CONSUMPTION MINIMIZATION OF THE URANIUM RESOURCES BY THE USE OF MIXED-OXIDE FUELED REACTORS

by

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GLOSSARY OF ACRONYMS

SWU - Separative Work Unit; a special unit used in determining the cost of enriched uranium by reflecting the work expended in its production.

LWR - Light Water Reactor; a reactor utilizing H_2O as the moderator-coolant.

MOX - Mixed Oxide; nuclear fuel that contains both UO_2 and PuO_2.

PWR - Pressurized Water Reactor

BWR - Boiling Water Reactor

SGR - Self-Generating Reactor; a light water reactor which utilizes its own spent fuel. This reactor type uses MOX fuel assemblies as well as UO_2 fuel assemblies.

APR - All Plutonium Reactor; a light water reactor utilizing only MOX fuel assemblies.

GESMO - Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Reactors.[13]

MTU - metric tons of uranium.

MTHM - metric tons of heavy metal; contains both uranium and plutonium.

ERDA - U.S. Energy Research and Development Administration

LOW - reactor growth scenario characterized by 400 operating nuclear reactors in the year 2000.

MID - reactor growth scenario characterized by 507 operating nuclear reactors in the year 2000.

HIGH - reactor growth scenario characterized by 600 operating nuclear reactors in the year 2000.

1. INTRODUCTION

1.1 Background and Motivation

Electrical power generation continues to be the fastest growing form of energy consumption in the United States. With the remarkable inventions of Thomas Edison in the latter nineteenth century, electricity began demonstrating itself to be a more convenient and cleaner form of energy for end uses than that produced by coal and oil.[1] Today, electricity is an integral part of our everyday lives and people are dependent on its instant availability. The implications of this dependence are very well demonstrated by the results of recent blackouts of New York City and the surrounding areas on November 11, 1965, and again on July 13, 1977.

The demand for electricity is currently growing about twice as fast as the total of all energy sources.[2] Electricity represents a continually increasing share of energy production, rising from 28 percent in 1974 to a predicted 37 percent in 1990. This represents a growth rate of about 5.4 percent per year.[2] In a 1976 study by Hanrahan[3], it was reported that in 1975, 29 percent of the total energy inputs went for the production of electricity. This is predicted to increase to about 44 percent in the year 2000. Hanrahan also concludes that the annual growth rate of electrical production will be 5.2 percent between 1975 and 1985, and then reduce to 4.5 percent between 1985 and 2000. In both cases, coal, oil, natural gas, and nuclear fission are expected to be available to produce the required amount of electricity.

The contribution of nuclear power for the purpose of electrical

production is dependent on several factors, amoung which are the economic competitiveness of nuclear power with fossil fuels, the emergence of new technologies such as solar power and fusion, the closing of the nuclear fuel cycle, and public attitudes toward nuclear power. Electrical generation by nuclear power has grown from 0.7 percent of the total electrical power production in 1970 to 8.6 percent in 1975. It is expected that nuclear energy could represent about 26 percent of the electrical power generation by 1985 and as high as 50 percent in the year 2000.[2,3] A recent survey by the Atomic Industrial Forum showed that nuclear power was used to provide from 33 to 60 percent of the electrical power distribution in several states.[4]

As the role of nuclear power in electrical production increases, so will the accumulation of spent uranium and plutonium that is contained in spent fuel. If these two components are recycled back into a reactor core as fresh fuel, a 20 percent reduction in separative work unit (SWU) requirements and a 33 percent reduction in natural feed requirements can be achieved.[5] This could effectively increase the nuclear fuel supply by about 25 percent.[6] A key factor in conserving the limited supply of nuclear fuel is, therefore, the determination of optimal mixed-oxide fuel blending policies. Once determined, this policy could be used to aid in the determination of an optimal reactor mix policy in order to minimize the consumption of natural uranium feed and the amount of plutonium outside the reactor core.

1.2 The Problem and Objective

The nuclear industry currently faces many complex problems. One

very important problem must involve the proper management of the rapidly decreasing supply of natural uranium. This problem results from three basic factors. Firstly, an increase in the demand for natural uranium will arise from the projected growth in the number of nuclear power plants. Secondly, a delay in the operation of reprocessing plants limits the availability of recyclable uranium and plutonium. Recycling the unused uranium and plutonium reduces the demand on the limited natural uranium supply. Finally, further delay in the fast breeder program suggests that the Light Water Reactor program (LWR) will have to increase the number of reactors to compensate for the projected role of the fast breeder program in electrical production. From this it can be seen that there is a definite need to conserve scarce natural uranium resources.

Another problem that the nuclear industry faces is the question of what to do with the spent fuel produced in the current LWRs. In light of the current federal administration's view on the utilization of plutonium, the options for dealing with spent fuel are considerably reduced. First, the plutonium-bearing fuel assemblies can be placed in either a permanent or a retrievable burial site (throwaway fuel cycle). Second, the spent fuel can remain in the reactor for a longer period of time allowing for additional heat generation by the fuel (extended burnup fuel cycle). Third, the spent fuel can be placed in another nuclear reactor which is specifically designed to utilize spent fuel (tandem fuel cycle). Fuel cycles involving chemical processing are not considered viable options as they lack administrative endorsement.

Since plutonium has an equal, if not greater, neutronic value as

a nuclear fuel than Uranium-235, the economics of plutonium utilization suggest that a reactor program using plutonium mixed with some form of uranium to form a mixed-oxide fuel should already be on a commercial scale. This program is also supported because uranium is a dwindling natural resource. The course of action suggested by these factors invloves the utilization of the plutonium currently being produced as fuel for mixed-oxide (MOX) reactors of the future.

Chemical processing is, however, a very diversified process. Firstly, the spent fuel can be partially reprocessed, extracting only the uranium, thereby leaving the plutonium in the waste product for permament disposal. Secondly, the spent fuel can be fully reprocessed, removing both uranium and plutonium separately. Finally, the spent fuel can be co-processed, extracting both uranium and plutonium simultaneously.

The objective of this effort is to address a key problem that must be resolved in determining stratagies for managing the natural uranium resources, Specifically, the objective is to determine an optimal scheduling of the different types of nuclear fuel in order to minimize the amount of natural uranium consumed each year. An additional objective is to minimize the amount of plutonium outside of a fuel assembly in order to minimize the possibility of diversion of nuclear materials. A model that addresses the problem is developed and presented along with the associated detailed derivation. Results from analyzing and solving the fuel scheduling model are also presented.

1.3 The Approach

Minimizing the consumption of the uranium resources includes pursuit

of a two-fold objective. First, a MOX fuel blending model is developed in order to determine the constituents necessary in the fabrication of MOX fuel at a minimum cost. Second, a reactor mix model is developed in order to determine what type of fuel, enriched uranium dioxide (UO_2) or MOX fuel, should be loaded into the various cores each year.

The objectives necessary to the development of the MOX fuel blending model are:

1. the identification of the possible constituents comprising MOX fuel,
2. the development of an appropriate optimization model describing the demand and availability of material quantities,
3. the implementation of a flexible computer code incorporating the developed mathematical model, and
4. the determination of cost-effective strategies involving the blending of MOX fuel.

The information obtained from the blending model will be further utilized in the reactor mix model.

The reactor mix model is a time-dependent decision problem influenced by growth of nuclear power capacity, supply and demand for spent fuel, and availability of reprocessing and fuel fabrication. The objectives necessary to the implementation of this model are:

1. the identification of processes which restrict the availability of reactor fuels to meet the projected reactor demands,
2. the development of an appropriate optimization model describing

the behavior of the nuclear industry with respect to the use of MOX fuels,

3. the implementation of an appropriate computer-oriented code incorporating the developed mathematical model and associated economic measures of effectiveness, and
4. the determination of appropriate cost-effective or consumption-effective strategies yielding definable fuel loading policies for the types of fuel in this study.

The thesis consists of eight chapters. Following the introductory remarks, additional material concerning the nuclear fuel cycle and current uncertainties in the nuclear fuel cycle are found in Chapter 2. Also included in the second chapter are the physical descriptions of the different fuel cycles that will be utilized. Chapter 3 presents a quantitative examination of the elements of the reactor mix model, which is developed in Chapter 5. An economic measure of effectiveness is evaluated in Chapter 4 based upon the economic gain that is realized by the recycle of plutonium and spent uranium. Also included in the fifth chapter is the development of the MOX fuel blending model. Results of the optimization model are presented in Chapter 6 for the three reactor growth scenarios. Conclusions follow in Chapter 7 with summary and recomendations discussed in Chapter 8.

1.4 Results

A detailed discussion of the results is found in Chapter 6. Complete tabular and graphic results for the reactor mix model are included

in Appendix A. These results may serve as a foundation upon which economically effective management decisions can be made concerning the consumption of the natural uranium resources. The principal results of the study are as follows:

1. gaseous diffusion tails and natural uranium are preferable to spent uranium and enriched natural uranium in the production of MOX fuel,
2. the use of spent uranium instead of natural uranium slightly increases the cost of the MOX blend, but aids in the conservation of the natural uranium resource,
3. the use of MOX fuel in light water, self-generating reactors allows for a 29 to 34 percent savings of the natural uranium resource, and a 12 to 14 percent reduction in the required SWU as compared to the no recycle option,
4. the reactor mix shows a heavy dependence on self-generating reactors in order to minimize uranium consumption (e.g., 375 reactors out of 507 are self-generating reactors),
5. no plutonium burner reactors are used,
6. reprocessing and MOX fuel fabrication capacities projected by ERDA are low when considered in conjunction with projected nuclear demand and the optimal reactor mix to minimize uranium consumption,
7. other capacities, i.e., UO_2 fuel fabrication and enrichment services, are adequate to meet nuclear reactor demands.

2. BACKGROUND

2.1 Current Uncertainties in the U.S. Nuclear Fuel Cycle

Since the disclosure of President Carter's "seven decisions" concerning nuclear energy on April 17, 1977, the future of the industry is particularly uncertain. A decision was made to defer indefinitely the commercial reprocessing and recycling of plutonium produced in the U.S. nuclear power program. This decision reflects the Carter administration's view that the nuclear power program can be viably and economically sustained without such reprocessing and recycling.[7] Further hesitancy by the government to make decisions or committments on such issues as licensing and environmental requirements for each component of the nuclear industry will have adverse effects on the development of a healthy nuclear industry.

The supply of the uranium resource and the demand for reactor fuel do not exhibit a constant relationship. The ability to balance this relationship, while trying to conserve the uranium resource, depends on the availability and recovery efficiency of uranium and plutonium from the tail end processes, as well as the mining, milling, and enrichment capabilities on the front end of the fuel cycle.[5] Any delay, whether permanent or temporary, will affect the operation of the other components in the nuclear industry and ultimately the growth of the industry. Unless prompt and intelligent decisions concerning the tail end processes of the nuclear fuel cycle are made soon, the future of nuclear energy seems rather uncertain.

2.2 An Overview of the Nuclear Fuel Cycle

The nuclear fuel cycle consists of a series of processes which nuclear fuel must undergo in order to extract needed energy from the resource. The processes that are involved can be categorized into three main divisions: the front end, irradiation, and the tail or back end.[5] The following is a brief summary of each process necessary in taking nuclear fuel from uranium ore through the reactor irradiation phase, eventually ending with radioactive waste disposal and recycle. Figure 2.1 illustrates most of the steps involved in the various phases of the nuclear fuel cycle.

The front end of the fuel cycle consists of the processes necessary to produce fuel assemblies that can be used in a nuclear reactor. There are six basic steps involved in the front end phase: uranium exploration; uranium mining; the milling of natural uranium; the conversion of uranium from U_3O_8 to uranium hexafluoride (UF_6); the isotopic enrichment of Uranium-235; and the fabrication of fuel assemblies.

Uranium exploration and its subsequent mining and milling take place primarily in the western sections of the United States, principally the Colorado Plateau, the Wyoming Basins and the Southern Costal Plains.[8] The uranium ore, which occurs naturally, appears in host rocks, such as sandstone and conglomerate, in concentrations of 2 to 5 pounds per ton of ore.[5] The mining of uranium is much like the processes involved in mining coal. Once mined, the uranium ore is processed at a mill in which the host rock and other minerals are removed from the uranium ore by mechanical and chemical steps. The uranium value is recovered as

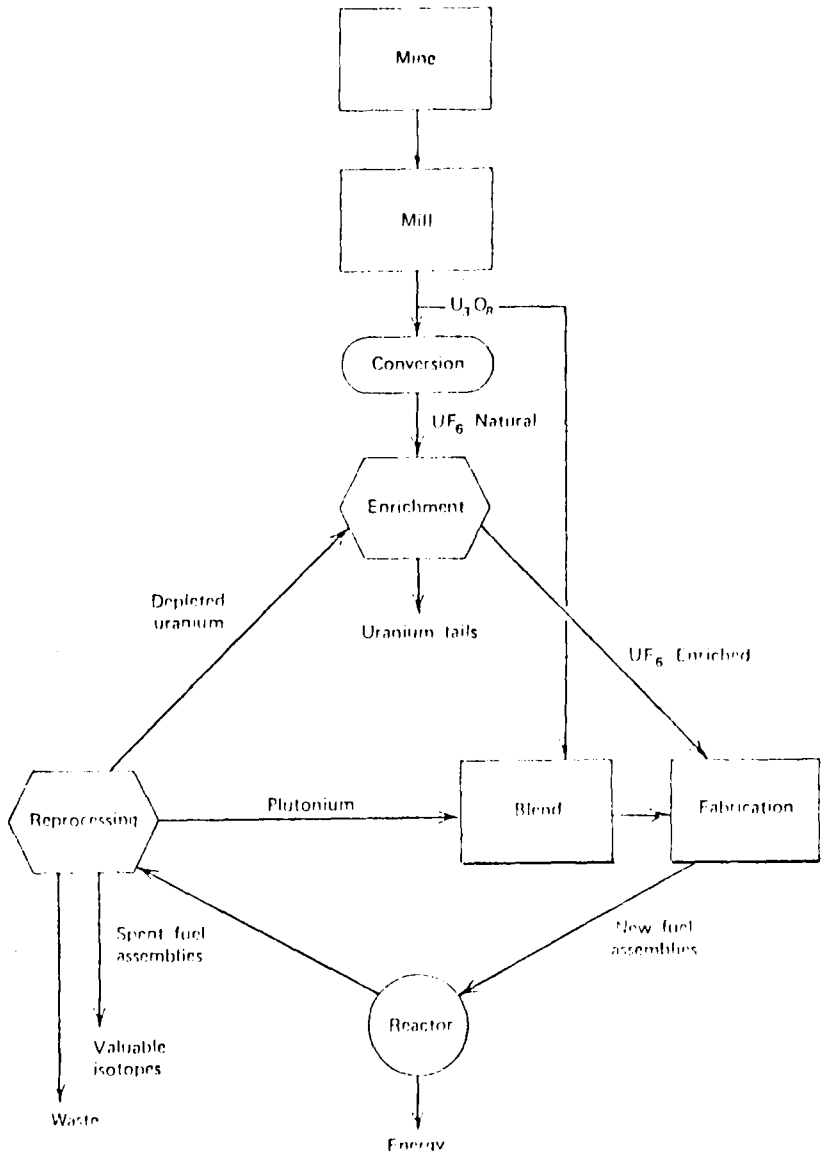

Figure 2.1. Nuclear Fuel Cycle[9]

yellowcake, a uranium salt containing approximately 70 to 80 percent U_3O_8.[5]

After milling, the uranium oxide (U_3O_8) is converted from a solid form to a gaseous form that is suitable for the enriching process, namely uranium hexafluoride (UF_6). This process utilizes three steps involving fluoride volatility and concludes with a high temperature fluoridation step.[5]

Following conversion to UF_6, the uranium compound is now ready for the enrichment process. Uranium found in nature contains approximately 0.7 percent Uranium-235, which is readily fissionable, and 99.3 percent Uranium-238. Since the fissile requirements of a reactor range from 2.5 to 4.0 percent, the Uranium-235 content of the UF_6 gas must be increased. As both isotopes react in the same chemical fashion, the gaseous diffusion process is employed. This process takes advantage of the differences in the physical weight of the two isotopes by making use of the differences in rates at which gases or vapors of different molecular weights diffuse through a porous barrier.[5] The porous barrier allows the lighter U-235 atoms to pass through, thus producing two output streams: a stream enriched in U-235 (enriched product) and a depleted stream (gaseous diffusion tails).

The final step in the front end of the fuel cycle is fuel fabrication. This process involves the chemical conversion of the enriched UF_6 into uranium dioxide (UO_2). This is then formed into pellets and inserted into rods that make up a fuel assembly. When this step is completed, the fuel assembly is ready for shipment to a nuclear reactor for irradiation.

The second major category in the nuclear fuel cycle is the irradiation phase. In this step, the fabricated fuel assemblies are placed in a reactor core where they remain for three to four years. During this time, energy is produced by the fissioning of U-235 and the fissile plutonium atoms which result from the neutronic absorption of U-238 atoms. As a result of the fissioning process, fission products are formed which must be removed before their disposal. For each kilogram of fuel, approximately 2000 million BTUs will be produced, resulting in the generation of 200,000 KWhe.[5] Also, at the end of a fuel assembly's life, appreciable amounts of U-235 and plutonium are left in the fuel which can be further used as fuel upon reprocessing the spent fuel.

The final phase, or tail end of the fuel cycle, consists of processes for dealing with spent fuel, such as disposal of radioactive wastes produced during irradiation, and the recovery of the unused uranium and plutonium residing in the spent fuel. Temporary fuel storage, transportation of spent fuel, reprocessing of spent fuel, and waste storage comprise the steps involved in the back end of the fuel cycle.

