DP-1360

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ECONOMIC ANALYSES OF LWR FUEL CYCLES

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PREPARED FOR THE U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION UNDER CONTRACT AT(07-2)-1

Printed in the United States of America

Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

Price: Printed Copy $4.00; Microfiche $3.00

662-1101
DP-1360

Distribution Category: UC-47

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Publication Date: May 1977

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ABSTRACT

An economic comparison was made of three options for handling irradiated light-water reactor (LWR) fuel. These options are reprocessing of spent reactor fuel and subsequent recycle of both uranium and plutonium, reprocessing and recycle of uranium only, and direct terminal storage of spent fuel not reprocessed. The comparison was based on a peak-installed nuclear capacity of 507 GWe by CY 2000 and retirement of reactors after 30 years of service. Results of the study indicate that:

- Through the year 2000, recycle of uranium and plutonium in LWRs saves about $12 billion (FY 1977 dollars) compared to the throwaway cycle, but this amounts to only about 1.3% of the total cost of generating electricity by nuclear power. If deferred costs are included for fuel that has been discharged from reactors but not reprocessed, the economic advantage increases to $17.7 billion.

- Recycle of uranium only (storage of plutonium) is ∿$7 billion more expensive than the throwaway fuel cycle and is, therefore, not considered an economically viable option.

- The throwaway fuel cycle ultimately requires >40% more uranium resources (U_3O_8) than does reprocessing spent fuel where both uranium and plutonium are recycled.

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INTRODUCTION

The nuclear fuel cycle is composed of a number of discrete operations before and after irradiation of fuel in the reactor. Those operations before irradiation are generally referred to as process steps in the front end of the fuel cycle and those after irradiation as the back end of the fuel cycle. Uranium ore mining and milling, uranium enrichment, and uranium fuel fabrication are process steps in the front end of the nuclear fuel cycles. Spent fuel reprocessing, recycle of mixed uranium-plutonium oxide (MOX) fuel, fabrication of MOX fuel, and waste management are process steps in the back end of the fuel cycle. If spent fuel is not reprocessed, the back end of the fuel cycle simply becomes permanent storage of spent fuel. The front end of the fuel cycle is well-developed and is providing fuel for commercial power reactors. Spent fuel is presently being stored underwater in basins until facilities become available either to reprocess and recycle uranium and plutonium or to permanently store fuel.

The Energy Research and Development Administration (ERDA) is supporting a program to develop missing technical information and to provide economic information needed to support decisions on the various options for the back end of the fuel cycle. Major options currently being considered include reprocessing of spent reactor fuel and subsequent recycle of both uranium and plutonium, reprocessing and recycle of uranium only (plutonium would be stored), and direct terminal storage of spent fuel without chemical reprocessing. In this report, the economics of reprocessing spent fuel are compared to those of the throwaway fuel cycle. When fuel is reprocessed, both recycle and perpetual storage of plutonium are considered.

SCOPE

The size of the commercial nuclear industry is assumed to follow the expansion schedule of Table 1 for the base capacity. High and low capacity schedules given in Table 1 were used to evaluate the sensitivity of the economics to the size of the industry. In all three cases, the ratio of pressurized-water reactors (PWR) to boiling-water reactors (BWR) is assumed to be two to one. After CY 2000, the capacity of the light-water reactor (LWR) nuclear industry is assumed to diminish as new sources of energy emerge, such as breeder reactors, fusion reactors, or solar power. Retirement of LWRs is assumed at a service life of 30 years. On this basis, the last LWR reactor fuel is assumed to have been processed or sent to terminal storage by CY 2041.

TABLE 1

Nuclear Capacity

Projection	*Reactor Type*	*CY*	*Total Capacity, GWe* *1980*	*1985*	*1990*	*1995*	*2000*
Base	PWR		48	103	178	266	338
	BWR		22	53	90	133	169
			70	156	268	399	507
High	PWR		51	114	201	306	400
	BWR		23	58	101	153	200
			74	172	302	459	600
Low	PWR		45	90	153	221	267
	BWR		21	46	77	111	133
			66	136	230	332	400

In addition to the assumed variation in nuclear capacity, a sensitivity study explores the effect on economics of increased spent fuel decay beyond the nominal one-year decay and of variations in the projected costs of U_3O_8, reprocessing, MOX fabrication, separative work, and waste management.

The fuel cycles are compared based on the economics accrued by CY 2000 and also with deferred costs assigned to each option. Deferred costs are calculated by reprocessing the backlog of irradiated fuel discharged by CY 2000, by assigning credits in mining and enrichment for recycled materials, and by completing the terminal storage of the wastes for each option. Other assumptions for the study are listed in Table 2.

TABLE 2

Assumptions for Study of LWR Fuel Cycles

1. Nuclear power schedule is not affected by option selected for the back end of the fuel cycle.

2. The required mining, separative work, and fuel fabrication for a fuel charge occur one year before the fuel is charged to the LWR.

3. Tails assay at the enrichment plants is assumed to be 0.25% ^{235}U.

4. Reprocessing plants operate at 40% capacity in first year, 67% capacity in second year, and 100% (1500 MTU/yr)[a] during later years. Allied-General Nuclear Services (AGNS) startup is assumed in 1981, and subsequent plants starting in 1986. A maximum of one new plant per year is assumed to be built after 1985.[b]

5. Plutonium recycle starts in 1983. Nominal fissile plutonium content of LWR fuel is 6.6 kg/MTU, and 7.5 kg/MTU with plutonium recycle.

6. MOX plants are collocated at reprocessing plants and are matched to reprocessing plant capacity. MOX plants operate at 50% full capacity in the first year of operation and 100% during later years.

7. Waste from reprocessing is transferred to geologic storage 10 years after reprocessing.

8. Discharged fuel is stored in water-cooled basins for 10 years before transfer to geologic storage (throwaway fuel cycle).

9. The discount rate is assumed to be 10%. No interest is charged on the recycle products.

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a. MTU is metric ton of uranium.

b. In the 5-year delay case, AGNS startup is delayed until 1986 and new plants until 1991. Two new plants per year are assumed to be built in the 5-year delay case.

COSTING METHOD

Computer Model

The economics of alternative LWR fuel cycles were calculated with the aid of a computer model of the nuclear fuel cycle (Figure 1). A cost center is provided in the model for each major fuel cycle step. Currently, the program requires as input a schedule of annual reactor capacity, reactor innage, and fuel characteristics for each reactor type as given in Table 3 for PWR and BWR.

The computer program primarily calculates the front end parameters (ore mining and milling, uranium enrichment, and uranium fuel fabrication) necessary to support the reactor schedule selected. Material quantities are calculated annually based on new fuel demands, tails assay, and specified reactor innage. Annual discharge of fuel is assumed; fuel assays are adjusted from the base content if the reactor innage differs from 75%.

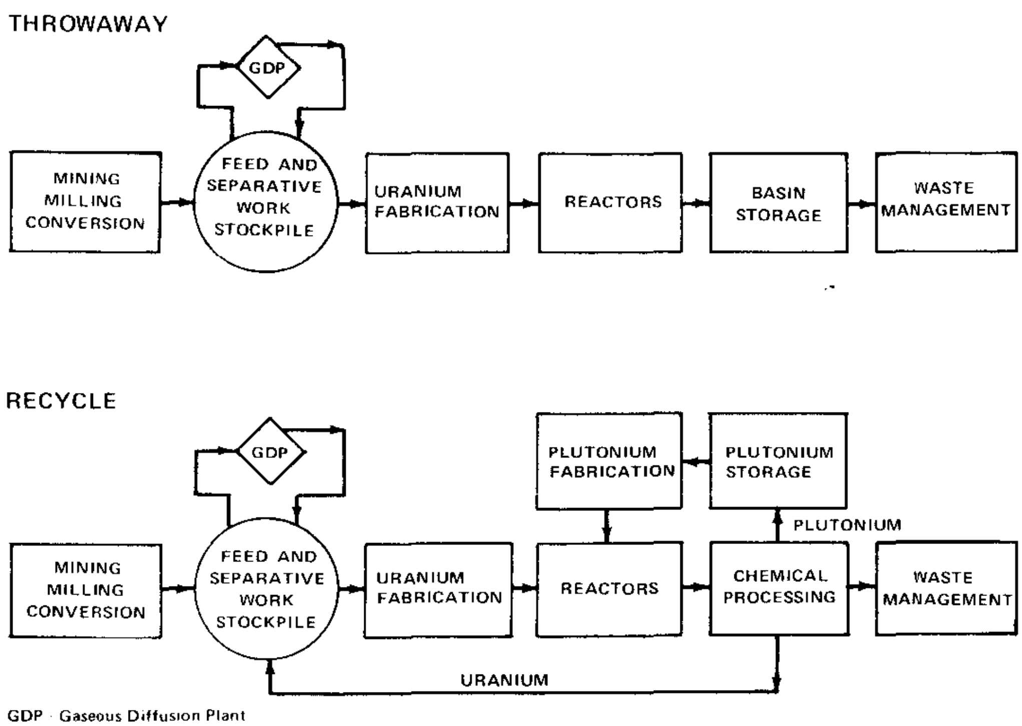

FIGURE 1. Cost Centers and Material Flows in Power Reactor Systems Model

TABLE 3

Fuel Charge Characteristics[a,b]

	PWR	*BWR*
Initial core, average		
Irradiation level, MWDth/MTU	22,600	17,000
Fresh fuel, MTU	76.38	117.20
Fresh fuel assay, wt % ^{235}U	2.260	2.030
Spent fuel, MTU	74.00	114.50
Spent fuel assay, wt % ^{235}U	0.740	0.860
Replacement loadings (annual rate without plutonium recycle; 75% plant factor)		
Irradiation level, MWDth/MTU	32,600	27,500
Fresh fuel, MTU	25.46	29.30
Fresh fuel assay, wt % ^{235}U	3.210	2.730
Spent fuel, MTU	24.30	28.20
Spent fuel assay, wt % ^{235}U	0.900	0.840
Fissile plutonium discharged, MT	0.178	0.173
Replacement loadings (annual rate with plutonium recycle; 75% plant factor)		
Irradiation level, MWDth/MTU	32,600	27,500
Fresh fuel, MTU	25.46	29.30
Fresh fuel assay, wt % ^{235}U	2.800	2.390
Fissile plutonium recycled, MT	0.167	0.163
Spent fuel, MTU	24.30	28.20
Spent fuel assay, wt % ^{235}U	0.900	0.840
Fissile plutonium discharged, MT	0.242	0.237

a. Derived from Reference 1.
b. For model reactors of 1000-MWE capacity. MWDth is thermal megawatt days.

