)	Total CTC ($M)	CTC for Driver Treatment	CTC for Blanket Treatment	CTC for Waste Processing	CTC for HLW Disposal
1A	40	550	150.1	133.2	81.3	185.6
1A	84	496	110.3	133.2	67.3	185.6
1B	40	558	155.0	133.2	83.8	185.6
1B	84	512	125.7	133.2	67.3	185.6
2A	40	594	150.1	143.9	159.7	140.0
2A	84	487	110.3	106.6	129.8	140.0
2B	40	526	155.0	140.6	143.0	87.5
2B	84	405	125.7	84.0	108.4	87.5
3	40	552	155.0	175.5	133.7	87.5
3	84	472	125.7	153.9	105.1	87.5

For clarification, the cost groupings in Table 7 are explained below.

Driver Treatment includes costs for the following:

1. Fuel receipt
2. Equipment for fuel receipt
3. Fuel treatment (pyroprocessing) operations
4. Engineering support for driver treatment

Blanket Treatment includes costs for the following:

1. Fuel treatment (pyroprocessing) operations (Options 2A, 2B, and 3)
2. Fuel treatment (MEDEC) operations (Options 1A and 1B)
3. Equipment to support MEDEC processing (Options 1A and 1B)
4. Engineering support for blanket treatment

Waste Processing includes costs for the following:

1. Complete development of metal waste equipment
2. Complete development of ceramic waste equipment
3. Metal waste processing (operations)
4. Ceramic waste processing (operations)
5. Engineering support of waste equipment
6. Ceramic waste process researcher support

HLW Disposal includes costs for the following:

1. Co-disposal of metal and ceramic waste
2. Disposal of sodium-free blanket fuel

The relatively high cost of blanket treatment for Option 3 is due to the high estimated cost of developing, building, and installing high-throughput electrorefining and cathode processing (CP) equipment. Under the study assumptions, there is neither time nor spent fuel inventory to recoup those development costs in Option 3 as compared to Options 2A or 2B. The waste processing cost for Option 2A is extremely high due to the long time period needed to treat the waste under that option. While Options 1A and 1B have been touted as *Minimum Treatment*, they are not the cheapest options due to the cost of waste treatment and disposal (see Table 6). First, it must be recognized that legacy salt waste already exists from blanket treatment. Ceasing processing of EBR-II blanket fuel would do nothing to alleviate the burden of treating existing salt waste accumulated in the Mark-V ER. There are currently about 560 kg of salt associated with the Mark-V ER that are contaminated with fission products as well as actinides. Approximately 6.8 MT of ceramic waste (HLW) would need to be produced from this salt—for only 2.5 MTHM treated. If Option 2B or 3 were to be pursued, the total salt associated with the Mark-V ER would increase to 1750 kg, resulting in 20.9 MT of ceramic waste—for 22.4 MTHM treated. A factor of 8.4 increase in fuel treated, thus, only results in a factor of 3.1 increase in the amount of ceramic waste. Second, there would be a significant cost to dispose of the sodium-free EBR-II blanket fuel.

Table 8 gives estimated completion dates, for driver treatment, blanket treatment, waste processing, and waste shipment. Annual breakdowns that include FTE's, cost, and mass of fuel and waste treated are given in the Appendix. As can be seen in Table 8, DOE's commitment to the State of Idaho to remove spent nuclear fuel by 2035 would not be met with Options 2A-40, 2B-40, or 3-40 were pursued.

Table 8. Estimated Completion Dates for Procession Options

Option	Staffing (hrs/wk)	Driver Treatment	Blanket Treatment	Waste Processing	HLW Disposal
1A	40	2025	2033	2027	2035
1A	84	2014	2030	2017	2035
1B	40	2025	2033	2027	2035
1B	84	2014	2033	2017	2035
2A	40	2025	2043	2045	2046
2A	84	2014	2022	2025	2035
2B	40	2025	2043	2045	2046
2B	84	2014	2021	2024	2035
3	40	2025	2034	2036	2037
3	84	2014	2020	2022	2035

7. Preferred Treatment Option

The preferred treatment alternative is to pyroprocess all remaining EBR-II fuel and FFTF fuel (Option 2B) using an 84-hr staffing level, with TRU and HEU recovered for new fuel fabrication. The major advantages are as follows.

1. Lowest cost option
2. Lowest amount of high level waste generated
3. Sodium hazard removed from all EBR-II and FFTF sodium-bonded metal fuel
4. Significant research, development and demonstration for GNEP and AFCI

5. Fuel treated and shipped out of the state well ahead of DOE's committed date to the State of Idaho
6. Transuranics recovered for an Advanced Burner Test Reactor (ABTR)
7. Minimal staffing level fluctuations (see Figure 9)

While there is an advantage in choosing Option 3—development of high-throughput electrorefining and cathode processing equipment—it is believed to be off-set by the cost advantage of Option 2B. As previously noted, the advantages of higher-throughput equipment await larger masses of sodium-bonded spent fuel than is required to be treated today. A work schedule optimized for use of existing electrorefining and cathode processor equipment, as assumed to be the case for Option 2B, should provide the data necessary to scale-up these processes when necessary. This operational experience would supplement the research and development activities on high-throughput electrorefining so a next generation electrorefiner could be installed in the Advanced Fuel Cycle Facility (AFCF).

