210/17
1-17

MASTER

ERDA-76/121

**Benefit Analysis
of Reprocessing
and Recycling
Light Water
Reactor Fuel**

**Energy Research and Development
Administration**

This document is
PUBLICLY RELEASABLE

W. R. C. Williams
Authorizing Official

Date: 8/10/91

December, 1976

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

This report was prepared by ERDA, and made publicly available pursuant to the provisions of Public Law 93-438, wherein it is specified that: "The Administrator shall disseminate scientific, technical, and practical information acquired pursuant to this title through information programs and other appropriate means, and shall encourage the dissemination of scientific, technical, and practical information relating to energy so as to enlarge the fund of such information and to provide that free interchange of ideas and criticism which is essential to scientific and industrial progress and public understanding."

This study was not intended to be completely new or independent of existing sources. It is, however, independent in approach and is believed to represent the best possible assessment of current data on the potential economic and resource benefits of reprocessing. As such, it will be used by ERDA management as a source of information in the decision making process. It is hoped that the views and findings in the report will prove to be of wide interest and will facilitate the exchange of ideas among those who share an interest in this field.

Cover

The arrows represent the closing of the LWR fuel cycle through reprocessing and recycle. The lighter shaded elements figuratively represent the displacement of standard reactor fuel elements with those fabricated using recycled materials.

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

TABLE OF CONTENTS

	<i>Page</i>
Foreword	1
Introduction	1
Analysis & Conclusions	2
The LWR Fuel Cycle	3
Front-End Components	4
Spent Fuel Recycle	4
Spent Fuel Disposal—Long Term Storage	5
Comparative Economics	5
Fuel Recycle Versus Spent Fuel Disposal	6
Summary of Base Case Results	7
Sensitivity Analysis	9
Summary of Sensitivity Analysis Results	12
Uranium Availability	14
Resources and Requirements	14
Production Capabliity	15
Breeder Impact	16
Appendix A—Supplementary Data	17

LIST OF ILLUSTRATIONS

<i>Figures</i>	<i>Page</i>
1 LWR Fuel Cycle	3
2 Uranium Price Schedule	6
3 Comparison of Cumulative Uranium Ore Requirements With and Without Recycle	8
4 Uranium Price Schedules	9
5 Range of Nuclear Power Generation Schedules	12
6 Summary of Sensitivity Analysis	13
7 Cumulative Savings Through 2000—Variation of Multiple Parameters	13
8 Uranium Resources—Current and Future Need	15
 <i>Tables</i>	
1 Major Assumptions	5
2 Base Case Cost Parameters	5
3 Base Case Cost Summary	8
4 Range of Variation of Parameters	12
5 U.S. Uranium Resources	14

FOREWORD

On October 28, 1976, the President announced major decisions regarding nuclear policy, with special emphasis on controlling worldwide proliferation of nuclear explosives capability. A key issue is the relationship between reprocessing irradiated reactor fuel and nonproliferation.

This report was prepared to gather the best available domestic (U.S. economic and resource data on two options for closing the Light Water Reactor (LWR) fuel cycle: reprocessing/recycle and throwaway of spent fuel. These data were evaluated, with others, in the President's nuclear policy review.

The President's principal policy decisions are quoted below:

"Reprocessing and recycling of plutonium should not proceed unless there is sound reason to conclude that the world community can effectively overcome the associated risks of proliferation . . . Avoidance of proliferation must take precedence over economic interests . . . The United States and other nations can and should increase their use of nuclear power for peaceful purposes even if reprocessing and recycling of plutonium are found to be unacceptable . . .

"The United States should no longer regard reprocessing of used nuclear fuel to produce plutonium as a necessary and inevitable step in the nuclear fuel cycle . . . we should pursue reprocessing and recycling in the future only if they are found to be consistent with our international objectives."

This report does not attempt to assess the proliferation impacts of fuel cycle options. Nor does it attempt to foreclose any option—reprocessing/recycle, throwaway, or alternative technologies not employing separated plutonium—from future Presidential decision.

ERDA is currently defining a reprocessing and recycle program consistent with the President's decisions, to ensure that these options are fully evaluated. This report represents a part of the economic data to be used in that evaluation.

The Government has been reprocessing and recycling fuel for many years. Irradiated fuel elements have

originated from nuclear material production for military and other purposes, naval propulsion systems, and research and test reactors. The processing of power reactor fuels uses an adaptation of the processes that have been developed by this country and others for military programs. The first private plant to reprocess irradiated fuels from power reactors in the 1960's is currently down for modifications. A second plant was mothballed before reaching the operational stage. Another private plant is in the final stages of its operating license review by NRC. A fourth company has filed a licensing application for the construction of a reprocessing plant complex.

Essential to the successful closing of the LWR fuel cycle is the existence of a program for the safe and environmentally acceptable management and control of radioactive wastes. ERDA has recently published a report, ERDA 76-43,* on alternatives for the management of wastes from nuclear power reactors. The report shows that the technologies are available to handle the waste from the back end of the fuel cycle. The alternatives described in the report and the economic data from this report will be considered in the preparation of the environmental impact statement on radioactive waste management.

INTRODUCTION

Fuel elements discharged from Light Water Reactors contain a considerable amount of residual fissile material (isotopes of uranium and plutonium). The high residual energy content of spent fuel has led to the implicit assumption that reprocessing and recycling is a necessity for the conservation of resources. This pattern is reflected outside the U.S., as well, where other countries are either building or contemplating building reprocessing plants to augment the fuel supply to nuclear power reactors.

This document examines the macro-economic impact of reprocessing and recycling fuel for nuclear power reactors and assesses the impact of reprocessing on the conservation of our natural uranium resources.

*ERDA 76-43 Alternatives for Managing Wastes From Reactors and Post-Fission Operations in the LWR Fuel Cycle.

The approach used compares the costs of an energy resource throwaway fuel cycle with a mode which closes the fuel cycle by recycling the residual fuel content. The energy resource throwaway (or simply throwaway) mode is defined as a fuel cycle in which discharged fuel elements from reactors are eventually transferred to a Federal repository for long term storage. The energy resource recycle mode, in contrast, recovers the residual fissile material for reuse as reactor fuel.

For the plutonium recycle cases, the plutonium is assumed to be used only in LWR's. This assumption avoids the complexity of handling the introduction of the breeder and consequently underestimates the value of plutonium since plutonium is of even greater value when used with breeder reactors.

The economics section compares the benefits and penalties of reprocessing and recycle with the throwaway cycle using the best current estimates for cost parameters. Recognizing the uncertainty in cost projections, a part of the economics section is devoted to an examination of the sensitivity of the results to a range of cost assumptions. The fuel cycle costs were accumulated (both undiscounted and discounted) through the year 2000 to obtain the economic impact over the long term. To examine the trend of the benefits of recycle if the study period were extended, a case was included which terminated LWR construction at 2000 but cumulated fuel cycle costs to 2030. Most of the reactors built by the year 2000 are expected to have an economic life well into the 21st century.

The second section of this report deals with the availability of natural uranium resources. U.S. resources will need to expand to meet projected growth in demands. The large expansion of production capacity will be a challenge to the U.S. uranium mining and milling industry. Additional requirements, to replace lack of recycled uranium and plutonium, would increase the sizable commitments of U.S. resources and would increase exploration and production needs, and increase pressure on uranium prices.

The third section of the document examines the importance of the LWR reprocessing and recycle industry in meeting the future plutonium needs of commercial breeder reactors. The breeder increases the utilization of uranium by using both U-235 and U-238 thereby appreciably extending the benefits attainable from our energy resources. A prerequisite for a successful breeder economy is a viable LWR fuel reprocessing industry since breeders will use plutonium recovered from LWR fuel as their initial fuel source.

Therefore, there is a strong added incentive to develop a broad fuel cycle capability to support a breeder economy. The breeder as a long term energy option is one of those identified in ERDA's Energy Plan* which is directed towards making U.S. energy independent.

ANALYSIS AND CONCLUSIONS

This study compares LWR fuel recycle with a throwaway cycle and concludes that fuel recycle is favorable on the basis of economics, as well as being highly desirable from the standpoint of utilization of uranium resources. The absence of a reprocessing and recycling capability could reduce possible LWR growth in later years. Assuming that sufficient reprocessing and recycling facilities are available, the total amount of uranium required through the year 2000 could be reduced by 25% with uranium and plutonium recycle. Utilization of recycled uranium will allow a more orderly expansion of the uranium producing industry. The additional uranium saved could be used for later fueling of reactors to be on line in the year 2000 or provide for additional nuclear power growth.