Operations subsequent to discharge of irradiated fuel (the back end of the fuel cycle) are hand-calculated because the initial version of the computer program does not include features to defer reprocessing or to schedule partial reprocessing of discharged fuel. Isotopic changes in uranium and plutonium with continued recycle are not accounted for by the computer code, but corrections are applied to the recycle cases.

Unit costs are specified by cost center and consist of operating costs and capital recovery costs (defined as plant capitalization times an appropriate fixed charge rate). Unit costs used in the report are shown in Table 4. All costs are expressed in FY 1977 dollars, and there is no escalation during the study. No interest charges are assumed for materials in inventory.

TABLE 4

Costs in FY 1977 Dollars

Uranium oxide cost, \$/lb U_3O_8 (including conversion to UF_6). Linear interpolation between values shown.

Cumulative Amount Mined, millions of tons U_3O_8	*Cost*
0	36
1	47
2	58
3	69
Enrichment cost, \$/kg separative work unit (SWU)	100
Uranium fabrication, \$/kg U	90
MOX fabrication penalty, \$/kg of fissile Pu[a]	5000
Plutonium storage, \$/(yr)(kg of fissile Pu)	300[b]
Separations cost, \$/kg U[c]	
Designed to process irradiated fuel that has decayed	
1 year; 1500 MTU/yr	280
5 years; 1500 MTU/yr	261
1 year; 3000 MTU/yr	209
1 year; 6000 MTU/yr	179
Shipping cost, \$/kg U	6
Waste management cost, \$/kg U	25
Storage of fuel assemblies, \$/kg U (throwaway fuel cycle)	90

a. Cost is in addition to uranium fabrication cost in MOX assembly.
b. For short storage times (less than permanent storage).
c. 25% annual charge on capital investment applied for commercial reprocessing.

Cost Centers

Mining

Uranium ore cost is assumed to increase as the ore deposits decrease in assay. The first pound of ore used in the studies costs \$35.21,* and the cost is assumed to increase \$11 for each million tons of U_3O_8 mined. Thus, the mining costs increase during the study period as shown in Figure 2. For comparison, lower ore costs are estimated in GESMO,[2] and higher costs are estimated by AGNS.[3] Uranium conversion is assumed to cost \$2/lb U_3O_8 (\$2.36/lb U).

* 100,000 metric tons was assumed to be consumed before the start of the study period.

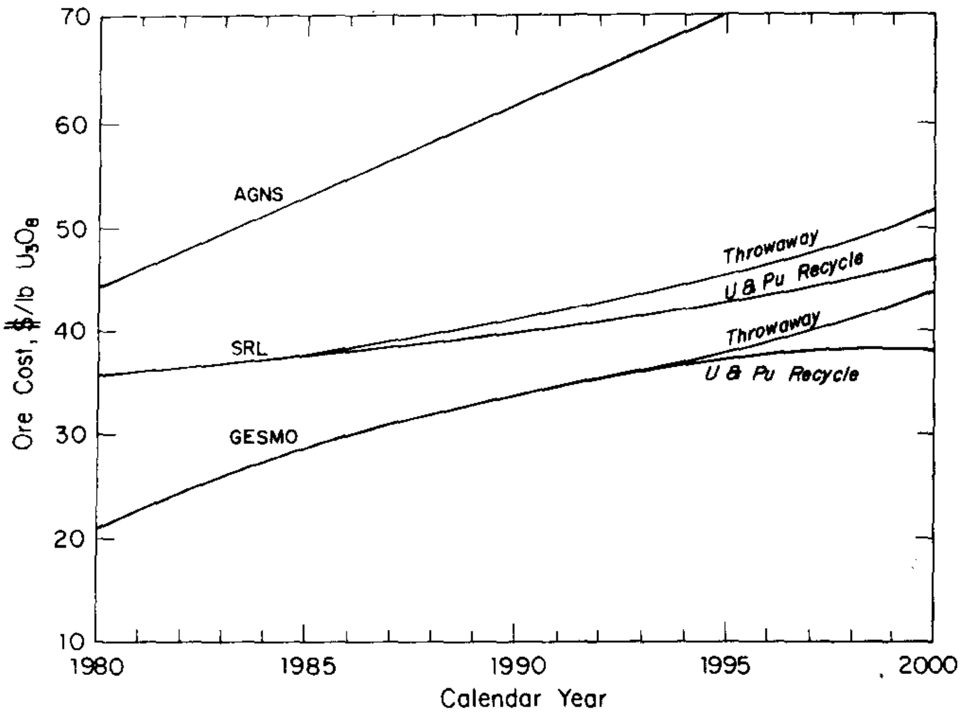

FIGURE 2. Forecasts of Uranium Ore Price

Enrichment

Enrichment services from the gaseous diffusion plant (GDP) are projected to be $61.30/SWU in FY 1977. Cost estimates for services from private enrichment plants have been about $75/kg (FY 1975 dollars, no interest or escalation on plant capital cost) for either diffusion plants or centrifuge plants. A cost of $100/kg (FY 1977 dollars) is assumed in the present study.

Fabrication

Uranium fuel fabrication costs ($90/kg) are believed to be similar to current commercial contracts for LWR fuel. An estimate of the cost of MOX fabrication facilities is given in Table 5; the costs are equivalent to a penalty of $5 per gram of fissile plutonium.

TABLE 5

MOX Fabrication Cost Estimate

Costs, millions of FY 1977 dollars

Year	*Construction Cost*	*Pre-Startup Cost*	*Interest at 8%*	*Capitalization Total*
1	15	2	1	18
2	30	5	3	38
3	40	8	6	54
4	20	12	9	41
5	-	10	11	21
Total	105	37	30	172

Annual MOX Fabrication Cost (350 MTHM/yr), millions of FY 1977 dollars[a]

Capital recovery	172 × 0.25 =	43
Labor		20
Materials and equipment replacement		20
		83
Unit Cost, $/kg heavy metal		236
Throughput, MTU/yr		
Uranium		335.5
Fissile plutonium		10.5

Annual Cost, millions of FY 1977 dollars

Uranium at $90/kg processed		30.2
Plutonium at $5/g penalty		52.5
	Total cost	82.7

a. MTHM is metric ton of heavy metal (uranium and plutonium).

Storage

Fuel storage basins are provided in LWR facilities to store fuel assemblies discharged during several years of plant operation. Additional storage basins will be needed for a throwaway fuel cycle or if reprocessing is deferred. A storage cost of $2.30/(kg)(yr) was used for all fuel cycles.

Plutonium storage costs were assumed to be $0.30 per gram of fissile plutonium per year. For evaluation of the fuel cycle with plutonium not recycled until after CY 2000, the same storage cost was assumed.

Reprocessing

Cost estimates for the back end of the fuel cycle are more uncertain because of emerging licensing requirements and few commercial ventures. Reprocessing costs shown in Table 4 are $280/kg for 1500-MTU/yr plant, $261/kg for same size plant but five years of fuel decay before reprocessing; at one-year decay, $209/kg for 3000-MTU/yr plant or $179/kg for 6000-MTU/yr plant.

Terminal Waste

Terminal waste costs are applied 10 years after the first reprocessing cost; terminal waste costs include transferring solidified high-level waste to geologic storage and appropriate terminal storage for the other lower level wastes generated with recycle.

Waste handling and terminal storage costs are also estimated for the throwaway fuel cycle. Annual fuel storage costs are assumed for 10 years in water-cooled basins ($23/kg for 10 years); the cost of encapsulation, shipping, and terminal emplacement of fuel is estimated as a one-time cost of $67/kg.

Discounting

No interest charges on the fuel between the time of acquisition by the utility until transfer to the reprocessor are included in the economic cases because discounting more appropriately accounts for the difference in timing in return of benefits to the fuel owner. The utility has bought the fuel and does not pay itself interest. In the throwaway fuel cycle, there are no interest charges because the irradiated fuel is a waste product and, hence, has no value. In recycle cases, an interest charge based on the net value of the fuel could be useful in comparing delay periods before reprocessing or in deciding on reprocessing rather than throwaway. Discounting the annual costs for each fuel cycle option also reveals differences in payout for options. For instance, the effects of differences in cash flow for variable periods of fuel decay (one year and five years) before reprocessing are accounted for by discounting. A discount rate of 10% is used in this report.

REPROCESSING SCHEDULES

Schedules for recycle facilities (Tables 6-11) were prepared based on the assumptions previously discussed. For the base nuclear capacity, six new reprocessing plants (1500 MTU/yr) are built by CY 2000 (Table 6). Inventory of fuel in storage during the study period is shown in Figure 3 for the nominal one-year fuel decay and in Figure 4 for the five-year fuel decay case. The material flows for the study cases are summarized in Table 12.