Once the fuel has reached its allowed burnup, (i.e. the maximum production of energy allowed per metric ton of fuel), it is removed from the reactor core and stored in a spent-fuel storage pool. This is to allow for the decay of after-heat and the radiation produced by the radioactive fission products that accumulate during the irradiation phase. This process usually requires several months, although the chief determinant of how long the fuel is to cool is based on the amount of Iodine-131 present in the fuel. Iodine-131 has a half-life of 8.14 days

and the decay of this element removes it as a problem in reprocessing.[5]

Upon cooling, the discharged spent fuel can be shipped from the power plant to the reprocessing facility. Here, residual uranium and plutonium are recovered and the radioactive fission products are concentrated for later disposal. The reprocessing of spent fuel is generally divided into three steps: the head-end treatment, separation or extraction, and product purification. The head-end treatment consists of removing the cladding from the fuel by dissolving the chopped fuel assemblies in nitric acid, discarding the cladding and grid structures. The most commonly preferred method for extracting uranium and plutonium is solvent extraction employing the Purex process. This process uses tributyl phosphate (TBP) dissolved in a kerosene-like hydrocarbon which acts as the separating agent.[10] By intimately forcing the organic TBP to flow countercurrent to the aqueous feed solution in an extraction column, the substances become more soluble in one solution than in the other and, therefore, can be separated effectively.

After the radioactive wastes are discharged from the reprocessing plant, they can be solidified into an insoluble, non-leachable form. Then, the solid wastes can be packaged and sent to a permanent disposal repository. Both the recovered uranium and plutonium can be recycled back into the nuclear fuel cycle. The recovered uranium can be re-enriched and used in the formation of other fuel elements. The recovered plutonium can be blended with uranium to produce MOX fuel elements.

In conclusion, uranium availability is the key factor which limits the use of domestic light water reactors.[11] Any process at either the

front or back end of the fuel cycle can limit the availability of uranium necessary for the production of energy. It is therefore imperative that the back end of the fuel cycle be closed in order to increase uranium supplies necessary for future energy needs.

2.3 Physical Description of Fuel Cycles

For the purpose of this study, three different fuel types (or cores) were chosen: an all UO_2 core, a self-generated plutonium recycle core, and a PuO_2 core. A typical Pressurized Water Reactor (PWR) and a typical Boiling Water Reactor (BWR) were chosen, both of which have the capability of utilizing each of the three fuel types. This effectively results in six types of reactors. The fuel cycles associated with each of the three fuel types will be discussed in more detail in the following sections.

2.3.1 The UO_2 Fuel Cycle

Since reprocessing has been discontinued in the United States, the nuclear industry is totally comprised of UO_2 light water reactors (UO_2-LWR). Presently there are sixty commercial operating reactors within the United States, ranging in capacity from 48 to 1130 MWe. Of these reactors, 25 are BWRs and 35 are PWRs.[12] The LWR's use fuel in which natural uranium is enriched from 0.7 percent U-235 to between 2.5 and 4.0 percent. The balance of the fuel is comprised of relatively non-fissionable U-238.

A nuclear reactor which contains U-238 in the fuel will produce plutonium as a byproduct of the neutron chain reaction. Two of the

most important fissile isotopes of plutonium are Plutonium-239 (Pu-239) and Plutonium-241 (Pu-241). Plutonium is formed when a U-238 nucleus absorbs a neutron, which transforms it into Neptunium-239 and finally beta decays into Pu-239. Other isotopes, such as Plutonium-240 (Pu-240), Plutonium-241 (Pu-241), and Plutonium-242 (Pu-242) are produced by further neutron absorption. Once formed, plutonium contributes to the fission process, thereby producing neutrons and heat.

Generally more than half of the plutonium produced in the UO_2 reactors subsequently fissions in place. Just before the time of discharge, more than half of the fissions occurring in the fuel are fissions of plutonium rather than uranium.[13] Thus the UO_2 reactors produce plutonium, some of which is consumed without external recycle.

At best, a nuclear power reactor can extract only about 2 per cent of the energy theoretically available from the uranium fuel. Since the energy yield is lower than that which is actually available, the reactor must be refueled periodically. Current reactors operate on a cycle in which portions of the core are replaced annually. It is assumed that a BWR discharges one-fourth of its core annually, while a PWR discharges one-third of its core annually.[13] The difference between the two reactors is attributed to core designs and operating characteristics of each.

Table 2.1 lists the fuel requirements for both a BWR and a PWR UO_2 reactor.[14] These fuel characteristics are based upon a reactor in which the design characteristics limit the electrical power production to 1000 MWe. Also affecting these fuel characteristics is the assumption that the reactor operates at the maximum 1000 MWe for 75

Table 2.1. UO_2-LWR Fuel and Discharge Characteristics[14]

Type	PWR	BWR
Power Rating (MWe)	1000	1000
Annual Discharge	1/3 Core	1/4 Core
Capacity Factor (%)	75.0	75.0
Initial Core		
Average Irradiation Level (MWd/MTU)	22600	17000
Amount of Fresh Fuel (kg-U)	76380	117200
Fresh Fuel Assay (wt % U-235)	2.26	2.03
Spent Fuel Assay (wt % U-235)	0.74	0.86
Equilibrium Core Reload		
Average Irradiation Level (MWd/MTU)	32600	27500
Amount of Fresh Fuel (kg-U)	25460	29300
Fresh Fuel Assay (wt % U-235)	3.21	2.73
Amount of Spent Fuel (kg-U)	24300	28200
Spent Fuel Assay (wt % U-235)	0.90	0.84
Amount of Fissile Pu Discharged (kg-Pu)	167.0	163.0

percent of the power production period.

Table 2.2 represents the isotopic composition of the plutonium at the time of discharge assuming a burnup of 27000 MWd/MTU.[13] This composition remains constant as long as no plutonium is recycled back into the reactor for further irradiation.

The fuel cycle associated with an all UO_2 reactor industry can include several different options. First, a no recycle option in which neither plutonium nor uranium are recycled. This will eliminate the necessity of reprocessing plants as outlined in section 2.2. The front-end and irradiation phases will remain the same, but the back-end phase will consist only of temporary spent-fuel storage, spent-fuel transportation and permanent disposal of spent fuel. As reprocessing is currently not a permitted option, the final disposal of spent fuel will be in the form of fuel assemblies.

Second, the spent fuel can be reprocessed and the recovered uranium can be recycled, with plutonium being put either in storage or in permanent disposal. Again, the front-end and the irradiation phases remain the same, but the back end becomes more involved. Reprocessing the spent fuel, conversion of the recovered uranium to UF_6, re-enrichment of the recovered uranium to produce an enriched product, and high level and transuranic waste storage and disposal are the operations that must be added to accommodate uranium recycle.

2.3.2 The SGR Fuel Cycle

When plutonium produced in a LWR is recovered, recombined with uranium, fabricated into fuel rods and reinserted into the same LWR

Table 2.2. Isotopic Content of Plutonium for UO_2-LWRs[13]

Equilibrium Core Discharge

Isotope	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Total Fissile
wt %	1.9	57.9	24.7	11.0	4.4	68.9

core, thereby displacing an equivalent number of U-235 enriched fuel rods, the resulting reactor can be described as a self-generating reactor (SGR).[13] The SGR recycles all fissile and nonfissile plutonium that it produces. The mixed oxide content in the reactor will continue to increase with time until an equilibrium condition is reached wherein about one-fourth of the core contains mixed oxide (MOX) fuel rods. At this point, the reactor is described as an equilibrium SGR.

Plutonium that is recovered from the spent fuel can be recombined with uranium having a lower U-235 content than that of fresh uranium fuel, which normally contains about 3.0 percent U-235, to make an equivalent reactor fuel. Therefore, the plutonium replaces some of the U-235 content in the fuel. This fuel is known as a mixed oxide fuel. This constitutes plutonium recycle. Since plutonium is predominately mixed with U-238 to form the MOX fuel, the uranium content of the fuel can be derived from low enriched product from the enrichment plant, recovered uranium from spent fuel, virgin natural uranium, or depleted uranium enrichment tails. The exact material that is to be mixed with the plutonium is to be determined so as to minimize the total fuel cost associated with the SGR.

The fuel cycle components associated with the SGR fuel cycle are similar to the UO_2 fuel cycle, but with plutonium recycle, two new processes are added to the fuel cycle. The reprocessing step is either added or modified to separate both uranium and plutonium from the spent fuel. First, the recovered plutonium must be converted into a solid form, namely plutonium dioxide (PuO_2). Then the PuO_2 is combined with UO_2, fabricated into ceramic fuel cylinders, encapsulated in fuel rods and

grouped into a fuel assembly. This step is commonly referred to as MOX fuel fabrication.

As stressed in the GESMO study[13], the introduction of MOX fuel produces only minor effects on reactor operations. Characteristics of the reactor design, such as fuel assembly geometry, coolant flow patterns and mechanical properties of the cladding and structural members are unchanged by the introduction of MOX fuel into the reactor. Although the nuclear properties of the MOX fuel differ somewhat from UO_2 fuel, the differences can be compensated for with proper core management.

Typical fuel characteristics are indicated in Table 2.3 for both a BWR and a PWR self-generating reactor operating under the same conditions as the UO_2 fuel cycle reactors. Table 2.4 represents the isotopic composition of plutonium for both the initial discharge of the spent fuel as well as the discharge under equilibrium conditions, assuming a burnup of 27000 MWd/MTU and 33000 MWd/MTU respectively.[14] Note that the initial discharge from the SGR has the same plutonium composition as the UO_2 reactor (using Table 2.2). This is because a SGR reactor begins as a UO_2 reactor and then becomes a SGR. This is also a part of the definition of a SGR.

2.3.3 The PuO_2 Fuel Cycle

The PuO_2 reactor, commonly referred to as a plutonium burner or an all plutonium-fueled reactor (APR), is defined to be a reactor which utilizes plutonium as the sole fissile addition to the natural or depleted uranium, which comprises the greater part of the fuel mass.[15]

Table 2.3. SGR-LWR Fuel and Discharge Characteristics[14]

Type	PWR	BWR
Power Rating (MWe)	1000	1000
Annual Discharge	1/3 Core	1/4 Core
Capacity Factor (%)	75.0	75.0
Equilibrium Core Reload		
Average Irradiation Level (MWd/MTU)	32600	27500
Amount of Fresh Fuel (kg-HM)	25460	29300
Percent of MOX Fuel (%)	25.0	25.0
Fresh Fuel Assay (wt % Fissile)	2.80	2.39
Amount of Fissile Pu Charged (kg-Pu)	167.0	163.0
Amount of Spent Fuel (kg-HM)	24300	28200
Spent Fuel Assay (wt % U-235)	0.90	0.84
Amount of Fissile Pu Discharged (kg-Pu)	167.0	163.0

Table 2.4. Isotopic Content of Plutonium for SGR-LWRs[13]

Isotope	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Total Fissile
wt %*	1.9	57.9	24.7	11.0	4.4	68.9
wt %**	3.4	41.7	29.2	15.2	10.4	57.0

Note: *for initial core discharge

Note: **for equilibrium core discharge

A plutonium burner utilizes plutonium generated from its own operation and from previous operating cycles of other uranium burning reactors.

The fuel characteristics of the PWR and BWR plutonium burners used in the development of this study are given in Table 2.5. The PWR fuel characteristics are based upon the same operating conditions as the PWR-SGR, while the BWR fuel characteristics are based upon a reactor that is designed to produce the maximum 1000 MW of electricity for 80 percent of the power production period. Table 2.6 represents the isotopic composition of plutonium for both the initial discharge of spent fuel as well as the discharge under equilibrium conditions, assuming the burnups given in Table 2.5. It is assumed that these reactors are operated as plutonium burners from startup, i.e. the initial core as well as sequential core loadings are comprised of MOX fuel. As the initial core loading requires roughly three times as much plutonium as is required for a reload, the startup of a new APR places a very high demand on plutonium production and fabricating capacity. Therefore, this will limit the possible rate of introduction of the APRs.

The fuel cycle components are very similar to the SGR fuel cycle. Since natural uranium or gaseous diffusion tails are used with the plutonium to produce the MOX fuel, the necessity of enrichment services is eliminated. This, of course, assumes that there is a large stockpile of gaseous diffusion tails available for use in the BWR-APRs. All other phases, irradiation and back end phases, remain the same as the SGR fuel cycle.

The PWR-APR is a Combustion Engineering System 80^{TM}[15] nuclear reactor and the BWR-APR is a General Electric BWR/6[16] nuclear reactor.

Table 2.5. PuO_2-LWR Fuel and Discharge Characteristics[15,16]

Type	PWR	BWR
Power Rating (MWe)	1000	1000
Annual Discharge	1/3 Core	1/4 Core
Capacity Factor (%)	75.0	75.0
Initial Core		
Average Irradiation Level (MWd/MTHM)	13200	-
Amount of Fresh Fuel (kg-HM)	102000	124000
Percent of MOX Fuel (%)	100.0	100.0
Fresh Fuel Assay (wt % Fissile)	5.40	4.30
Amount of Fissile Pu Charged (kg-Pu)	4280	5024
Equilibrium Core Reload		
Average Irradiation Level (MWd/MTHM)	34200	27718
Amount of Fresh Fuel (kg-HM)	30000	31000
Percent of MOX Fuel (%)	100.0	100.0
Fresh Fuel Assay (wt % Fissile)	5.40	4.30
Amount of Fissile Pu Charged (kg-Pu)	1427	1256
Amount of Spent Fuel (kg-HM)	26833	29588
Spent Fuel Assay (wt % U-235)	0.003	0.001
Amount of Fissile Pu Discharged (kg-Pu)	1276	862

Table 2.6. Isotopic Content of Plutonium for PuO_2-LWRs[15,16]

Isotope	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242	Total Fissile
For PWR:						
wt %*	-	-	-	-	-	62.4
wt %**	-	-	-	-	-	48.9
For BWR:						
wt %*	1.5	58.8	25.5	10.5	3.7	69.2
wt %**	2.4	45.0	32.6	14.4	5.6	59.4

Note: *for initial core discharge

Note: **for equilibrium core discharge

The diluent for the PWR consists of natural uranium, while gaseous diffusion tails are used for the BWR.

3. QUANTITATIVE EXAMINATION OF THE ELEMENTS OF THE REACTOR MIX PROBLEM

In this chapter, the principal elements of the reactor mix problem are examined in detail. A background is given on LWR growth projections, reprocessing and enrichment capacity forecasts, and fuel fabrication capability forecasts. Also discussed in this chapter are cost projections for separative work units (SWU), natural uranium feed, and the cost of gaseous diffusion tails. Chapter 4 complements the analysis presented in this chapter by discussing the value of uranium and plutonium residing in spent fuel. On the basis of this quantitative examination, a reactor mix model is developed, as presented in Chapter 5.

3.1 LWR Growth Projections

In the past, the electrical power generating industry has grown at an average annual rate of 7 percent, representing a doubling time of 10 years.[3] This is largely due to an increasing population and a rising per capita consumption of electricity. Due to energy conservation and a decrease in the population growth rate, the consumption of electricity is expected to increase at 5.8 percent per annum through 1985 and then decline to 4.75 percent per annum through the year 2000.[13] This varies slightly from the projections reported in a 1976 study by Hanrahan.[3]

In 1975, about 8.6 percent of the electricity consumed in the U.S. came from nuclear power plants.[2] As of March 1, 1977, 60 commercial LWRs, with a total generating capacity of 42,571 MWe, had been completed and licensed to operate. In addition to these, 147 LWR plants are on

order or under construction. This represents an additional 105 PWRs and 42 BWRs producing 160,317 MWe of electrical generating capacity.[12] Projections established by the U.S. Energy Research and Development Administration (ERDA) conclude that a low growth of nuclear generating capacity will be most likely through the year 2000. The industry will be composed solely of LWRs without the influence of the fast breeder program. The ERDA forecast specifically projects an installed nuclear capacity of 156,000 MWe in 1985 and 507,000 MWe in the year 2000.[14] Table 3.1 (MID case) represents this projected LWR growth by reactor type. As concluded by ERDA, the projections for nuclear energy presumes that in the short term, nuclear power plants continue to be delayed by numerous problems, thus creating slippages in construction. During the long term, high capital cost and long lead times are expected to limit the installed LWR nuclear capacity to about 33 percent of the total generating capacity in the year 2000.[14] Tables 3.2 and 3.3 represent lower and higher growth rates of nuclear power LWRs than originally assumed. This data provides a basis for sensitivity analysis. Figure 3.1 provides a graphic comparison of all three growth rates. This is to provide insight into the reactor mix problem.

3.2 Reprocessing Capability Forecast

At the present time, there are no commercial reprocessing plants operating in the United States. Due to uncertainties in regulatory requirements and the present policy of the U.S. Government, the implementation of technology necessary in closing the fuel cycle has been, for the most part, indefinitely delayed. If the fuel cycle is closed, three

Table 3.1. Nuclear Reactor Schedule - MID Case[14]

Year	Total Capacity* (GWe)	BWR Capacity* (GWe)	PWR Capacity* (GWe)
1976	43.00	17.00	26.00
1977	51.00	18.00	33.00
1978	57.00	18.00	39.00
1979	62.00	19.00	43.00
1980	70.00	22.00	48.00
1981	80.00	26.00	54.00
1982	100.00	34.00	66.00
1983	117.00	40.00	77.00
1984	135.00	47.00	88.00
1985	156.00	53.00	103.00
1986	179.00	62.00	117.00
1987	201.00	70.00	131.00
1988	222.00	76.00	146.00
1989	245.00	82.00	163.00
1990	268.00	90.00	178.00
1991	293.00	98.00	195.00
1992	320.00	107.00	213.00
1993	345.00	115.00	230.00
1994	372.00	124.00	248.00
1995	399.00	133.00	266.00
1996	424.00	141.00	283.00
1997	447.00	149.00	298.00
1998	468.00	156.00	312.00
1999	488.00	163.00	325.00
2000	507.00	169.00	338.00

Note: *Based on equivalent number of 1000 MWe reactors.