On the basis of current estimates, the economic benefits of reprocessing and recycle to the year 2000 exist over a broad range of variables. The cumulative cost advantage is 7% of the total fuel cycle costs for the base case comparison and could be as high as 16% when all assumptions are changed to favor recycle. However, when all assumptions are chosen to favor the throwaway cycle, the throwaway mode has a 2% advantage. In this latter case, retaining one variable such as the separative work charge at its base case value, results in essentially a breakeven situation for the two fuel cycle modes. Extending the base case analysis through the year 2030 results in a 20% improvement relative to the throwaway mode for the 2000-2030 time period and an overall savings of 14% for the total study period.

Without recycle, uranium demand will be greater, and uranium prices would be higher. The same price versus quantity relationship was used for both the recycle and throwaway mode, which ignores the effect of the rate of utilization on price. The savings with recycle are therefore somewhat understated, since one would expect the uranium price schedule for the throwaway cycle to be higher, reflecting the greater level of demand. The savings attributable to fuel re-

*ERDA 76-1 A National Plan for Energy Research, Development and Demonstration: Creating Energy Choices for the Future.

cycle would increase further if breeder growth occurs as their power cost would be less than for LWR's.

Although favorable fuel cycle economics demonstrate an advantage for recycling LWR fuel material, uranium availability and natural resource conservation are also important considerations. Without recycle the residual fissile content of spent fuel could never be utilized. Without recycle, production levels in the year 2000 would increase from 86,000 to 126,000 tons U_3O_8 and this would involve many more mines and mills. To support production capacity, a commensurate natural resource base must be maintained. The increased annual requirements by the year 2000 would necessitate the establishment of over one million tons of U_3O_8 in the ore reserve and probable potential categories, to assure adequate production capacity.

Recycle of uranium and plutonium would result in the generation of additional energy from a given amount of natural uranium and thus assist in achieving energy independence. The reduction in uranium requirements is equivalent to providing the additional fuel necessary to increase the installed electrical generating capacity of 500,000 MWe in the year 2000 assumed in the base case of this report to a level of 650,000 MWe. This 150,000 MWe difference is equal to 30% of today's total (fossil, nuclear, and hydro-electric) installed electrical generating capacity.

THE LWR FUEL CYCLE

Figure 1 identifies the components of the LWR fuel cycle for the throwaway mode and the recycle mode. The following discussion of individual components elaborates on the purpose and status of each.

FIGURE 1

LWR FUEL FLOW DIAGRAM

Front-end Components

The front-end components or pre-irradiation portion of the LWR fuel cycle encompass the extraction and treatment of uranium prior to its use in the reactor. This includes uranium mining, milling, conversion to UF_6 , enrichment, conversion to UO_2 and fuel fabrication.

Uranium occurs in nature in a low concentration ore form. The uranium in the chemical state of U_3O_8 comprises only about .16% of the naturally occurring uranium ore. The uranium bearing ore is crushed and the uranium extracted for subsequent conversion to gaseous uranium hexafluoride (UF_6). The fissile uranium isotope, U-235, constitutes only 0.71% of the total naturally occurring uranium; the remainder is essentially U-238. The enrichment of UF_6 is required to increase the abundance of U-235 for use in the LWR's. Enrichment is currently achieved by a gaseous diffusion technique. Enriched gaseous UF_6 is converted into UO_2 , which is formed into pellets, sintered and then loaded into stainless steel or zircalloy tubes and sealed to complete the fuel assembly.

Projected nuclear power growth requires that uranium exploration, mining and milling activities be expanded very rapidly. To achieve this goal, a comprehensive government program, National Uranium Resource Evaluation (NURE) was established about two years ago. The purposes of this program are threefold: to identify areas favorable for uranium exploration, to assess more completely the uranium resource base, and to improve exploration and extraction technology. The program is designed to provide a systematic and extensive survey of the contiguous U.S. and Alaska. NURE is expected to identify localities that are favorable for detailed exploration by industry and to provide an initial estimate of the resources in such localities. This will provide a more comprehensive basis for estimating potential uranium ore resources that may be available in future years.

While present gaseous diffusion plants are government operated, the need for additional enrichment capacity in the mid-1980's to support the projected growth of nuclear power has provided impetus for private industry to consider constructing commercial enrichment facilities. The technology for an alternative method, gas centrifuge, is also being developed. However, for planning purposes the government owned gaseous diffusion plant method still serves as the basis for projections of separative work costs.

Government programs are underway to support the contracted demand for uranium enrichment. The Cas-

cade Improvement Program (CIP) will increase the efficiency of the diffusion plants by incorporating the most recent advances in diffusion technology. The Cascade Upgrading Program (CUP) will upgrade the improved diffusion plants to permit operations at higher power levels which will further increase the capacity of the facilities. Future legislation may be introduced to permit the Government to assist private uranium enrichment projects during a transition period until they become operable.

The UO_2 fuel fabrication industry evolved in conjunction with LWR development and growth. This element of the fuel cycle is one of the most commercially stable and mature of all fuel cycle elements.

Spent Fuel Recycle

In the recycle mode, irradiated fuel elements discharged from the reactor are stored for a period at the reactor site to allow fission product decay. The spent fuel is then shipped to a reprocessing plant where the fuel assemblies are sheared into small pieces and the fuel removed from the cladding by dissolution. The uranium, plutonium, and fission product wastes are partitioned, decontaminated and concentrated by several stages of solvent extraction. The uranium and plutonium liquid nitrates are then converted to PuO_2 and UF_6 . PuO_2 is mixed with natural UO_2 for subsequent fabrication into LWR fuel elements. Because the high exposure plutonium causes high radiation levels, special provisions such as shielding and remote operation must be used for the mixed-oxide fabrication. UF_6 is re-enriched at the gaseous diffusion plants for subsequent fabrication into LWR fuel elements. The high and low level liquid waste streams are held in interim storage prior to solidification and transportation to terminal storage facilities.

The first domestic commercial reprocessing plant operated from 1966 to 1972 and was shut down for modification and expansion. A second reprocessing plant has been mothballed pending completion of further studies. A third commercial reprocessing plant, expected to be licensed for commercial operation in early 1977, has been delayed. A fourth company has filed a licensing application for construction of a reprocessing plant complex (separations plant, solidification plant, and mixed oxide fabrication plant). At present there is no capability for reprocessing spent commercial reactor fuels.

Since the Nuclear Regulatory Commission has not sanctioned the use of mixed oxide fuel in LWRs on a large scale, no major commercial facilities exist for fabricating mixed oxide fuel. One company has applied for a construction permit.

Current regulations allow storage of high level waste as a liquid for no more than five years prior to solidification, and require delivery to a terminal isolation facility no more than ten years after processing the fuel. Isolation of these relatively small volumes of radioactive waste is currently expected to be accomplished by emplacing them within deep, stable geologic formations accessible by mining.

Spent Fuel Disposal—Long Term Storage

The "back-end" of the throwaway fuel cycle consists of storage and isolation of the spent fuel as shown in Figure 1. The spent fuel, after removal from the reactor, is stored in pools until the heat generation decays sufficiently to permit transportation within heavily shielded containers or "casks." The elements would then be encapsulated in a high integrity material prior to loading in the casks for transport by motor carrier or rail carrier to a Federal permanent storage repository.

To date no irradiated fuel elements have been placed in permanent isolation. Utilities thus far have held their spent fuel in water cooled basins at reactor sites and potential future reprocessing sites.

COMPARATIVE ECONOMICS

The economic impact of reprocessing and recycling spent LWR fuels relative to a throwaway fuel cycle was calculated based on assumptions for the base case shown in Table 1. The approach identified component requirements for a specified reactor growth schedule and then applied unit costs to each requirement. The flow of nuclear fuel materials associated with the relevant nuclear growth schedules was calculated both with and without recycle. Using the assumptions shown in Table 1 and the unit costs shown in Table 2, the total fuel cycle costs through the year 2000 for each mode were computed. The benefits of the fuel recycle mode were then calculated by subtracting the total fuel cycle costs of the two modes through the year 2000.