The back end fuel cycle options affect the schedules for new enrichment facilities. A hypothetical combination of demands for alternative fuel cycles with the base reactor schedule and an assumed foreign enrichment demand is shown in Table 13. The enrichment demand assumed is about half the total non-communist world demand. With recycle of uranium and plutonium, about one less new enrichment plant (9000 MT SWU/yr) is needed by CY 2000.

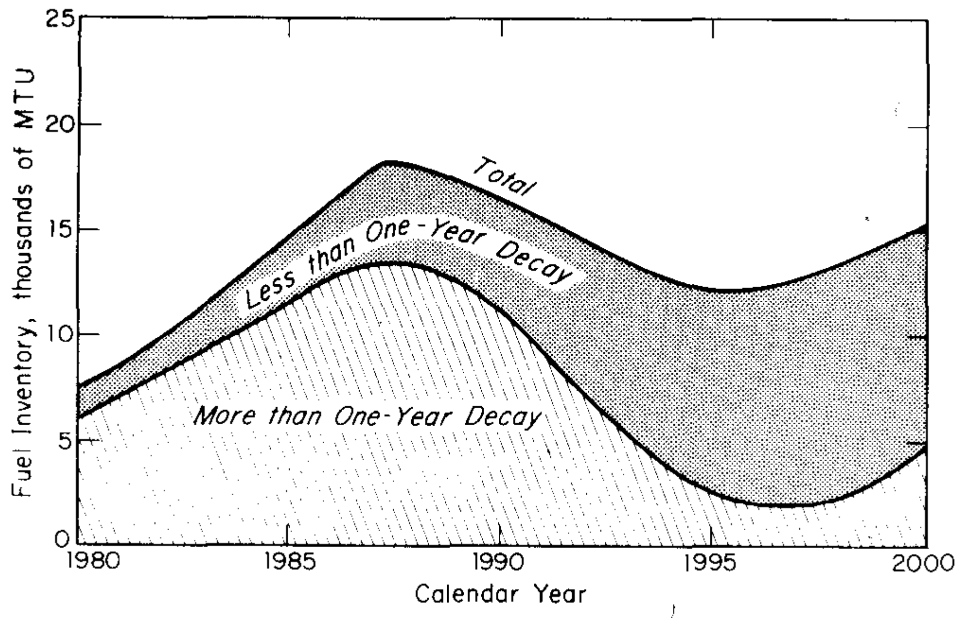

FIGURE 3. Fuel Storage with One-Year Fuel Decay Before Reprocessing

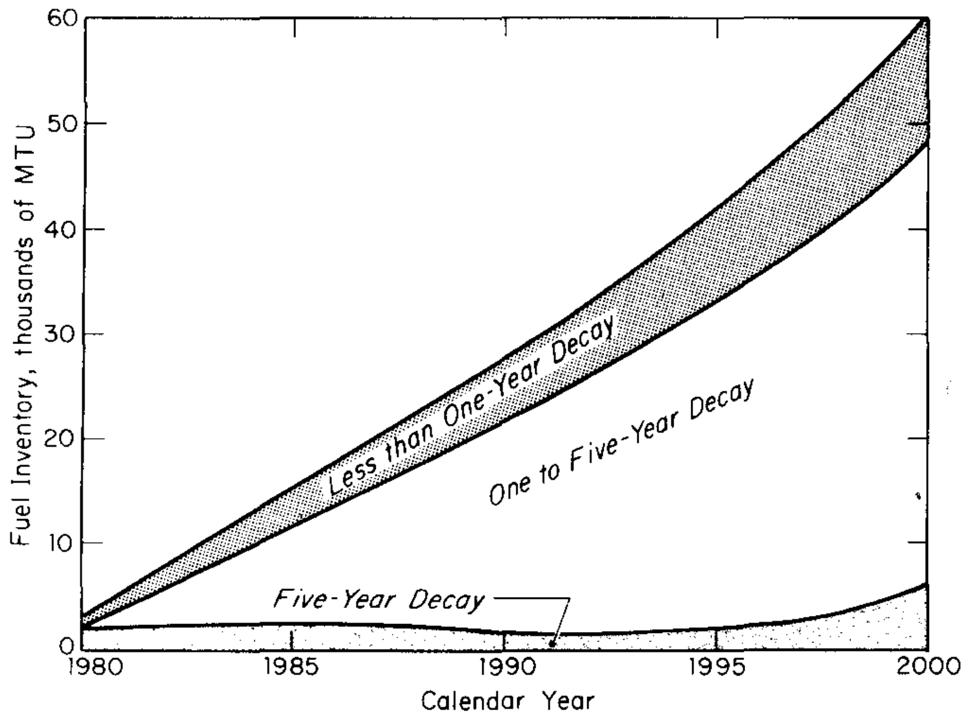

FIGURE 4. Fuel Storage with Five-Year Fuel Decay Before Reprocessing

TABLE 6

Recycle Schedule with One-Year Fuel Decay for 1500-MTU/yr Plants (507 GWe)

			Separations						
CY	*Fuel Discharged, MTU*	*Cumulative Inventory 1-yr Decay, MTU*	*Number of Plants* *New Startup*	*Operating*	*Production, MTU/yr*	*Inventory Unprocessed, MTU*	*Cumulative U Processed, MT*	*Annual Fissile Pu Processed, MT*	*MOX Production, MTHM*
1976	937	1,623[a]		0	0	1,623	0	0	
1977	1,111	2,560		0	0	2,560	0	0	
1978	1,310	3,671		0	0	3,671	0	0	
1979	1,455	4,981		0	0	4,981	0	0	
1980	1,591	6,436		0	0	6,436	0	0	
1981	1,797	8,027	AGNS[b]	1	600	7,427	600	4.0	
1982	2,059	9,824		1	1,000	8,224	1,600	6.6	
1983	2,583	11,883		1	1,500	8,780	3,100	9.9	175
1984	3,024	14,466		1	1,500	9,866	4,600	9.9	350
1985	3,493	17,490		1	1,500	11,390	6,100	9.9	350
1986	4,029	20,983	1	2	2,100	12,783	8,200	13.9	350
1987	4,625	25,012	1	3	3,100	13,712	11,300	20.5	525
1988	5,193	29,637	1	4	4,600	13,737	15,900	30.4	875
1989	5,727	34,830	1	5	6,100	12,830	22,000	40.3	1,225
1990	6,310	40,557	1	6	7,600	10,957	29,600	50.2	1,575
1991	6,901	46,867		6	8,500	8,767	38,100	63.7	1,925
1992	7,541	53,768		6	9,000	6,668	47,100	67.5	2,100
1993	8,233	61,309		6	9,000	5,209	56,100	67.5	2,100
1994	8,874	69,542	1	7	9,600	3,842	65,700	72.0	2,100
1995	9,566	78,416		7	10,000	2,716	75,700	75.0	2,275
1996	10,257	87,982		7	10,500	1,782	86,200	78.8	2,450
1997	10,895	98,239		7	10,500	1,539	96,700	78.8	2,450
1998	11,483	109,134		7	10,500	1,934	107,200	78.8	2,450
1999	12,018	120,617		7	10,500	2,917	117,700	78.8	2,450
2000	12,529	132,635		7	10,500	4,435	128,200	78.8	2,450
2001	-[c]	145,164		7	10,500	6,464	138,700	78.8	2,450
2002	-	-		7	6,464	0	145,164	48.5	2,450
2003	-	-		7					260

a. Spent fuel discharged before CY 1976.
b. Indicates year of startup for AGNS and new separations plants (1500 MTU/yr). Plants operate at 40% capacity in first year, 67% in second year, and 100% thereafter.
c. Not applicable.

TABLE 7

Recycle Schedule with Five-Year Fuel Decay for Base Nuclear Capacity (507 GWe)

CY	U_3O_8 *Production, MT*	*Annual Enrichment Production, 1000 MT SWU*	*Annual Discharge, MTU*	*Chemical Processing, MTU*	*Fissile Pu Separated, MT*	*MOX Production, MTHM*
			1,623[a]			
1976	11,743	16	937			
1977	12,253	18	1,111			
1978	13,199	20	1,310			
1979	15,811	22	1,455			
1980	22,331	23	1,591			
1981	24,126	23	1,797	600[b]	4.0	
1982	24,737	23	2,059	1,000	6.6	
1983	26,947	24	2,583	1,500	9.9	175[c]
1984	31,685	24	3,024	1,500	9.9	350
1985	37,053	37[d]	3,493	1,500	9.9	350
1986	40,860	37	4,029	1,500	9.9	350
1987	42,577	37	4,625	2,100[b]	13.9	350
1988	46,143	46[d]	5,193	2,500	16.5	525[c]
1989	50,026	46	5,727	3,000	19.8	700
1990	53,491	55[d]	6,310	3,600[b]	23.8	700
1991	58,332	55	6,901	4,000	26.4	875[c]
1992	61,586	64[d]	7,541	4,500	29.7	1,050
1993	65,706	64	8,233	5,100[b]	33.7	1,050
1994	69,444	64	8,874	5,500	41.3	1,225[c]
1995	72,753	73[d]	9,566	6,000	45.0	1,400
1996	75,508	73	10,257	6,600[b]	49.3	1,400
1997	77,536	82[d]	10,895	7,000	52.5	1,575[c]
1998	78,661	91	11,483	8,100[b]	60.8	1,750
1999	80,503	91	12,018	8,500	63.8	1,925[c]
2000	72,421	91	12,529	9,000	67.5	2,100
2001	-[e]	-	-	9,600[b]	72.0	-
2002	-	-	-	10,000	75.0	-
2003	-	-	-	10,500	78.8	-
2004	-	-	-	10,500	78.8	-
2005	-	-	-	10,500	78.8	-
2006	-	-	-	10,500	78.8	-
2007	-	-	-	464	2.3	-
Total	1,165,430	1,199	145,164	145,164	1,059.0	17,850[f]

a. Spent fuel discharged before CY 1976.
b. Indicates year of startup for AGNS and new separations plants (1500 MTU/yr).
c. Indicates year of startup of MOX plants. Plants operate at 50% capacity in first year and 100% thereafter (capacity equivalent to associated separations plant). 5% of MOX production is retained in pipelines.
d. Indicates year of startup of new enrichment plants (9000 MT SWU/yr).
e. Not applicable.
f. An additional 15,480 MT of MOX containing plutonium recovered from fuel discharged through CY 2000 is charged to reactors after CY 2000.

