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A COMPARATIVE ASSESSMENT OF THE ECONOMICS OF PLUTONIUM DISPOSITION INCLUDING COMPARISON WITH OTHER NUCLEAR FUEL CYCLES*

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A Comparative Assessment of the Economics of Plutonium Disposition Including Comparison With Other Nuclear Fuel Cycles*

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ABSTRACT

The U.S. Department of Energy Office of Fissile Materials Disposition (DOE/MD) has been evaluating three technologies for the disposition of approximately 50 metric tons of surplus plutonium from defense-related programs: reactors, immobilization, and deep boreholes. As part of the process supporting an early CY 1997 Record of Decision (ROD), a comprehensive assessment of technical viability, cost, and schedule has been conducted by DOE/MD and its national laboratory contractors. Oak Ridge National Laboratory has managed and coordinated the life-cycle cost (LCC) assessment effort for this program. This paper discusses the economic analysis methodology and the results prior to ROD. Other objectives of the paper are to discuss major technical and economic issues that impact plutonium disposition cost and schedule. Also to compare the economics of a once-through weapons-derived MOX nuclear fuel cycle to other fuel cycles, such as those utilizing spent fuel reprocessing.

The reactor option is technically mature as evidenced by the use of mixed-oxide (MOX) fuel in Europe. The use of MOX made from weapons-grade plutonium in the United States has many institutional and political issues that heavily impact cost and schedule. Among these are the following: (1) use of existing U.S. or Canadian reactors, partially complete reactors, or new reactors; (2) ownership of MOX fuel facilities in the United States; (3) licensing of new facilities; (4) monetary or other incentives to utility-reactor owners needed for utility participation; (5) public acceptance of MOX transportation and use; and (6) the future market for electrical energy generated by nuclear power and the potential for revenues to offset plutonium disposition costs (for government-owned reactors).

The immobilization option cost issues are coupled more tightly to the process design and the ultimate outcome of the ongoing research and development programs. The cost of disposing of the glass or ceramic immobilized form in a federal repository will also depend on the results of the qualification program for these new waste forms.

The deep borehole direct-disposal option could have attractive LCCs if no institutional issues impact the cost or schedule for this option. Based on experience with the proposed Yucca Mountain Project for spent fuel and defense waste disposal and the Waste Isolation Pilot Plant for transuranic waste, the possibilities for difficulties with site selection and qualification are considerable.

To evaluate the economics of these technologies on an equitable basis, a set of cost estimating

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guidelines and a common cost-estimating format were utilized by all three technology teams. This paper also includes the major economic analysis assumptions and the compar ative constant-dollar and discounted-dollar LCCs.

INTRODUCTION

A goal of the U.S. Department of Energy Office of Fissile Materials Disposition (DOE/MD) is to minimize the incremental cost impact to the government and taxpayers. Although the national security benefits clearly outweigh the costs involved, significant budget pressures are projected throughout program execution. Timing and allocation of costs were assessed. The following cost-related performance factors or figures-of-merit were considered in evaluating the extent to which a particular disposition variant is cost-effective.

Investment and Startup Cost

Investment and startup cost refers to research and development (R&D), construction, retrofit, and program infrastructure costs that are incurred early in the program. In government accounting, the sum of these is the total project cost (TPC).

Total Life-Cycle Cost

For large government projects such as the Fissile Materials Disposition Program (FMDP), there is the need to consider not only the costs to design and construct the project but also the costs to operate the facilities over their lifetimes and for safe decontamination and decommissioning (D&D). For this reason, the total life-cycle costing (TLCC) approach is used for cost estimating to obtain the true "cradle-to-grave" costs. This costing methodology also makes comparison of competing plutonium disposition alternatives more meaningful. Many of the alternatives being considered have different operating lifetimes, and TLCC allows schedule differences (that affect cash flows) to be correctly reflected in overall costs.

TLCC includes adjustments for revenues that may be produced by electric power production or sales of fuel. However, it does not include the sunk (pre-FY 1997) costs of existing facilities or other costs that would be incurred whether or not any action on plutonium disposition is taken. If the constant-dollar cash flows are discounted year by year, and the resulting net present value (NPV) sums are added, a discounted total life-cycle cost (DTLCC) is obtained. This figure-of-merit is often preferred because it takes into account the time value of money.