For the specified reactor growth schedule, uranium and enrichment requirements are calculated based upon typical reactor characteristics for PWR's and BWR's. For projections of plants beyond the near

term, two-thirds are assumed to be PWR's and one-third, BWR's. The uranium and enrichment requirements summarized in Appendix A are properly sequenced such that mining, milling, and enrichment occur one year prior to reactor insertion to allow time for fuel fabrication, inspection, and shipment.

Light-water reactors are assumed to charge and discharge part of the fuel annually. In the initial years the reprocessing and refabrication of the fissile material contained in the spent fuel is constrained because of a lack of facilities. Thus extended storage for the spent fuel is required until recycle facilities are available. For the non-recycle mode, the spent fuel is allowed to cool for ten years in a water-filled basin prior to encapsulation and storage in a terminal manner.

TABLE 1—MAJOR ASSUMPTIONS

1. The time interval extends from 1976 to 2000.
2. No breeder plutonium fuel requirements are considered.
3. Fuel reprocessing plant schedules assume reprocessing starts in 1981, and follows the schedule shown in the Appendix. All plants operate at 40% capacity the first year, 67% the second, and 100% thereafter.
4. In recycle cases, plutonium recycle to LWR's is assumed to start in 1983 and continues through the year 2000; plutonium fuel fabrication plants operate at 50% of capacity the first year and 100% thereafter.
5. In the throwaway fuel cycle, discharged fuel is stored for 10 years in fuel storage basins and then transferred to terminal storage. No reprocessing or recycle is performed during the study period.
6. The tails assay for enrichment services is assumed to be 0.25%.
7. Economic differences between cases are evaluated undiscounted and selected cases are evaluated using a 10% discount rate.

TABLE 2—BASE CASE COST PARAMETERS

(1977 Dollars)

1. Uranium Price Schedule
See Figure 2
2. Separative Work Cost—\$100/SWU
3. Spent Fuel Storage and Disposal Cost—\$90/Kg Fuel Processed
4. Reprocessing Cost—\$280/Kg
5. Reprocessing Plant Capacity—1500 MTU/Yr
6. Spent Fuel Cooling Time—1 Year
7. Reprocessing Waste Management Cost—\$25/Kg Fuel Reprocessed
8. LWR Growth—500 GWe in year 2000
9. Uranium Fabrication—\$90/Kg U
10. MOX Fabrication—\$5/gm Pu Penalty (equivalent to \$260/Kg MOX)
11. Plutonium Storage—\$300/Kg Fissile Pu—Yr
12. Fuel Shipping Cost—\$6/Kg

Fuel Recycle Versus Spent Fuel Disposal

The following cost data serve as the basis used in the cost comparison of fuel recycle versus throwaway:

1. The uranium ore price schedule shown in Figure 2 is based on current ore contracts and estimated future market prices for uranium ore.
2. Enrichment services charges are based on \$100/SWU.
3. Although the fabrication of UO_2 fuel for LWR's is a well established commercial operation, actual contract prices are generally treated as company confidential data. Based on a 1500 MTU/yr fabrication plant costing \$130 million, \$90/Kg was calculated for the base case UO_2 fuel fabrication price.
4. The construction cost of a 1500 MTU (5 MTU/day, 300 days/yr) reprocessing complex (separation, waste solidification, and plutonium conversion) in accordance with appropriate safety, environmental, and safeguards criteria is assumed to be \$1 billion (exclusive of interest during construction). This estimate is based on preliminary studies performed by E. I. duPont, ERDA's prime contractor at its Savannah River Plant. Annual operating costs are estimated to be on the order of \$60 million. An eight-year
- lead time for construction assumes three years of "front-end" time for design of the plant, which includes site selection, preparation and submission of a Preliminary Safety Analysis Report and an Environmental Report to the NRC, final corporate approval, and five years of actual construction. A 20 year economic life is assumed for the facility, with the first two years of operation at 600 MTU and 1000 MTU respectively. Applying a 25% fixed charge rate to the total capital cost, including interest on construction, reprocessing services are estimated to cost \$280/Kg U. A 25% fixed charge rate corresponds to a weighted cost of capital of 13% after taxes for a twenty-year plant life; the 13% represents an average for a typical industry investment.
5. No large mixed-oxide fuel (MOX) fabrication facilities currently exist. The high radiation levels associated with handling LWR plutonium dictate that mixed oxide fuel fabrication facilities be specifically designed with remote handling capability and increased shielding. Appropriate safeguard systems must also be developed, designed and incorporated into the system in accordance with NRC regulations. A fabrication cost penalty of \$5/gm, or \$260/Kg total, (for

FIGURE 2

MOX at 3.2% fissile Pu) was assumed for such a plant.

6. Although high-level waste from reprocessing plants will probably be isolated in stable geologic formations, cost estimates for this form of storage can be estimated from detailed Retrievable Surface Storage Facility (RSSF) studies performed by Atlantic Richfield Hanford Company, since the two concepts have common elements. These include receiving, inspection, recanning, ventilation and cooling capability, and shielded transport. The features of the major facilities required for handling radioactive materials are also similar in both schemes. The cost of the terminal waste isolation, which includes repository disposition of high-level waste, hulls and other TRU-contaminated solids, is estimated at \$25/Kg fuel processed.
7. In the throwaway fuel cycle ten year basin storage, at a cost of \$20/Kg, was assumed to reduce the heat load to the desired level. As with the high level wastes in (6) above, detailed cost estimates for the RSSF concept were adjusted to estimate the cost of geologic isolation. The cost estimates are comparable because both schemes include similar elements. Based on a ten-year storage period and a \$70/Kg encapsulation and isolation charge, the overall storage cost estimate is \$90/Kg of fuel discharged.
8. For the base comparison, a growth schedule of 500 GWe of LWR generating capacity in the year 2000 was assumed. Since approximately 40 GWe is already installed, and 220 GWe is on order, an additional 240 GWe is required by the year 2000 to achieve the assumed base case figure. This represents a reasonably achievable rate based on past history. 500 GWe is consistent with current forecasts.

Summary of Base Case Results

Based on these assumptions, the total fuel cycle expenditures* without recycle through the year 2000 amount to \$241.4 billion (1977 dollars) versus \$224.8 billion with recycle. This represents a net savings of \$16.6 billion (\$2.0 billion discounted @ 10%) for the same period.

From the summary in Table 3, the fuel cycle cost advantage for recycle is 7% over the corresponding throwaway cycle. Assuming the generated power cost is about 75% reactor cost and 25% fuel cost, the

range of costs for the back end of the fuel cycle are estimated to affect the generation cost of power by 2% or approximately 0.5 mills/KWhr.

Since the benefits and penalties in resources and fuel cycle costs associated with LWR fuel recycle are realized over a period of years, the annual fuel cycle costs were discounted to account for these time differences. By converting all dollar flows to a present value basis using a time-discounting procedure more emphasis is placed on near-term expenditures. The use of discount rates in analyzing the costs associated with depletion of natural resources and the effect on the nation's future must be approached with a great deal of caution.

Several factors which would have the effect of increasing the cost savings projected for fuel recycle were not considered in this analysis. First, large uranium pipeline inventories exist in the front end of the LWR fuel cycle. These inventory levels are a function of virgin uranium requirements; thus, because less virgin material is required in the recycle mode, there is an additional cost penalty associated with the throwaway mode. Secondly, uranium prices were projected as a function of cumulative demand without regard for the annual rate of utilization. The effect of annual demand was not considered due to the difficulty of estimating it with any degree of accuracy.

In the recycle calculation, reprocessing capacity is added as required to reduce the backlog of stored irradiated fuel as rapidly as possible within the study constraints, without providing excess annual capacity at the end of the campaign. About 143,000 MTU of fuel is reprocessed by the year 2000 and less than 1000 MTU remain in storage. Nine reprocessing plants (1500 MTU/yr) are required in addition to those presently contemplated. If the analyses were normalized to reflect the operation of only one reprocessing plant for a period of 20 years, approximately 28,500 MTU would be reprocessed. Assuming the costs and benefits of the total industry analysis apply to the single plant case this would result in a savings of \$3.3 billion.