TABLE 8

Recycle Schedule with Five-Year Delay Before Reprocessing (507 GWe)

CY	U_3O_8 *Production, MT*	*Annual Enrichment Production, 1000 MT SWU*	*Annual Discharge, MTU*	*Chemical Processing, MTU*	*Fissile Pu Separated, MT*	*MOX Production, MTHM*
			1,623[a]			
1976	11,743	16	937			
1977	12,253	18	1,111			
1978	13,199	20	1,310			
1979	15,811	22	1,455			
1980	22,331	23	1,591			
1981	25,138	23	1,797			
1982	27,076	23	2,059			
1983	31,051	24	2,583			
1984	35,637	24	3,024			
1985	40,988	37[b]	3,493			
1986	43,048	37	4,029	600[c]	4.0	
1987	44,992	37	4,625	1,000	6.6	175[d]
1988	49,487	46[b]	5,193	1,500	9.9	350
1989	54,302	46	5,727	1,500	9.9	350
1990	58,679	55[b]	6,310	1,500	9.9	350
1991	61,676	55	6,901	2,700[c]	17.8	525[d]
1992	59,963	55	7,541	4,700[c]	31.0	875[d]
1993	58,457	64[b]	8,233	7,700[c]	50.8	1,400[d]
1994	58,224	64	8,874	9,500	62.7	2,100[d]
1995	60,674	73[b]	9,566	10,500	69.3	2,450
1996	65,309	73	10,257	10,500	78.8	2,450
1997	68,847	82[b]	10,895	10,500	78.8	2,450
1998	72,613	82	11,483	10,500	78.8	2,450
1999	75,950	91[b]	12,018	10,500	78.8	2,450
2000	68,365	91	12,529	10,500	78.8	2,450
2001	-[e]	-	-	10,500	78.8	-
2002	-	-	-	10,500	78.8	-
2003	-	-	-	10,500	78.8	-
2004	-	-	-	10,500	78.8	-
2005	-	-	-	9,464	71	-
Total	1,135,823	1,181	145,164	145,164	1,052	20,830[f]

a. Spent fuel discharged before CY 1976.
b. Indicates year of startup of new enrichment plants (9000 MT SWU/yr).
c. Indicates year of startup for AGNS and new separations plants (1500 MTU/yr). Plants operate at 40% capacity in first year, 67% in second year, and 100% thereafter.
d. Indicates year of startup of MOX plants. Plants operate at 50% capacity in first year and 100% thereafter (capacity equivalent to associated separations plant). 5% of MOX production is retained in pipelines.
e. Not applicable.
f. An additional 12,500 MT of MOX containing plutonium recovered from fuel discharged through CY 2000 is charged to reactors after CY 2000.

TABLE 9

Recycle Schedule for High Nuclear Capacity (600 GWe)

CY	*Annual Discharge, MTU*	*Chemical Processing, MTU*	*Fissile Pu Separated, MT*	*MOX Production, MTHM*
	1,623[a]			
1976	937			
1977	1,164			
1978	1,310			
1979	1,455			
1980	1,644			
1981	1,899	600[b]	4.0	
1982	2,114	1,000	6.6	
1983	2,817	1,500	9.9	175[c]
1984	3,336	1,500	9.9	350
1985	3,908	1,500	9.9	350
1986	4,442	2,100[b]	13.9	350
1987	5,036	3,100[b]	20.5	525[c]
1988	5,631	4,600[b]	30.4	875[c]
1989	6,321	6,100[b]	40.3	1,225[c]
1990	7,032	7,600[b]	50.2	1,575[c]
1991	7,778	8,500	63.8	1,925[c]
1992	8,572	9,000	67.5	2,100
1993	9,370	9,600[b]	72.0	2,100
1994	10,189	10,000	75.0	2,275[c]
1995	11,009	10,500	78.8	2,450
1996	11,802	11,100[b]	83.3	2,450
1997	12,569	11,500	86.3	2,625[c]
1998	13,312	12,000	90.0	2,800
1999	14,050	12,600[b]	94.5	2,800
2000	14,743	13,000	97.5	2,975[c]
2001	-[d]	13,500	101.3	-
2002	-	13,163	98.8	-
Total	164,063	164,063	1,204	29,925[e]

a. Spent fuel discharged before CY 1976.

b. Indicates year of startup for AGNS and new separations plants (1500 MTU/yr). Plants operate at 40% capacity in first year, 67% in second year, and 100% thereafter.

c. Indicates year of startup of MOX plants. Plants operate at 50% capacity in first year and 100% thereafter (capacity equivalent to associated separations plant). 5% of MOX production is retained in pipelines.

d. Not applicable.

e. An additional 7910 MT of MOX containing plutonium recovered from fuel discharged through CY 2000 is charged to reactors after CY 2000.

TABLE 10

Recycle Schedule for Low Nuclear Capacity (400 GWe)

CY	*Annual Discharge, MTU*	*Chemical Processing, MTU*	*Fissile Pu Separated, MT*	*MOX Production, MTHM*
	1,623[a]			
1976	937			
1977	1,087			
1978	1,208			
1979	1,330			
1980	1,517			
1981	1,696	600[b]	4.0	
1982	2,035	1,000	6.6	
1983	2,296	1,500	9.9	175[c]
1984	2,687	1,500	9.9	350
1985	2,997	1,500	9.9	350
1986	3,511	2,100[b]	13.9	350
1987	4,162	3,100[b]	20.5	525[c]
1988	4,677	4,600[b]	30.3	875[c]
1989	5,056	5,500	36.3	1,225[c]
1990	5,511	6,000	39.6	1,400
1991	5,917	6,600[b]	49.5	1,400
1992	6,379	7,000	52.5	1,575[c]
1993	6,918	7,500	56.3	1,750
1994	7,429	8,100[b]	60.8	1,750
1995	7,944	8,500	63.8	1,925[c]
1996	8,534	9,000	67.5	2,100
1997	8,989	9,000	67.5	2,100
1998	9,375	9,000	67.5	2,100
1999	9,702	9,000	67.5	2,100
2000	10,095	9,000	67.5	2,100
2001	-[d]	9,000	67.5	-
2002	-	4,512	33.8	-
Total	123,612	123,612	903	24,150[e]

a. Spent fuel discharged before CY 1976.

b. Indicates year of startup of AGNS and new separations plants (1500 MTU/yr). Plants operate at 40% capacity in first year, 67% in second year, and 100% thereafter.

c. Indicates year of startup of MOX plants. Plants operate at 50% capacity in first year and 100% thereafter (capacity equivalent to associated separations plant). 5% of MOX production is retained in pipelines.

d. Not applicable.

e. An additional 4120 MT of MOX containing plutonium recovered from fuel discharged through CY 2000 is charged to reactors after CY 2000.

TABLE 11

Extended Reprocessing Schedule (CY 2001-2030)

CY	*LWR Fuel Discharged, MTU*	*LWR Fuel[a] Separated, MTU/yr*	*Pu Fuel Fabricated, MT*	*Fissile Pu in Storage, MT*	*LWR Capacity, GWe in Operation During Year*
2001	13,551	11,100	77.7	1.7	499
2002	13,245	11,100	77.7	1.7	492
2003	13,056	11,100	77.7	1.7	485
2004	12,866	11,100	77.7	1.7	478
2005	12,682	11,100	77.7	1.7	471
2006	12,427	11,100	77.7	1.7	464
2007	12,303	11,100	77.7	1.7	456
2008	11,968	11,100	77.7	1.7	450
2009	11,809	11,100	77.7	1.7	445
2010	11,906	11,100	77.7	1.7	437
2011	11,836	11,100	77.7	1.7	427
2012	12,221	11,100	77.7	1.7	407
2013	11,481	11,100	77.7	1.7	390
2014	11,131	11,100	77.7	1.7	372
2015	10,779	11,100	77.7	1.7	351
2016	10,456	11,100	67.2	12.2	328
2017	9,774	11,100	67.2	22.7	306
2018	9,086	11,100	63	37.4	285
2019	8,652	11,100	52.5	62.6	262
2020	8,142	11,100	52.5	87.8	239
2021	7,651	9,000	42	108.8	214
2022	7,148	9,000	42	129.8	187
2023	6,321	9,000	31.5	161.3	162
2024	5,818	9,000	31.5	192.8	135
2025	5,127	9,000	21	234.8	108
2026	4,300	7,500	21	266.3	83
2027	3,562	6,000	10.5	297.8	60
2028	2,835	3,832	10.5	314.1	39
2029	2,248	2,835	0	333.9	19
2030	1,695	2,248	0	349.6	0

a. The extended study assumed that the Nuclear Fuel Service plant would restart in 1981 and reprocess 600 MTU/yr at full capacity in addition to the plants shown in Table 6. However, the total fuel reprocessed is not significantly different.