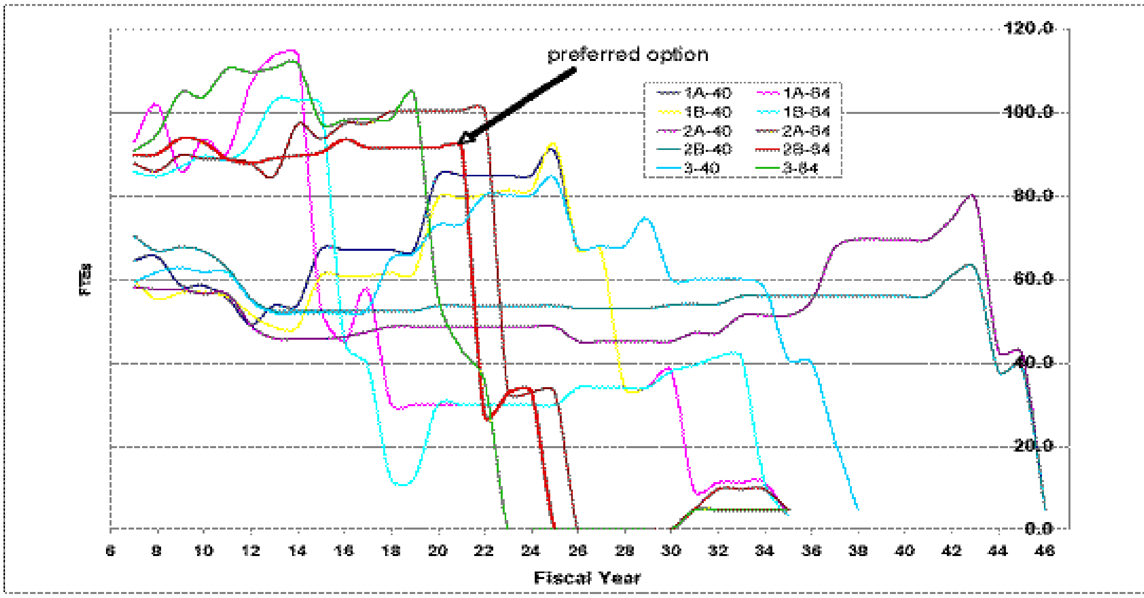
In Table 9, the cost to completion for Option 2B-84 is further sub-divided by fuel type and activity. In contrast with Table 7, FFTF and EBR-II driver fuels are considered separately, with the given FFTF costs coming from a formal cost analysis [ref. 15]. Previously, equipment costs were spread between treatment and waste processing, but they are called out specifically in Table 9. Likewise, fuel shipment and receipt was previously lumped together with processing in the treatment category, but in Table 9 it is considered separately.

Table 9. Summary of Scenario 2B-84 Costs Organized by Fuel Type and Activity

	Fuel Type			
Activity	**EBR-II Driver at MFC & INTEC ($M)**	**FFTF Driver ($M)**	**EBR-II Blanket ($M)**	**Total Cost ($M)**
Ship, Receive, Store and Prep	11.4	9.59	0	21.0
Equipment	9.8	4.96	33.3	48.1
Fuel Treatment	77.9	20.2	63.9	161.9
Waste Processing	30.1	2.99	53.9	87.0
HLW Disposal	30.2	3.00	54.2	87.5
Total Cost ($k)	159	40.7	205	405.5

In Figure 9, the required staffing level by year is given for each option considered in this study. The preferred option, 2B-84, is attractive in the sense that it requires a steady staffing level until FY2021, after which time staffing can be drastically reduced. This is preferred over other options in which staffing requirements fluctuate over the life of the project, since expertise and experience cannot be easily replaced after a staffing reduction.

Figure 9. Staffing Levels Required for Each Processing Option Tracked by Year



The preferred option meets the necessary treatment requirements while providing valuable research development and demonstration data on pyroprocessing technology. The accelerated processing helps to minimize technical risks due to equipment aging and maintains trained technical staff in the pyroprocessing technology for potential application in advanced fuel cycles.

8. References

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9. Appendix

Technical Risks

Common Technical Risks

- Pyroprocessing expertise at INL is being eroded due to periodic cuts in funding. If this trend is not reversed, there may be inadequate technical expertise and leadership to implement any of the options for the given cost estimates.

Recruitment of new research staff to fill in the void will be much more expensive due to initial hiring costs and additional time necessary to develop the necessary expertise.

- Processing equipment that currently exists in FCF (electrorefiners, cathode processor, choppers, and casting furnace) is over 10 years old and may need unforeseen repairs and/or upgrades to carry out the planned activities. Commercial components used in equipment will become obsolete and will not be available as replacement parts. This will require expensive redesign and/or reengineering. Also, the radiation resistant electrical wiring that is used on in-cell equipment is nominally rated at cumulative exposure of 10^8 Rad. Wiring around equipment with fields higher than 10^3 R/hr will have to be replaced after 10 to 15 years of exposure.
- The ceramic waste calculations are based on an assumed limit of 0.3 mole fraction of NaCl in the salt (and Pu limits of 12 kg and 50 kg for the Mark-IV and Mark-V electrorefiners, respectively). This is currently a best estimate for a salt composition with a low enough melting point to sustain electrorefining, based on available experimental data. More melting point experiments need to be performed to verify that this is a practical limit. Furthermore, the effect of high fission product concentrations on both the melting point and electrorefining needs to be studied experimentally.
- The complete ceramic waste production process has not yet been qualified and none of the equipment has been run enough to establish robustness of the process and durability of the equipment.
- Dross is currently formed from reaction of uranium with cathode processor and casting furnace crucible coatings. While it has been assumed for these options that this dross can be blended with the zeolite and glass and incorporated into the ceramic waste, this process has not been tested. If this process turns out to be impossible to implement or the waste forms turn out to be unacceptable, either advanced crucibles need to be developed that do not result in dross formation or oxide reduction process equipment will need to be developed for dross treatment. Development costs for the oxide reduction process are not included in the current estimates. However, recent experiments with a novel hafnium nitride coated crucible appear to indicate that dross production can be dramatically reduced in the future.
- It has been assumed that the increased staffing for operations will be able to be filled by the local talented personnel resource pool. This is a risky assumption due to the shift of INL personnel to other activities combined with the time required to hire and train new operations personnel (1-2 years).
- It is assumed that the experimental fuels stored in four-inch fuel storage cans (FIFSC) can be retrieved from temporary storage for treatment at the same rate currently obtained when retrieving Mark IICS and Mark III EBR-II fuels.