Table 3.2. Nuclear Reactor Schedule - LOW Case[14]

Year	Total Capacity* (GWe)	BWR Capacity* (GWe)	PWR Capacity* (GWe)
1976	42.00	17.00	25.00
1977	47.00	17.00	30.00
1978	52.00	17.00	35.00
1979	59.00	19.00	40.00
1980	66.00	21.00	45.00
1981	79.00	26.00	53.00
1982	89.00	30.00	59.00
1983	104.00	36.00	68.00
1984	116.00	40.00	76.00
1985	136.00	46.00	90.00
1986	161.00	56.00	105.00
1987	181.00	63.00	118.00
1988	196.00	67.00	129.00
1989	214.00	72.00	142.00
1990	230.00	77.00	153.00
1991	248.00	83.00	165.00
1992	269.00	90.00	179.00
1993	289.00	96.00	193.00
1994	309.00	103.00	206.00
1995	332.00	111.00	221.00
1996	350.00	116.00	234.00
1997	365.00	122.00	243.00
1998	378.00	126.00	252.00
1999	390.00	130.00	260.00
2000	400.00	133.00	267.00

Note: *Based on equivalent number of 1000 MWe reactors.

Table 3.3. Nuclear Reactor Schedule - HIGH Case[14]

Year	Total Capacity* (GWe)	BWR Capacity* (GWe)	PWR Capacity* (GWe)
1976	45.00	18.00	27.00
1977	51.00	18.00	33.00
1978	57.00	18.00	39.00
1979	64.00	20.00	44.00
1980	74.00	23.00	51.00
1981	82.00	27.00	55.00
1982	109.00	37.00	72.00
1983	129.00	44.00	85.00
1984	151.00	52.00	99.00
1985	172.00	58.00	114.00
1986	195.00	67.00	128.00
1987	218.00	76.00	142.00
1988	245.00	84.00	161.00
1989	273.00	91.00	182.00
1990	302.00	101.00	201.00
1991	333.00	111.00	222.00
1992	364.00	122.00	242.00
1993	396.00	132.00	264.00
1994	428.00	143.00	285.00
1995	459.00	153.00	306.00
1996	489.00	163.00	326.00
1997	518.00	173.00	345.00
1998	547.00	182.00	365.00
1999	574.00	192.00	382.00
2000	600.00	200.00	400.00

Note: *Based on equivalent number of 1000 MWe reactors.

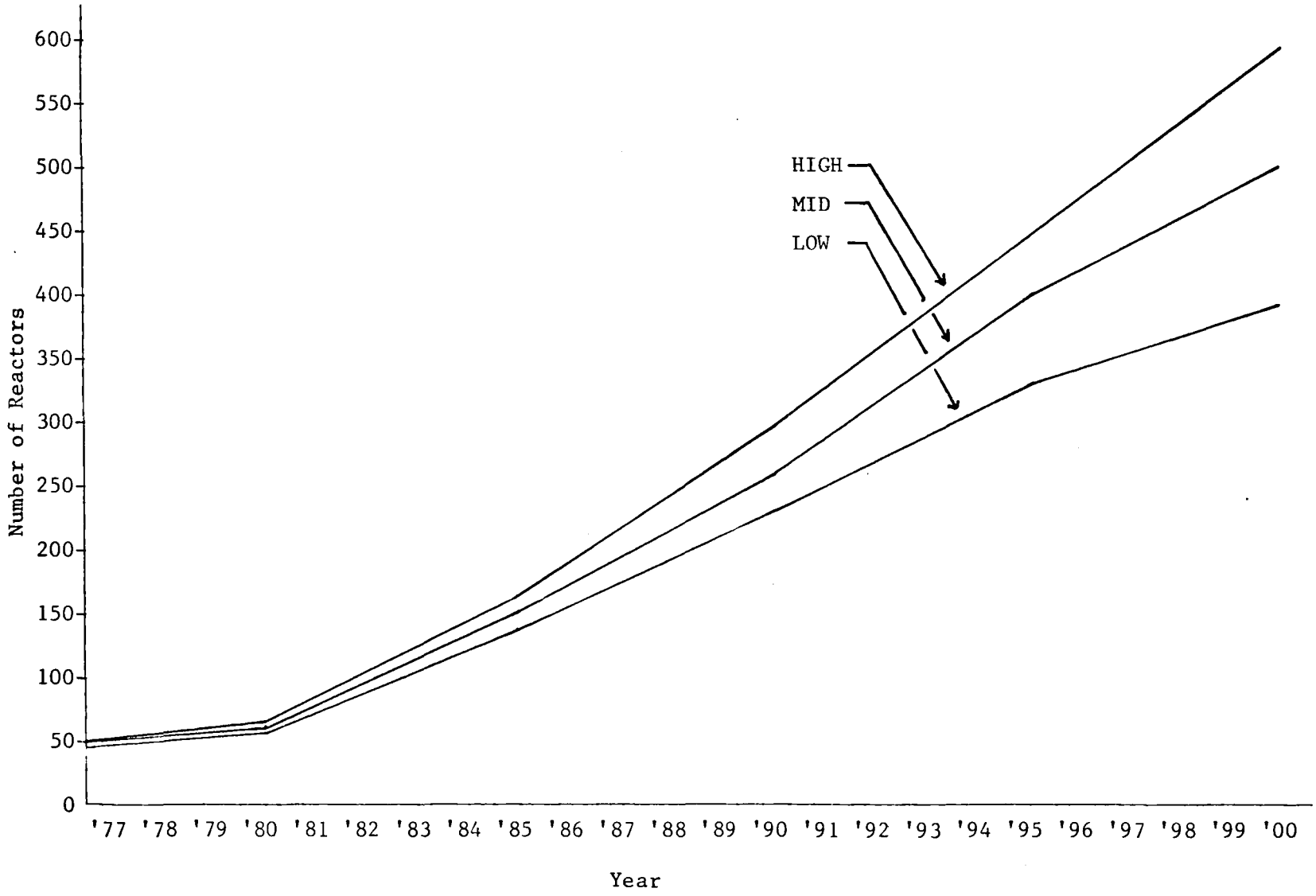

Figure 3.1. Nuclear Reactor Growth Projections

benefits from the reprocessing of spent fuel and the recycling of uranium and plutonium will be realized. Firstly, the ability to recycle uranium and plutonium would increase the effective amount of the uranium resource and allow for a longer availability of natural uranium. This increases the energy available from the uranium resource. Secondly, there would be a reduction in the cost of nuclear power, as compared to an industry with no recycle.[6] Finally, there would be an easing of the problem of radioactive waste disposal.[13]

The first plant built to reprocess commercial light water reactor spent fuel was the West Valley, New York plant, operated by Nuclear Fuel Services, Inc. From 1966 to 1972, the company reprocessed some 630 metric tons of spent fuel with irradiation exposures of up to 32,000 MWd/MTU. In 1972, the plant was closed in order to modify the reprocessing capacity and efficiency from 300 MT of spent fuel per year to 750 MT per year. As extensive modifications were planned for the plant, the then Atomic Energy Commission (AEC) decided that a new construction permit and operating license would be required. From last report, the estimated costs of the continually increasingly extensive modifications had risen from $15 million to $600 million, and Nuclear Fuel Services had withdrawn its application to the Nuclear Regulatory Commision (NRC) for permission to reopen the plant.[17]

A second plant, located at Morris, Illinois, was constructed by General Electric Company, Inc. The Midwest Reprocessing Plant ran into serious technical difficulties, prior to startup, with an innovative wet-dry process. The plant was originally designed with a 300 MT per year capacity, but in 1974 was declared "inoperable in its present form"

due to problems in handling fine radioactive solids.[10, 17, 18]

In 1968, the Allied General Nuclear Services announced plans to build the Barnwell Nuclear Fuel Plant in Barnwell, South Carolina. Construction began on the 1500 MT per year (5 MT per day) facility in 1971 and is now complete.[17] Full operation of the plant is pending decisions by the NRC and ERDA on two "tail end" facilities, plutonium conversion and waste solidification, that might be necessary before the plant can begin operating. At present, the Allied General request for an operating license is in jeopardy. Additional problems have also arisen due to the current moratorium on reprocessing.

A fourth plant, to be built by Exxon Nuclear Company, Inc., will be located at Oak Ridge, Tennessee. The plant is designed to have a 1500 MT per year capacity. Construction of the plant is awaiting final approval from the NRC.[13]

Although the future reflects a great deal of uncertainty with regard to spent fuel reprocessing, many feel that reprocessing is inevitable. ERDA assumes that AGNS will begin reprocessing in 1982, followed by Exxon Nuclear in 1986. Table 3.4 reflects the projected growth of reprocessing plants for the three scenarios. New plants are assumed to operate at 40 percent capacity the first year, 67 percent capacity the second year, and 100 percent capacity thereafter.[14]

A 1975 study by Voltin and Draper estimated that the real cost of reprocessing would increase 1.9 percent annually.[19] Assuming that the cost of reprocessing is $200 per kgU in 1976[5], at a modest inflation rate of 6 percent per year, the cost of reprocessing will be $396.48 per kgU in 1985 and $1240.35 per kgU by the year 2000. Table 3.5

Table 3.4. Reprocessing Capacity Schedules[14]

Total Capacity - MTU/yr

Year	MID Case	LOW Case	HIGH Case
1976	0	0	0
1977	0	0	0
1978	0	0	0
1979	0	0	0
1980	0	0	0
1981	600*	600*	600*
1982	1,000	1,000	1,000
1983	1,500	1,500	1,500
1984	1,500	1,500	1,500
1985	1,500	1,500	1,500
1986	2,100*	2,100*	2,100*
1987	3,100*	3,100*	3,100*
1988	4,600*	4,600*	4,600*
1989	6,100*	5,500	6,100*
1990	7,600*	6,000	7,600*
1991	8,500	6,600*	8,500
1992	9,000	7,000	9,000
1993	9,000	7,500	9,600*
1994	10,000*	8,100*	10,000
1995	10,500	8,500	10,500
1996	10,500	9,000	11,100*
1997	10,500	9,000	11,500
1998	10,500	9,000	12,000
1999	10,500	9,000	12,600*
2000	10,500	9,000	13,000

Note: *Indicates startup of new reprocessing plant.

Table 3.5. Reprocessing Cost Projection[5,19]

Year	Cost $/kg-U	Year	Cost $/kg-U
1976	215.80	1989	579.87
1977	232.85	1990	625.68
1978	251.24	1991	675.11
1979	271.09	1992	728.44
1980	292.51	1993	785.99
1981	315.62	1994	848.08
1982	340.55	1995	915.08
1983	367.45	1996	987.37
1984	396.48	1997	1065.37
1985	427.80	1998	1149.54
1986	461.60	1999	1240.35
1987	498.07	2000	1338.34
1988	537.41		

summarizes the estimated cost of reprocessing through the year 2000.

3.3 Enrichment Capability Forecast

At the present time, all of the enrichment services for the U.S. nuclear industry are provided by three government-owned and contractor-operated gaseous diffusion plants (GDP). The facilities at Oak Ridge, Tennessee, and at Puducah, Kentucky are operated by Union Carbide Corp., Nuclear Division, and the plant at Portsmouth, Ohio is operated by Goodyear Atomic Corp.[13]

The federal government is currently engaged in modifying and upgrading the three gaseous diffusion plants to increase their capacity to produce enriched uranium necessary for use in nuclear reactors. The capacity increases will be achieved in two phases: The Cascade Improvement Program (CIP) and the Cascade Uprating Program (CUP). These will result in about a 60 percent increase in the productive capacity to yield an annual capacity of 27.7 million SWU per year by 1981. Presently, the three facilities operate at a production level of 17.2 million SWU per year.[13]

In the 1976 GESMO report, it was stated that the demand for enriched uranium will exceed production capabilities in the first half of the 1980's. In order to avoid a shortage, additional model plants of 9 million SWU per year capacity must be available in the 1980's. With plutonium and uranium recycle, it is anticipated that the total demand for seperative work in the year 2000 will be 91 million SWU in ten enrichment plants.[14] The additional industry requirements may be met by expanding the existing gaseous diffusion plants, by constructing

additional GDPs, by installing gas centrifuge facilities, or by any combination of these approaches. Table 3.6 represents a projected schedule of separative capacity through the year 2000 for the three scenarios.

The cost of enriching uranium is measured in terms of a unit called a separative work unit (SWU). The various components necessary in computing a SWU cost include electrical power costs, operation costs, plant test programs, and depreciation.[20]

The Voltin and Draper study estimates that the real price per SWU for fixed-committment contracts will increase 1.4 percent annually.[19] Recently, however, ERDA has announced that the price of SWU, for a fixed-committment contract, will increase from its present cost of $61.30 to $74.85 per SWU, effective November 29, 1977. This represents a 22.10 percent increase. Similarly, for requirement contracts, the cost will increase from its present value of $69.80 to $83.15 on March 29, 1978. This represents an increase of 19.13 percent. The increase in SWU prices has resulted from increased electrical costs, costs for advanced technology, and costs for construction projects.[21] Tables 3.7 and 3.8 represent current and predicted SWU and natural feed costs, as estimated by the Tennessee Valley Authority.[22] Cost projections for SWU are very dependent on the erratic behavior of the various cost components, making the projections more susceptible to sudden and substantial changes.

Table 3.9 represents a subjective cost projection for obtaining gaseous diffusion tails produced by the enrichment plant. In a study by Fennern[23] it was estimated that the cost of obtaining 1 kg of gas-

Table 3.6. Enrichment Capacity Schedules[14]

Total Capacity - Million SWU/yr

Year	MID Case	LOW Case	HIGH Case
1976	16.0	16.0	16.0
1977	18.0	18.0	18.0
1978	20.0	20.0	20.0
1979	22.0	22.0	22.0
1980	23.0	23.0	23.0
1981	23.0	23.0	23.0
1982	23.0	23.0	23.0
1983	24.0	24.0	24.0
1984	24.0	24.0	24.0
1985	28.0	28.0	28.0*
1986	37.0*	28.0	37.0*
1987	37.0	37.0*	46.0*
1988	37.0	37.0	46.0
1989	46.0*	37.0	46.0
1990	46.0	46.0*	55.0*
1991	46.0	46.0	55.0
1992	55.0*	46.0	64.0*
1993	55.0	55.0*	64.0
1994	64.0*	55.0	73.0*
1995	73.0*	64.0*	82.0*
1996	82.0*	64.0	82.0
1997	82.0	73.0*	91.0*
1998	91.0*	73.0	91.0
1999	91.0	82.0*	100.0*
2000	91.0	82.0	100.0

Note: *Indicates startup of new enrichment plant.

Table 3.7. Separative Work Cost Projection[22]

Year	SWU Cost $/SWU	Year	SWU Cost $/SWU
1976	63.00	1989	153.00
1977	71.00	1990	155.00
1978	77.00	1991	157.00
1979	81.00	1992	160.00
1980	85.00	1993	162.00
1981	99.00	1994	164.00
1982	114.00	1995	167.00
1983	129.00	1996	169.00
1984	143.00	1997	172.00
1985	145.00	1998	175.00
1986	147.00	1999	177.00
1987	149.00	2000	175.00
1988	151.00		

Table 3.8. Uranium Feed Cost Projection[22]

Year	Feed Cost $/kg-$UF_6$	Year	Feed Cost $/kg-$UF_6$
1976	62.00	1989	170.00
1977	68.00	1990	192.00
1978	77.00	1991	216.00
1979	88.00	1992	236.00
1980	99.00	1993	251.00
1981	106.00	1994	262.00
1982	112.00	1995	273.00
1983	115.00	1996	284.00
1984	119.00	1997	295.00
1985	126.00	1998	309.00
1986	130.00	1999	322.00
1987	141.00	2000	335.00
1988	154.00		

Table 3.9. Gaseous Diffusion Tails Cost Projection[23]

Year	Cost $/kgU	Year	Cost $/kgU
1976	3.00	1989	10.34
1977	3.30	1990	11.37
1978	3.63	1991	12.51
1979	3.99	1992	13.76
1980	4.39	1993	15.14
1981	4.83	1994	16.65
1982	5.31	1995	18.32
1983	5.84	1996	20.15
1984	6.42	1997	22.17
1985	7.06	1998	24.39
1986	7.77	1999	26.83
1987	8.55	2000	29.51
1988	9.40		

eous diffusion tails in 1974 was $2.50. Assuming a 10 percent annual increase in the price of gaseous diffusion tails, the cost is expected to be $6.48 in 1985, increasing to $27.09 in the year 2000. The major component influencing the increasing cost of gaseous diffusion tails is the rising cost of storage and transportation of the depleted uranium.

Figures 3.2, 3.3, and 3.4 present a graphic view of the increasing costs associated with SWU, natural uranium, and gaseous diffusion tails.