TABLE 12

Cumulative Material Flows[a]

	CY 1976-2000	*CY 1976-2020*	*CY 1976-2041*
Base Capacity (507 GWe)			
U_3O_8 Mined, MT			
Throwaway	1,381,300	2,873,000	3,022,000
Uranium and Plutonium Recycle	1,047,300	2,050,000	2,105,000
Uranium Recycle[b]	1,182,400		
Uranium Reprocessed, MT	128,200	350,000	421,000
Fissile Plutonium Separated, MT	935	2,400	2,900
High Capacity (600 GWe)[b]			
U_3O_8 Mined, MT			
Throwaway	1,584,000		
Uranium and Plutonium Recycle	1,212,000		
Uranium Recycle	1,368,000		
Uranium Reprocessed, MT	137,400		
Fissile Plutonium Separated, MT	1,004		
Low Capacity (400 GWe)[b]			
U_3O_8 Mined, MT			
Throwaway	1,150,300		
Uranium and Plutonium Recycle	864,000		
Uranium Recycle	979,000		
Uranium Reprocessed, MT	110,000		
Fissile Plutonium Separated, MT	801		
Five-Year Fuel Decay Before Reprocessing (507 GWe)[b]			
U_3O_8 Mined, MT			
Uranium and Plutonium Recycle	1,165,000		
Uranium Reprocessed, MT	83,100		
Fissile Plutonium Separated, MT	594		
Five-Year Delay Before Start of Reprocessing (507 GWe)[b]			
U_3O_8 Mined, MT			
Uranium and Plutonium Recycle	1,136,000		
Uranium Reprocessed, MT	93,700		
Fissile Plutonium Separated, MT	666		

a. Mining costs were calculated by assuming 100,000 MT of uranium ore was mined before the start of the study.
b. Study terminated after CY 2000.

TABLE 13

Enrichment Schedule for Base Nuclear Capacity (507 GWe)

	Enrichment Demand, 1000 MT SWU							*Enrichment Production*						*Cumulative Inventory, 1000 MT SWU*		
	Domestic			*Assumed*	*Total Domestic plus Foreign plus Increment*[a]			*Throwaway*		*U Recycle*		*U, Pu Recycle*				
CY	*Throw-away*	*U Recycle*	*U, Pu Recycle*	*Foreign Demand*	*Throw-away*	*U Recycle*	*U, Pu Recycle*	*No. of Plants*	*1000 MT SWU*	*No. of Plants*	*1000 MT SWU*	*No. of Plants*	*1000 MT SWU*	*Throw-away*	*U Recycle*	*U, Pu Recycle*
1976	6.1	6.1	6.1	5.1	12.0	12.0	12.0	3[b]	16	3[b]	16	3[b]	16	19.0	19.0	19.0
1977	6.5	6.5	6.5	6.4	13.1	13.1	13.1	3	18	3	18	3	18	23.9	23.9	23.9
1978	7.0	7.0	7.0	7.7	14.9	14.9	14.9	3	20	3	20	3	20	29.0	29.0	29.0
1979	8.3	8.3	8.3	8.6	17.1	17.1	17.1	3	22	3	22	3	22	33.9	33.9	33.9
1980	10.5	10.5	10.5	9.4	20.2	20.2	20.2	3	23	3	23	3	23	36.7	36.7	36.7
1981	12.8	12.8	12.6	9.2	22.2	22.2	22.0	3	23	3	23	3	23	37.5	37.5	37.7
1982	14.0	13.9	13.3	8.9	23.0	22.9	22.2	3	23	3	23	3	23	37.5	37.6	38.5
1983	16.1	15.7	14.6	10.2	26.6	26.2	25.1	3	24	3	24	3	24	34.9	35.4	37.4
1984	18.5	18.2	17.1	11.4	30.3	29.9	28.8	3	24	3	24	3	24	28.6	29.5	32.6
1985	21.3	21.5	19.9	13.0	34.7	35.0	33.3	4	37	4	37	3	28	30.9	31.5	27.3
1986	23.5	23.4	21.6	14.6	38.5	38.3	35.5	4	37	4	37	4	37	29.4	30.2	28.8
1987	25.5	25.1	22.1	17.1	43.0	42.6	39.5	4	37	4	37	4	37	23.4	24.6	26.3
1988	28.1	27.4	23.2	19.6	48.2	47.5	43.2	5	46	5	46	4	37	21.2	23.1	20.1
1989	30.7	29.7	24.2	19.4	50.2	49.3	43.7	5	46	5	46	5	46	17.0	19.8	22.4
1990	33.5	32.6	25.4	19.2	53.0	52.1	44.9	6	55	6	55	5	46	19.0	22.7	23.5
1991	36.5	35.3	28.5	20.6	57.5	56.3	49.4	6	55	6	55	5	46	16.5	21.4	20.1
1992	38.9	37.8	30.9	22.0	61.3	60.2	53.3	7	64	7	64	6	55	19.2	25.2	21.8
1993	42.0	41.0	34.1	26.2	68.8	67.9	60.9	7	64	7	64	6	55	14.4	21.3	15.9
1994	44.8	43.7	36.3	30.3	75.7	74.7	68.3	8	73	8	73	7	64	11.7	19.6	11.6
1995	47.2	45.9	37.9	33.0	80.7	79.4	71.2	9	82	9	82	8	73	13.0	22.2	13.4
1996	49.4	48.5	40.3	35.7	85.6	84.7	76.6	9	82	9	82	9	82	10.4	19.5	18.8
1997	51.4	50.5	42.3	39.5	91.5	90.6	82.3	10	91	10	91	9	82	9.9	19.9	18.5
1998	53.3	52.5	43.6	43.3	97.2	96.3	87.4	11	100	10	91	10	91	12.7	14.6	22.1
1999	55.1	54.5	46.3	48.2	103.9	103.4	95.2	11	100	11	100	10	91	8.8	11.2	17.9
2000	52.0	51.4	43.2	53.0	105.2	104.6	96.4	11	100	11	100	10	91	3.6	6.6	12.5
Total	733.0	718.9	615.8	531.7	1274.4	1261.4	1156.5		1262		1253		1154			

a. "Increment" included for process holdup is defined as follows:
Increment = 0.1[Domestic + Foreign Demand)year i - (Domestic + Foreign Demand)year i-1].

b. Production from three existing gaseous diffusion plants to 28,000 MT SWU as projected in Reference 4. Additional plants (9000 MT SWU/yr) added as shown.

RESULTS

Fuel Cycle Costs

The fuel cycle costs are given in Tables 14, 15, and 16 for the base capacity, the high capacity, and the low capacity, respectively. Costs are itemized by cost center for each fuel cycle, and total costs are compared to the throwaway fuel cycle. Two cost breakdowns are shown: costs through CY 2000 and costs with the deferred costs associated with the fuel discharged by CY 2000 included.

Recycle of uranium (plutonium stored) is $7 billion more expensive than the throwaway fuel cycle with deferred costs and credits included. The savings with uranium recycle are chiefly in mining costs (about 15% less ore is consumed) but are insufficient to offset the cost of reprocessing. The cost difference between the recycle of uranium only and the throwaway fuel cycle is insensitive to the size of the nuclear industry. The largest difference is calculated for the low growth case because the ore savings are less significant with that schedule.

The recycle of uranium and plutonium has economic advantages over a throwaway fuel cycle. The advantage is $12 billion for the base case by CY 2000 and varies about $3 billion for the high and low nuclear capacities. With deferred costs included, primarily for waste and credits for recycle of uranium and plutonium in inventory at CY 2000, the advantage for recycle increases to $17.7 billion for the base capacity, $13 billion for low capacity, and over $23 billion for high capacity.

There is no economic advantage or penalty in requiring five years of fuel decay before reprocessing. Although the specific power of the fuel decreases, no major simplification of reprocessing is identified. The savings accrued by CY 2000 are over $1 billion more with a shorter decay period. A correction for ^{241}Pu is required because a larger fraction of this fissile isotope decays to nonfissile ^{241}Am with longer decay. When deferred costs are included, the higher unit cost of uranium ore after CY 2000 yields higher future savings when the larger inventory of fuel is reprocessed, and recovered products are recycled. Thus, an apparent advantage of $1 billion is calculated for the five-year decay case. However, as discussed below, this advantage disappears with discounting the costs. The additional decay case was only evaluated with the base reactor capacity. A five-year delay in the start of reprocessing was also evaluated, and costs were very similar to the other full recycle options.