Option-specific Technical Risks

- The MEDEC cost estimate prepared earlier assumed that sodium treatment and solidification could be done outside the HFEF hot cell. Since small amounts of Cs were detected in the sodium removed from samples of EBR-II blanket [ref.

16], this may no longer be likely, and costs for remote treatment will be higher. These higher costs are not included in this report. This risk applies only to Options 1A and 1B.

- The given cost estimate for MEDEC assumes that full-length blanket assemblies would be treated with only a single cut made in the plenum region. However, high sodium removal from blanket fuel has only been demonstrated using a small-scale furnace filled with 0.72-inch fuel segments [ref. 16]. Mass transfer limitations may necessitate chopping the blanket assemblies into small segments, which would increase the process cost and lengthen its schedule. This risk applies only to Options 1A and 1B.
- It has been assumed that the Pu-limit in the Mark-V ER can be raised to 50 kg, but the current limit is only 16 kg. The technical basis for raising the limit to 50 kg has been documented previously [ref. 17]. However, some of the assumptions that were made for the calculations need to be tested by experiment [ref. 18]. In particular, it needs to be determined how much Pu contamination in the product collector should be expected when running with a high concentration of $PuCl_3$ in the salt. A lower Pu limit is not a showstopper for any of the options, but the cost and schedule will have to be re-calculated if the limit is lower than assumed. This risk applies to Options 2A, 2B, and 3.
- Permission will be needed from the federal government to fabricate fast reactor fuel. Other regulatory hurdles, such as NEPA, will need to be revisited to support this activity. Modification to safeguards and security may be required. This applies to Options 2B and 3.
- The liquid cadmium cathode (LCC) is the default technology for group actinide removal from the salt. It has been tested successfully at the engineering scale in the Mark-V ER but with salt that contained a relatively low concentration of fission products. It needs to be demonstrated that the LCC process can be used to produce low-contamination U/TRU deposits when the electrorefiner salt has become highly contaminated with fission products. This technical risk applies to Options 2B and 3.
- Development of high-throughput electrorefiner technology faces significant challenges including efficient product recovery, high decontamination factors, and durable materials of construction. Minimal research is currently being performed to address these challenges. This applies only to Option 3.
- Concepts have not yet been proposed for a high-throughput cathode processor. Advancement in crucible material technology is imperative in order to minimize time and cost associated with crucible preparation. This applies only to Option 3.

Cost and Throughput Calculation Results for Spent Metal Fuel Processing Options Study

The following tables give estimates of staffing levels, cost, and processing throughput for each assessed processing option broken down by year.

Table 1A-40: Costs and Throughputs for Scenario 1A-40 (Minimum Fuel Scenario with HEU blended into LEU ingots for interim storage on a 9-80s schedule).

	Units	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**
Programmatic Personnel	FTEs	64.5	65.4	58.6	58.6	55.5	49.2	53.8	53.9	67.0	67.0	67.0
Nominal Annual Costs with Contingencies	$k	13,291	14,557	11,859	11,859	11,233	9,729	10,832	10,849	14,055	14,055	14,055
Driver Inventory at End of Fiscal Year	kgHM	2,400	2,260	2,120	1,980	1,840	1,700	1,560	1,420	1,280	1,140	1,000
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900
Driver Fuel Treated During the Fiscal Year	kgHM	140	140	140	140	140	140	140	140	140	140	140
Blanket Fuel Treated During the Fiscal Year	kgHM											
Metal Waste Form Produced During the Fiscal Year	kg		70	140	140	140	140	140	145	200	200	200
Ceramic Waste Form Produced During the Fiscal Year	kg						438	875	875	875	875	875

Table 1A-40: Costs and Throughputs for Scenario 1A-40, continued.

	Units	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**
Programmatic Personnel	FTEs	67.0	67.0	84.9	84.9	84.9	84.9	84.9	90.5	66.9	66.9	34.0
Nominal Annual Costs with Contingencies	$k	14,055	14,055	19,501	19,501	19,501	19,501	19,501	20,478	17,431	17,431	10,122
Driver Inventory at End of Fiscal Year	kgHM	860	720	580	440	300	160	20				
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,900	18,480	17,060	15,640	14,220	12,800	11,380	9,960	8,540	7,120
Driver Fuel Treated During the Fiscal Year	kgHM	140	140	140	140	140	140	140	20			
Blanket Fuel Treated During the Fiscal Year	kgHM			1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420
Metal Waste Form Produced During the Fiscal Year	kg	200	200	200	200	200	200	200	200			
Ceramic Waste Form Produced During the Fiscal Year	kg	875	875	875	875	875	875	875	2,250	4,000	4,000	

Table 1A-40: Costs and Throughputs for Scenario 1A-40, continued.