3.4 Fuel Fabrication Capacity Forecast

3.4.1 UO_2 Fabrication Capacity Forecast

The feed material used in the fabrication of fuel for LWRs is uranium hexafluoride (UF_6) that has been enriched to about 2 to 4 percent in the U-235 isotope at the enrichment plant. The enriched UF_6 gas is converted to UO_2 powder, which is then formed into pellets, sintered, and then loaded and sealed into Zircaloy or stainless steel tubes.

Currently, two types of conversion processes are used to convert UF_6 gas to UO_2 powder. In one process, UF_6 is reacted with water and ammonia to yield a precipitate of ammonium diuranate and large volumes of liquid effluents. This method is usually called the wet ammonium diuranate process. In the other process, often referred to as the dry conversion process or direct conversion, UF_6 is reacted with steam and hydrogen to yield UO_2 powder. The latter process, when fully developed, will produce lower volumes of effluents containing less pollutants than the first process.[13]

At the present time, the UO_2 fuel fabrication industry consists of

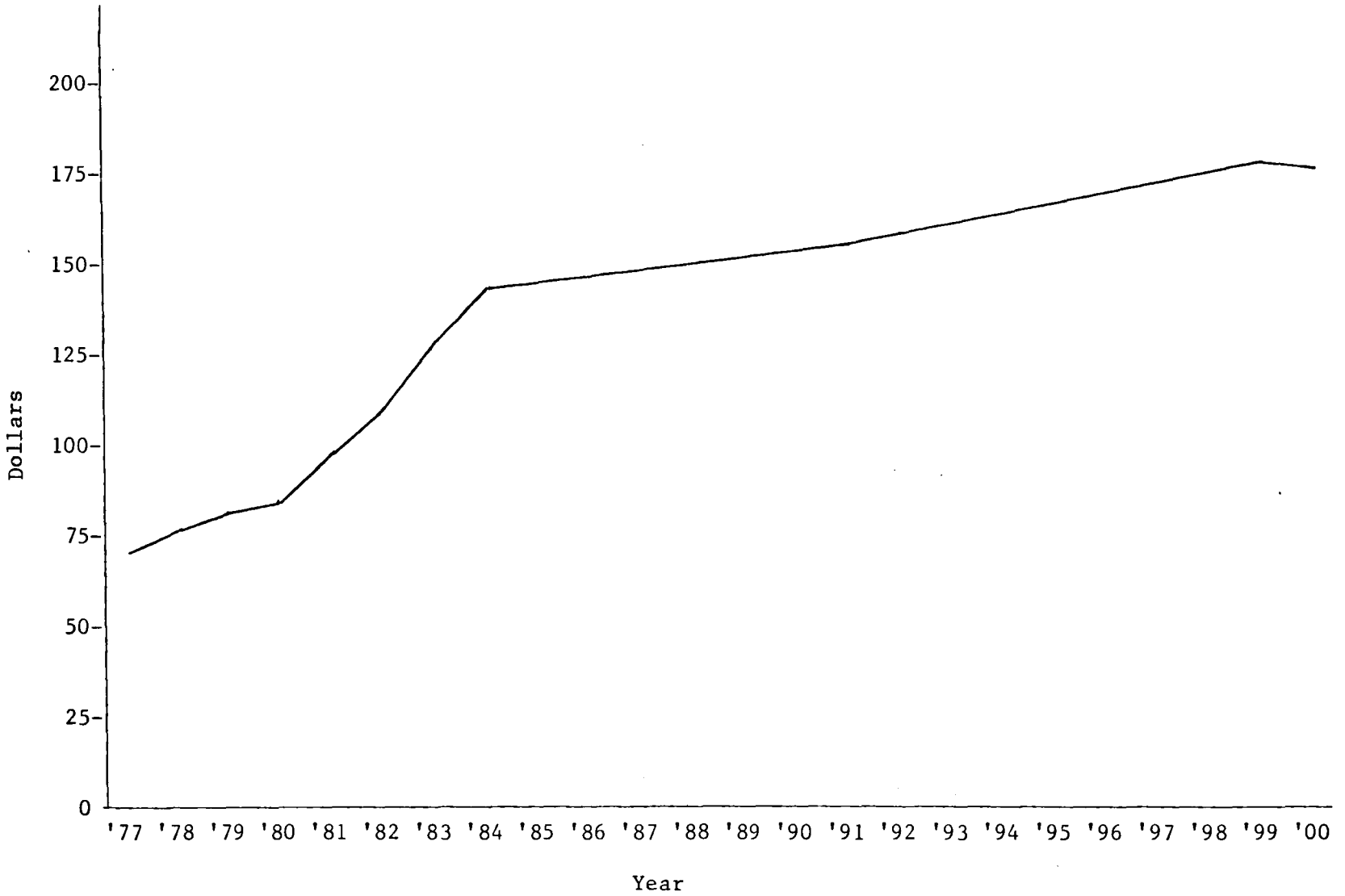

Figure 3.2. SWU Cost Projections

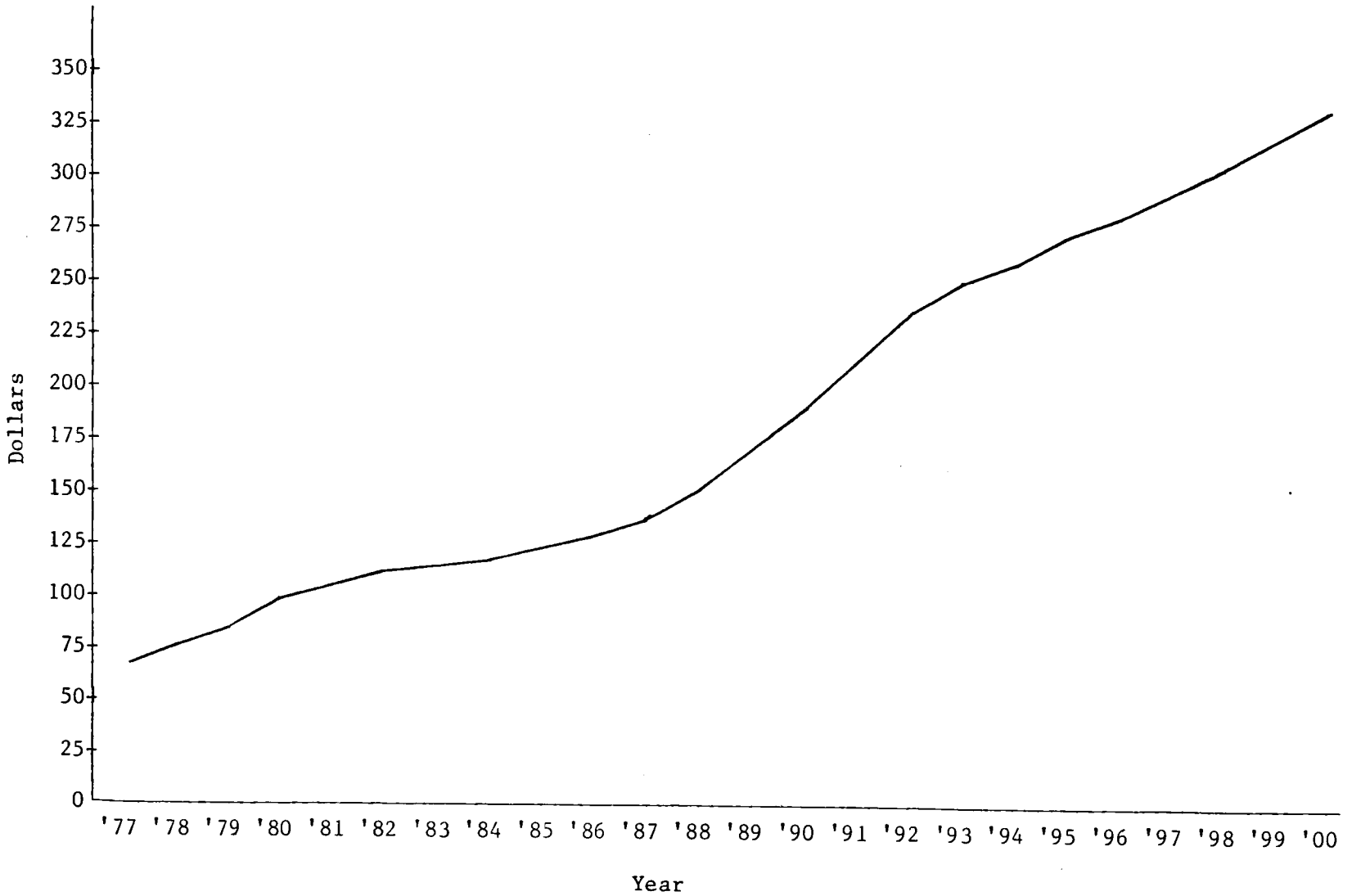

Figure 3.3. Natural Uranium Cost Projections

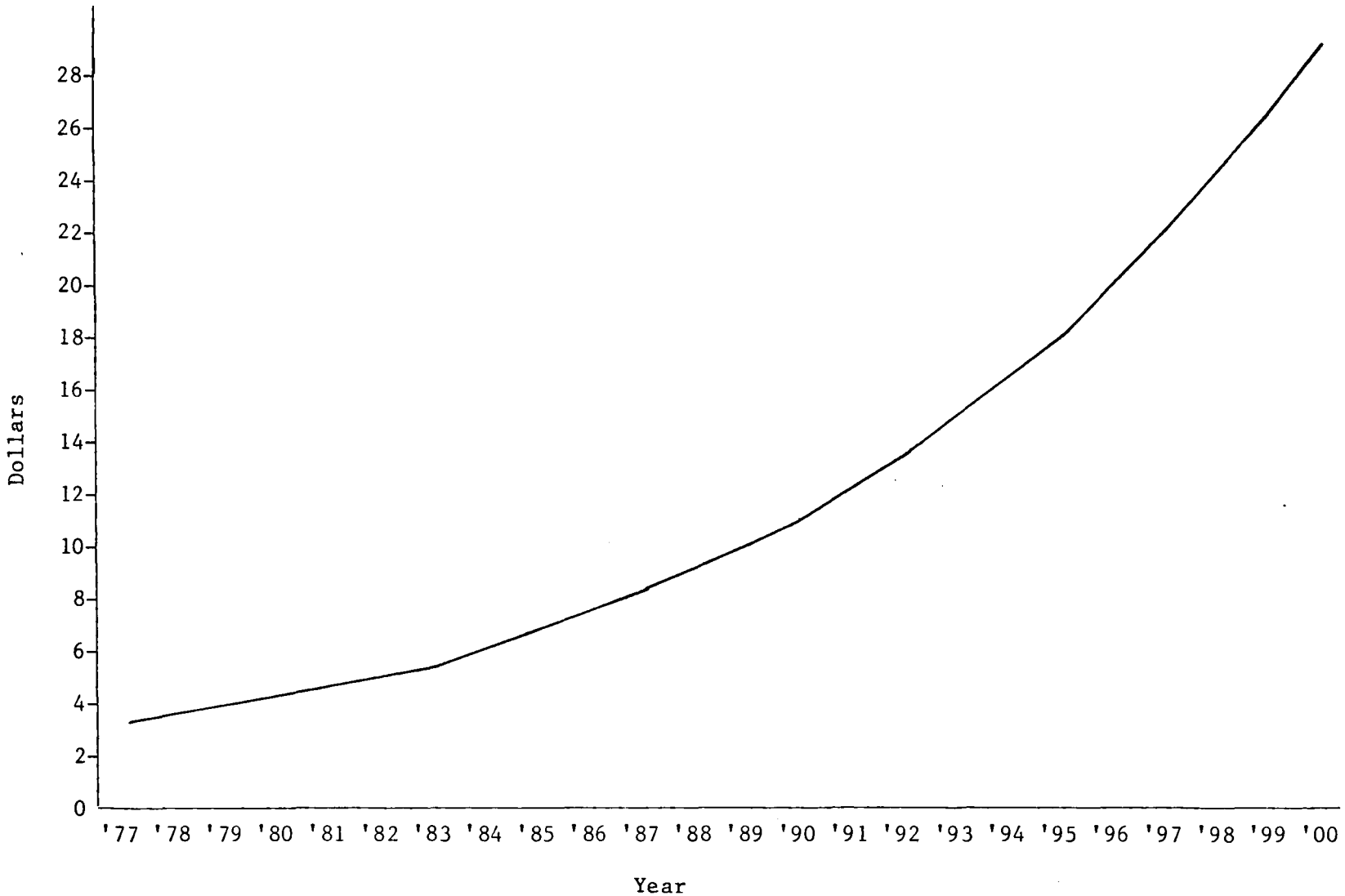

Figure 3.4. Gaseous Diffusion Tails Cost Projections

seven companies involved in the fabrication of LWR-UO_2 fuel. Current capacity of the industry is 2700 MTU per year in fuel assemblies.[13] This is expected to be adequate in meeting LWR needs through the year 1979. By the year 2000, it is expected that between 13500 and 13800 MT of UO_2 fuel assemblies will be required, assuming no plutonium recycle. With plutonium recycle, about 10900 MT of UO_2 fuel assemblies will be required. To increase production, it is expected that the present plants will be upgraded to 6300 MTU per year, and that any additional plants will be constructed having 1500 MTU per year capacity each. Table 3.10 represents the ERDA UO_2 fuel fabrication projections for the three scenarios. It is assumed that the plants will operate at 50 percent capacity the first year and 100 percent capacity the following years.[13,14]

Voltin and Draper estimate that fabrication costs will increase at a rate of 1.4 percent per annum.[19] Table 3.11 represents the UO_2 fabrication cost projections as derived by Puechl.[24]

3.4.2 MOX Fabrication Capacity Forecast

The recycling of plutonium as fuel for LWRs requires production of a mixed uranium dioxide-plutonium dioxide (MOX) fuel. Currently this step is not a part of the fuel cycle. MOX fuel rods may be used to form separate fuel assemblies of MOX fuel (PWR concept), or islands of MOX fuel surrounded by enriched UO_2 rods to form a single fuel assembly (BWR concept).[13, 25]

Currently five companies have the capability of producing MOX fuel on a pilot scale, with a total annual capacity of 50 to 75 MTHM (metric tons of heavy metal, uranium and plutonium) per year.[13] Due to

Table 3.10. UO_2 Fabrication Capacity Schedules[14]

Total Capacity - MTU/yr

Year	MID Case	LOW Case	HIGH Case
1976	1,800	1,800	1,800
1977	1,800	1,800	1,800
1978	2,000	2,000	2,000
1979	2,400	2,400	2,400
1980	2,800	2,400	3,000
1981	3,500	2,800	3,700
1982	4,200	3,500	4,500
1983	4,800	4,200	5,300
1984	5,300	4,800	5,800
1985	5,800	5,300	7,050*
1986	6,300	5,300	7,800
1987	6,300	5,300	7,800
1988	6,300	5,300	8,550*
1989	7,050*	5,800	9,300
1990	7,800	6,300	10,050*
1991	8,550*	7,050*	10,800
1992	9,300	7,800	10,800
1993	10,050*	7,800	11,550*
1994	10,800	8,550*	12,300
1995	10,800	9,300	12,300
1996	10,800	9,300	12,300
1997	10,800	9,300	12,300
1998	11,550*	9,300	12,300
1999	12,300	9,300	12,300
2000	12,300	9,300	12,300

Note: *Indicates startup of new UO_2 Fabrication plants.

Table 3.11. UO_2 Fabrication Cost Projection[24]

Year	Cost $/kg-$UO_2$	Year	Cost $/kg-$UO_2$
1976	199.70	1989	165.40
1977	182.60	1990	169.34
1978	164.50	1991	173.50
1979	147.25	1992	177.55
1980	130.00	1993	181.75
1981	133.75	1994	185.85
1982	137.40	1995	189.87
1983	141.10	1996	193.80
1984	145.00	1997	197.75
1985	148.80	1998	201.30
1986	153.10	1999	205.10
1987	157.10	2000	208.68
1988	161.10		

uncertainties surrounding reprocessing and recycling, no commercial plants are presently available.

Production of fuel rods containing MOX fuel pellets is a combination of chemical and mechanical operations. One chemical process that is available is the oxalate process. In this process, plutonium nitrate, $Pu(NO_3)_4$, is converted to PuO_2 powder by the addition of oxalic acid. This powder is then mechanically blended with ceramic grade UO_2 to produce a mixed oxide ready for fabricating into fuel pellets. Alternatively, MOX powder can be produced by the coprecipitation of ammonium diuranate (ADU) and plutonium hydroxide mixed crystals by the addition of ammonia to a mixture of the nitrate solutions.[13]

Implementation of plutonium recycle in LWRs will require the production of about 25000 MTHM as fuel assemblies over the 25 year period and about 2450 MTHM in the year 2000 (MID case).[13, 14] Table 3.12 indicates the ERDA anticipated production capacity of MOX fuel for the three scenarios. MOX plants are assumed to operate at 50 percent capacity the first year and 100 percent capacity thereafter. Table 3.13 reflects projected MOX fabrication costs through the year 2000.[24]

Table 3.12. MOX Fabrication Capacity Schedules[14]

Total Capacity - MTHM/yr

Year	MID Case	LOW Case	HIGH Case
1976	0	0	0
1977	0	0	0
1978	0	0	0
1979	0	0	0
1980	0	0	0
1981	0	0	0
1982	0	0	0
1983	175*	175*	175*
1984	350	350	350
1985	350	350	350
1986	350	350	350
1987	525*	525*	525*
1988	875*	875*	875*
1989	1,225*	1,225*	1,225*
1990	1,575*	1,400	1,575*
1991	1,925*	1,400	1,925*
1992	2,100	1,575*	2,100
1993	2,100	1,750	2,100
1994	2,100	1,750	2,275*
1995	2,275*	1,925*	2,450
1996	2,450	2,100	2,450
1997	2,450	2,100	2,625*
1998	2,450	2,100	2,800
1999	2,450	2,100	2,800
2000	2,450	2,100	2,975*

Note: *Indicates startup of new MOX Fabrication plant.