TABLE 14

Fuel Cycle Costs for Base Nuclear Capacity (507 GWe), billions of FY 1977 dollars

	CY 1976-2000					*CY 1976 to End of Study*[a]				
	U and Pu Recycle 1-yr Decay	*U and Pu Recycle 5-yr Decay*	*U and Pu Recycle 5-yr Delay*	*U Recycle*	*Throwaway*	*U and Pu Recycle 1-yr Decay*	*U and Pu Recycle 5-yr Decay*	*U and Pu Recycle 5-yr Delay*	*U Recycle*	*Throwaway*
Mining	100.3	113.5	110.1	115.4	138.5	95.5	94.8	95.3	112.5	138.5
Separative work	61.6	65.8	64.3	71.9	73.2	60.1	60.3	60.0	71.8	73.2
Uranium fabrication	16.0	16.9	16.6	18.5	18.5	16.0	16.9	16.6	18.5	18.5
Fuel storage	0.4	1.2	1.2	0.4	2.1	0.4	1.6	1.4	0.4	3.6
Chemical reprocessing	36.8	22.2	27.1	36.8	0	41.5	38.8	41.5	41.5	0
Plutonium storage	0.3	0.2	0.1	1.9	0	0.4	0.4	0.3	2.3	0
MOX fabrication	6.9	4.4	5.2	0	0	8.3	8.3	8.3	0	0
Terminal waste	0.7	0.5	0.2	0.7	2.7	3.6	3.6	3.6	3.6	9.7
Total	223.0	224.7	224.8	245.6	235.0	225.8	224.7	227.0	250.6	243.5
Difference from throwaway	-12.0	-10.3	-10.2	+10.6	-	-17.7	-18.8	-16.5	+7.1	-

a. Includes deferred costs and credits. Deferred costs are defined as costs required to complete processing, storage, and disposal of irradiated fuel discharged through CY 2000. Credit for recovered uranium and plutonium is applied to reduce the mining and separative work costs incurred through CY 2000.

TABLE 15

Fuel Cycle Costs for High Nuclear Capacity (600 GWe), billions of FY 1977 dollars

	CY 1976-2000			*CY 1976 to End of Study*[a]		
	U and Pu Recycle	*U Recycle*	*Throwaway*	*U and Pu Recycle*	*U Recycle*	*Throwaway*
Mining	118.8	137.0	163.0	110.5	132.1	163.0
Separative work	71.5	82.5	83.9	69.2	82.3	83.9
Uranium fabrication	18.7	21.2	21.2	18.7	21.2	21.2
Fuel storage	0.6	0.6	2.4	0.7	0.7	4.1
Chemical reprocessing	39.5	39.5	0	46.9	46.9	0
Plutonium storage	0.3	2.1	0	0.5	2.7	0
MOX fabrication	7.4	0	0	9.4	0	0
Terminal waste	0.7	0.7	2.9	4.1	4.1	11.0
Total	257.3	283.6	273.4	260.0	290.0	283.2
Difference from throwaway	-16.1	+10.2	-	-23.2	+6.8	-

a. Includes deferred costs. Deferred costs are defined as costs required to complete processing, storage, and disposal for the fuel discharged through CY 2000. Credit for recovered uranium and plutonium in recovered fuel is applied to reduce mining and separative work costs incurred through CY 2000.

TABLE 16

Fuel Cycle Costs for Low Nuclear Capacity (400 GWe), billions of FY 1977 dollars

	CY 1976-2000			*CY 1976 to End of Study*[a]		
	U and Pu Recycle	*U Recycle*	*Throwaway*	*U and Pu Recycle*	*U Recycle*	*Throwaway*
Mining	80.6	92.9	111.8	76.7	90.7	111.8
Enrichment	51.3	60.1	61.1	50.2	60.0	61.1
Uranium fabrication	13.1	15.3	15.3	13.1	15.3	15.3
Fuel storage	0.4	0.4	1.9	0.5	0.5	3.1
Chemical reprocessing	31.0	31.0	0	35.4	35.4	0
Plutonium storage	0.3	1.7	0	0.3	2.2	0
MOX fabrication	5.0	0	0	7.1	0	0
Terminal waste	0.6	0.6	2.5	3.1	3.1	8.3
Total	182.3	202.0	192.6	186.4	207.2	199.6
Difference from throwaway	-9.3	+9.4	-	-13.2	+7.6	-

a. Includes deferred costs.

Discounted Costs

The alternative fuel cycles for the base nuclear capacity were discounted at 10% per year to determine whether the ranking of economic benefits were time-dependent. Results are shown in Table 17 without accounting for the added ^{241}Pu decay. The discounted benefits for recycle of uranium and plutonium are about $2 billion through CY 2000 (relative to throwaway) and increase to ∿$4 billion if the two fuel cycles are compared through CY 2020 or 2041. The discounted costs are essentially equal for fuel decay for either one or five years, or for a five-year delay.

Sensitivity Study

The cost differences between fuel cycles are calculated with the unit costs specified in Table 4. In addition, the costs were varied to determine the effect on the economics. The results are given in Table 18 and are also shown in Figure 5.

Mining costs are about 50% of the total fuel cycle costs with recycle and more in the throwaway fuel cycle. Thus, uncertainties in the future cost of uranium ore have a major bearing on the economics of fuel cycle. The ore cost variations assumed cause a ±$5 billion impact on the cost advantage of recycle. Other studies use different ore price costs as shown in Figure 2.

Chemical reprocessing cost is another major variable in the sensitivity study. The variation of ±25% in capital cost is evaluated because of the limited experience in building and licensing reprocessing plants. The impact of the variation is about ±$8 billion. Estimates of the economic advantage of reprocessing plants with higher capacity than 1500 MTU/yr are shown in Figure 5. With 3000 MTU/yr, the lower reprocessing cost given in Table 3 provides an additional $10 billion cost advantage for recycle. With 6000 MTU/yr, the advantage of recycle is increased by $14 billion; however, such large plants are major extrapolations of experience. Reprocessing charges that are competitive with the price of uranium ore are shown in Figure 6 based on the costs used in this study.

Variations in other cost parameters do affect the fuel cycle costs, but much less than ore price and reprocessing. Terminal waste costs are uncertain but are judged to be representative and appropriate for comparisons of fuel cycles. If more stringent requirements raise the cost of terminal waste storage, the same requirements would raise the cost of terminal spent fuel storage.

TABLE 17

Discounted Fuel Cycle Costs for Base Nuclear Capacity (507 GWe), billions of FY 1977 dollars

	CY 1976-2000					*CY 1976-2000 (Includes Deferred Costs)*				
			U and Pu Recycle					*U and Pu Recycle*		
	Throwaway	*U Recycle*	*1-yr Decay*	*5-yr Decay*[a]	*5-yr Delay*	*Throwaway*	*U Recycle*	*1-yr Decay*	*5-yr Decay*	*5-yr Delay*
Discounted total fuel cycle cost	59.13	61.56	57.16	57.40	57.60	59.63	61.65	57.31	57.33	57.67
Difference from throwaway	-	+2.43	-1.97	-1.73	-1.53	-	+2.02	-2.32	-2.30	-1.96

	CY 1976-2020		*CY 1976-2041*	
	Throwaway	*U and Pu Recycle 1-yr Decay*	*Throwaway*	*U and Pu Recycle 1-yr Decay*
Discounted total fuel cycle cost	74.20	70.14	74.69	70.50
Difference from throwaway	-	4.06	-	4.19

a. Discounted costs include no correction for added ^{241}Pu decay with 5-year fuel decay.

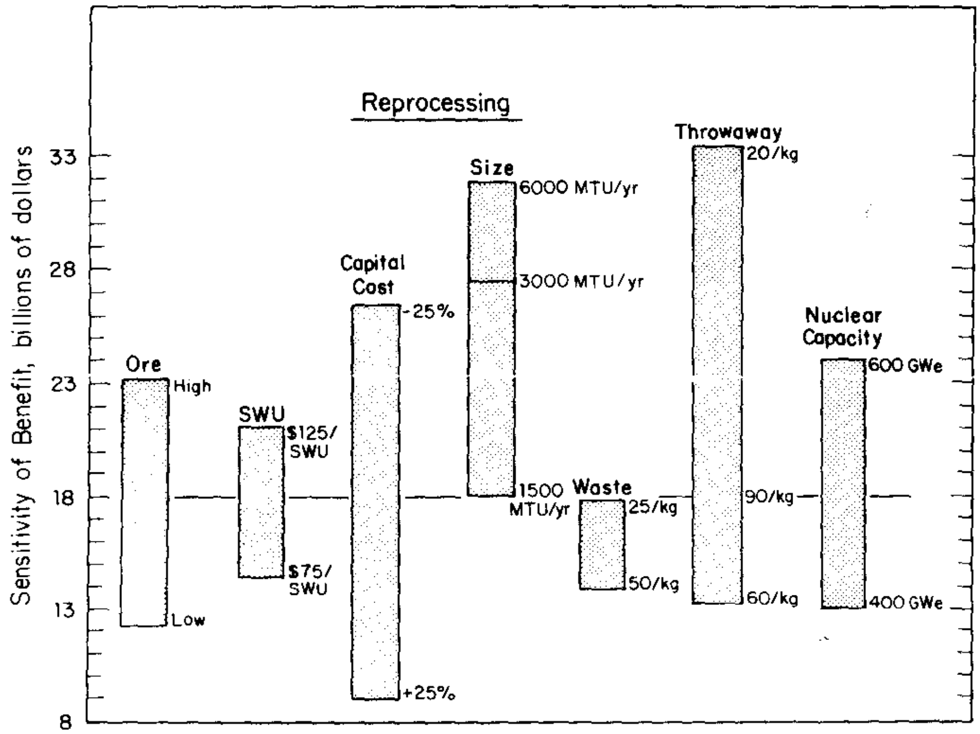

FIGURE 5. Sensitivity of Fuel Cycle Costs

TABLE 18

Sensitivity Cost Studies for Base Nuclear Capacity (507 GWe), billions of FY 1977 dollars

	Total Cost Difference Throwaway - Recycle	
	CY 2000	*Total Study*[a]
Ore Price Schedule		
Base - Recycle Throwaway	12.0	17.7
High[b] - Recycle Throwaway	16.9	23.2
Low[c] - Recycle Throwaway	7.0	12.2
Separative Work		
Base - Recycle Throwaway	12.0	17.7
$125/SWU - Recycle Throwaway	15.0	21.1
$75/SWU - Recycle Throwaway	9.1	14.4
Reprocessing		
Base	12.0	17.7
+25% Capital Charge	4.3	9.0
-25% Capital Charge	19.7	26.4
Reprocessing Waste Management Cost - Recycle		
Base - $25/kg	12.0	17.7
$50/kg	11.2	14.0
Spent Fuel Storage and Disposal Cost - Throwaway		
Base - $90/kg	12.0	17.7
Low - $60/kg	10.9	13.3
High - $200/kg	16.6	33.6

a. Includes deferred costs beyond the end of the study period.
b. The high ore price schedule assumes the price of ore increases $16/lb per million tons mined rather than $11/lb.
c. The low ore price schedule assumes the price of ore increases $6/lb per million tons mined rather than $11/lb.