Ensuring a "Level Playing Field"

Early in the FMDP evaluation process, a set of cost- estimating guidelines and a 24-category life-cycle cost (LCC) estimating format were supplied to the Alternative Teams who were responsible for developing each plutonium disposition technology (Table I). (Teams of national laboratory scientists and engineers were assembled to perform the research and planning to support each technology.) This was done to ensure comparability between estimates and assist in the decision-making process. The Alternative Teams for each of the three technologies were responsible for preparation of LCCs, which were then reviewed for completeness and adherence to the guidelines. Much of the cost data came from 1993 and 1994 plutonium disposition feasibility studies by reactor vendors, reactor cost data bases at Oak Ridge National Laboratory (ORNL), the Department of Energy (DOE) plutonium-handling sites such as the Savannah River Site (SRS), and the two weapons research laboratories [Lawrence Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL)] and their architect/engineer (AE) subcontractors. The FMDP multi-laboratory Systems Analysis Team had the role of "leveling" the cost data (i.e., ensuring their comparability). Note that the focus in these studies was TLCC to the federal government, and specifically those costs that will be borne by FMDP. Costs to private concerns such as utilities, fuel suppliers, and others are not the focus of this study; however, they may have been used during the estimating process to calculate costs that are ultimately passed on to the FMDP. (An example would be the cost of MOX fuel from a privately owned fabrication facility specifically built to meet government plutonium disposition needs.)

MAJOR COST CATEGORIES

The 24 LCC categories requested by ORNL in Table I can be rolled into three higher level categories: investment cost, recurring costs, and D&D costs.

Investment Plus Startup or TPC

TPC is essentially the sum of the "up-front" costs needed to bring a facility into full-capacity operation as discussed in Sect. 1.A. This total includes planning, R&D, environmental safety and health (ES&H) studies [including National Environmental Policy Act (NEPA)], site qualification, quality assurance (QA) planning, permitting, licensing, safety analysis, design, construction, project management, initial spare equipment items, facility startup, staff training, the operational readiness review, and manual preparation.

Recurring Costs

Recurring costs are incurred during normal facility operation after startup and include plant staffing cost (including fringe benefits and taxes), costs of process consumables and maintenance materials, utility costs, administrative and plant overheads, transportation costs for nuclear materials, oversight costs, fees to the facility management contractor, capital replacement items, waste-handling costs, and payments in-lieu-of taxes to local communities.

D&D Costs

These costs are incurred at facility end-of-life to decommission and remove process equipment and to decontaminate any process buildings to a safe or "habitable" state in which no adverse ES&H consequences result from their continued existence on the site.

Revenues

A special category is that of revenues. For some reactor alternatives, the federal government may benefit from the sale of the following items:

1. Electricity—If the government owns the nuclear power plant, electricity will be sold.
2. MOX fuel—If the government owns the MOX fuel and sells it to a private utility reactor owner, the fuel would probably be sold at a price close to that of an energy-equivalent amount of uranium fuel.
3. Reactor power plant—If the government owns the power plant during the duration of the plutonium disposition campaign, it may wish to sell the plant to a utility at the end of the campaign. This removes the government from the business of selling electricity.

GENERAL ASSUMPTIONS FOR THE PLUTONIUM DISPOSITION ALTERNATIVE COST ESTIMATES

Variants Evaluated

To support a January 14, 1997, ROD, the following 16 technology variants were examined. It was assumed in all cases that 50 metric tons (MT) of plutonium would be dispositioned. Variants 1-6 apply to reactor technology, 7-12 apply to immobilization, 13 and 14 involve the deep borehole option, and 15 and 16 relate to hybrid plutonium disposition.