Table 3.13. MOX Fabrication Cost Projection[24]

Year	Cost $/kgHM	Year	Cost $/kgHM
1976	306.25	1989	419.80
1977	311.00	1990	430.48
1978	317.00	1991	441.80
1979	323.00	1992	453.00
1980	330.00	1993	463.00
1981	339.00	1994	473.80
1982	348.00	1995	482.60
1983	358.00	1996	493.80
1984	368.00	1997	503.50
1985	378.40	1998	512.10
1986	387.50	1999	521.80
1987	397.50	2000	529.70
1988	409.00		

4. SPENT FUEL VALUE

An important part of the spent fuel picture is the determination of a value for plutonium and spent uranium residing in spent fuel. Spent fuel may be considered a "mineral" which can be "mined" (reprocessed) to recover the unused nuclear fuel.[26] The value of these "minerals" will depend largely on the market demand for the recovered products and the "production" (reprocessing) costs. The analysis of the value of spent fuel provides important parameters necessary in solving the MOX fuel blending model and the reactor mix model developed in Chapter 5.

4.1 Uranium Value of Spent Fuel

The uranium recovered in the reprocessing facility can be recycled back into the nuclear fuel feed stream. LWRs, when operating under equilibrium conditions, will discharge spent fuel with a fissile uranium assay (U-235) higher than that of natural uranium. This characteristic of spent fuel can provide a savings in natural uranium and separative work.

The savings, in terms of the amount of natural uranium feed and separative work required, is directly proportional to the price of the enriched product from the enrichment facility. Enrichment expenses in a gaseous diffusion plant are reflected in separative work, whose cost encompasses the energy consumption needed to produce the enriched uranium.

Upon analyzing the gaseous diffusion cascade,[27] a fuel value for

enriched uranium product can be calculated on the basis of the unit cost of separative work and the unit cost of natural uranium feed. This is represented by:

$$D = C_s((2x_p-1)\ \ln \frac{x_p}{1-x_p} - (2x_w-1)\ \ln \frac{x_w}{1-x_w} +$$

$$\frac{x_p-x_w}{x_f-x_w}((2x_w-1)\ \ln \frac{x_w}{1-x_w} - (2x_f-1)\ \ln \frac{x_f}{1-x_f}))$$

$$+ C_f \frac{x_p-x_w}{x_f-x_w} \qquad (4.1)$$

where

D = price of enriched product, \$/kg;

C_s = unit cost of separative work, \$/kg;

C_f = unit cost of natural uranium feed, \$/kg;

x_p = assay of Uranium-235 in the enriched product stream, weight fraction;

x_f = assay of Uranium-235 in the feed stream, weight fraction,

x_w = assay of Uranium-235 in the diffusion plant tails, weight fraction.

Utilizing the discharge assays of the spent nuclear fuel for the PWR and BWR systems given in Table 2.1, the spent uranium values can be calculated. Calculations for determining these uranium values are based on an enrichment plant tails assay of 0.25 percent and the product enrichment being the spent fuel assay. By substituting this data into Equation 4.1, the value of the recovered uranium is given by:

1. PWR (UO_2 reactor)

$$D = (0.19491)C_s + (1.40998)C_f - C_c \tag{4.2}$$

2. BWR (UO_2 reactor)

$$D = (0.12710)C_s + (1.27983)C_f - C_c \tag{4.3}$$

where C_c is added to represent the unit cost of conversion of uranium to UF_6 gas. Table 4.1 reflects uranium conversion cost projections through the year 2000.[28]

The results indicate that for the reference PWR-UO_2 reactor (using Equation 4.2), the spent uranium can reduce the front end requirements of natural uranium feed by 1.41 units and separative work by 0.19 units. A similar interpretation can be applied to the reference BWR-UO_2 reactor (using Equation 4.3). Formulas 4.2 and 4.3 corrected for losses during reprocessing and fabrication are rewritten as:

$$D = ((0.19491)C_s + (1.40998)C_f - C_c)(1 - n_1 - n_2) \tag{4.4}$$

$$D = ((0.12710)C_s + (1.27983)C_f - C_c)(1 - n_1 - n_2) \tag{4.5}$$

where

n_1 = loss during reprocessing[13] (= 0.005),

n_2 = loss during fabrication[13] (= 0.003).

A similar analysis can be applied to the data for the reference SGR reactor systems found in Table 2.3, producing the same results as found in Equations 4.4 and 4.5. Projections for spent uranium values (using Equations 4.4 and 4.5) from 1976 to 2000 can be found in Table 4.2 for the PWR and BWR systems. This is obtained upon applying the cost data

Table 4.1. Uranium Conversion Cost Projection[28]

Year	Cost $/kg-U	Year	Cost $/kg-U
1976	4.32	1989	5.70
1977	4.41	1990	5.82
1978	4.50	1991	5.93
1979	4.59	1992	6.05
1980	4.68	1993	6.17
1981	4.77	1994	6.30
1982	4.87	1995	6.42
1983	4.97	1996	6.55
1984	5.06	1997	6.68
1985	5.17	1998	6.81
1986	5.27	1999	6.94
1987	5.48	2000	7.08
1988	5.59		

Table 4.2. Spent Uranium Value Projections

Year	for PWR $/kg-U	for BWR $/kg-U	Year	for PWR $/kg-U	for BWR $/kg-U
1976	94.61	82.37	1989	261.71	229.47
1977	104.46	90.91	1990	292.75	257.53
1978	118.12	103.00	1991	326.59	288.14
1979	134.19	117.38	1992	355.03	313.79
1980	150.26	131.76	1993	376.27	332.97
1981	162.67	142.33	1994	391.92	347.06
1982	173.87	151.74	1995	407.76	361.28
1983	180.86	157.34	1996	423.41	375.37
1984	189.07	164.09	1997	439.24	389.59
1985	199.14	173.12	1998	459.28	407.61
1986	205.03	178.35	1999	477.72	424.24
1987	220.59	192.36	2-00	495.38	440.35
1988	239.05	209.01			

for separative work, natural uranium feed, and uranium conversion found in Tables 3.7, 3.8, and 4.1.

From the above formulas, it is shown that the values of the uranium recovered from the spent fuel is related to the prices of natural uranium and separative work less the conversion costs. Since uranium is a scarce commodity, its price will obey the laws of supply and demand. In other words, as the supply of uranium decreases, the price will increase.

4.2 Plutonium Value

The value of plutonium residing in spent nuclear fuel depends on the manner in which the plutonium is used. In order to establish a value, it is necessary to distinguish between plutonium price and plutonium value.[26] A "use value" is defined as the amount of money the user is willing to pay in order to use the commodity. A "market price" reflects the balance between supply and demand. In light of the current moratorium on the reprocessing of spent nuclear fuel and the use of plutonium in commercial reactors, the establishment of a firm market price for plutonium is impractical.

However, for the purpose of this study, an "artificial market", based upon the use value (limiting value for plutonium in the plutonium market), is used. In order to define the use value, it is necessary to know the technical and economic circumstances of plutonium utilization.[26] Since 1.0 gram of fissile plutonium can replace approximately 0.85 grams of U-235[5], it is obvious that the plutonium market is linked with the uranium price and uranium enrichment services costs.

Plutonium that is generated in the light water reactors can be used

in several different ways. These ways consist of: in situ (some plutonium that is formed in the reactor is consumed before it is recycled), for recycle in LWRs, for the High Temperature Gas Reactor based upon plutonium fuel design, and for early fuelings of the fast reactors.[26] For the purpose of this study, it will be assumed that only LWRs are expected to contribute to the nuclear generating capacity through the end of the century. More specifically, plutonium will be used only in situ and in recycle, thereby establishing a plutonium market.

Fissile plutonium is constantly being produced in an operating reactor as a result of radiative capture of neutrons in the U-238 nucleus. As more and more fissile plutonium (Pu-239 and Pu-241) is created, the more it participates in the general fission reactions, like U-235. In addition, it becomes more important in the in situ consumption. The quantity of plutonium available for in situ consumption is a direct function of the neutronic characteristics of the reactor and the degree of core burnup. No value can be assigned to the plutonium produced in the reactor core since it is freely available for use without reprocessing.

The unburned portion of the plutonium remaining in the spent fuel can be chemically separated (reprocessed) from the uranium and fission products contained in the spent fuel. This plutonium can be further utilized in the same reactor or other reactors as fuel in the form of a mixed-oxide. The effect of this recycled plutonium in the reactor will depend on the isotopic composition of the plutonium, since the composition varies with the core burnup. As stated earlier, the purpose for recycling the plutonium is to establish an "artificial market" in order

to compute a value for plutonium.

There are several different ways in which the value of plutonium can be established. The most frequently used method is the "indifference" or "break-even" method that was proposed by Eschbach.[29] The indifference method defines the plutonium value as the value yielding the same fuel cycle cost whether the plutonium discharged is sold or recycled. For this method, firm numerical values for each fuel cycle cost component for both enriched uranium fuel and plutonium recycle must be known, leaving only the value of plutonium unknown. Due to the present uncertainties surrounding reprocessing and plutonium recycle, a firm plutonium market has not been established. Since this method depends heavily upon the establishment of a well-defined plutonium market and the cost components of the mixed-oxide fuel cycle, it seems that this method is not useful in light of the present situation.

A second method for calculating the plutonium value is derived by Deonigi.[13] A generalized equation establishes a relationship between fully enriched uranium(93% enriched), Pu-242 penalty factor, and the differential fabrication cost correction for mixed-oxide fuel above that of uranium fuel.[13] Deonigi shows that the plutonium value is expressed by:

$$V(Pu) = U(A-1.6R) - \frac{\text{Pu Fabrication Penalty; \$/kg-MOX}}{\text{grams fissile Pu/kg fuel}} \qquad (4.6)$$

where

A = plutonium replacement value (relative worth of Pu-239 to U-235 as a fissile material, gm U-235/gm Pu-fissile),

U = the cost of fully enriched uranium (93% wt) at the fabrication plant - \$/kg, and

R = ratio of concentration of Pu-242 to the concentration of fissile plutonium(Pu-239 and Pu-241).

For the purpose of this study, neither of the above methods are used. The value of plutonium is best realized by considering the savings in the reduction of requirements for natural uranium feed and separative work units that result from plutonium recycle.

In the GESMO study[13], an evaluation on the amount of savings in uranium ore and separative work realized by plutonium recycle was conducted. This evaluation is based on present offerings of the major fuel suppliers. It was found that one gram of fissile plutonium in a PWR is equivalent to 0.1906 kgs of separative work plus 0.180 kgs of natural uranium. A similar analysis for the BWR indicates that one gram of fissile plutonium is equivalent to 0.2037 kgs of separative work plus 0.1870 kgs of natural uranium. The actual value of plutonium, at a specific time, depends upon the quantity of fissile plutonium available at that time. Therefore, a correction is allowed for the decay of Pu-241. Other factors that effect the value of plutonium are the losses during reprocessing and MOX fuel fabrication, and the cost difference between MOX fuel fabrication and uranium fuel fabrication. Hence, the effective value of plutonium is summarized in the following formula:

$$V(Pu) = (C_s \times A + C_f \times B)\ (1 - n_1 - n_2 - n_3) - \frac{\Delta FC}{g} \qquad (4.7)$$

where

$V(Pu)$ = plutonium value, \$/gm - fissile;

C_s = unit cost of separative work, \$/kg;

C_f = unit cost of natural uranium feed, \$/kg;

n_1 = Loss during reprocessing[13] (= 0.005);

n_2 = loss during fabrication[13] (= 0.003);

n_3 = loss in fissile Pu during reprocessing and fabrication due to decay of Pu-241 (= 0.01);

g = number of grams of fissile Pu per kg of MOX fuel, g/kg;

ΔFC = plutonium fabrication penalty, \$/kg.

The factors A (equivalent to one gram of fissile plutonium in terms of separative work units), and B (equivalent to one gram of fissile plutonium in terms of natural uranium), which vary with the type of reactor, are summarized in Table 4.3.

The savings realized from plutonium recycle are dependent on the price that one must pay for natural uranium and separative work, less the fuel fabrication penalty, in the year in which the recycle occurs. In a study by Puechl[24], an estimate was made (Tables 3.6 and 3.7) of uranium and mixed-oxide fuel fabrication cost up to the year 2000. Results of plutonium values (using Equation 4.7), for the SGR and PuO_2 reactors, are summarized in Tables 4.4 and 4.5.

Table 4.3. Plutonium Value for Uranium Feed and Separative Work Equivalents[13]

Equivalents to 1 gm of Pu (fissile)	Type of reactor	
	PWR	BWR
A = SWU Equivalent - kg	0.1906	0.180
B = Natural U Equivalent - kg	0.2037	0.1870

Table 4.4. Plutonium Value Projections

for Self-generating Reactors

Year	for PWR $/kg-Pu	for BWR $/kg-Pu	Year	for PWR $/kg-Pu	for BWR $/kg-Pu
1976	20.13	17.74	1989	52.94	46.86
1977	21.99	19.28	1990	57.45	50.94
1978	23.99	20.91	1991	62.37	55.40
1979	26.05	22.59	1992	66.67	59.29
1980	28.08	24.23	1993	69.81	62.14
1981	31.90	27.76	1994	72.10	64.17
1982	35.70	31.27	1995	74.69	66.52
1983	38.87	34.19	1996	76.97	68.55
1984	42.06	37.13	1997	79.55	70.88
1985	43.58	38.47	1998	82.70	73.74
1986	44.57	39.34	1999	85.46	76.22
1987	46.92	41.45	2000	87.51	78.05
1988	49.60	43.85			

Table 4.5. Plutonium Value Projections

for Plutonium Burner Reactors

Year	for PWR $/kg-Pu	for BWR $/kg-Pu	Year	for PWR $/kg-Pu	for BWR $/kg-Pu
1976	21.95	19.89	1989	57.29	51.99
1977	24.19	21.87	1990	61.92	56.21
1978	26.61	23.99	1991	66.96	60.80
1979	29.07	26.14	1992	71.38	64.84
1980	31.51	28.27	1993	74.63	67.80
1981	35.42	31.90	1994	77.04	69.99
1982	39.31	35.52	1995	79.71	72.42
1983	42.59	38.57	1996	82.12	74.61
1984	45.88	41.62	1997	84.78	77.04
1985	47.51	43.10	1998	88.03	80.01
1986	48.59	44.07	1999	90.88	82.60
1987	51.04	46.29	2000	93.01	84.53
1988	53.85	48.85			

5. MODEL DEVELOPMENT

Previous discussion has demonstrated the need for devising effective stategies for the recycling of plutonium and spent uranium in order to minimize the consumption of natural uranium. This chapter consists of four sections. The first section deals with the development of a MOX fuel blending model that is used to determine optimal MOX fuel blending policies at a minimum cost. In this model, the amount of MOX fuel and plutonium required is fixed, leaving the type and quantity of uranium necessary for blending to be determined. The development of the reactor mix model is discussed in the second section. This model aids in determining the optimal mix of UO_2, SGR, and APR reactors in order to minimize natural uranium depletion. The third section presents a summary of the information pertinent to the implementation of these models. The last sections discusses the implementation of these models.

5.1 Formulation of the MOX Fuel Blending Model

In order for a nuclear reactor to utilize plutonium as a nuclear fuel, the highly fissile plutonium must first be diluted, by blending it with relatively non-fissile uranium. The objective of this part of the study is to produce a methodology that identifies the components and their associated quantities that must be blended with plutonium to produce MOX fuel at a minimum cost for the SGRs only. If the components are defined to be the ingredients and the required quantity of MOX fuel labeled as the product, the problem of identifying the components can be formulated as an optimization problem. To do this, the following

variables are defined:

y_n = the quantity of ingredient n in kilograms (kg) where,

n = 1 plutonium

n = 2 spent uranium or enriched uranium derived from spent uranium

n = 3 natural uranium

n = 4 gaseous diffusion tails

n = 5 enriched uranium derived from natural uranium;

C_n = the total unit cost associated with obtaining the nth ingredient ($/kg),

D = the total quantity of MOX fuel demanded (kg),

a_D = the equivalent U-235 enrichment demanded in the MOX fuel (%),

a_n = the equivalent U-235 enrichment of the nth ingredient (%),

d_1 = the quantity of plutonium demanded (kg),

S_2 = the quantity of spent uranium available for blending (kg),

S_3 = the quantity of natural uranium available for blending (kg),

S_4 = the quantity of gaseous diffusion tails available for blending (kg).