Almost 1000 MT of fissile plutonium is recycled which, when combined with the recycled uranium, reduces the cumulative ore mining requirements through the year 2000 by about 25% (compared to throw-away). See Figure 3. In the throwaway fuel cycle the production rate of U_3O_8 must be increased by a factor of 13 between 1975 and the year 2000. If recycling is

* Excluding reactor costs which would be identical with and without fuel recycle.

used, the factor is reduced to 9. In developing the plutonium fuel recycle schedule, allowance was made to account for several factors which are difficult to handle rigorously, such as the buildup of higher isotopes of plutonium, the effect of U-236, and anticipated plutonium process losses. To compensate for economic losses due to these factors, the availability of plu-

tonium was reduced by 25%. Fabrication plants are sized to match the output of a 1500 MTU/yr reprocessing plant, and 8 plants are required.

A summary of the material flows, reprocessing schedules, and fuel cycle costs which form the basis for these results is presented in Appendix A.

TABLE 3—BASE CASE COST SUMMARY

	Throwaway	Recycle
Amount of Material Through the Year 20000 (Thousands of Metric Tons)		
Uranium Reprocessed	0	144
Fissile Plutonium Processed	0	1.0
U ₃ O ₈ Mined	1392	1025
Cost Elements Through the Year 2000 (Billions of FY 1977 Dollars)		
Mining	135.9	95.4
Enrichment	73.8	60.5
Uranium Fabrication	18.7	18.7
MOX Fabrication and Pu Storage	0	5.1
Spent Fuel Storage/Disposal	13.0	0
Chemical Reprocessing & Waste Disposal	0	45.1
TOTAL	241.4	224.8
TOTAL with 10% Discounting	58.1	56.1
Cost Advantage	—	16.6
Discounted @ 10%	—	2.0
Total Power Cost	948.6	932.0
Power Generated, KW hr $\times 10^{12}$	37.2	37.2
Generated Power Cost, Mills/KW hr	25.5	25.0

FIGURE 3

**COMPARISON OF
CUMULATIVE URANIUM ORE REQUIREMENTS
WITH AND WITHOUT RECYCLE**

Sensitivity Analysis

The range of uncertainty associated with predicting the future values of fuel cycle parameters requires that each component be separately examined to determine its impact (or sensitivity) on the overall study conclusions. The following describes the variations from the base comparison considered and the results that were obtained:

1. Uranium Price Schedules

Although the base uranium price schedule discussed earlier is considered a reasonable estimate of future prices, the complex relationship between requirements and reserves, market conditions, and general economic factors warrants the examination of variations of the base schedule.

To illustrate the impact on recycle incentives of varying rates of uranium price increase, the alternative price schedules shown in Figure 4 were assumed.

The table below illustrates how variations in uranium prices impact the economics of recycle. The first column in the table (and successive

tables) shows the variation in total expenditure for the fuel cycle component in question with variation in assumed unit cost. The second column gives the corresponding total fuel cycle savings. In the case of the higher price schedule the total calculated savings with recycle is \$21.9 billion through the year 2000. This savings is reduced to \$11.3 billion when the lower price schedule is used in the computation.

(Billions of 1977 Dollars)

	Difference in Uran- ium Cost With Recycle	Total Fuel Cycle Savings With Recycle
Higher Price Schedule	45.8	21.9
Base Price Schedule	40.5	16.6
Lower Price Schedule	35.2	11.3

2. Uranium Enrichment Charges

Experience from present government plants supports the assumed base case enrichment charge of \$100/SWU, for equivalent commercial serv-

ices from new privately owned plants. Technological advancements in enrichment plant hardware could result in reduced separative work costs in the future; however, the concepts which are advanced to the point of engineering feasibility indicate no such reduction. Increases in power costs may drive the cost of enrichment services upward. Although the general trend in estimates of future enrichment services favors increases more than decreases a range of $\pm 25\%$ in the unit separative work charge was assumed to examine the economic impact of these eventualities. An increase (or decrease) of 25% in the unit charge for separative work varies the savings by \$3.3 billion.

(Billions of 1977 Dollars)

	Difference in Separative Work Cost With Recycle	Total Fuel Cycle Savings With Recycle
\$125/SWU	16.6	19.9
Base Case—\$100/SWU	13.3	16.6
\$75/SWU	10.0	13.3

3. Reprocessing Plant Investment

In the absence of an extended, large scale demonstration of commercial reprocessing, there is uncertainty as to what the commercial reprocessing charge will be. Estimation of the probable charge for reprocessing services depends largely on the assumed capital costs of the required facilities. The base case assumes that a 1500 MTU reprocessing complex costs \$1 billion to construct. To assess the impact of varying this assumption, a range of $\pm 25\%$ of the base case capital expenditures was considered. Such a change in capital costs results in a \$60/Kg variation in the estimated reprocessing charge. This results in a range of reprocessing charges of \$220–\$340/kg, and variation of the calculated savings with recycle of $\pm \$8.6$ billion. Recent estimates of reprocessing plant capital costs such as \$600 million by AGNS and \$700 million by EEI would support the lower ranges.

4. Economics of Scale for a Reprocessing Plant

To take advantage of economics of scale, future commercial facilities might be larger than the 1500 MTU/yr plant assumed in the base case. To examine this option, a case was analyzed

using a 3000 MTU/yr reprocessing complex estimated to cost \$1.5 billion to construct (exclusive of interest during construction) which resulted in a unit charge of \$215/Kg and an increased incentive of \$10.9 billion to recycle relative to the 1500 MTU/yr base case reprocessing complex. Plants larger than 3000 MTU/yr might result in further savings with recycle; although the large capital requirement might be a compensating disincentive to the investor.

5. Cooling Period for Spent Fuel

Another variation was considered in which spent fuel was allowed to cool five years prior to reprocessing rather than one year.

Since fuels thus cooled have lower specific power, simplifications of the reprocessing plant flow sheet are possible. This results in lower estimated capital cost and a corresponding decrease in the unit charge (\$260/kg). This decrease in reprocessing cost is offset by increased pool storage costs and the deferral of feed and separative work savings five years. The study calculations indicate that in the aggregate this scenario is slightly less attractive than the base comparison with savings of \$16.5 billion (\$1.9 billion discounted). The impact of variations in reprocessing plant assumptions is summarized below.

(Billions of 1977 Dollars)

	Reprocessing Cost	Total Fuel Cycle Savings
1500 MTU Reprocessing Plant \$1 Billion Cost, \$280/kg charge 1 Yr. spent fuel decay	40.9	16.6
1500 MTU Reprocessing Plant \$1.25 Billion Cost, \$340/kg charge 1 Yr. spent fuel decay	49.5	8.0
1500 MTU Reprocessing Plant \$.75 Billion Cost, \$220/kg charge 1 Yr. spent fuel decay	32.3	25.2
1500 MTU Reprocessing Plant \$.97 Billion Cost, \$260/kg charge 5 Yr. spent fuel decay	25.7	16.5
3000 MTU Reprocessing Plant \$1.5 Billion Cost, \$215/kg charge 1 Yr. spent fuel cooling	30.5	27.5

6. Terminal Waste Isolation

A recent study of waste management technical alternatives identified several waste management options available to satisfactorily isolate or dispose of high level solidified waste. The

cost of terminal isolation depends on which technique is ultimately employed, and some may cost significantly more than the \$25/kg assumed in the base case. A \$50/kg reprocessed waste disposal cost was examined to reflect the higher cost associated with some alternative waste management options. The economic impact of employing the more costly waste management is a reduction of the fuel cycle savings from \$16.6 billion to \$13.0 billion.

(Billions of 1977 Dollars)

	Reprocessing Waste Management Cost	Total Fuel Cycle Savings With Recycle
\$25/Kg Fuel Reprocessed	3.6	16.6
\$50/Kg Fuel Reprocessed	7.2	13.0

7. Spent Fuel Disposition

The actual scheme that would be used to dispose of spent fuel if the throwaway fuel cycle is adopted is uncertain at this time. Both retrievable surface storage followed by permanent geologic isolation and direct geologic storage have been considered. The cost of spent fuel isolation varies depending on the specific nature of the scheme being considered. To examine the sensitivity of the results to variations of this parameter a range of \$60/kg to \$200/kg was examined. The \$60/Kg estimate reflects continued pool storage whereas the \$200/kg would provide for more sophisticated isolation techniques than currently believed to be required. The range of \$60/kg to \$200/kg encompasses the various estimates that have appeared in recent literature. The impact on the cost of storage and disposition of spent fuel using the unit costs discussed above, and the corresponding calculated savings achievable with recycle is illustrated in the following table.