1. Two partially complete light-water reactors (LWRs).
2. Two to four existing Canadian deuterium-uranium (CANDU) heavy-water reactors (HWRs).
3. Five existing utility-owned pressurized-water reactors (PWRs) with a government-owned MOX fabrication facility.
4. Five existing utility-owned PWRs with a privately owned MOX fabrication facility.
5. Four existing utility-owned boiling-water reactors (BWRs) with a collocated plutonium processing (PuP)/MOX fabrication facility.
6. Five existing utility-owned PWRs with both domestic and European MOX fabrication (allows

plutonium disposition to start before completion of a U.S. MOX plant or "Quick Start").

7. A new greenfield vitrification facility.
8. A new greenfield ceramic immobilization facility.
9. An adjunct melter vitrification facility using the SRS Defense Waste Processing Facility (DWPF).
10. A can-in-canister vitrification facility using the SRS DWPF.
11. A can-in-canister ceramic immobilization facility using the SRS DWPF.
12. An electrometallurgical immobilization facility utilizing glass-bonded zeolite (GBZ) technology.
13. Immobilized disposition in deep boreholes.
14. Direct disposition in deep boreholes.
15. 32.5 MT plutonium to three existing PWRs plus 17.5 MT plutonium to can-in-canister vitrification.
16. 32.5 MT plutonium to two existing CANDU HWRs plus 17.5 MT plutonium to can-in-canister vitrification.

The facility requirements, technical viability, schedules, and costs associated with these 16 options are discussed in the Alternative Team technical summary reports issued by each team (Ref. 1-8) and the technical summary reports (Ref. 9-10) issued by DOE/MD. This paper will summarize LCCs estimated for each of these options. Some of the basic assumptions for development of the estimates are discussed below. The costs for the reactor cases are consistent with those in the reactor alternative summary reports (Ref. 11-14). These reports include business-related costs such as fees paid to utilities that are not considered in Ref. 9.

Facility Requirements

For all cases, LCCs are calculated by facility. Two or more facilities are needed to complete the total end-to-end plutonium disposition project. It is assumed that the process starts with metal plutonium weapons parts ("pits") or other stable and packaged forms such as alloys or oxides. The end state is isolation of the plutonium form from the environment in a geologically stable location. If the form is accessible, it must meet the "spent fuel standard" as defined in the National Academy of Sciences plutonium disposition study (Ref. 15) and subsequently revised by DOE.

Facilities can be classified as either "front end" or "back end." For the reactor options, the front-end facilities are the PuP facility that converts the plutonium feed forms to a plutonium oxide powder suitable for the next front-end facility, the MOX fabrication facility. For the borehole options, the front-end facility is a PuP facility that produces stable physical forms that can be grouted or packaged for emplacement in a borehole. For the immobilization options, the PuP facility produces an oxide suitable for dissolution in glass or a ceramic or GBZ form. For vitrification immobilization options, the PuP facility includes the front-end melter that prepares a glass frit for eventual use in a larger melter that is located in a hot cell.

Back-end facilities are those that do the real disposition task. For the reactor options, they consist of the reactors and the geologic repository that accepts the spent MOX fuel. For the borehole option, the back-end facilities are the four boreholes themselves, which include the packaging and emplacement buildings at the borehole site. For the immobilization options, the back-end facilities consist of the hot-cell facility (where the cesium or high-level waste form is mixed with the plutonium form from the PuP facility and additional glass or ceramic matrix) and the geologic repository that accepts the waste containers or "logs" from the hot-cell facility. The hybrid options use PuP facilities that can produce separate feeds (pits and clean metal for MOX, mixed forms for immobilization) for both a MOX fabrication facility and a can-in-canister vitrification facility (hot cell located in the existing SRS DWPF).

Discounting Assumptions

The total discounted-dollar cost is calculated by spreading the constant-dollar cash flows in a manner consistent with the project schedule and then discounting these cash flows at 5% real discount rate as acceptable to the Office of Management and Budget. This discount rate is consistent with the federal government's costs of borrowing.