The objective is to minimize the total MOX fuel cost, subject to the constraints imposed by the demand for fuel and the availability of each ingredient. The objective can be mathematically represented in the following manner:

$$\text{Min:} \quad Z = \sum_{n=1}^{5} C_n y_n . \tag{5.1}$$

Seven basic constraints must be satisfied. The first constraint assures that the demand for MOX fuel is met. This can be expressed as:

$$\sum_{n=1}^{5} y_n = D. \tag{5.2}$$

The next constraint requires that the equivalent U-235 fissile content of the MOX fuel be satisfied:

$$\sum_{n=1}^{5} a_n y_n = a_D D. \tag{5.3}$$

The third constraint requires that the amount of plutonium that is used in the blending process is equal to that demanded by the blending process. This is simply stated as an equality constraint, expressed as:

$$y_1 = d_1. \tag{5.4}$$

A fourth constraint requires that the quantity of spent uranium used in blending is no greater than that available for blending. In this situation, the spent uranium is transferred directly from the reprocessing plant to the MOX fuel fabrication plant. The spent uranium does not necessarily require re-enrichment, namely:

$$y_2 \leq s_2. \tag{5.5}$$

Alternately, the fourth constraint can require that the quantity of spent uranium necessary in producing enriched uranium used in blending is no greater than that available for re-enrichment. In this situation, the reprocessed spent uranium is further enriched before being

transferred to the MOX fuel fabrication plant, namely:

$$\left[\frac{a_5 - a_4}{a_2 - a_4}\right] y_2 \leq S_2. \tag{5.6}$$

The fifth constraint restricts the amount of natural uranium that can be directly blended with the plutonium or that can be used to produce enriched uranium, y_5, to be no greater than the natural uranium available for blending. This is expressed as:

$$y_3 + \left[\frac{a_5 - a_4}{a_3 - a_4}\right] y_5 \leq S_3. \tag{5.7}$$

The sixth constraint requires that the amount of gaseous diffusion tails that are blended with the plutonium be no greater than those available:

$$y_4 \leq S_4. \tag{5.8}$$

The final constraint assures that the decision variables, y_n, will be nonnegative:

$$y_n \geq 0 \qquad \forall\ n. \tag{5.9}$$

This formulation is a linear program. It reflects the material use costs of MOX fuel blending, but does not include the costs of the physical blending process. This is because these costs are not affected by the choice of ingredients.

5.2 Formulation of the Reactor Mix Model

Existing commercial light water reactors use only slightly enriched uranium as fuel. With the implementation of reprocessing and spent-fuel recycle, the use of plutonium as a nuclear fuel becomes possible. The objective of this part of the study is to produce a methodology that identifies the types of fuels that should be used in future nuclear reactors in order to minimize the consumption of natural uranium. If the types of fuel are viewed as activities competing for limited production capabilities in order to meet the reactor fuel demand, then the problem can be formulated as an optimization problem.

In order to construct the reactor mix model, three index sets must be defined. First, it is necessary to distinguish the periods in the planning horizon. This is necessary since the ability to make decisions rests with the activities occurring during a particular time period. For this purpose, the index set t is defined:

$$t = \left[1,\ 2,\ 3,\ .\ .\ .\ ,\ T\right], \tag{5.10}$$

where T represents the number of years in the planning horizon. For the purpose of this study, the number of years in the planning horizon is twenty-five years.

In order to distinguish and denote a particular reactor requiring fuel, it is necessary to define an index that can describe each reactor operating in a given time period. For this purpose, the identities of the individual reactors are defined by the index set j as:

$$j = \left[1,\ 2,\ 3,\ .\ .\ .\ ,\ J(t)\right], \tag{5.11}$$

where J(t) denotes the total number of reactors of all types operating in the time period t.

To be able to distinguish each type of fuel, it becomes necessary not only to classify each reactor as a type of reactor, but also to identify the types of fuel that can be utilized in each reactor type. The index set

$$i = \left[1, 2, 3, \ldots, I\right], \tag{5.12}$$

is defined to represent this classification, where I denotes the total number of combinations of reactor types and fuel types being considered. For the purpose of this study, six different reactor-fuel types are considered:

$i = 1$ PWR - UO_2

$i = 2$ BWR - UO_2

$i = 3$ PWR - SGR

$i = 4$ BWR - SGR

$i = 5$ PWR - PuO_2

$i = 6$ BWR - PuO_2.

Note that types 1 and 2 use only uranium as fuel, while types 3 through 6 use a mixture of plutonium and uranium as fuel. Using the defined index sets, it is now possible to describe the variables of the reactor mix model.

A decision as to the types of fuel that should be used in a particular reactor in any one year can be represented by:

$$X_{ijt} = \begin{cases} 1 & \text{, if type i fuel is used in reactor j in period t} \\ 0 & \text{, if type i fuel is not used in reactor j in period t.} \end{cases}$$

The objective is to minimize the total consumption of natural uranium subject to constraints reflecting the availability of spent fuel and the capacities of reprocessing, fuel enrichment, and fuel fabrication facilities. This objective is expressed as:

$$\text{Min:} \quad Z = \sum_{t=1}^{T} \sum_{j=1}^{J(t)} \sum_{i=1}^{I} C^2_{ijt} X_{ijt}. \tag{5.13}$$

Pursuit of the objective is constrained by ten equations representing the demand for each fuel and the available capacity to produce the fuels. To simplify discussion of the various constraints, the following variables are defined:

q_{ijt} = the quantity of type i fuel required to fuel reactor j in time period t,

F^1 = the subset of I that corresponds to MOX fuel,

M_t = the MOX fuel fabrication capacity in time period t,

F^2 = the subset of I that corresponds to UO_2 fuel,

U^1_t = the UO_2 fuel fabrication capacity in time period t,

d_i = the SWU requirement for production of 1 kg of type i fuel,

U^2_t = the SWU capacity in time period t,

e_i = the percent of 1 kg of offload spent fuel of type i fuel that is recyclable Pu,

h_i = the percent of 1 kg of offload spent fuel of type i fuel that is recyclable U,

s_{ijt} = the quantity of spent fuel of type i fuel offloaded from reactor j in time period t,

R_t = the reprocessing capability in time period t,

C^1_{ijt} = the cost of using type i fuel in reactor j in time period t,

N_t = the total amount of money available to purchase fuel in time period t,

b_i = the percent of Pu in 1 kg of type i fuel,

g_i = the percent of recycled U in 1 kg of type i fuel,

P_{t-1} = the recyclable Pu stockpile,

Q_{t-1} = the recyclable U stockpile.

The first constraint assures that each reactor will be fueled or refueled with one and only one type of fuel. In this model formulation, a PWR is restricted to three types of fuel: a UO_2 fuel, a SGR fuel, or a PuO_2 fuel. Likewise, the BWR is restricted to the same three types of fuel. Generally, each reactor j in time period t can be fueled with one and only one type of fuel. This is represented by:

$$\sum_{i=1}^{I} X_{ijt} = 1 \qquad \forall\ j,\ t. \qquad (5.14)$$

The second constraint expresses the limitation imposed on the use of plutonium as a nuclear fuel due to the capacity to fabricate plutonium into a fuel assembly form. The number of reactors that can utilize plutonium are limited by the capacity to produce the required fuel. In any period t, the quantity of MOX fuel demanded cannot exceed the MOX fuel fabrication capacity in period t-1 plus the unused fabrication

capacities in periods prior to t-1. This is denoted by:

$$\sum_{i\in F^1} \sum_{j=1}^{J(t)} q_{ijt}X_{ijt} \leq M_{t-1} + \sum_{\tau=1}^{t-1} \left[M_{\tau-1} - \sum_{i\in F^1} \sum_{j=1}^{J(\tau)} q_{ij\tau}X_{ij\tau} \right] \quad \forall\ t. \qquad (5.15)$$

A similar constraint is also imposed on the use of uranium as a nuclear fuel. Again, the quantity of UO_2 fuel demanded is period t cannot exceed the UO_2 fuel fabrication capacity in the period t-1 plus the unused fabrication capacities in the periods prior to t-1. This is represented by:

$$\sum_{i\in F^2} \sum_{j=1}^{J(t)} q_{ijt}X_{ijt} \leq U^1_{t-1} + \sum_{\tau=1}^{t-1} \left[U^1_{\tau-1} - \sum_{i\in F^2} \sum_{j=1}^{J(\tau)} q_{ij\tau}X_{ij\tau} \right] \forall\ t. \qquad (5.16)$$

Next, the total amount of enrichment services demanded in period t cannot exceed the enrichment capability in period t-1. Only reactors involving slightly enriched uranium will require enriching services. Thus:

$$\sum_{i\in F^1 \cup F^2} \sum_{j=1}^{J(t)} d_i q_{ijt}X_{ijt} \leq U^2_{t-1} \qquad \forall\ t. \qquad (5.17)$$

Another constraint affecting the availability of plutonium fuel is the reprocessing capacity. In order for plutonium to be fabricated into fuel assemblies it must first be recovered from spent fuel by reprocessing.

Therefore, the amount of plutonium and spent uranium that is demanded for recycle in period t is limited to the quantity of spent fuel that can be reprocessed in period t-2, plus reprocessed spent fuel from periods prior to t-2. This is represented by:

$$\sum_{i=1}^{I} \sum_{j=1}^{J(t)} (b_i + g_i) q_{ijt} X_{ijt} \leq R_{t-2} +$$

$$\sum_{\tau=1}^{t-1} \left[R_{\tau-2} - \sum_{i=1}^{I} \sum_{j=1}^{J(\tau-1)} (b_i + g_i) q_{ij\tau} X_{ij\tau} \right] \quad \forall\ t. \qquad (5.18)$$

The sixth constraint allows for a monetary analysis of the reactor mix problem. Generally, the total amount of money spent to acquire all types of nuclear fuels cannot exceed some value, N_t. Thus:

$$\sum_{j=1}^{J(t)} \sum_{i=1}^{I} C^1_{ijt} X_{ijt} \leq N_t \qquad \forall\ t, \qquad (5.19)$$

where,

$C^1_{ijt} = f(\alpha_{it}, q_{ijt})$, and

α_{it} = the unit cost of type i fuel in time period t.

The next constraint represents the supply versus demand for plutonium for each period in the planning horizon. Specifically, the total quantity of plutonium utilized in period t must not exceed the available supply, which consists of a Pu stockpile plus that which is available from spent fuel offloaded in period t-2. Mathematically,

$$\sum_{i=1}^{I} \sum_{j=1}^{J(t)} b_i q_{ijt} X_{ijt} \leq P_{t-1} + \sum_{i=1}^{I} \sum_{j=1}^{J(t-3)} e_i s_{ijt-2} X_{ijt-2} \quad \forall\ t, \quad (5.20)$$

where the Pu stockpile is expressed as:

$$P_{t-1} = \sum_{\tau=1}^{t-1} \left[\sum_{i=1}^{I} \sum_{j=1}^{J(\tau-3)} e_i s_{ij\tau-2} X_{ij\tau-2} - b_i q_{ij\tau} X_{ij\tau} \right] \forall\ t. \quad (5.21)$$

A similar constraint represents the recycled uranium supply versus demand:

$$\sum_{i=1}^{I} \sum_{j=1}^{J(t)} g_i q_{ijt} X_{ijt} \leq Q_{t-1} + \sum_{i=1}^{I} \sum_{j=1}^{J(t-3)} h_i s_{ijt-2} X_{ijt-2} \quad \forall\ t, \quad (5.22)$$

where the uranium stockpile is expressed as:

$$Q_{t-1} = \sum_{\tau=1}^{t-1} \left[\sum_{i=1}^{I} \sum_{j=1}^{J(\tau-3)} h_i s_{ij\tau-2} X_{ij\tau-2} - g_i q_{ij\tau} X_{ij\tau} \right] \forall\ t. \quad (5.23)$$

If desired, one can cause a specific reactor to remain using a fuel type once it has gone to that fuel type. The ninth constraint allows for specific decision variables to be set to either 0 or 1, thus restricting the choice of fuel type for particular reactors:

$$\begin{aligned} X_{\beta\Gamma\Delta} &= 0 \\ X_{\beta'\Gamma'\Delta'} &= 1. \end{aligned} \quad (5.24)$$

In this analysis, this constraint is not utilized.

The final constraint assures that all the decision variables are nonnegative:

$$X_{ijt} \leq 0. \qquad \forall\ i, j, t. \qquad (5.25)$$

5.3 The Reference Case

In order to investigate the properties of the two models, a reference case is assumed and the decision variable values for that case are determined. The reference case selected for the MOX fuel blending model includes a typical PWR and BWR requiring MOX fuel in the self-generating recycle mode. For both reactors, 25 percent of the annual fuel reload consists of MOX fuel, the remaining 75 percent is enriched uranium.[13] The PWR requires 6365 kg of MOX fuel at an equivalent U-235 fissile content of 2.8 percent, while the BWR requires 7325 kg at an equivalent 2.39 percent enrichment.[14] The parameter values are accordingly estimated for 1984. Separative work is assumed to cost $129.00/SWU and natural uranium is assumed to have a price of $115.00 per kg UF_6.[22] The required separative work and uranium feed quantities are computed using the standard enrichment equations.[30] From this, the values for plutonium and spent uranium are determined (see Tables 4.2 and 4.4). Gaseous diffusion tails are assumed to cost $5.84/kg.[23] In addition, the amount of spent uranium that can be utilized by the PWR and BWR for blending is limited to the amount of spent uranium that each reactor generates, 24300 kg and 28200 kg respectively. Other fuel characteristics are listed in Tables 2.3 and 2.4. Utilizing these parameter values, the model is analyzed to determine which ingredients in what quantities should be blended to satisfy the demands for MOX fuel while minimizing the cost of the MOX fuel.

Tables 5.1 and 5.2 represent a summary of the information used in

Table 5.1. Summary of Data Information for the PWR* MOX Blending Model

C_n ($/kg):

C_1 = 38870.00

C_2 = 180.86

C_3 = 115.00

C_4 = 5.84

C_5 = 228.08

a_D = 0.028

D = 6365 kg

d_1 = 292.98 kg***

a_n (%):

a_1 = 0.4845**

a_2 = 0.009

a_3 = 0.00711

a_4 = 0.0025

a_5 = 0.01

S_2 = 24300 kg

S_3 = 99999.0 kg****

S_4 = 99999.0 kg****

*Based on fuel delivered in 1984, indicating costs are incurred in previous year (1983).

**0.4845 = 0.85 x 0.57 (0.57 from Table 2.4, corrected to equivalent U-235 content).

***167.0 kg ÷ 0.57 (from Tables 2.3 and 2.4).

****arbitrary large number

Table 5.2. Summary of Data Information for the BWR* MOX Blending Model

C_n ($/kg):

C_1 = 34170.00

C_2 = 157.34

C_3 = 115.00

C_4 = 5.84

C_5 = 187.29

a_D = 0.0239

D = 7325.0 kg

d_1 = 285.96 kg***

a_n (%):

a_1 = 0.4845**

a_2 = 0.0084

a_3 = 0.00711

a_4 = 0.0025

a_5 = 0.009

S_2 = 28200.0 kg

S_3 = 99999.0 kg****

S_4 = 99999.0 kg****

*Based on fuel delivered in 1984, indicating costs are incurred in previous year (1983).

**0.4845 = 0.85 x 0.57 (0.57 from Table 2.4, corrected to equivalent U-235 content).

***163.0 kg ÷ 0.57 (from Tables 2.3 and 2.4).

****arbitrary large number

implementing the MOX fuel blending model for both the PWR-SGR and the BWR-SGR, respectively.

In order to demonstrate the utility of the reactor mix model, a reference case, corresponding to projected growths in nuclear reactor electrical production, reprocessing capacity, enrichment capacity, and fuel fabrication capacity, is analyzed. Information for these projections are defined as the MID case or reference case. Tables 3.1, 3.4, 3.6, 3.9, and 3.11 represent the MID case data as published by ERDA.[14] In addition, cost projections for reprocessing, separative work, uranium feed, gaseous diffusion tails, and fuel fabrication are utilized (see Tables 3.5, 3.7, 3.8, 3.9, 3.10, and 3.12). Incorporating these cost and capacity projections, the model is analyzed to determine which types of fuels must be utilized each year in order to minimize the amount of natural uranium consumed.

Table 5.3 represents a summary of the information used in the implementation of the reactor mix model for the MID case.

5.4 Implementation of the Models

The MOX fuel blending model and the reactor mix model are both implemented on the Virginia Polytechnic Institute and State University IBM Computer System 370, using a linear program[31] and a proprietary mathematical programming system--MPS III[32], respectively. Appendices B and C provide information pertinent to the implementation of the MPS--III computer program. The execution time for a typical LP run for the MOX fuel blending model is on the order of 0.5 seconds, while the execution time for the reactor mix model is on the order of 12 hours.

Table 5.3. Summary of Data Information for Reactor Mix Model (MID Case)

T -- 25 years

$J(t)$ -- use Table 3.1, column 1 (e.g., $J(25)$ = 507 reactors)

I -- 6 reactor-fuel types

C^2_{ijt} -- based upon fuel type, quantity, and enrichment (e.g., C^2_{147} = 162922 kg)

q_{ijt} -- from Tables 2.1, 2.3, and 2.5 (e.g., q_{147} = 25460 kg)

F^1 -- 4 reactor-fuel types which utilize plutonium

M_t -- use Table 3.12, column 1 (e.g., M_{15} = 1575 MTHM)

F^2 -- 2 reactor-fuel types which utilize only uranium

U^1_t -- use Table 3.10, column 1 (e.g., U^1_{15} = 7800 MTU)

d_i -- based upon fuel type, quantity, and enrichment (e.g., d_1 = 107140 SWU)

U^2_t -- use Table 3.6, column 1 (e.g., U^2_{15} = 46.0 million SWU)

R_t -- use Table 3.4, column 1 (e.g., R_{15} = 7600 MTHM)

C^1_{ijt} -- based upon fuel type, quantity, and enrichment (e.g., C^1_{147} = \$33.96 million)

N_t -- arbitrarily large number (e.g., N_{15} = \$99.99 billion)

S_{ijt} -- from Tables 2.1, 2.3, and 2.5 (e.g., S_{147} = 24592, or 24300 + 167 ÷ 0.57)

e_i -- from Tables 2.1, 2.3, and 2.5 (e.g., e_1 = 292.98 ÷ 24592 =1.19%)

h_i -- from Tables 2.1, 2.3, and 2.5 (e.g., h_1 = 24300 ÷ 24592 =98.81%)

b_i -- from Tables 2.1, 2.3, and 2.5 (e.g., b_1 = 292.98 ÷ 6365 = 4.60%)

g_i -- from Tables 2.1, 2.3, and 2.5 (e.g., g_1 =6072.02 ÷ 6365 =95.40%)

The reactor mix problem contains an average of 14,000 decision variables and 6000 constraints, implying a 14,000 x 6000 a_{ij} matrix which overwhelms the default working storage of the MPS[32] program. By manipulating the job control language and using an IBM Utility package, the problem is segmented by partial optimization and data preservation, thus producing 24 segments requiring 12 hours of computer time and yielding the desired results.