(Billions of 1977 Dollars)

	Throwaway Cycle Spent Fuel Storage/ Disposal Costs	Total Fuel Cycle Savings With Recycle
\$200/kg spent fuel storage/ disposal	28.9	32.5
\$90/kg spent fuel storage/ disposal	13.0	16.6
\$60/kg spent fuel storage/ disposal	8.7	12.3

8. Nuclear Power Growth Schedules

There is a multitude of factors which can affect the growth of nuclear power in this country. Among them are public acceptance, safeguards considerations, regulatory and licensing actions, technological advancements, and the development of alternative energy sources. The complex interaction of Government, industry and public actions both within and outside our nation could cause significant variations in nuclear power growth. Another oil embargo or shortage of any other energy producing commodity could increase the necessity for rapid growth of the nuclear power industry. Conversely increased licensing delays or lack of public acceptance of the widespread use of nuclear power could further impede the progress.

Since it is impossible to predict the possible impact of these actions on the future nuclear growth, it is necessary to examine the economic impact of plutonium recycle using a range of nuclear growth schedules. A range of 500 GWe $\pm$ 100 GWe of LWR capacity by the year 2000 was examined. These growth schedules are graphically shown in Figure 5. There is currently 260 GWe's of nuclear capacity operating or contractually committed. Thus, the additional capacity represented by any of these projections required to meet the forecasted levels in the year 2000 should be readily achievable in the 1976 to 1990 time frame. Using the 600 GWe growth schedule increased the calculated economic incentive to reprocess and recycle from \$16.6 billion to \$21.4 billion. The 400 GWe case resulted in a reduction of the incentive to \$12.6 billion.

9. Extended Base Case

To assess the delayed benefits of reprocessing and recycle to reactors built just prior to the year 2000 and partially compensate for end effects in the analysis, an extended base comparison terminating in the year 2030 is considered. For this analysis, no additional reactors are assumed built after 2000, (and reactor retirements (30 year lifetime) reduce the installed LWR generating capacity to 239 GWe by the year 2020.) This results in increased benefits from recycle relative to the throwaway fuel cycle of \$76.7 billion (\$4.2 billion discounted to 1977). This represents about a 20% improvement in cost benefit relative to the throwaway mode for the 2000-2030 time period.

For this comparison, one less reprocessing plant

and mixed-oxide fabrication plant is assumed to be required because the size of the recycle business would be defined by 1990–1995 if no reactors are built after 2000. Overcapacity would presumably be avoided to assure a sufficient plant operating period at full capacity to recover the initial investment. (This results in a gradual increase in fuel inventory from 1996 to 2016. In addition, demands for pipeline inventories in mining and milling decrease in the year 2000.) The effects create inherent differences between costs incurred by 2000 in the extended case and those costs in the base comparison. Because the thirty year life for reactors would extend the bulk of the benefits into the post 2000 time frame, this planning horizon is possibly more appropriate for use in long range comparisons.

Summary of Sensitivity Analysis Results

The range of costs considered for each fuel cycle cost component is summarized in Table 4, and a summary of the sensitivity analysis results is displayed graphically in Figure 6 to demonstrate the relative impact of each parameter. The results of multiple parameter variations are additive with the exception of the variation in nuclear growth schedule. The impact of simultaneous changes of all parameters is shown in Figure 7 where it is particularly noteworthy that the assumptions chosen for the base case show a definite skewing in favor of the throwaway cycle. In the "least favorable" combination, all parameters were changed in the way that would reduce the net benefits of recycle. The benefits are thus reduced to –\$4.9 billion. In this latter case, retaining one variable such as the price of separative work at its base

FIGURE 5

TABLE 4—RANGE OF VARIATION OF PARAMETERS

1. Uranium Price Schedule	See Figure 4
2. Separative Work Cost	\$75/SWU—\$125/SWU
3. Spent Fuel Storage and Disposal Cost	\$60/Kg—\$200/Kg Fuel Processed
4. Reprocessing Cost	\$220/Kg—\$340/Kg
5. Reprocessing Plant Capacity	1500 MTU/Yr—3000 MTU/Yr
6. Spent Fuel Cooling Time	1–5 Years
7. Reprocessing Waste Management Cost	\$25/Kg—\$50/Kg Fuel Reprocessed
8. LWR Growth	400 GWe—600 GWe (LWR) in year 2000
9. Tails Assay	Constant—25% U-235
10. Uranium Fabrication	Constant—\$90/Kg U
11. MOX Fabrication	Constant—\$260/Kg Heavy Metal
12. Plutonium Storage	Constant—\$300/Kg Fissile Pu—Yr

FIGURE 6
SUMMARY OF SENSITIVITY ANALYSIS

FIGURE 7
CUMULATIVE SAVINGS THROUGH 2000 -
VARIATION OF MULTIPLE PARAMETERS

case value, results in essentially a breakeven situation for the two fuel cycle modes. Comparatively, the "most favorable" combination of parameter values increased the benefits by \$29.5 billion to \$46.1 billion. In addition a case was examined in which the higher cost of each range was used for each component in both the throwaway and the recycle modes. This increased the economic benefits of recycle versus throwaway by \$12.3 to \$28.9 billion.

URANIUM AVAILABILITY

Resources and Requirements

Estimates of U.S. natural uranium resources are shown in Table 5. Ore reserves, delineated by drilling, at the \$15 cutoff cost level are 430,000 tons U_3O_8 . These ores average 0.13% U_3O_8 compared to 0.16% for the average grade of ores currently being mined. Additional reserves at higher costs (to \$30 per pound and average grade of 0.08% U_3O_8) which will be used in the future increase the reserve total to 640,000 tons U_3O_8 . Probable potential resources, estimated from analysis of mineral trends in the producing districts, are estimated to be 655,000 tons at the \$15 cost level and 1,060,000 tons at the \$30 cost level. Reserves and probable potential resources are the firmest portion of the resource estimates and are considered a prudent base for long range planning. Addition of possible and speculative resources brings the totals to 2.1 million tons and 3.6 million tons re-

spectively. An additional 140,000 tons are projected to be available as a byproduct of copper and phosphate production.

For a nuclear capacity of 500 GWe in the year 2000, the cumulative demand for natural uranium would be about 1.1 million short tons of U_3O_8 with uranium and plutonium recycle. This quantity is equal to the total of U.S. uranium ore reserves and probable potential resources available at a production cost of \$15 or less per pound U_3O_8 . Without recycle the cumulative natural uranium demand would increase to about 1.5 million short tons of U_3O_8 through the year 2000. This is well above the \$15 reserves plus probable potential and is about 80% of the \$30 reserves plus probable potential resources.

To meet annual demands with recycle, uranium production will have to grow from the current level of around 12,000 tons of U_3O_8 per year to 50,000 tons per year by 1990 and about 86,000 tons per year by the year 2000. This will require a major undertaking in exploration and expansion of production facilities. The absence of recycle would result in annual production rates of about 70,000 tons U_3O_8 by 1990 and about 126,000 tons of U_3O_8 in the year 2000. Analysis of current resources and potential production capability, as shown in Figure 8, indicates considerable doubt that the latter levels could be attained from identified domestic resources. Availability of foreign uranium in substantial quantities is uncertain.

TABLE 5—U.S. URANIUM RESOURCES

January 1, 1976
Tons U_3O_8

\$/lb. U_3O_8 Cutoff Cost	Reserves	Potential			Total
		Probable	Possible	Speculative	
\$10	270,000	440,000	420,000	145,000	1,275,000
\$10-15 Increment	160,000	215,000	255,000	145,000	775,000
\$15	430,000	655,000	675,000	290,000	2,050,000
\$15-30 Increment	210,000	405,000	595,000	300,000	1,510,000
\$30	640,000	1,060,000	1,270,000	590,000	3,560,000
By Product 1975-2000 ^a	140,000	—	—	—	140,000
	780,000	1,060,000	1,270,000	590,000	3,700,000

^a By-product of phosphate and copper production.

Production Capability

U.S. industry has reported plans to expand production to a level of 27,000 tons per year by the year 1979. Analysis of industry plans and of production levels attainable from currently estimated resources indicate that levels of around 60,000 tons per year could be attained by around 1990 with vigorous development of resources and construction of new mines and mills. This level could be attained with \$15 resources, but to be sustained over an extended period would likely require use of higher cost resources with the attendant requirement for larger production facilities.