Ownership Assumptions

For most of the scenarios considered, the facilities are owned by the government (DOE/MD). The main exception is a possible private MOX fabrication facility and utility-owned commercial reactors whose owners are reimbursed for their irradiation services. Government-owned facilities are assumed to be operated and managed by private corporations on a fee basis. The contractors' annual fee for the PuP facility and the MOX fuel fabrication facility is calculated as 2% of the annual recurring costs. For this study, a private LWR reactor operator is assumed to receive a fee of $25M per reactor pair per year for the first 5 years of the plutonium disposition mission, followed by $10M per reactor pair per year thereafter (reflecting decreasing financial risk after 5 successful years). This fee assumption is not based on any actual DOE/utility negotiations but is included primarily to recognize the possibility of a fee arrangement for the reactor options.

Existing Facility Cost Savings

It was also recognized that many of the options could benefit economically from the use of existing facilities or buildings at DOE sites that already have a plutonium-handling infrastructure such as transuranic (TRU) waste facilities, Perimeter Intrusion Detection and Assessment System (PIDAS) fences, a trained security force, and analytical laboratories. Three of the immobilization options are configured to take advantage of the SRS DWPF. All except the CANDU and the borehole options assume that a government geologic high-level waste repository will be available to accept the spent-fuel forms or the waste canisters from the U.S. reactor or immobilization options, respectively. The candidate site for the first such repository to be located on government land is the Yucca Mountain Project in Nevada.

COST SUMMARY

All costs presented are costs to the government (FMDP) and are in 1996 constant dollars unless otherwise noted. Table II shows a comparison of LCCs for all of the reactor alternatives; it includes fees, electricity revenues, and MOX sales revenues where appropriate. [MOX is supplied by DOE/MD to private reactor owners at an energy-equivalent price for a corresponding amount of low enriched uranium (LEU) or natural uranium for CANDU fuel]. Table III shows the LCCs for the immobilization and borehole options in a slightly different format, but with the same high-level cost figures-of-merit. Table IV summarizes the two hybrid options considered. Figures 1 and 2 summarize the undiscounted and discounted LCCs for all options in graphical form.

Reactor Options

The evolutionary reactor option requires the highest up-front cost (nearly $7 billion) to the government. DOE is reluctant to make a large investment that also puts it in the power production business. In constant dollars, the partially complete reactor option's LCC appears very promising (mainly because of the revenues), but it also requires a large initial cost to the government to complete the reactor. (Information from the Tennessee Valley Authority's partially complete Bellefonte Plant was used to develop this estimate.)

Of all the existing LWR variants, the five-PWR base case has the lowest overall cost. The private MOX fuel fabrication facility case has the lowest up-front cost to the government; however, the overall LCC is higher because of the interest and investment returns required for privatization of the MOX fuel fabrication facility enterprise. With new PuP and new greenfield MOX collocated facilities, the four-BWR case has the highest up-front cost because of the use of new front-end facilities rather than the use of BWRs vis-a-vis PWRs. The overall LCC, however, is less than

$200M greater than the five-PWR base case. The schedule advantages of the five-PWR "Quick Start" case come at a cost of less than $205M over the base case. Compared to existing LWRs, the CANDU existing reactor option suffers economically from two factors: (1) CANDU natural uranium fuel has a very low unit cost compared to LEU fuel, thus the credit to DOE for uranium fuel displaced is nearly an order of magnitude smaller, and (2) the heavy metal throughput associated with a CANDU MOX fabrication plant is much larger than for an LWR MOX fuel plant, thus LCCs could be larger.

Immobilization Options

Table III shows the strong economic incentive associated with the use of immobilization options that make use of the DWPF at SRS. Construction of greenfield immobilization facilities is estimated to be prohibitively expensive. In terms of cost and schedule, the two can-in-canister options are the most economically attractive.

Deep Borehole Options

Of the two borehole options, the direct disposal borehole option is the more economically attractive as a result of less processing and simpler packaging prior to emplacement. The borehole has cost and schedule uncertainties associated with siting that could not be quantified for these estimates.

Hybrid Options

The hybrid options have schedule, political, and performance assurance advantages that could affect the small cost disadvantage when compared to the pure reactor or pure immobilization options. The possibility for a Quick Start hybrid using some European MOX fabrication also exists.