	Units	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**		**TOTAL**
Programmatic Personnel	FTEs	34.0	38.0	39.5	41.4	41.4	11.4	3.4		**1686**
Nominal Annual Costs with Contingencies	$k	10,122	33,362	38,612	45,612	45,612	37,170	12,250		**550,000**
Driver Inventory at End of Fiscal Year	kgHM									
Blanket Inventory at End of Fiscal Year	kgHM	5,695	4,270	2,850	1,425					
Driver Fuel Treated During the Fiscal Year	kgHM									**2,540**
Blanket Fuel Treated During the Fiscal Year	kgHM	1,425	1,425	1,420	1,425	1,425				**19,900**
Metal Waste Form Produced During the Fiscal Year	kg									**3,115**
Ceramic Waste Form Produced During the Fiscal Year	kg									**21,188**

Table 1A-84: Costs and Throughputs for Scenario 1A-84 (Minimum Fuel Scenario with HEU blended into LEU ingots for interim storage on a 7-12s schedule).												
	Units	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**
Programmatic Personnel	FTEs	92.7	101.7	85.8	93.5	90.4	106.5	113.7	113.9	53.2	45.0	57.6
Nominal Annual Costs with Contingencies	$k	18,384	20,625	18,419	18,419	17,794	21,500	24,488	24,522	11,914	10,312	14,607
Driver Inventory at End of Fiscal Year	kgHM	2,340	2,040	1,680	1,320	960	600	240				
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	18,480
Driver Fuel Treated During the Fiscal Year	kgHM	200	300	360	360	360	360	360	240			
Blanket Fuel Treated During the Fiscal Year	kgHM											1,420
Metal Waste Form Produced During the Fiscal Year	kg		200	400	400	400	400	441	450	424		
Ceramic Waste Form Produced During the Fiscal Year	kg						2,000	4,000	4,000	4,000	4,000	3,188

Table 1A-84: Costs and Throughputs for Scenario 1A-84, continued.												
	Units	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**
Programmatic Personnel	FTEs	30.0	30.0	30.0	30.0	30.0	30.0	30.0	30.0	34.0	34.0	34.0
Nominal Annual Costs with Contingencies	$k	8,442	8,442	8,442	8,442	8,442	8,442	8,442	8,442	10,122	10,122	10,122
Driver Inventory at End of Fiscal Year	kgHM											
Blanket Inventory at End of Fiscal Year	kgHM	17,060	15,640	14,220	12,800	11,380	9,960	8,540	7,120	5,695	4,270	2,850
Driver Fuel Treated During the Fiscal Year	kgHM											
Blanket Fuel Treated During the Fiscal Year	kgHM	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,425	1,425	1,420
Metal Waste Form Produced During the Fiscal Year	kg											
Ceramic Waste Form Produced During the Fiscal Year	kg											

Table 1A-84: Costs and Throughputs for Scenario 1A-84, continued.									
	Units	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**	**TOTAL**
Programmatic Personnel	FTEs	34.0	38.0	9.5	11.4	11.4	11.4	3.4	**1415**
Nominal Annual Costs with Contingencies	$k	10,122	33,362	30,170	37,170	37,170	37,170	12,250	**496,000**
Driver Inventory at End of Fiscal Year	kgHM								
Blanket Inventory at End of Fiscal Year	kgHM	1,425							
Driver Fuel Treated During the Fiscal Year	kgHM								**2,540**
Blanket Fuel Treated During the Fiscal Year	kgHM	1,425	1,425						**19,900**
Metal Waste Form Produced During the Fiscal Year	kg								**3,115**
Ceramic Waste Form Produced During the Fiscal Year	kg								**21,188**

Table 1B-40: Costs and Throughputs for Scenario 1B-40 (Minimum Fuel Scenario with HEU processed into a form usable in commercial fuel on a 9-80s schedule).												
	Units	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**
Programmatic Personnel	FTEs	59.8	55.2	56.9	56.9	55.9	51.7	48.6	48.6	60.7	60.7	60.8
Nominal Annual Costs with Contingencies	$k	15,079	14,403	13,593	12,769	12,418	11,356	10,731	10,731	13,727	13,727	13,744
Driver Inventory at End of Fiscal Year	kgHM	2,400	2,260	2,120	1,980	1,840	1,700	1,560	1,420	1,280	1,140	1,000
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900
Driver Fuel Treated During the Fiscal Year	kgHM	140	140	140	140	140	140	140	140	140	140	140
Blanket Fuel Treated During the Fiscal Year	kgHM											
Metal Waste Form Produced During the Fiscal Year	kg		70	160	160	160	160	160	160	160	160	165
Ceramic Waste Form Produced During the Fiscal Year	kg						750	750	750	750	750	750

Table 1B-40: Costs and Throughputs for Scenario 1B-40, continued.												
	Units	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**
Programmatic Personnel	FTEs	61.5	61.5	79.4	79.4	80.2	81.5	81.5	92.2	66.9	66.9	34.0
Nominal Annual Costs with Contingencies	$k	13,878	13,878	19,324	19,324	19,501	19,766	19,766	22,065	17,431	17,431	10,122
Driver Inventory at End of Fiscal Year	kgHM	860	720	580	440	300	160	20				
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,900	18,480	17,060	15,640	14,220	12,800	11,380	9,960	8,540	7,120
Driver Fuel Treated During the Fiscal Year	kgHM	140	140	140	140	140	140	140	20			
Blanket Fuel Treated During the Fiscal Year	kgHM			1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420
Metal Waste Form Produced During the Fiscal Year	kg	200	200	200	200	200	200	200	200			
Ceramic Waste Form Produced During the Fiscal Year	kg	750	750	750	750	875	1,063	1,063	2,688	4,000	4,000	