The cost of production facilities with the recycle mode, for about 90 new mine/mill complexes (averaging 1,000 tons U_3O_8 per year each), will total about \$10 billion through the year 2000. For the no recycle case, 120 new mine/mill complexes will be needed through the year 2000 with capital costs of about \$13–15 billion.

Experience has shown that to assure continued uranium production to meet market demands, to allow orderly sales contracting, and to provide a basis for amortization of investments, a substantial industry ore reserve and resource base must be maintained. Experience indicates that an industry-wide minimum reserve equal to the following 10 years production will be needed. Such a level has been met in recent years and production capacity has been adequate, but there have been concerns about the adequacy of the resource base for meeting demands over the next 5 to 15 years.

Cumulative uranium production through the year 2000 is estimated to be about 1.1 million short tons U_3O_8 for the base case under recycle conditions. For these same conditions, the 10-year forward reserve which will be needed in the year 2000—estimated at 800,000 short tons U_3O_8 —is about equal to today's 780,000 tons \$30 reserves and byproduct. This means that between now and the year 2000, 1.1 million tons of U_3O_8 or an average of 44,000 tons per year will have to be developed from potential resources and converted into reserves to account for the 1.1 million tons of production as estimated above. Exploration costs for this will total about \$5 billion. Without recycle, the cumulative demand for U_3O_8 through the year 2000 is estimated at 1.5 million tons. This total of 2.5 million tons of U_3O_8 is 1.7 million tons greater than the current reserve, and this 1.7 million will have to be developed into reserves from potential resources over the next 25 years at an annual development rate of about 68,000 tons U_3O_8 per year and a total cost of 8 to 10 billion dollars.

In addition to a minimum ore reserve position, additional potential resources must be identified to assure continued delineation of new ore reserves. Analysis of production capacity attainable from reserves and probable potential indicates future levels that will be needed. Figure 8 shows the relationship between U.S. resource requirements and resource levels in the year 2000, considering cumulative production, ore reserves and probable potential, with and without recycle. In the no recycle case a total of 1.2 million tons

FIGURE 8

more U_3O_8 would be required than in the recycle case or a total of 5.0 versus 3.8 million tons by the year 2000. This would make a significant difference in the utilization of known resources and in the required long term resource development efforts.

In summary, projected growth in uranium demand even with recycle of uranium and plutonium will require use of a substantial portion of currently estimated U.S. uranium resources, a substantial part of which remains to be discovered. A large effort in exploration and development of new mines and mills will be needed. There are limits to the levels of production capacity that are considered attainable from currently known U.S. resources. If recycle is not available, the commitment of resources and the level of exploration and production must be substantially higher to meet the nuclear power growth projections beyond current commitments. Uranium availability could restrict the level of nuclear capacity that can be supported at any particular time. There is an inherent risk in the existence and timely discovery and development of natural resources. The unavailability of recycled uranium and plutonium would add a highly undesirable additional element to that risk.

BREEDER IMPACT

ERDA 76-1* states that "The capability of the nation to draw on nuclear energy to meet the electric and other energy requirements of this country beyond this century will depend on having available a proven, environmentally safe commercial breeder system by the 1990's . . ." It is further stated that "(It is) the lack of advanced fuel and core materials . . . which prohibits LMFBR power plants from generating new

* ERDA 76-1 A National Plan For Energy Research, Development & Demonstration: Creating Energy Choices For The Future.

fissionable material at a rate commensurate with the national growth in electric power demand."

The obvious source of fuel for LMFBR reactors is the plutonium contained in LWR spent fuel. The fissile plutonium contained in 11 annual discharges of a 1000 MWe LWR is sufficient to provide fuel for one 1000 MWe LMFBR initial core. Five additional annual LWR discharges are required to provide enough plutonium for the first LMFBR reload or a total of 3.2 MT of fissile plutonium. Even if the breeder reactor fuel cycle achieves self-sufficiency after one discharge/reload, the introduction rate of breeder generating capacity is dependent on and limited by the capability to recover plutonium from spent LWR fuel.

The economic section of this report assumed the recycle of all available plutonium in LWR's. This assumption introduces a bias in favor of the throw-away fuel cycle, in that it ignores the enhanced value of plutonium in a breeder reactor economy. Thus all of the results presented represent a baseline (or minimal) measure of the incentive to recover and reuse the fissile content of spent LWR fuel.

Beyond the requirement for direct input of LWR plutonium into the breeder program, the latter also stands to derive considerable indirect benefit from having a commercial LWR reprocessing industry as a forerunner to LMFBR reprocessing operations. Though differences in the reprocessing operation will exist for the two fuel cycles, (these are likely to be mainly in the head end) in general the similarities are such that LWR experience would be of considerable value to the LMFBR. As the LWR industry develops, the availability of a broad engineering and technical capability to apply to the emerging LMFBR requirements would be an extremely valuable asset. Conversely, the lack of a strong LWR reprocessing and recycle industry would delay the contribution of the breeder to meeting our long-term energy needs.

APPENDIX A
SUPPLEMENTARY DATA

**COMPARISON OF FUEL CYCLE COSTS (AND LIABILITIES)
INCURRED BETWEEN 1976 and 2000
FOR THE THROWAWAY AND RECYCLE OPERATING MODES**

BASE COMPARISON
(Billions of 1977 Dollars)

	THROWAWAY	RECYCLE	DIFFERENCE
Mining	135.9	95.4	+ 40.5
Separative Work	73.8	60.5	+13.3
Uranium Fabrication	18.7	18.7	—
Chemical Reprocessing	—	40.9	—40.9
Pu Storage	—	.1	— .1
Pu Fabrication	—	5.0	— 5.0
Spent Fuel Storage and Disposal *	13.0	—	+ 13.0
Interim Fuel Storage and Reprocessing Waste Disposal *	—	4.2	— 4.2
Total	241.4	224.8	+ 16.6
Fuel Cycle Costs, Mills/kwh	6.5	6.0	.5

* Some Fuel irradiated before the year 2000 has remaining pool storage and disposal liability at the year 2000. Also, some fuel reprocessed before the year 2000 generates waste which is disposed of after the year 2000. These costs are included in the total.

BASE CASE MATERIAL FLOW

500 GW (e)

Year	Fuel Dis- charged, MTU	Cumulative Inventory, 1-Yr Cooled, MTU	Separa- tions Capacity, MTU/Year	Inventory Unproc- essed, MTU	Total Uranium Processed, MTU	Fissile Plutonium Separated, MTU/Year	Plutonium Fuel, MTU/Yr of Fissile Pu		Inventory of Separated Fissile Pu, MT
							Fabricated	Recycled (75% of Fabricated)	
1976	1,111	1,867		1,867					
1977	1,310	2,987		2,978					
1978	1,455	4,288		4,288					
1979	1,591	5,743		5,743					
1980	1,797	7,334		7,334					
1981	2,059	9,131	^a (1) 600	8,531	600	4.2			4.2
1982	2,583	11,190	1,000	9,590	1,600	7.0			11.2
1983	3,024	13,773	^a (2) 1,740	10,433	3,340	12.2	^b (1) 5.3	4.0	18.1
1984	3,493	16,797	1,900	11,557	5,240	13.3	^b (2) 15.8	11.9	15.6
1985	4,029	20,290	2,100	12,950	7,340	14.7	21.0	15.8	9.3
1986	4,625	24,319	^a (3) 2,700	14,279	10,040	18.9	21.0	15.8	7.2
1987	5,193	28,944	^a (4) 3,700	15,204	13,740	25.9	^b (3) 26.3	19.7	6.8
1988	5,727	34,137	^a (5) 5,200	15,197	18,940	36.4	^b (4) 36.8	27.6	6.4
1989	6,310	39,864	^a (6) 6,700	14,224	25,640	46.9	^b (5) 47.3	35.5	6.0
1990	6,901	46,174	^a (7) 8,200	12,334	33,840	57.4	^b (6) 57.8	43.4	5.6
1991	7,541	53,075	9,100	10,135	42,940	63.7	63.0	47.3	6.3
1992	8,233	60,616	^a (8) 10,200	7,476	53,140	71.4	^b (7) 68.3	51.2	9.4
1993	8,874	68,849	10,600	5,109	63,740	74.2	73.5	55.1	10.1
1994	9,566	77,723	11,100	2,883	74,840	77.7	73.5	55.1	14.3
1995	10,257	87,289	11,100	1,349	85,940	77.7	^b (8) 73.5	55.1	18.5
1996	10,895	97,546	11,100	506	97,040	77.7	78.8	59.1	17.4
1997	11,483	108,441	11,100	301	108,140	77.7	84.0	63.0	11.1
1998	12,018	119,924	11,100	684	119,240	77.7	84.0	63.0	4.8
1999	12,529	131,942	^a (9) 11,700	1,002	130,940	81.9	84.0	63.0	2.7
2000	13,012	144,471	12,100	1,231	143,040	84.7	84.0	63.0	3.4

^a Indicates year of startup of new separations plants.