Although the reactor mix model is developed as an integer program (IP), linear program solution techniques are utilized to obtain the solution. By using LP procedures, a continuous optimal solution results, having some decision variables expressed as fractions of integer values. Due to problem size and insufficient computer storage space, the non-integer values are rounded, by hand, to integer values. This results in an optimal integer solution that is not necessarily feasible after rounding off.

6. RESULTS

The discussion of the results is divided into two sections. The results of the MOX fuel blending model are presented in Section 6.1. Section 6.2 presents discussion of the optimal scheduling of MOX fueled reactors for the three reactor growth scenarios: LOW, MID, and HIGH. Some of the tabular and graphic results for the reactor mix model are also presented in Appendix A.

6.1 Results of the MOX Fuel Blending Model

Before plutonium can be used as a nuclear fuel, it must be blended with uranium to produce the desired fissile content of the fuel mixture. To attain this, two possible blending schemes are examined to determine the minimum cost for MOX fuel delievered in the year 1984.

The first situation examined (Case 1) allows plutonium to be blended with natural uranium, spent uranium, gaseous diffusion tails, and enriched uranium derived from natural uranium. Results for this case are examined first on the basis that unlimited quantities of spent uranium, gaseous diffusion tails, and natural uranium are available for blending. Then, the supply of natural uranium is allowed to go to zero for the purpose of testing the solution sensitivity. The quantities of fuel demanded and their associated fuel characteristics for the PWR-SGR and the BWR-SGR are discussed in Section 2.3.2.

The second situation examined (Case 2) allows the enrichment of the spent uranium to reach the same fissile enrichment level as the enriched uranium derived from natural uranium. Again, the supply of natural

uranium is allowed to go to zero.

Results of these situations indicate that 4575.09 kg of natural uranium and 1496.93 kg of gaseous diffusion tails must be blended with the 292.98 kg of plutonium to produce the MOX fuel for the PWR-SGR at a minimum cost. Likewise, for the BWR-SGR, 4105.17 kg of natural uranium and 2933.87 kg of gaseous diffusion tails must be blended with the 285.96 kg of plutonium to produce the MOX fuel at a minimum cost. However, as the supply of natural uranium becomes more restricted, the demand for spent uranium increases, resulting in an increase in the cost of the MOX fuel. Figures 6.1 and 6.2 depict the results obtained by varying the supply of natural uranium for the PWR-SGR and the BWR-SGR, respectively.

As can be observed from Figure 6.1, a 0.57 percent increase in cost is incurred if no natural uranium is used in the fuel (Case 1). Similarly, for Case 2, a 0.85 percent cost increase is incurred. In contrast to these PWR-SGR costs presented in Figure 6.1, Figure 6.2 shows the BWR-SGR costs increasing by smaller percentages: 0.36 percent for Case 1 and a 0.51 percent for Case 2.

Based on the material quantities used in the blending of MOX fuel at a minimum cost, projections for MOX fuel cost are determined through the year 2000. This is represented in Table 6.1 and is later used in the reactor mix model.

6.2 Results of the Reactor Mix Model

Several situations were analyzed using the IP model in order to compare effective reactor fuel loading schedules, for MOX and UO_2 fuels,

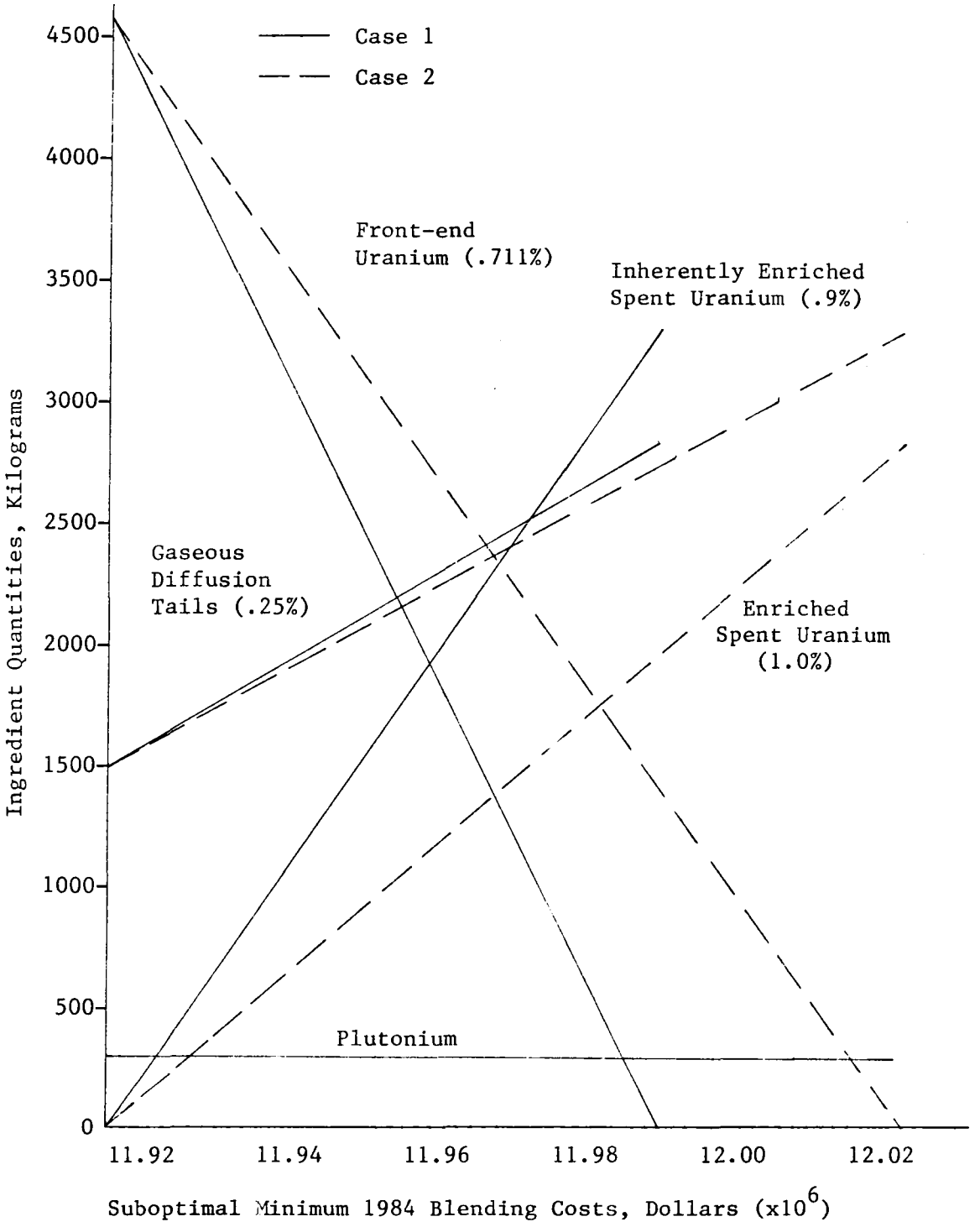

Figure 6.1. Effect of Constrained Natural Uranium Capacity on PWR-SGR Fuel Blending Composition and Cost

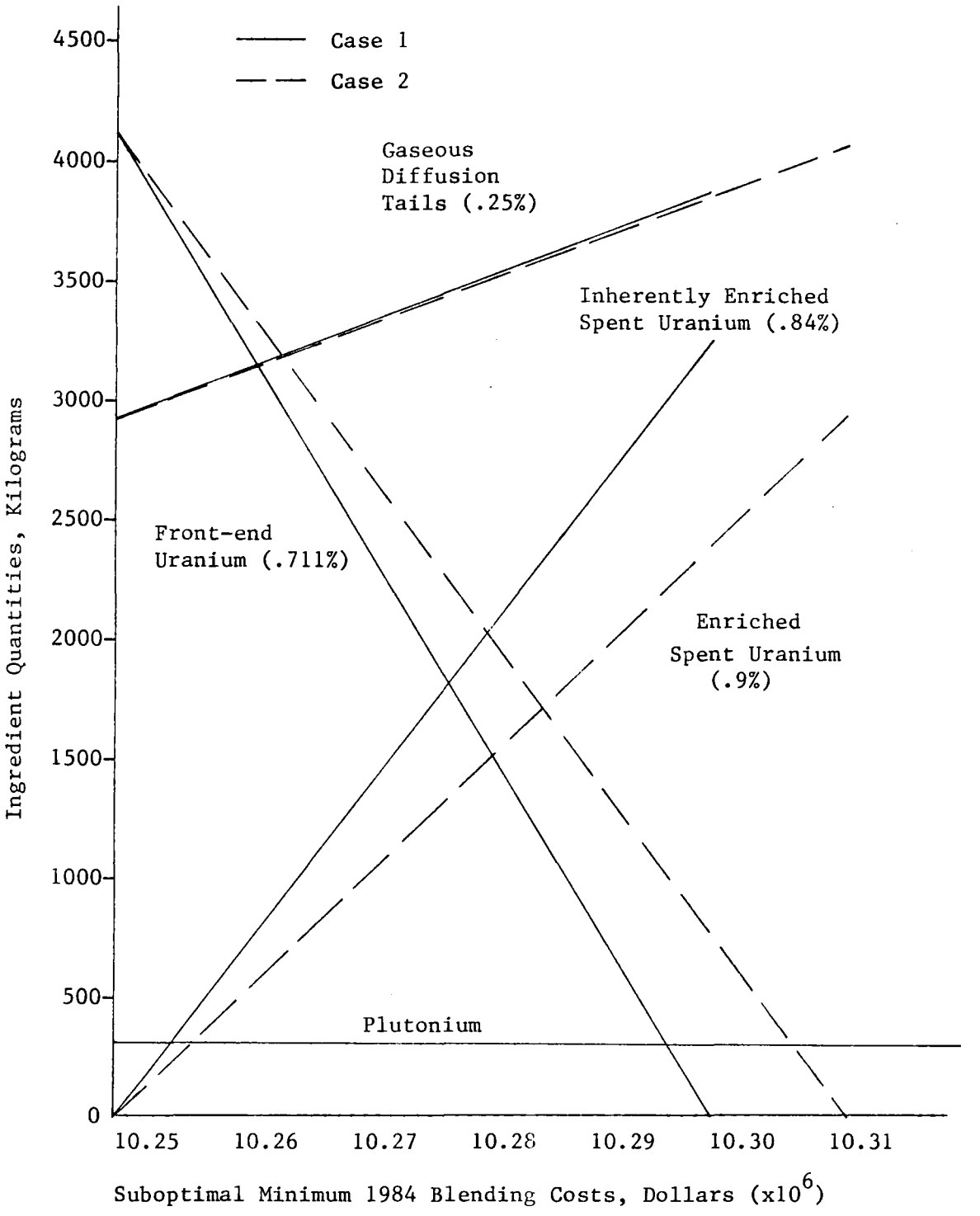

Figure 6.2. Effect of Constrained Natural Uranium Capacity on BWR-SGR Fuel Blending Composition and Cost

Table 6.1. Annual Minimum MOX Fuel Cost for a SGR Reactor

Quantity - Millions of Dollars

Year	PWR - SGR	BWR - SGR
1984	11.92	10.26
1985	12.88	11.13
1986	13.35	11.54
1987	13.66	11.81
1988	14.40	12.46
1989	15.25	13.20
1990	16.30	14.13
1991	17.73	15.39
1992	19.28	16.76
1993	20.63	17.96
1994	21.62	18.84
1995	22.35	19.47
1996	23.16	20.19
1997	23.88	20.82
1998	24.69	21.54
1999	25.68	22.42
2000	26.55	23.23

under three different reactor growth scenarios. The results of the analyses for the three reactor growth scenarios, presented in Chapter 3, are compared to the no recycle option for that particular reactor growth scenario. In addition, it is determined that MOX fuel fabrication limits the utilization of MOX fuel, so this parameter is increased by 50 percent to investigate its effect on the solution.

As a frame of reference, ERDA has estimated that the current uranium resource is about 3.7 million tons (or 3.37 million metric tons).[8] This represents approximately 2.85 million metric tons of UF_6.

6.2.1 LOW Case Scenario

The LOW reactor growth scenario assumes a slow rate of growth for the nuclear industry, reaching only 400 operating reactors in the year 2000. Also assumed is that reprocessing will be re-initiated in 1981, with MOX fuel fabrication starting in 1983. This permits the introduction of MOX fuel assemblies into LWRs starting in 1984.

Table 6.2 represents the anticipated UF_6 consumption incurred if there is no recycle of plutonium and spent uranium. A cummulative total of 945172 MT of UF_6 is consumed if there is no recycle, as compared to 644131 MT of UF_6 (Table 6.3) if spent nuclear fuel is recycled back into self-generating reactors. This represents a 32 percent savings in the total amount of UF_6 required. Figure 6.3 graphically represents the annual demands for UF_6 for both the no recycle and recycle cases.

At this point, it is necessary to note that additional tables and figures describing the behavior of the results for components of the nuclear industry are presented in Appendix A.

Table 6.2. UF_6 Consumption (No Recycle) - LOW Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	6517	2647	9164	9164
1978	7331	2647	9978	19142
1979	8146	3893	12039	31181
1980	8961	4204	13165	44346
1981	11242	6384	17626	61972
1982	11567	6540	18107	80079
1983	14011	8409	22420	102499
1984	14989	8097	23086	125585
1985	19225	9966	29161	154746
1986	21994	13392	35386	190132
1987	23461	13080	36541	226673
1988	24601	12302	36903	263576
1989	27371	13548	40919	304495
1990	28511	14326	42837	347332
1991	30792	15727	46519	393851
1992	33725	17284	51009	444860
1993	36006	17752	53758	498618
1994	37798	19309	57107	555725
1995	40893	21022	61915	617640
1996	42360	20399	62759	680399
1997	42523	21800	64323	744722
1998	43989	21489	65478	810200
1999	44967	22112	67079	877279
2000	45781	22112	67893	945172

Table 6.3. UF_6 Consumption (With Recycle) - LOW Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	6517	2647	-	-	-	-	9164	9164
1978	7331	2647	-	-	-	-	9978	19142
1979	8146	3893	-	-	-	-	12039	31181
1980	8961	4204	-	-	-	-	13165	44346
1981	11242	6384	-	-	-	-	17626	61972
1982	11567	6540	-	-	-	-	18107	80079
1983	14011	8409	-	-	-	-	22420	102499
1984	10590	8097	1927	-	-	-	20614	123113
1985	10427	9966	3853	-	-	-	24246	147359
1986	13197	13392	3853	-	-	-	30442	177801
1987	14663	13080	3853	-	-	-	31596	209397
1988	11242	12302	5994	-	-	-	29538	238935
1989	8146	11056	8421	1101	-	-	28724	267659
1990	7494	5762	9206	3786	-	-	26248	293907
1991	7657	5294	10133	4612	-	-	27696	321603
1992	8798	8253	10918	3993	-	-	31962	353565
1993	9124	6696	11775	4888	-	-	32483	386048
1994	8635	19309	12774	-	-	-	40718	426766
1995	9449	7163	13773	6127	-	-	36512	463278
1996	8798	4360	14700	7091	-	-	34949	498227
1997	6517	4671	15771	7573	-	-	34532	532759
1998	5865	3737	16698	7848	-	-	34148	566907
1999	5376	18842	17341	1446	-	-	43005	609912
2000	4725	3114	17983	8399	-	-	34221	644133