Table 1B-40: Costs and Throughputs for Scenario 1B-40, continued.										
	Units	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**		**TOTAL**
Programmatic Personnel	FTEs	34.0	38.0	39.5	41.4	41.4	11.4	3.4		**1610**
Nominal Annual Costs with Contingencies	$k	10,122	33,362	38,612	45,612	45,612	37,170	12,250		**558,000**
Driver Inventory at End of Fiscal Year	kgHM									
Blanket Inventory at End of Fiscal Year	kgHM	5,695	4,270	2,850	1,425					
Driver Fuel Treated During the Fiscal Year	kgHM									**2,540**
Blanket Fuel Treated During the Fiscal Year	kgHM	1,425	1,425	1,420	1,425	1,425				**19,900**
Metal Waste Form Produced During the Fiscal Year	kg									**3,115**
Ceramic Waste Form Produced During the Fiscal Year	kg									**21,188**

Table 1B-84: Costs and Throughputs for Scenario 1B-84 (Minimum Fuel Scenario with HEU processed into a form usable in commercial fuel on a 7-12s schedule).												
	Units	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**
Programmatic Personnel	FTEs	85.8	84.8	86.9	89.5	88.5	92.6	102.7	102.7	101.7	45.0	39.7
Nominal Annual Costs with Contingencies	$k	20,172	20,177	19,460	19,148	18,797	19,504	21,708	21,708	21,845	10,305	9,156
Driver Inventory at End of Fiscal Year	kgHM	2,330	2,040	1,700	1,360	1,020	680	340				
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900
Driver Fuel Treated During the Fiscal Year	kgHM	210	290	340	340	340	340	340	340			
Blanket Fuel Treated During the Fiscal Year	kgHM											
Metal Waste Form Produced During the Fiscal Year	kg		250	365	500	500	500	500	500			
Ceramic Waste Form Produced During the Fiscal Year	kg						2,000	4,000	4,000	4,000	4,000	3,188

Table 1B-84: Costs and Throughputs for Scenario 1B-84, continued.												
	Units	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**
Programmatic Personnel	FTEs	12.1	12.1	30.0	30.0	30.0	30.0	30.0	30.0	34.0	34.0	34.0
Nominal Annual Costs with Contingencies	$k	2,996	2,996	8,442	8,442	8,442	8,442	8,442	8,442	10,122	10,122	10,122
Driver Inventory at End of Fiscal Year	kgHM											
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,900	18,480	17,060	15,640	14,220	12,800	11,380	9,960	8,540	7,120
Driver Fuel Treated During the Fiscal Year	kgHM											
Blanket Fuel Treated During the Fiscal Year	kgHM			1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420	1,420
Metal Waste Form Produced During the Fiscal Year	kg											
Ceramic Waste Form Produced During the Fiscal Year	kg											

Table 1B-84: Costs and Throughputs for Scenario 1B-84, continued.										
	Units	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**		**TOTAL**
Programmatic Personnel	FTEs	34.0	38.0	39.5	41.4	41.4	11.4	3.4		**1435**
Nominal Annual Costs with Contingencies	$k	10,122	33,362	38,612	45,612	45,612	37,170	12,250		**512,000**
Driver Inventory at End of Fiscal Year	kgHM									
Blanket Inventory at End of Fiscal Year	kgHM	5,695	4,270	2,850	1,425					
Driver Fuel Treated During the Fiscal Year	kgHM									**2,540**
Blanket Fuel Treated During the Fiscal Year	kgHM	1,425	1,425	1,420	1,425	1,425				**19,900**
Metal Waste Form Produced During the Fiscal Year	kg									**3,115**
Ceramic Waste Form Produced During the Fiscal Year	kg									**21,188**

Table 2A-40: Costs and Throughputs for Scenario 2A-40												
	Units	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**
Programmatic Personnel	FTEs	58.3	57.6	57.6	56.6	56.6	49.1	46.0	45.9	45.9	46.3	47.5
Nominal Annual Costs with Contingencies	$k	12,798	13,297	13,935	12,760	12,760	10,899	10,274	10,255	10,255	10,344	10,570
Driver Inventory at End of Fiscal Year	kgHM	2,400	2,260	2,120	1,980	1,840	1,700	1,560	1,420	1,280	1,140	1,000
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,800	19,700	19,600	19,500	19,400	19,300	19,200	19,100	19,000	18,900
Driver Fuel Treated During the Fiscal Year	kgHM	140	140	140	140	140	140	140	140	140	140	140
Blanket Fuel Treated During the Fiscal Year	kgHM		100	100	100	100	100	100	100	100	100	100
Metal Waste Form Produced During the Fiscal Year	kg		80	80	80	80	80	80	75	75	75	135
Ceramic Waste Form Produced During the Fiscal Year	kg						250	250	250	250	313	313
Metal Waste Form Produced During the Fiscal Year	kg		80	80	80	80	80	80	75	75	75	135
Ceramic Waste Form Produced During the Fiscal Year	kg						250	250	250	250	313	313

Table 2A-40: Costs and Throughputs for Scenario 2A-40, continued.												
	Units	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**
Programmatic Personnel	FTEs	48.7	48.7	48.7	48.7	48.7	48.7	48.7	48.7	45.2	45.2	45.2
Nominal Annual Costs with Contingencies	$k	10,816	10,816	10,816	10,816	10,816	10,816	10,816	11,036	10,068	10,068	10,068
Driver Inventory at End of Fiscal Year	kgHM	860	720	580	440	300	160	20				
Blanket Inventory at End of Fiscal Year	kgHM	18,800	18,700	18,600	18,500	18,400	18,300	18,200	17,200	16,200	15,200	14,200

Driver Fuel Treated During the Fiscal Year	kgHM	140	140	140	140	140	140	140	20			
Blanket Fuel Treated During the Fiscal Year	kgHM	100	100	100	100	100	100	100	1,000	1,000	1,000	1,000
Metal Waste Form Produced During the Fiscal Year	kg	200	200	200	200	200	200	200	200	200	200	200
Ceramic Waste Form Produced During the Fiscal Year	kg	313	313	313	313	313	313	313	313	313	313	313

Table 2A-40: Costs and Throughputs for Scenario 2A-40, continued.