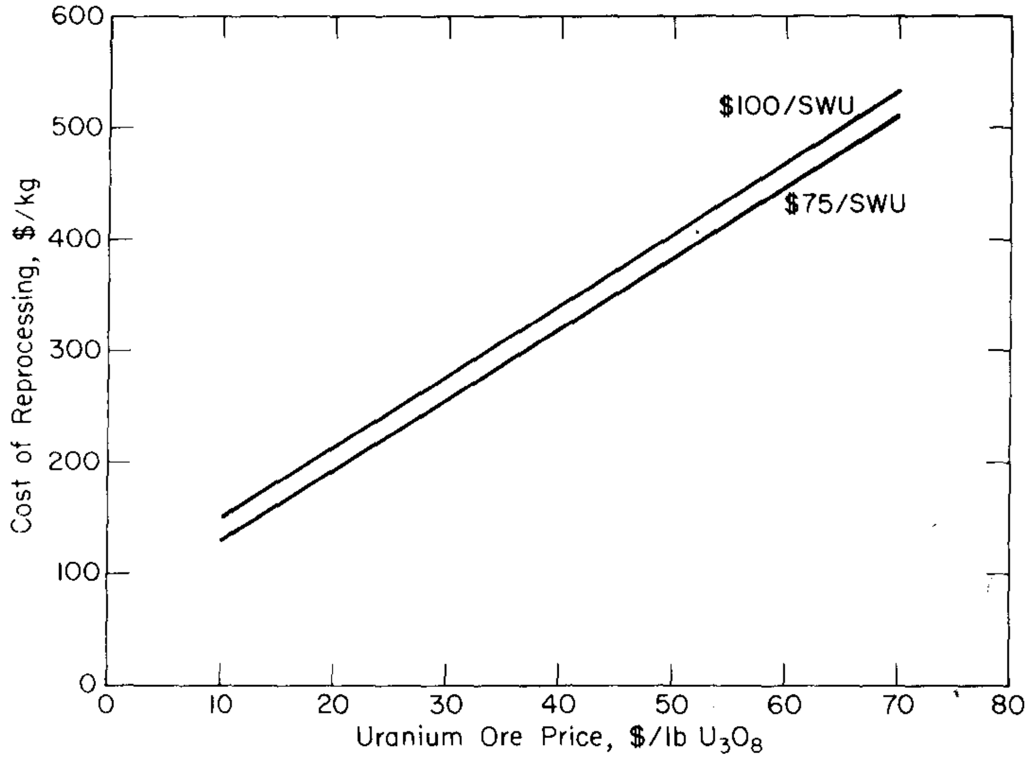

FIGURE 6. Breakeven Cost of Reprocessing

Life Cycle Study

Utilities make long-term plans when selecting among power options and investigate fuel supplies for plant lifetimes (nominal 30 years or longer). Thus, the economic studies should include the forecasts of fuel cycle costs during the years after reactors are first built.

The costs of the fuel cycles are extended through CY 2041 in Table 19. The advantage of recycle increases to over $50 billion by CY 2020 and to almost $77 billion by CY 2041. The largest cost factor is the increased mining cost with long-term reactor operation. As shown in Table 12, the throwaway fuel cycle requires over 40% more ore when extended into the next century. If the extended costs are discounted (Table 17), the cost advantage of recycle when considered through CY 2041 is $4 billion.

TABLE 19

Fuel Cycle Costs Through CY 2041, billions of FY 1977 dollars

	CY 2000-2020		*CY 2000-2041*		
	Throwaway	*U and Pu Recycle*	*Throwaway*	*U and Pu Recycle*	*Difference*
Mining	206.3	114.4	230.1	118.0	112.2
Separative work	81.2	61.8	89.3	65.6	23.6
Uranium fabrication	18.9	18.9	20.8	20.8	0
Fuel storage	5.7	1.3	8.1	1.6	6.5
Chemical reprocessing	0	63.5	0	83.2	-83.2
Plutonium storage	0	0.1	0	0.9	-0.9
Plutonium fabrication	0	7.8	0	8.8	-8.8
Terminal waste	14.6	5.2	25.5	9.7	15.8
Subtotal	326.7	273.0	373.8	308.6	65.2
Total (1976-2041)	-	-	-	-	76.7
Discounted					4.2

CONSERVATISMS

The major conservatism applied in this economic study is to reduce the amount of fissile plutonium recovered from the LWR fuel by 5% before recycling fuel to the LWR and developing credits for reduced mining and enrichment cost. Some conservatism in calculating economic benefits is necessary to allow for inventories, building schedules, and yields. Explicit calculations of ^{236}U and ^{242}Pu effects have now been completed and are detailed in the appendix. A ^{236}U penalty of $2.2 billion plus a ^{242}Pu penalty of $2.1 billion are included in the costs of recycle.

The costs for the fuel cycle with uranium recycle but plutoium stored for later use include a penalty of $3.7 billion for ^{236}U. The cost for a uranium recycle is $7 billion more than for throwaway (deferred costs included). Reprocessing cannot compete with the throwaway option if the plutonium fuel is not used. The premium for recovering and storing the plutonium is estimated as about $8 billion by CY 2000 or slightly more than the cost difference between the uranium recycle and the throwaway fuel cycle.

COMPARISON OF RESULTS TO AGNS STUDY

Other studies of the economics of LWR recycle have been made. Two results of this SRL study are compared to similar calculations by AGNS:[2] the cost difference between the throwaway fuel cycle and recycle of uranium and plutonium, and the cost difference between throwaway and uranium recycle only.

The two studies require considerable adjustments for comparability of scope because this SRL study is associated with the LWR industry, and the AGNS study is based on 20-year operation of a single reprocessing plant. As shown in Table 20, the SRL results (normalized to 20-plant years of reprocessing) indicate a $3 billion benefit from recycle of uranium and plutonium versus $10 billion (AGNS). About $3 billion of the difference is attributed to the lower reprocessing cost predicted by AGNS for their plant. A lower reprocessing cost may be reasonable for the AGNS plant because much of it was built before the severe inflation of the last few years. All but 5% of the difference can be explained by the greater savings in ore demands and enrichment services predicted by the AGNS model for fueling a closed system of 50 reactors by recycle from one reprocessing plant. Less savings accrue in the SRL system study that models expanding use of nuclear power. Both studies agree that recycle of plutonium is vital to realize the cost savings of recycle. Recycle of uranium only reduces the benefit (compared to the throwaway fuel cycle) from $10 billion to $1.9 billion (AGNS); SRL projects the uranium recycle to be more expensive than the throwaway fuel cycle. A similar attempt to explain the differences in the two studies (Table 20) based on reprocessing cost and recycle model differences results in fair agreement. With the ^{236}U penalty developed in each study applied to the uranium recycle case, the comparable numbers are $0.6 billion (AGNS) versus -$0.2 billion (SRL).

TABLE 20

Comparison of Results to AGNS Study

	AGNS	*SRL*	*SRL Adjusted to AGNS Base*
LWR fuel reprocessed, MTU	29,250	145,164	
Cost advantage of uranium and plutonium of recycle, billions of dollars			
Reported	10.22	17.7	
Adjusted to AGNS base		3.4	
Difference to reconcile			6.8
Model effects			
Mining			2.2
Enrichment			0.9
Unit cost effects			
Mining			0.2
Enrichment			-.08
Reprocessing			3.3
Total			6.5
Reported cost benefit of uranium recycle (plutonium stored), billions of dollars	1.87	-7.1	
Cost adjustments, billions of dollars			
Mining		-7.7	
Enrichment		-2.6	
Reprocessing		16.3	
Total		-1.1	
Corrected for ^{236}U penalty	0.64		-0.2

APPENDIX – PENALTY FOR ISOTOPIC CHANGES WITH RECYCLE (^{236}U and ^{242}Pu)

Uranium recovered from LWR fuel for recycle contains ^{236}U from neutron absorption in ^{235}U. When the recycled uranium is used as feed for an enrichment process (gaseous diffusion or centrifuge), some of the ^{236}U remains in the enriched product. A higher ^{235}U content is required in the product to produce fuel with the same reactivity as fuel made from natural uranium. Some of the incremental ^{235}U added is recovered when this fuel is reprocessed. In addition, the amount of plutonium produced in the subsequent irradiation is changed.

The plutonium assay is also affected by successive recycle in thermal reactors. The fissile fraction (^{238}Pu, ^{239}Pu, ^{241}Pu) tends to decrease, and the ^{242}Pu content gradually increases. The plutonium fuel value relative to ^{235}U decreases in thermal reactors.

The cost penalties for changes in isotopic composition are shown in the following table. Two study intervals are evaluated for uranium and plutonium recycle: the near-term study from CY 1976-2000 and the LWR life cycle study from CY 1976-2041.