GENERATION OF ELECTRICAL ENERGY FROM REACTOR-BASED DISPOSITION ALTERNATIVES

Large quantities of electrical energy would be produced from disposition of 50 MT of plutonium if a reactor-based alternative were implemented. Between 2.3 and 5.1 x 10^{11} kWh of electrical energy would be produced from MOX fuel. This is enough electrical energy to meet the present-day electrical demand of Boston, Massachusetts, and much of the surrounding area (1.5 million people, 600 mile^2) for about 18 to 40 years, or of the entire state of Massachusetts for 8 to 18 years. The hybrid case, for which 32.5 MT of plutonium is incorporated into MOX fuel for use in three LWRs, would produce ~2.9 x 10^{11} kWh, which could meet the Boston area electrical demand for about 21 years or the demand for all of Massachusetts for 9 years.

COST UNCERTAINTIES

The reactor disposition option using MOX fuel has few cost uncertainties related to technical factors. Most uncertainties are related to business arrangements (e.g., the incentive fees to utilities for irradiation services, possible increases in the repository fee for spent MOX fuel, and the need to pay for replacement power during reactor modifications). Other MOX cost uncertainties arise from the cost effects of schedule delays due to licensing and the possibility of legal intervention. Because many European reactors use MOX, there is no question that MOX use is technically and commercially feasible. New government-owned reactors carry a very high cost risk because of the uncertain electricity revenues that would result in a highly deregulated electricity market in which nuclear power is becoming less competitive.

The major uncertainties for the borehole option are the costs of finding, qualifying, and licensing a new DOE site for the four boreholes needed to accommodate 50 MT of plutonium. Most of the technical issues for borehole disposal have been resolved as part of other deep-drilling projects.

The immobilization option is not a mature disposition technology. The present concepts are still subject to material compatibility issues and basic plutonium disposition chemistry/glass performance uncertainties that could affect the size, design, and costs of the facilities required. It is anticipated that ongoing R&D and pilot plant work will resolve many of these issues in the future.

The dollar values associated with these uncertainties are discussed in detail in Ref. 10.

ECONOMIC COMPARISON TO OTHER FUEL CYCLES

It is useful to compare the fuel portion of the busbar cost of electricity from weapons-derived MOX in the U.S. with that of other "open" cycles (with direct geologic disposal of spent fuel) and with "closed" fuel cycles (with reprocessing of spent fuel to obtain plutonium and unburned uranium.) Using a spreadsheet model, several cases were examined for a reference 1000-MW(e) LWR and a 1000 MW(e) LMFBR using material balances given in the second edition of Nuclear Chemical Engineering, Benedict, Pigford, and Levi (Ref. 16). Whether operating on low enriched uranium (LEU @ 3.3% ^{235}U) or MOX (plutonium enrichment depending on source), the LWRs were assumed to operate at a capacity factor of 80%, a thermal efficiency of 32.5%, a burnup of 33,000 MWd/MTHM, a fuel exposure time of 1100 days, and an annual equilibrium fuel feed rate of 27.3 MTHM/year. Table 5 shows the economic inputs in constant dollars for the various fuel cycle materials and services.

Table 6 shows similar input parameters for a 1000 MW(e) "break even" LMFBR with a burnup of 67,600 MWd/MTHM, a capacity factor of 80%, a thermal efficiency of 42%, and a driver core exposure time of 728 days. With both radial and axial blankets surrounding the driver core, the cycle is self-sustaining with a very small amount of excess plutonium produced. The reactor feed rate is 1.63 MT plutonium per year or 7.9 MTHM/year as 17 weight % plutonium MOX fuel.

Table 7 shows the levelized constant dollar total fuel cycle cost output from the cost model for the five fuel cycles listed in Tables 5 and 6 above. The results show that the high price of reprocessing drives the fuel cost for the "closed" fuel cycles higher than for the "open" fuel cycles, even with uranium ore priced at \$40/lb U_3O_8, the historically high price. Even at 12 mills/kWh, however, the fuel portion of the busbar cost of electricity is a relatively small part of the total busbar generation cost from nuclear power (typically 45 to 100 mills/kWh if capital is included). The recovery of the large capital investment is usually half or more of the total generation cost. The major incentive for reprocessing is not necessarily economic; however, security of fuel supply and lower waste volumes to national repository systems may be the primary motivations to reprocess.