	Units	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35-46**		**TOTAL**
Programmatic Personnel	FTEs	45.2	45.2	47.3	47.3	51.4	51.4	696		**2076**
Nominal Annual Costs with Contingencies	$k	10,068	10,068	10,512	10,512	11,398	11,398	284,601		**593,656**
Driver Inventory at End of Fiscal Year	kgHM									
Blanket Inventory at End of Fiscal Year	kgHM	13,200	12,200	11,200	10,200	9,200	8,200			
Driver Fuel Treated During the Fiscal Year	kgHM									**2,540**
Blanket Fuel Treated During the Fiscal Year	kgHM	1,000	1,000	1,000	1,000	1,000	1,000	8,200		**19,900**
Metal Waste Form Produced During the Fiscal Year	kg	200	200	200	200	200	200	1,800		**6,040**
Ceramic Waste Form Produced During the Fiscal Year	kg	313	313	625	625	1,250	1,250	38,675		**48,113**

Table 2A-84: Costs and Throughputs for Scenario 2A-84

	Units	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**
Programmatic Personnel	FTEs	87.8	86.0	89.8	88.8	88.8	87.9	84.8	97.2	93.7	97.4	97.4
Nominal Annual Costs with Contingencies	$k	18,859	18,845	20,238	19,064	19,064	18,713	18,088	20,748	20,330	21,127	21,127
Driver Inventory at End of Fiscal Year	kgHM	2,330	2,040	1,700	1,360	1,020	680	340				
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,650	19,400	19,150	18,900	18,650	18,400	18,150	16,550	14,050	11,550
Driver Fuel Treated During the Fiscal Year	kgHM	210	290	340	340	340	340	340	340			
Blanket Fuel Treated During the Fiscal Year	kgHM		250	250	250	250	250	250	250	1,600	2,500	2,500
Metal Waste Form Produced During the Fiscal Year	kg		200	400	400	400	400	400	400	400	400	400
Ceramic Waste Form Produced During the Fiscal Year	kg						1,250	1,250	3,125	3,125	3,688	3,688

Table 2A-84: Costs and Throughputs for Scenario 2A-84, continued.

	Units	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**
Programmatic Personnel	FTEs	100.2	100.4	100.5	100.5	100.5	32.9	32.9	32.9			

Nominal Annual Costs with Contingencies	$k	21,708	21,756	21,760	21,760	21,540	7,324	7,324	7,324			
Driver Inventory at End of Fiscal Year	kgHM											
Blanket Inventory at End of Fiscal Year	kgHM	9,050	6,550	4,050	1,550							
Driver Fuel Treated During the Fiscal Year	kgHM											
Blanket Fuel Treated During the Fiscal Year	kgHM	2,500	2,500	2,500	2,500	1,550						
Metal Waste Form Produced During the Fiscal Year	kg	441	449	450	450	450						
Ceramic Waste Form Produced During the Fiscal Year	kg	3,988	4,000	4,000	4,000	4,000	4,000	4,000	4,000			

Table 2A-84: Costs and Throughputs for Scenario 2A-84, continued.

	Units	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**		**TOTAL**
Programmatic Personnel	FTEs			4.9	9.7	9.7	9.7	4.9		**1640**
Nominal Annual Costs with Contingencies	$k			17,500	35,000	35,000	35,000	17,500		**487,000**
Driver Inventory at End of Fiscal Year	kgHM									
Blanket Inventory at End of Fiscal Year	kgHM									
Driver Fuel Treated During the Fiscal Year	kgHM									**2,540**
Blanket Fuel Treated During the Fiscal Year	kgHM									**19,900**
Metal Waste Form Produced During the Fiscal Year	kg									**6,040**
Ceramic Waste Form Produced During the Fiscal Year	kg									**48,113**

Table 2B-40: Costs and Throughputs for Scenario 2B-40

	Units	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**
Programmatic Personnel	FTEs	70.5	66.7	67.6	66.6	62.6	55.5	52.4	52.4	52.4	52.4	52.4
Nominal Annual Costs with Contingencies	$k	15,306	14,913	15,740	14,565	13,025	11,344	10,718	10,718	10,718	10,718	10,718
Driver Inventory at End of Fiscal Year	kgHM	2,400	2,260	2,120	1,980	1,840	1,700	1,560	1,420	1,280	1,140	1,000
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,800	19,700	19,600	19,500	19,400	19,300	19,200	19,100	19,000	18,900
Driver Fuel Treated During the Fiscal Year	kgHM	140	140	140	140	140	140	140	140	140	140	140
Blanket Fuel Treated During the Fiscal Year	kgHM		100	100	100	100	100	100	100	100	100	100
Metal Waste Form Produced During the Fiscal Year	kg		100	150	150	150	150	150	150	150	150	150
Ceramic Waste Form Produced During the Fiscal Year	kg						313	313	313	313	313	313