^b Indicates year of startup for new MOX plants (10.5 MT up Pu_r/yr).

**COMPARISON OF FUEL CYCLE COSTS (AND LIABILITIES)
INCURRED BETWEEN 1976 and 2000
FOR THE THROWAWAY AND RECYCLE OPERATING MODES**

HIGH REACTOR GROWTH COMPARISON (600 GWe)
(Billions of 1977 Dollars)

	THROWAWAY	RECYCLE	DIFFERENCE
Mining	160.7	111.9	+ 48.8
Separative Work	84.6	69.4	+15.2
Uranium Fabrication	21.5	21.5	0.0
Chemical Reprocessing	0.0	46.7	-46.7
Pu Storage	0.0	.1	- .1
Pu Fabrication	0.0	5.7	- 5.7
Spent Fuel Storage and Disposal *	14.7	0.0	+ 14.7
Interim Fuel Storage and Reprocessing Waste Disposal *	0.0	4.8	- 4.8
Total	281.5	260.1	21.4
Fuel Cycle Costs, Mills/kwh	6.7	6.1	.7

* Some Fuel irradiated before the year 2000 has remaining pool storage and disposal liability at the year 2000. Also, some fuel reprocessed before the year 2000 generates waste which is disposed of after the year 2000. These costs are included in the total.

HIGH GROWTH SCHEDULE MATERIAL FLOWS **600 GW (e)**

Year	Fuel Discharged, MTU	Cumulative Inventory, 1-Yr Cooled, MTU	Separations Capacity, MTU/Year	Inventory Unprocessed, MTU	Total Uranium Processed, MTU	Fissile Plutonium Separated, MTU/Year	Plutonium Fuel, MTU/Yr of Fissile Pu		Inventory of Separated Fissile Pu, MT
							Fabricated	Recycled (75% of Fabricated)	
1976	1,164	1,867		1,867					
1977	1,310	3,031		3,031					
1978	1,455	4,341		4,341					
1979	1,644	5,796		5,796					
1980	1,899	7,440		7,440					
1981	2,114	9,339	^a (1) 600	8,739	600	4.2			4.2
1982	2,817	11,453	1,000	9,853	1,600	7.0			11.2
1983	3,336	14,270	^a (2) 1,740	10,930	3,340	12.2	^b (1) 5.3	4.0	18.1
1984	3,908	17,606	1,900	12,366	5,240	13.3	^b (2) 15.8	11.9	15.6
1985	4,442	21,514	2,100	14,174	7,340	14.7	21.0	15.8	9.3
1986	5,036	25,956	^a (3) 2,700	15,916	10,040	18.9	21.0	15.8	7.2
1987	5,631	30,992	^a (4) 3,700	17,252	13,740	25.9	^b (3) 26.3	19.7	6.8
1988	6,321	36,623	^a (5) 5,200	17,683	18,940	36.4	^b (4) 36.8	27.6	6.4
1989	7,032	42,944	^a (6) 6,700	17,304	25,640	46.9	^b (5) 47.3	35.5	6.0
1990	7,778	49,976	^a (7) 8,200	16,136	33,840	57.4	^b (6) 57.8	43.4	5.6
1991	8,572	57,754	^a (8) 9,700	14,214	43,540	67.9	^b (7) 68.3	51.2	5.2
1992	9,370	66,326	10,600	12,186	54,140	74.2	73.5	55.1	5.8
1993	10,189	75,696	^a (9) 11,700	9,856	65,840	81.9	^b (8) 78.8	59.1	8.9
1994	11,009	85,885	12,100	7,945	77,940	84.7	84.0	63.0	9.6
1995	11,802	96,894	^a (10) 12,800	6,154	90,740	89.6	^b (9) 89.3	67.0	9.9
1996	12,569	108,696	13,200	4,756	103,940	92.4	94.5	70.9	7.8
1997	13,312	121,265	^a (11) 14,300	3,025	118,240	100.1	^b (10) 99.8	74.8	8.1
1998	14,050	134,577	14,700	1,637	132,940	102.9	105.0	78.8	6.0
1999	14,743	148,627	15,100	587	148,040	105.7	105.0	78.8	6.7
2000	15,405	163,370	15,100	230	163,140	105.7	105.0	78.8	7.4

^a Indicates year of startup of new separations plants.

^b Indicates year of startup for new MOX plants (10.5 MT up Pu_t/yr).

**COMPARISON OF FUEL CYCLE COSTS (AND LIABILITIES)
INCURRED BETWEEN 1976 and 2000
FOR THE THROWAWAY AND RECYCLE OPERATING MODES**

LOW REACTOR GROWTH COMPARISON (400 GWe)
(Billions of 1977 Dollars)

	THROWAWAY	RECYCLE	DIFFERENCE
Mining	109.6	76.5	+ 33.1
Separative Work	61.4	50.4	+11.1
Uranium Fabrication	15.4	15.4	—
Chemical Reprocessing	—	34.8	—34.8
Pu Storage	—	.1	— .1
Pu Fabrication	—	4.2	— 4.2
Spent Fuel Storage and Disposal *	11.1	—	+ 11.1
Interim Fuel Storage and Reprocessing Waste Disposal *	—	3.5	— 3.5
Total	197.5	184.9	12.6
Fuel Cycle Costs, Mills/kwh	6.2	5.8	.4

* Some Fuel irradiated before the year 2000 has remaining pool storage and disposal liability at the year 2000. Also, some fuel reprocessed before the year 2000 generates waste which is disposed of after the year 2000. These costs are included in the total.

LOW GROWTH SCHEDULE MATERIAL FLOWS
400 GW (e)

Year	Fuel Discharged, MTU	Cumulative Inventory, 1-Yr Cooled, MTU	Separations Capacity, MTU/Year	Inventory Unprocessed, MTU	Total Uranium Processed, MTU	Fissile Plutonium Separated, MTU/Year	Plutonium Fuel, MTU/Yr of Fissile Pu		Inventory of Separated Fissile Pu, MT
							Fabricated	Recycled (75% of Fabricated)	
1976	1,087	1,867		1,867					
1977	1,208	2,954		2,954					
1978	1,330	4,162		4,162					
1979	1,517	5,492		5,492					
1980	1,696	7,009		7,009					
1981	2,035	8,705	^a (1) 600	8,105	600	4.2			4.2
1982	2,296	10,740	1,000	9,140	1,600	7.0			11.2
1983	2,687	13,036	^a (2) 1,740	9,696	3,340	12.2	^b (1) 5.3	4.0	18.1
1984	2,997	15,723	1,900	10,483	5,240	13.3	^b (2) 15.8	11.9	15.6
1985	3,511	18,720	2,100	11,380	7,340	14.7	21.0	15.8	9.3
1986	4,162	22,231	^a (3) 2,700	12,191	10,040	18.9	21.0	15.7	7.2
1987	4,677	26,393	^a (4) 3,700	12,653	13,740	25.9	^b (3) 26.3	19.7	6.8
1988	5,056	31,070	^a (5) 5,200	12,130	18,940	36.4	^b (4) 36.8	27.6	6.4
1989	5,511	36,126	^a (6) 6,700	10,486	25,640	46.9	^b (5) 47.3	35.5	6.0
1990	5,917	41,637	7,600	8,397	33,240	53.2	52.6	39.5	6.6
1991	6,379	47,554	8,100	6,214	41,340	56.7	52.6	39.5	10.7
1992	6,918	53,933	8,100	4,493	49,440	56.7	52.6	39.5	14.8
1993	7,429	60,851	8,100	3,311	57,540	56.7	^b (6) 57.9	43.4	13.6
1994	7,944	68,280	8,100	2,640	65,640	56.7	63.1	47.3	7.2
1995	8,534	76,224	^a (7) 8,700	1,884	74,340	60.9	63.1	47.3	5.0
1996	8,989	84,758	9,100	1,318	83,440	63.7	63.1	47.3	5.6
1997	9,375	93,747	9,600	707	93,040	67.2	63.1	47.3	9.7
1998	9,702	103,122	9,600	482	102,640	67.2	63.1	47.3	13.8
1999	10,005	112,824	9,600	584	112,240	67.2	^b (7) 68.4	51.3	12.6
2000	10,258	122,829	9,600	989	121,840	67.2	73.6	55.2	6.2

^a Indicates year of startup of new separations plants.