The "utility" cost of using weapons-grade plutonium in MOX depends on the point at which the utility rather than the U.S. Government bears the fuel cycle cost. If the fabricator is provided “free”clean PuO_2 powder ready for fabrication into MOX fuel bundles, the levelized cost to the utility of using MOX can be equivalent to or less that that of LEU fuel, provided that the MOX unit fabrication cost is less than the equivalent LEU combined front-end fuel cycle costs. If the utility has to bear the costs of converting weapons parts ("pits") to powder, the unit fabrication cost would double. The U.S. Government, however, intends to cover this conversion cost, and may even provide further financial incentives for existing U.S. utilities to perform the MOX irradiation mission.

SUMMARY

On December 9, 1996, DOE announced its intent to pursue two of the options considered above: (1) the use of existing US utility reactors using MOX fuel produced first in Europe followed by a U.S. government-financed MOX plant in the U.S., and (2) the can-in-canister immobilization approach, which would make use of existing facilities at DOE’s SRS. The MOX option would disposition the plutonium contained in clean metals and oxides (mostly weapons “pits”), and the immobilization option would be used for the less pure plutonium found in alloys, residues, and other forms at DOE sites. The rationale for the "dual path" decision is discussed in the January 14, 1997, ROD document (Ref. 17). The results of the immobilization R&D program and the MOX fuel/irradiation services procurement program over the next 2 years will give a much clearer picture of the financial resources that will be ultimately needed to complete the U.S. plutonium-disposition program.

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Table I
Life Cycle Cost Estimate 24-Category Format

Category	Cost category description	Category	Cost category description
	Preoperational or OPC up-front costs:		Other LCCs:(recurring)
1	R&D	13	O&M staffing
2	NEPA, licensing, permitting	14	Consumables including utilities
3	Conceptual design	15	Major capital replacements or upgrades
4	Implementation plans: QA, site qualification, S&S	16	Waste handling and disposal
5	Post-construction startup	17	Oversight
6	Risk contingency	18	M&O contractor fees
		19	Pay'mts In Lieu of Taxes to local governments
OPC	TOTAL OF CATEGORIES 1-6 (OPC)		TOTAL RECURRING COSTS (SUM OF CATEGORIES 13-19)
	Capital or TEC up-front costs:		Other LCCs:(other)
7	Title I, II, III engineering, design, and inspection	20	D&D
8a	Capital equipment	21	Revenues (if applicable)
8b	Direct and indirect construction/modification	22	Fees to privately owned facility
9	Construction management	23	Transportation of plutonium forms to facility
10	Initial spares (technology dependent)	24	Storage of Pu at existing DNFSB 94-1 site facility
11	Allowance for Indeterminates		
12	Risk Contingency	OLCC	TOTAL OTHER LCC (SUM OF CATEGORIES 13-24)
TEC	TOTAL OF CATEGORIES 7-12 (TEC)		
TPC	TOTAL INVESTMENT OR UP-FRONT COST (TPC = OPC + TEC)	TLCC	GRAND TOTAL ALL LCC (SUM OF TPC + OTHER LCC IN 1996$)