Table 2B-40: Costs and Throughputs for Scenario 2B-40, continued.												
	Units	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**
Programmatic Personnel	FTEs	52.4	52.4	53.7	53.7	53.7	53.7	53.7	53.7	53.1	53.1	53.1
Nominal Annual Costs with Contingencies	$k	10,718	10,718	10,984	10,984	10,984	10,984	10,984	10,984	10,854	10,854	10,854
Driver Inventory at End of Fiscal Year	kgHM	860	720	580	440	300	160	20				
Blanket Inventory at End of Fiscal Year	kgHM	18,800	18,700	18,600	18,500	18,400	18,300	18,200	17,200	16,200	15,200	14,200
Driver Fuel Treated During the Fiscal Year	kgHM	140	140	140	140	140	140	140	20			
Blanket Fuel Treated During the Fiscal Year	kgHM	100	100	100	100	100	100	100	1,000	1,000	1,000	1,000
Metal Waste Form Produced During the Fiscal Year	kg	150	150	150	150	150	150	150	150	150	150	150
Ceramic Waste Form Produced During the Fiscal Year	kg	313	313	500	500	500	500	500	500	938	938	938

Table 2B-40: Costs and Throughputs for Scenario 2B-40, continued.										
	Units	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35-46**		**TOTAL**
Programmatic Personnel	FTEs	53.1	53.9	54.0	54.0	56.1	56.1	598		**2163**
Nominal Annual Costs with Contingencies	$k	10,854	11,010	11,039	11,044	11,486	11,486	200,791		**526,000**
Driver Inventory at End of Fiscal Year	kgHM									
Blanket Inventory at End of Fiscal Year	kgHM	13,200	12,200	11,200	10,200	9,200	8,200			
Driver Fuel Treated During the Fiscal Year	kgHM									**2,540**
Blanket Fuel Treated During the Fiscal Year	kgHM	1,000	1,000	1,000	1,000	1,000	1,000	8,200		**19,900**
Metal Waste Form Produced During the Fiscal Year	kg	150	191	199	200	200	200	1,800		**6,040**
Ceramic Waste Form Produced During the Fiscal Year	kg	938	938	938	938	1,250	1,250	19,700		**34,263**

Table 2B-84: Costs and Throughputs for Scenario 2B-84												
	Units	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**
Programmatic Personnel	FTEs	89.8	90.0	93.8	92.8	88.8	87.9	88.9	89.6	90.4	93.5	91.5
Nominal Annual Costs with Contingencies	$k	19,924	20,385	21,778	20,604	19,064	18,709	18,967	18,884	19,369	20,282	19,812
Driver Inventory at End of Fiscal Year	kgHM	2,330	2,040	1,700	1,360	1,020	680	340				
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,400	18,900	18,400	17,900	17,400	16,900	16,400	14,800	12,300	9,800
Driver Fuel Treated During the Fiscal Year	kgHM	210	290	340	340	340	340	340	340			
Blanket Fuel Treated During the Fiscal Year	kgHM		500	500	500	500	500	500	500	1,600	2,500	2,500

Metal Waste Form Produced During the Fiscal Year	kg		200	400	400	400	400	400	400	441	499	500
Ceramic Waste Form Produced During the Fiscal Year	kg						1,250	1,875	2,500	2,500	2,500	2,500

Table 2B-84: Costs and Throughputs for Scenario 2B-84, continued.

	Units	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**
Programmatic Personnel	FTEs	91.5	91.5	91.5	91.5	27.2	32.9	32.9				
Nominal Annual Costs with Contingencies	$k	19,812	19,812	19,812	19,812	6,088	7,309	7,309				
Driver Inventory at End of Fiscal Year	kgHM											
Blanket Inventory at End of Fiscal Year	kgHM	7,300	4,800	2,300								
Driver Fuel Treated During the Fiscal Year	kgHM											
Blanket Fuel Treated During the Fiscal Year	kgHM	2,500	2,500	2,500	2,300							
Metal Waste Form Produced During the Fiscal Year	kg	500	500	500	500							
Ceramic Waste Form Produced During the Fiscal Year	kg	2,500	2,500	2,500	2,500	3,138	4,000	4,000				

Table 2B-84: Costs and Throughputs for Scenario 2B-84, continued.

	Units	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**		**TOTAL**
Programmatic Personnel	FTEs			4.9	4.9	4.9	4.9	4.9		**1481**
Nominal Annual Costs with Contingencies	$k			17,500	17,500	17,500	17,500	17,500		**405,000**
Driver Inventory at End of Fiscal Year	kgHM									
Blanket Inventory at End of Fiscal Year	kgHM									
Driver Fuel Treated During the Fiscal Year	kgHM									**2,540**
Blanket Fuel Treated During the Fiscal Year	kgHM									**19,900**
Metal Waste Form Produced During the Fiscal Year	kg									**6,040**
Ceramic Waste Form Produced During the Fiscal Year	kg									**34,263**

Table 3-40: Costs and Throughputs for Scenario 3-40.

	Units	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**
Programmatic Personnel	FTEs	59.4	61.7	62.7	61.7	61.7	55.0	51.9	51.9	51.9	51.9	52.7
Nominal Annual Costs with Contingencies	$k	13,291	13,184	14,011	12,836	12,836	11,243	10,618	10,618	10,618	10,618	10,773
Driver Inventory at End of Fiscal Year	kgHM	2,400	2,260	2,120	1,980	1,840	1,700	1,560	1,420	1,280	1,140	1,000

Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,800	19,700	19,600	19,500	19,400	19,300	19,200	19,100	19,000	18,900
Driver Fuel Treated During the Fiscal Year	kgHM	140	140	140	140	140	140	140	140	140	140	140
Blanket Fuel Treated During the Fiscal Year	kgHM		100	100	100	100	100	100	100	100	100	100
Metal Waste Form Produced During the Fiscal Year	kg		50	100	100	100	100	100	100	100	100	141
Ceramic Waste Form Produced During the Fiscal Year	kg						375	375	375	375	375	375

Table 3-40: Costs and Throughputs for Scenario 3-40, continued.