^b Indicates year of startup for new MOX plants (10.5 MT up Pu₂/yr).

**COMPARISON OF FUEL CYCLE COSTS (AND LIABILITIES)
INCURRED BETWEEN 1976 and 2000
FOR THE THROWAWAY AND RECYCLE OPERATING MODES**

5 YR FUEL DECAY CASE
(Billions of 1977 Dollars)

	THROWAWAY	RECYCLE	DIFFERENCE
Mining	135.9	108.4	+27.5
Separative Work	73.8	64.8	+ 9.0
Uranium Fabrication	18.7	18.7	0
Chemical Reprocessing	0.0	25.7	-25.7
Pu Storage	0.0	.1	- .1
Pu Fabrication	0.0	3.3	-3.3
Spent Fuel Storage and Disposal *	13.0	0.0	+13.0
Interim Fuel Storage and Reprocessing Waste Disposal *	0.0	3.9	- 3.9
Total	241.4	224.9	16.5
Fuel Cycle Costs, Mills/kwh	6.5	6.0	.5

* Some Fuel irradiated before the year 2000 has remaining pool storage and disposal liability at the year 2000. Also, some fuel reprocessed before the year 2000 generates waste which is disposed of after the year 2000. These costs are included in the total.

5 YEAR FUEL DECAY CASE

500 GW(e)

Year	Inventory of 5 Year Decay Fuel	Separations Capacity, MTU/Year	Inventory Unproc- essed, MTU	Total Uranium Processed, MTU	Fissile Plutonium Separated, MTU/Year	Plutonium Fuel, MTU/Yr of Fissile Pu		Inventory of Separated Fissile Pu, MT
						Fabricated	Recycled (75% of Fabricated)	
1980	1,867							
1981	2,978	^a (1) 600	2,378	600	4.2			4.2
1982	4,288	1,000	2,688	1,600	7.0			11.2
1983	5,743	^a (2) 1,740	2,403	3,340	12.2	^b (1) 5.3	4.0	18.1
1984	7,334	1,900	2,094	5,240	13.3	^b (2) 15.8	11.9	15.6
1985	9,131	2,100	1,791	7,340	14.7	21.0	15.8	9.3
1986	11,190	2,100	1,750	9,440	14.7	21.0	15.8	3.0
1987	13,773	^a (3) 2,700	1,633	12,140	18.9	21.0	15.8	0.9
1988	16,797	3,100	1,557	15,240	21.7	21.0	15.8	1.6
1989	20,290	3,600	1,450	18,840	25.2	21.0	15.8	5.8
1990	24,319	^a (4) 4,200	1,279	23,040	29.4	^b (3) 26.3	19.7	8.9
1991	28,944	4,600	1,304	27,640	32.2	31.5	23.6	9.6
1992	34,137	^a (5) 5,700	797	33,340	39.9	^b (4) 36.8	27.6	12.7
1993	39,864	6,100	424	39,440	42.7	42.0	31.5	13.4
1994	46,174	6,600	134	46,040	46.2	^b (5) 47.3	35.5	12.3
1995	53,075	6,600	435	52,640	46.2	52.5	39.4	6.0
1996	60,616	^a (6) 7,200	776	59,840	50.4	52.5	39.4	3.9
1997	68,849	^a (7) 8,200	809	68,040	57.4	52.5	39.4	8.8
1998	77,723	9,100	583	77,140	63.7	^b (6) 57.8	43.4	14.7
1999	87,289	9,600	549	86,740	67.2	63.0	47.3	18.9
2000	97,546	9,600	1,206	96,340	72.2	^b (7) 68.3	51.4	17.6

^a Indicates year of startup of new separations plants.

^b Indicates year of startup for MOX plants (10.5 of Pu₁/yr).

**COMPARISON OF FUEL CYCLE COSTS (AND LIABILITIES)
INCURRED BETWEEN 1976 and 2000
FOR THE THROWAWAY AND RECYCLE OPERATING MODES**

3000 MTU PLANT CASE
(Billions of 1977 Dollars)

	THROWAWAY	RECYCLE	DIFFERENCE
Mining	135.9	95.0	+ 40.9
Separative Work	73.8	60.5	+ 13.3
Uranium Fabrication	18.7	18.7	0.0
Chemical Reprocessing	—	30.5	— 30.5
Pu Storage	—	.1	— .1
Pu Fabrication	—	5.0	— 5.0
Spent Fuel Storage and Disposal *	13.0	—	+ 13.0
Interim Fuel Storage and Reprocessing Waste Disposal *	—	4.1	— 4.1
	241.4	213.9	27.5
Mills/kwh	6.5	5.8	.7

* Some Fuel irradiated before the year 2000 has remaining pool storage and disposal liability at the year 2000. Also, some fuel reprocessed before the year 2000 generates waste which is disposed of after the year 2000. These costs are included in the total.

**3000 MTU PLANT CASE
500 GW (e)**

Year	Fuel Discharged, MTU	Cumulative Inventory, 1-yr Cooled, MTU	Separations Capacity, MTU/Year	Inventory Unprocessed, MTU	Total Uranium Processed, MTU	Fissile Plutonium Separated, MT/Yr	Plutonium Fuel, MT/Yr of Fissile Pu		Inventory of Separated Fissile Pu, MT
							Fabricated	Recycled (75% of Fabricated)	
1976	1,111	1,867		1,867					
1977	1,310	2,978		2,978					
1978	1,455	4,288		4,288					
1979	1,591	5,743		5,743					
1980	1,797	7,334		7,334					
1981	2,059	9,131	^a (1) 600	8,531	600	4.2			4.2
1982	2,583	11,190	1,000	9,590	1,600	7.0			11.2
1983	3,024	13,773	^a (2) 1,740	10,433	3,340	12.2	^b (1) 5.3	4.0	18.1
1984	3,493	16,797	1,900	11,557	5,240	13.3	^b (2) 15.8	11.9	15.6
1985	4,029	20,290	2,100	12,950	7,340	14.7	21.0	15.8	9.3
1986	4,625	24,319	^a (3) 3,300	13,679	10,640	23.1	21.0	15.8	11.4
1987	5,193	28,944	4,100	14,204	14,740	28.7	^b (3) 26.3	19.7	13.8
1988	5,727	34,137	5,100	14,297	19,840	35.7	^b (4) 36.8	27.6	12.7
1989	6,310	39,864	^a (4) 6,300	13,723	26,140	44.1	^b (5) 47.3	35.5	9.5
1990	6,901	46,174	7,100	12,933	33,240	49.7	52.5	39.4	6.7
1991	7,541	53,075	8,100	11,734	41,340	56.7	^b (6) 57.8	43.4	5.6
1992	8,233	60,616	^a (5) 9,300	9,975	50,640	65.1	63.0	47.2	7.7
1993	8,874	68,849	10,100	8,108	60,740	70.7	^b (7) 68.3	51.2	10.1
1994	9,566	77,723	11,100	5,882	71,840	77.7	73.5	55.1	14.3
1995	10,257	87,289	11,100	4,348	82,940	77.7	73.5	55.1	18.5
1996	10,895	97,546	11,100	3,505	94,040	77.7	^b (8) 78.8	59.1	17.4
1997	11,483	108,441	11,100	3,300	105,140	77.7	84.0	63.0	11.1
1998	12,018	119,924	11,100	3,683	116,240	77.7	84.0	63.0	4.8
1999	12,529	131,942	^a (6) 12,300	3,401	128,540	86.1	84.0	63.0	6.9
2000	13,012	144,471	13,100	2,830	141,640	91.7	^b (9) 89.3	67.0	9.3

^a Indicates year of startup of new separations plants.

^b Indicates year of startup for MOX plants (10.5 of Pu_f/yr).