	Cost, billions of FY 1977 dollars		
		U and Pu Recycle	
	U Recycle	CY 2000	CY 2041
Benefit of recycle over throwaway			
Mining	27.9	42.5	150
Enrichment	3.4	15.5	36
	31.3	58.0	∿195[a]
Gross penalty for inventories, calculation methods, schedules, isotopic effects	-	-	30
Calculated penalty effects with recycle			
^{236}U			
Mining	1.7	0.6	4.3
Enrichment[b]	2.0	1.6	3.0
^{242}Pu			
Mining	-	1.3	10
Enrichment	-	0.8	5
Total	3.7	4.3	∿22
Benefit with penalty	27.6	54.7	∿200
Net benefit	-	∿18	∿75-80

a. The breakdown of the benefit is about half for uranium and half for plutonium. With the LWR restricted to a 20% plutonium loading, about 10% of the plutonium recovered could not be recycled. If the constraint on LWR loading were relaxed to 40%, the plutonium not recycled would be reduced to <3% and the benefit would be increased from $186 billion to $195 billion.

b. Includes 0.2% allowance for separative work performed on ^{236}U.

EFFECT OF ^{236}U

Compensation for the presence of ^{236}U in LWR fuel made from recycled uranium requires an additional 0.3 gram of ^{235}U per gram of ^{236}U; about half the ^{236}U in the feed is rejected to the tails stream. The amount of ^{236}U in the reactor fuel depends on the number of recycles and the ratio between recycled uranium and natural uranium used to fuel the nuclear industry. In this study, the recycled uranium is about 15% of the total uranium feed during CY 1976-2000.

SRL Analysis

Cell calculations were made to represent PWR fuels containing variable amounts of ^{236}U to estimate the impact of ^{236}U. The reactivity transient for 33,000 MWD exposure (no initial ^{236}U) was matched by adding ^{235}U as summarized below.

	k_{eff}		Uranium Content, %			
	Exposure, MWD		^{236}U		^{235}U	
Type of Fuel	*0*	*33,000*	*Start*	*End*	*Start*	*End*
Virgin	1.053	0.838	0	0.41	3.200	0.9452
Early recycle	1.053	0.838	0.12	0.52	3.239	0.9700
Eqilibrium[5]	1.053	0.837	0.40	0.77	3.313	1.0187

More than half the extra ^{235}U added to compensate for ^{236}U is recovered when the irradiated fuel is recovered. In addition, the fissile plutonium formed varies with ^{235}U content as shown below.

Type of Fuel	*Fissile Pu per kg U Charged, g*	*Change in Pu Equivalent, ^{235}U, %*	*Equivalent ^{235}U at Dicharge, %*
Virgin	8.864	Base	0.9452
Early recycle	8.967	0.008	0.978
Equilibrium	9.169	0.023	1.042

The plutonium replacement for ^{235}U is based on 1 gram of fissile plutonium equivalent to 0.75 gram of ^{235}U.[6]

The feed and separative work burned up for the recycled uranium are calculated for plutonium and uranium recycle with 0.25% ^{235}U tails assay at the gaseous diffusion plant.

Type of Fuel	*Feed,*[a] *kg U/kg*	*Separative Work, kg SWU/kg*	*Feed Penalty Factor, kg U/kg*	*Enrichment Penalty Factor, kg SWU/kg*
Virgin	4.891	3.9592	-	-
Early recycle	4.9046	3.9963	0.0135	0.0371
Equilibrium	4.925	4.061	0.034	0.102

The ^{236}U cost effects for CY 1976-2000 with deferred costs are conservatively estimated based on equilibrium impact on separative work and feed:

Separative Work

$$145{,}164 \text{ MTU} \times 0.102 \frac{\text{kg SWU}}{\text{kg recycled}} \times \frac{\$100}{\text{kg SWU}} = \$1.48 \text{ billion}$$

Mining

$$6{,}400^{b} \text{ tons ore} \times \frac{2000 \text{ lb}}{\text{ton}} \times \frac{\$49.3}{\text{lb}} = \frac{\$0.63 \text{ billion}}{\$2.1 \text{ billion}}$$

The ^{236}U penalty for uranium recycle can also be calculated from the uranium content data (not corrected for the added fissile plutonium) as follows:

Type of Fuel	*Feed,*[a] *kg U/kg*	*Separative*[a] *Work, kg SWU/kg*	*Feed Penalty Factor, kg U/kg*	*Enrichment Penalty Factor, kg SWU/kg*
Virgin	4.8911	3.9592	-	-
Early recycle	4.9219	4.0073	0.0308	0.0482
Equilibrium	4.9768	4.0919	0.0857	0.1327

a. The change in separative work and feed content of LWR fuel is calculated from Ref. 7 and ^{235}U assay charged and the equivalent ^{235}U discharged.

b. (0.034)(145,164) = 4,935 MTU, 5,820 MT ore or 6,400 tons of ore.

The cost effects for CY 1976-2000 with deferred costs are:

Separative Work

$$145{,}162 \text{ MTU} \quad 0.1327 \quad \frac{\$100}{\text{kg SWU}} = \$1.93 \text{ billion}$$

Feed or Mining

$$16{,}138 \text{ tons}^{a} \times \frac{2000 \text{ lb}}{\text{ton}} \times \frac{\$51}{\text{lb}} = \$1.65 \text{ billion}$$

$$\text{Total} = \$3.6 \text{ billion}$$

The ^{236}U penalty for only uranium recycle is greater than for recycle of both uranium and plutonium.

The feed and separative work effects in fueling LWRs are the major cost penalty for ^{236}U in recycled uranium. In addition, some separative work is performed on the ^{236}U when feed containing ^{236}U is enriched to ~3.0% ^{235}U. The effect of ^{236}U on the enrichment process itself has been estimated to be less than 0.2% in Ref. 5 or about $0.1 billion for CY 1976-2000.

^{242}Pu PENALTY

The continued recycle of plutonium in LWR increases the non-fissile fraction of the plutonium and requires more plutonium to replace the same amount of ^{235}U. The analysis was made with the relationship: 1 g of fissile plutonium displaces 0.8 g of ^{235}U. A minor correction is developed for the assumption that all the LWR plutonium is recycled (none is diverted to the breeder reactor program) based on the GESMO analysis of plutonium replacement value with 25,000 MTHM recycled. The calculations summarized below indicate ~8% (or $2.1 billion) correction is required to the uncorrected benefit for 33,000 MTHM of MOX recycled:

	CY 1986	*1987-1991*	*1991-1995*	*1996-1998*	*1999 to End of Study*
Plutonium replacement value (PRV), g ^{235}U per g fissile Pu[1]	0.79	0.77	0.76	0.75	0.74
Plutonium correction MT[b]	0.12	9	9	13	20

a. (0.0857)(145,164) = 12,440 MTU, 14,670 MT of ore or 16,138 tons of ore.

b. Plutonium recovered × $(1 - \frac{\text{PRV}}{0.80})$.

The total plutonium correction is 51 metric tons or 5.1% of the total fissile plutonium recycled during the study. The amount of MOX recycled in the SRL study (33,000 MTHM) is 32% greater than the 25,000 MTHM recycled in GESMO. The ^{242}Pu correction would be linearly increased to 6.7% (or to 8.9% if the effect depends on the square of the amount of MOX recycled). A penalty of 8% is judged to be appropriate; the cost effect is (0.08)(26.7) or $2.1 billion. The breakdown is estimated as $0.8 billion for separative work and $1.3 billion for added mining.

Ore Effects - Near-Term Study

Fuel Cycle	*Ore Consumption Corrections* ^{236}U	^{242}Pu	*Total*	*Total Ore, MTU* *Throwaway*	*Recycle*	*Throwaway/ Recycle*
U and Pu	5,820	9,240	15,060	1,381,325	1,000,000	1.38
U only	14,670		14,670	1,381,325	1,155,000	1.20

Long-Term Study

Similar corrections are estimated for the life cycle study:

Isotope	*Added Ore, MT U_3O_8*	*Cost Penalty, billions of FY 1977 dollars*
^{236}U		
Enrichment	-	4.3
Mining	16,900	2.8
^{242}Pu		
Enrichment	-	5
Mining	61,600	10
Total	∿80,000	22

The ore consumed without recycle, 3,022,000 MT of ore, is ∿43% greater than with recycle (2,105,000 MT). The calculated penalty ($22 million) is less than the allowance used in the study.

GESMO Methods[2]

The penalty used in GESMO is $2 billion more than the penalty derived and used in the SRL study. The ^{236}U penalty is estimated in Ref. 2 to require 0.75 gram of ^{235}U in the fuel per kilogram of recycled uranium (0.42% ^{236}U in recovered uranium; 60% of the ^{236}U in the feed is assumed to reach the product stream). No credit is assumed for recovering the extra ^{235}U added by reprocessing the fuel. The added feed and enrichment needed at 0.25% ^{235}U tails assay to compensate for the ^{236}U are:

Type of Fuel	*Fuel Assay, % ^{235}U*	*Feed, kgU/kg*[a]	*Enrichment, kg SWU/kg U*[a]
Virgin	2.663	5.2363	3.156
GESMO recycle	2.735	5.3990	3.3012
Difference		0.1627	0.1452

a. From Ref. 7.

Therefore, the feed penalty is 0.1625 kg U/kg recycled and the separative work penalty is 0.145 kg SWU/kg recycled. The cost penalty is as follows:

Feed	*Cost Penalty, billions of FY 1977 dollars*
23,662 kg of uranium (30,700 tons of ore)	3.08
Separative work = 21 million SWU	2.10
Total	5.18

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