	Units	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**
Programmatic Personnel	FTEs	64.8	66.2	73.2	73.2	80.2	80.2	80.2	84.3	67.9	67.9	67.9
Nominal Annual Costs with Contingencies	$k	16,780	17,062	22,368	22,368	27,674	27,674	27,674	28,779	14,206	14,206	14,206
Driver Inventory at End of Fiscal Year	kgHM	860	720	580	440	300	160	20				
Blanket Inventory at End of Fiscal Year	kgHM	18,800	18,700	18,600	18,500	18,400	18,300	18,200	17,200	15,600	13,600	11,600
Driver Fuel Treated During the Fiscal Year	kgHM	140	140	140	140	140	140	140	20	0		
Blanket Fuel Treated During the Fiscal Year	kgHM	100	100	100	100	100	100	100	1,000	1,600	2,000	2,000
Metal Waste Form Produced During the Fiscal Year	kg	249	300	300	300	300	300	300	300	300	300	300
Ceramic Waste Form Produced During the Fiscal Year	kg	375	438	438	438	438	438	438	1,063	2,750	2,750	2,750

Table 3-40: Costs and Throughputs for Scenario 3-40, continued.

	Units	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35-38**		**TOTAL**
Programmatic Personnel	FTEs	74.6	60.1	60.1	60.1	60.1	57.9	107.3		**1908**
Nominal Annual Costs with Contingencies	$k	15,620	12,526	12,526	12,526	12,526	30,026	92,272		**552,000**
Driver Inventory at End of Fiscal Year	kgHM									
Blanket Inventory at End of Fiscal Year	kgHM	9,600	7,600	5,600	3,600	1,600				
Driver Fuel Treated During the Fiscal Year	kgHM									**2,540**
Blanket Fuel Treated During the Fiscal Year	kgHM	2,000	2,000	2,000	2,000	2,000	1,600			**19,900**
Metal Waste Form Produced During the Fiscal Year	kg	300	300	300	300	300	300			**6,040**
Ceramic Waste Form Produced During the Fiscal Year	kg	3,750	1,563	1,563	1,563	1,563	1,563	8,138		**34,263**

Table 3-84: Costs and Throughputs for Scenario 3-84

	Units	**FY07**	**FY08**	**FY09**	**FY10**	**FY11**	**FY12**	**FY13**	**FY14**	**FY15**	**FY16**	**FY17**

Programmatic Personnel	FTEs	90.7	94.8	104.6	103.6	110.6	109.7	110.7	111.7	97.5	98.3	98.4
Nominal Annual Costs with Contingencies	$k	23,984	23,989	30,500	29,325	34,631	34,276	34,535	34,724	20,852	21,337	21,921
Driver Inventory at End of Fiscal Year	kgHM	2,330	2,040	1,700	1,360	1,020	680	340				
Blanket Inventory at End of Fiscal Year	kgHM	19,900	19,900	19,900	19,900	19,900	19,900	19,900	19,900	18,700	16,000	11,000
Driver Fuel Treated During the Fiscal Year	kgHM	210	290	340	340	340	340	340	340			
Blanket Fuel Treated During the Fiscal Year	kgHM									1,200	2,700	5,000
Metal Waste Form Produced During the Fiscal Year	kg		250	400	400	400	400	400	450	450	491	500
Ceramic Waste Form Produced During the Fiscal Year	kg						1,250	1,875	1,875	3,125	3,125	3,125

Table 3-84: Costs and Throughputs for Scenario 3-84, continued.

	Units	**FY18**	**FY19**	**FY20**	**FY21**	**FY22**	**FY23**	**FY24**	**FY25**	**FY26**	**FY27**	**FY28**
Programmatic Personnel	FTEs	98.4	104.2	56.1	43.1	35.5						
Nominal Annual Costs with Contingencies	$k	21,921	23,159	12,372	9,347	7,857						
Driver Inventory at End of Fiscal Year	kgHM											
Blanket Inventory at End of Fiscal Year	kgHM	6,000	1,000									
Driver Fuel Treated During the Fiscal Year	kgHM											
Blanket Fuel Treated During the Fiscal Year	kgHM	5,000	5,000	1,000								
Metal Waste Form Produced During the Fiscal Year	kg	500	500	500	399							
Ceramic Waste Form Produced During the Fiscal Year	kg	3,125	4,000	4,000	4,375	4,388						

Table 3-84: Costs and Throughputs for Scenario 3-84, continued.

	Units	**FY29**	**FY30**	**FY31**	**FY32**	**FY33**	**FY34**	**FY35**		**TOTAL**
Programmatic Personnel	FTEs			4.9	4.9	4.9	4.9	4.9		**1492**
Nominal Annual Costs with Contingencies	$k			17,500	17,500	17,500	17,500	17,500		**472,000**
Driver Inventory at End of Fiscal Year	kgHM									
Blanket Inventory at End of Fiscal Year	kgHM									
Driver Fuel Treated During the Fiscal Year	kgHM									**2,540**
Blanket Fuel Treated During the Fiscal Year	kgHM									**19,900**
Metal Waste Form Produced During the Fiscal Year	kg									**6,040**
Ceramic Waste Form Produced During the Fiscal Year	kg									**34,263**