Table II

Comparison of LCCs for Reactor Variants

Cost category description	Five-existing PWR base case (government MOX fabrication)	Five-PWR base case with private MOX fabrication	Four-existing BWR case with new collocated PuP/MOX	Five-existing PWR base case with Quick Start (European and U.S. government MOX fabrication)	Existing CANDU case (2 to 4 units with U.S. government fabrication)	Two partially complete PWRs with government MOX fabrication (revenues @ 29 mills/kWh)	Two new evolutionary PWRs with government fabrication (revenues @ 29 mills/kWh)
	Utility-owned reactors					Government-owned reactors	
Undiscounted costs (constant 1996 $M)							
Up-front (investment) cost for all facilities	954	554	1378	980	871	3054	6876
Operations costs including transportation for all facilities	1995	1075	2114	1855	2292	4284	4663
D&D costs for all relevant facilities	229	169	456	229	239	371	248
Fee to reactor owners or contracted operators	433	433	482	515	269	235	215
Revenues from sale of MOX to privately owned utility at uranium equivalent price	-1387	-1387	-2006	-1387	-320	0	0
Payment for EuroMOX fabrication	0	0	0	237	0	0	0
Payment for private U.S. MOX fabrication	0	2007	0	0	0	0	0
Gross electricity revenues (government-owned reactors)	0	0	0	0	0	-7888	-7152
Revenue sharing (government-owned reactors)	0	0	0	0	0	734	0
Reactor salvage value (government-owned reactors)	0	0	0	0	0	-2586	-2242
Total LCC	2224	2852	2424	2429	3351	-1796	2609
Discounted costs (1996 $M)							
Up-front (investment) cost for all facilities	687	400	953	706	628	2187	4194
Operations costs including transportation for all facilities	965	528	895	970	1080	1759	1733
D&D costs for all relevant facilities	83	62	147	89	84	131	78
Fee to reactor owners or contracted operators	231	204	173	229	123	89	69
Revenue from sale of MOX at uranium equivalent price	-658	-597	-817	-725	-145	0	0
Payment for EuroMOX fabrication	0	0	0	173	0	0	0
Payment for private U.S. MOX fabrication	0	863	0	0	0	0	0
Electricity revenues (government-owned reactors)	0	0	0	0	0	-2975	-2312
Revenue sharing (government-owned reactors)	0	0	0	0	0	277	0
Reactor salvage value (government-owned reactors)	0	0	0	0	0	-628	-519
Total discounted LCCs	1308	1460	1351	1442	1770	840	3243

TABLE III
LCCs for immobilization and borehole options

	IMMOBILIZATION OPTIONS						DEEP BOREHOLE OPTIONS	
	Glass Immobilization			Ceramic Immobilization		Other Imm.		
Facility/Cost category description	Greenfield vitrification with greenfield PuP facility	Vitrification adjunct melter at SRS using DWPF; PuP in existing SRS F-area	Vitrification can-in-canister at SRS using DWPF; PuP in existing F-area	Greenfield ceramic immobilization with greenfield PuP facility	Ceramic can-in-canister at SRS using DWPF; PuP in existing SRS F-area	ANL electrometallurgical GBZ treatment; PuP in existing ANL-W facilities	Direct disposition in deep boreholes with PuP in existing SRS F-area	Disposal of Immobilized Pu in coated ceramic pellets in grout without canisters;PuP in existing SRS F-area
Front-end facility costs (constant 1996 $M)								
Pu-processing up-front cost	1000	342	342	858	342	730	244	583
Pu-processing 10-year operations cost	900	822	822	760	822	834	740	1239
Pu-processing D&D cost	80	159	159	63	159	56	64	270
Back-end facility costs (constant 1996 $M)								
Hot-cell immobilization up-front cost	1030	681	222	950	222	460	865	765
Hot-cell immobilization 10-year operations cost	1727	1278	165	1664	165	854	643	698
Hot-cell immobilization D&D cost	73	47	2	58	2	15	28	19
Repository costs at $500K/canister	300	300	100	320	100	480	0	0
TOTAL undiscounted LCC	5110	3629	1812	4673	1812	3429	2584	3574
TOTAL discounted LCC at 5% discount rate	2550	1830	990	2330	990	1710	1550	2100

Table IV

Life Cycle Costs for Hybrid Reactor/Can-in-Canister Vitrification Options

Facility/Cost category description (All costs in constant 1996$M)	LWR Hybrid Case: Three LWRs & US MOX fabrication facility for 32.5 MT Pu + Vit Can-in-canister for 17.5 MT Pu; PuP facility located in existing SRS F-area handles all 50 MT Pu.	CANDU Hybrid Case: Two CANDU reactors & US MOX fabrication facility for 32.5 MT Pu + Vit Can-in-canister for 17.5 MT Pu; PuP facility located in existing SRS F-area handles all 50 MT Pu.
FRONT-END FACILITY COSTS:		
Pu-processing up-front cost (for 50 MT Pu)	343	343
Pu-processing 10 year operations cost	823	823
Pu-processing D&D cost	159	159
MOX fabrication up-front cost (for 32.5 MT Pu)	350	450
MOX fabrication operations cost	711	1171
MOX fabrication D&D cost	50	70
Credit to DOE for displacement of U by MOX	-925	-273
BACK-END FACILITY COSTS:		
Hot-Cell Immobilization up-front cost (DWPF)	222	222
Hot-Cell Immobilization 10 yr operations cost	52	52
Hot-Cell Immobilization D&D cost	2	2
Reactor-related up-front cost (incremental)	205	99
Reactor-related operations costs (incremental)	70	29
Incentive fee to reactor owner	270	184
Reactor-related D&D costs (incremental)	0	0
Repository costs at $500K/canister (Immobiliz.)	35	35
Incremental repository cost for spent MOX fuel	0	0
TOTAL Undiscounted LIFE CYCLE COST	2367	3366
TOTAL Discounted LCC at 5% discount rate	1371	1867

Table V. Economic inputs to LWR model

Open cycle using all LEU fuel

Ore cost (mining and milling)	\$40/lb U_3O_8
Conversion cost (U_3O_8 to UF_6)	\$8/kg U
Uranium enrichment cost (3.3%^{235}U product assay, 0.3%^{235}U tails assay)	\$100/SWU
Fabrication cost (from UF_6 to fuel bundles)	\$200/kg HM
Waste disposal (spent fuel to repository)	\$0.001/kWh

Open cycle using MOX fuel with plutonium derived from weapons

Plutonium enrichment in MOX fuel	4.3 weight % plutonium
Conversion of "pits" to PuO_2 powder[a]	\$1300/kg HM as MOX
Fabrication of PuO_2 powder to fuel bundles[a]	\$1375/kg HM as MOX
Waste disposal (spent fuel to repository)	\$0.001/kWh
Plutonium cost as metal	zero (surplus material)

Closed cycle using reprocessed uranium (REPU) only, no plutonium recycle

Uranium services	Same as open cycle using all LEU fuel
Reprocessing cost (includes REPUF6 production)	\$1000/kg HM
High-level waste disposal as vitrified logs to repository (1360 kg HM/log equivalent)	\$0.5 M/log
Plutonium credit (based on potential plutoniumuse as 5% plutonium MOX fuel priced at LEU fuel equivalent)	-\$940/kg HM as MOX

Closed cycle with use of both REPU and reactor-grade plutonium from reprocessing; three1000 MW(e) reactors: two LEU burners providing plutonium for one MOX burner

LEU reactor fuel cycle costs	Same as open cycle using all LEU fuel
Plutonium enrichment in MOX fuel (reactor grade)	5 weight % plutonium
MOX fuel fabrication (PuO_2 to fuel bundles)	\$1500/kg HM as MOX
Reprocessing cost (includes PuO_2 production and REPUF6 production)	\$1000/kg HM
Depleted UF_6 to UO_2 conversion	\$8/kg uranium
Repository costs	Same as closed cycle using REPU only

[a] Assumes operations in new U.S. government-owned facilities

Table VI. Economic inputs to LMFBR model

Depleted uranium blanket fabrication cost	\$500/kg uranium
PuO2 fabrication cost as 17 weight % plutonium MOX	\$2500/kg HM as MOX
Reprocessing (driver and blanket fuel including oxide production)	\$1500/kg HM
Repository cost (HLW in vitrified logs)	\$0.5M/log

Table VII. Levelized fuel cycle cost for five different fuel cycles (one mill = 0.001 U.S. \$)

LWRs	
Once through LEU (3.3% ^{235}U)	6.5 mills/kWh
Once through weapons-derived MOX (4.3% plutonium)	11.7 mills/kWh with pit conversion cost included 6.3 mills/kWh with clean PuO_2 from pit conversion at no cost
Recycle of REPU only, no MOX	7.6 mills/kWh
Recycle of both REPU and reactor grade plutonium	9.7 mills/kWh
FBRs	
LMFBR	10.8 mills/kWh