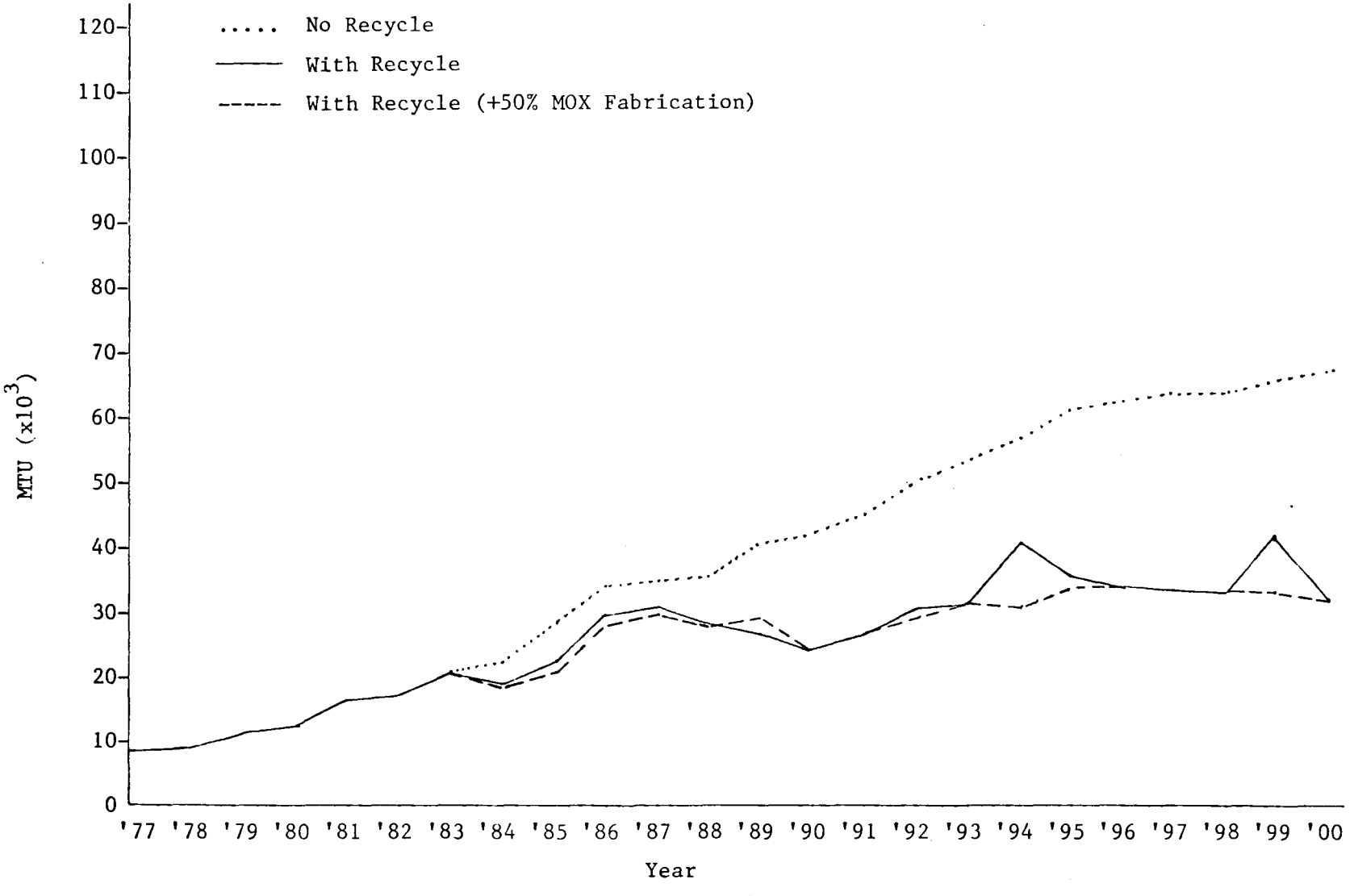

Figure 6.3. UF_6 Consumption - LOW Case

By the year 2000, there will be 252 PWRs and 122 BWRs operating as self-generating reactors (Table A.1, Figures A.1 and A.2), the remaining reactors being fueled with UO_2 fuel. To sustain the MOX fueled reactors, a total of 22015 MT of MOX fuel is fabricated (Table A.2 and Figure A.3), requiring 85041 MT of reprocessed spent fuel (Table A.3 and Figure A.4).

A total of 605.44 million SWU (Table A.4) are required for the no recycle case. With recycle, a total of 521.69 million SWU are required (Table A.5 and Figure A.5), resulting in a 14 percent savings. This is less than the anticipated 20 percent reported by the Atlantic Council.[5]

The total amount of UO_2 fuel fabrication for the recycle case (Table A.6) represents a 14 percent savings over the 157863 MT of UO_2 fuel fabrication required by the no recycle case (Table A.7 and Figure A.6). This is expected since part of the fuel is fabricated in a MOX fuel fabrication plant.

One final parameter that is necessary in the comparison of alternative strategies is the cost incurred by each strategy. For the no recycle case, a total of $324.50 billion is spent just to obtain the required nuclear fuels (Table A.8). The recycle option offers an 8 percent reduction in the overall cost of the nuclear fuels (Table A.9 and Figure A.7). This assumes that the capital costs associated with constructing and maintaining each type of nuclear reactor are relatively the same.

Tables A.10 through A.16 represent the behavior of the nuclear industry if the ability to fabricate MOX fuel is increased by 50 percent. For this case, 620059 MT of UF_6 are required to support the recycle industry. This represents a 34 percent savings in UF_6 requirements over the no recycle case. In addition, it was found that a 50 percent

increase in the amount of MOX fabrication capacity did not result in an appreciable increase in the conservation of UF_6. Results also indicate that no reactors are found to be operating as plutonium burners.

6.2.2 MID Case Scenario

The MID reactor growth scenario assumes a moderate rate of growth for the nuclear industry, reaching 507 operating reactors in the year 2000. As assumed in the LOW case, reprocessing will be re-initiated in 1981 with MOX fuel fabrication starting in 1983. This again permits the introduction of MOX fuel assemblies into LWRs starting in 1984.

Table 6.4 represents the anticipated UF_6 consumption incurred if there is no recycle of plutonium and spent uranium in the MID case. A cummulative total of 1136686 MT of UF_6 is consumed if there is no recycle, as compared to 792644 MT of UF_6 (Table 6.5) if spent nuclear fuel is recycled back into self-generating reactors. Comparable to the results of the LOW case, a 30 percent savings in the total amount of UF_6 required is realized. Figure 6.4 graphically represents the annual demands for UF_6 for both the no recycle and recycle cases.

In the year 2000, 312 PWRs and 63 BWRs will be operating as self-generating reactors, the remaining 26 PWRs and 106 BWRs being fueled with UO_2 fuel (Table A.17 and Figures A.8 and A.9). To sustain the MOX fueled reactors for the MID case, a total of 25702 MT of MOX fuel is fabricated (Table A.18 and Figure A.10), requiring 99293 MT of reprocessed spent fuel (Table A.19 and Figure A.11).

A total of 728.53 million SWU (Table A.20) are required for the no recycle case. With recycle, a total of 626.62 million SWU (Table A.21

Table 6.4. UF_6 Consumption (No Recycle) - MID Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	7657	3270	10927	10927
1978	8309	2803	11112	22039
1979	8309	3426	11735	33774
1980	9449	4827	14276	48050
1981	10753	5917	16670	64720
1982	14663	9032	23695	88415
1983	16129	9032	25161	113576
1984	17921	10589	28510	142086
1985	21669	11056	32725	174811
1986	23624	13859	37483	212294
1987	25905	14637	40542	252836
1988	28674	14637	43311	296147
1989	32096	15572	47668	343815
1990	33888	17752	51640	395455
1991	37309	19000	56309	451764
1992	40568	20866	61434	513198
1993	43011	21645	64656	577854
1994	46270	23513	69783	647637
1995	49202	24915	74117	721754
1996	51646	25693	77339	799093
1997	53438	26939	80377	879420
1998	55393	27562	82955	962425
1999	57186	28652	85838	1048263
2000	59304	29119	88423	1136686

Table 6.5. UF_6 Consumption (With Recycle) - MID Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	7657	3270	-	-	-	-	10927	10927
1978	8309	2803	-	-	-	-	11112	22039
1979	8309	3426	-	-	-	-	11735	33774
1980	9449	4827	-	-	-	-	14276	48050
1981	10753	5917	-	-	-	-	16670	64720
1982	14663	9032	-	-	-	-	23695	88415
1983	16129	9032	-	-	-	-	25161	113576
1984	11893	12146	1927	-	-	-	25966	139542
1985	13197	11056	3711	-	-	-	27964	167506
1986	15803	13859	3425	-	-	-	33087	200593
1987	15966	14637	4353	-	-	-	34956	235549
1988	14663	14637	6137	-	-	-	35437	270986
1989	10753	14793	9348	3442	-	-	38336	309332
1990	10101	11523	10419	2754	-	-	34797	344119
1991	10753	7630	11632	5025	-	-	35040	379159
1992	11567	6852	12702	6196	-	-	37317	416476
1993	11242	6384	13915	6747	-	-	38288	454764
1994	11567	6852	15200	7366	-	-	40985	495749
1995	11730	7007	16413	7917	-	-	43067	538816
1996	11242	24603	17698	4819	-	-	58362	597178
1997	10753	13392	18982	5989	-	-	49116	646294
1998	9287	8409	20195	8468	-	-	46359	692653
1999	8635	5450	21266	10257	-	-	45608	738261
2000	8472	19309	22265	4337	-	-	54383	792644

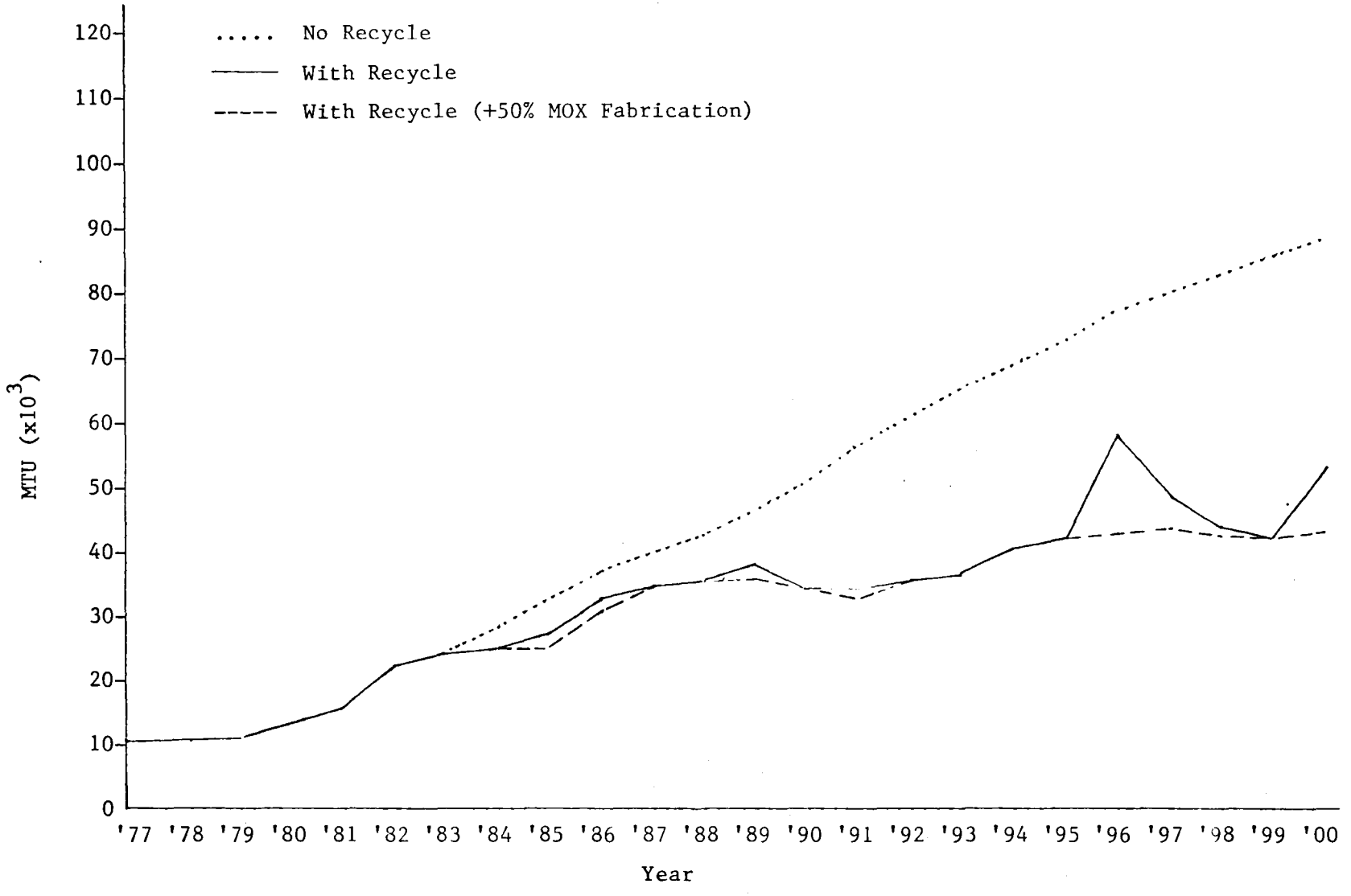

Figure 6.4. UF_6 Consumption - MID Case

and Figure A.12) are required, resulting in a 14 percent savings. This savings is comparable to the savings obtained in the LOW case.

The total amount of UO_2 fuel fabrication required for the recycle case (Table A.22) represents a 13 percent savings over the 189680 MT of UO_2 fuel fabrication required by the no recycle case. (Table A.23 and Figure A.13). Again, this is expected since part of the fuel is fabricated in a MOX fuel fabrication plant.

The total monetary expenditure required in producing the fuels for the no recycle case is $395.36 billion (Table A.24). The recycle option offers an 8 percent reduction in the overall cost of the nuclear fuels (Table A.25 and Figure A.14). This again assumes that the capital costs associated with constructing and maintaining each type of nuclear reactor are relatively equivalent.

Tables A.26 through A.32 represent the behavior of the nuclear industry if the ability to fabricate MOX fuel is increased by 50 percent. For the MID case, 758196 MT of UF_6 are required to support an industry that has 312 PWRs and 152 BWRs operating as self-generating reactors in the year 2000. This represents a 33 percent savings in UF_6 requirements over the no recycle case. Again it was found that it is not necessary to implement a 50 percent increase in the amount of MOX fabrication capacity in order to conserve a great quantity of UF_6. Results also indicate that no reactors are found to be operating as plutonium burners.

6.2.3 HIGH Case Scenario

The HIGH reactor growth scenario assumes a healthy rate of growth

for the nuclear industry, reaching 600 operating reactors in 2000. As assumed in the LOW and MID cases, reprocessing will be re-initiated in 1981 with MOX fuel fabrication starting in 1983. This again permits the introduction of MOX fuel assemblies into LWRs starting in 1984.

Table 6.6 represents the anticipated UF_6 consumption incurred if there is no recycle of plutonium and spent uranium for the HIGH case. A cummulative total of 1302369 MT of UF_6 is consumed if there is no recycle, as compared to 930579 MT of UF_6 (Table 6.7) if spent nuclear fuel is recycled back into self-generating reactors. Comparable to the results of the MID case, a 29 percent savings in the total amount of UF_6 required is realized. Figure 6.5 graphically represents the annual demands for UF_6 for both the no recycle and recycle cases.

In the year 2000, 365 PWRs and 65 BWRs will be operating as self-generating reactors, the remaining 35 PWRs and 135 BWRs being fueled with UO_2 fuel (Table A.33 and Figures A.15 and A.16). To sustain the MOX fueled reactors for the HIGH case, a total of 26880 MT of MOX fuel is fabricated (Table A.34 and Figure A.17), requiring 103796 MT of reprocessed spent fuel (Table A.35 and Figure A.18).

A total of 834.06 million SWU (Table A.36) are required for the no recycle case. With recycle, a total of 730.96 million SWU (Table A.37 and Figure A.19) are required, resulting in a 12 percent savings. This savings is lower than those observed in the LOW and MID cases.

The total amount of UO_2 fuel fabrication required for the recycle case (Table A.38) represents a 12 percent savings over the 217599 MT of UO_2 fuel required by the no recycle case (Table A.39 and Figure A.20). Again, this is expected since part of the fuel is fabricated in a MOX

Table 6.6. UF_6 Consumption (No Recycle) - HIGH Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	7331	2803	10134	10134
1978	8309	2803	11112	21246
1979	8798	4049	12847	34093
1980	10590	4983	15573	49666
1981	10264	6073	16337	66003
1982	17270	10433	27703	93706
1983	18084	10122	28206	121912
1984	20691	11834	32525	154437
1985	23461	11834	35295	189732
1986	25416	14637	40053	229785
1987	27697	16039	43736	273521
1988	32421	16817	49238	322759
1989	36495	17440	53935	376694
1990	38938	20243	59181	435875
1991	43011	21800	64811	500686
1992	45944	24136	70080	570766
1993	50180	25226	75406	646172
1994	53275	27406	80681	726853
1995	56697	28496	85193	812046
1996	59629	30053	89682	901728
1997	62399	31455	93854	995582
1998	65983	32545	98528	1094110
1999	67776	34569	102345	1196455
2000	71034	34880	105914	1302369

Table 6.7. UF_6 Consumption (With Recycle) - HIGH Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	7331	2803	-	-	-	-	10134	10134
1978	8309	2803	-	-	-	-	11112	21246
1979	8798	4049	-	-	-	-	12847	34093
1980	10590	4983	-	-	-	-	15573	49666
1981	10264	6073	-	-	-	-	16337	66003
1982	17270	10433	-	-	-	-	27703	93706
1983	18084	10122	-	-	-	-	28206	121912
1984	16292	11834	1927	-	-	-	30053	151965
1985	14663	11834	3853	-	-	-	30350	182315
1986	16618	14637	3853	-	-	-	35108	217423
1987	18899	16039	3853	-	-	-	38791	256214
1988	19062	16817	5852	-	-	-	41731	297945
1989	14174	17440	9776	-	-	-	41390	339335
1990	12708	16039	11489	1859	-	-	42095	381430
1991	13360	13236	12988	3855	-	-	43439	424869
1992	13197	10433	14344	6058	-	-	44032	468901
1993	14011	10744	15842	6402	-	-	46999	515900
1994	13848	13703	17269	6058	-	-	50878	566778
1995	13685	17907	18839	4681	-	-	55112	621890
1996	13197	16662	20338	5920	-	-	56117	678007
1997	12545	20866	21836	4681	-	-	59928	737935
1998	12871	20866	23264	5163	-	-	62164	800099
1999	11567	21800	24620	5645	-	-	63632	863731
2000	11567	24759	26047	4475	-	-	66848	930579

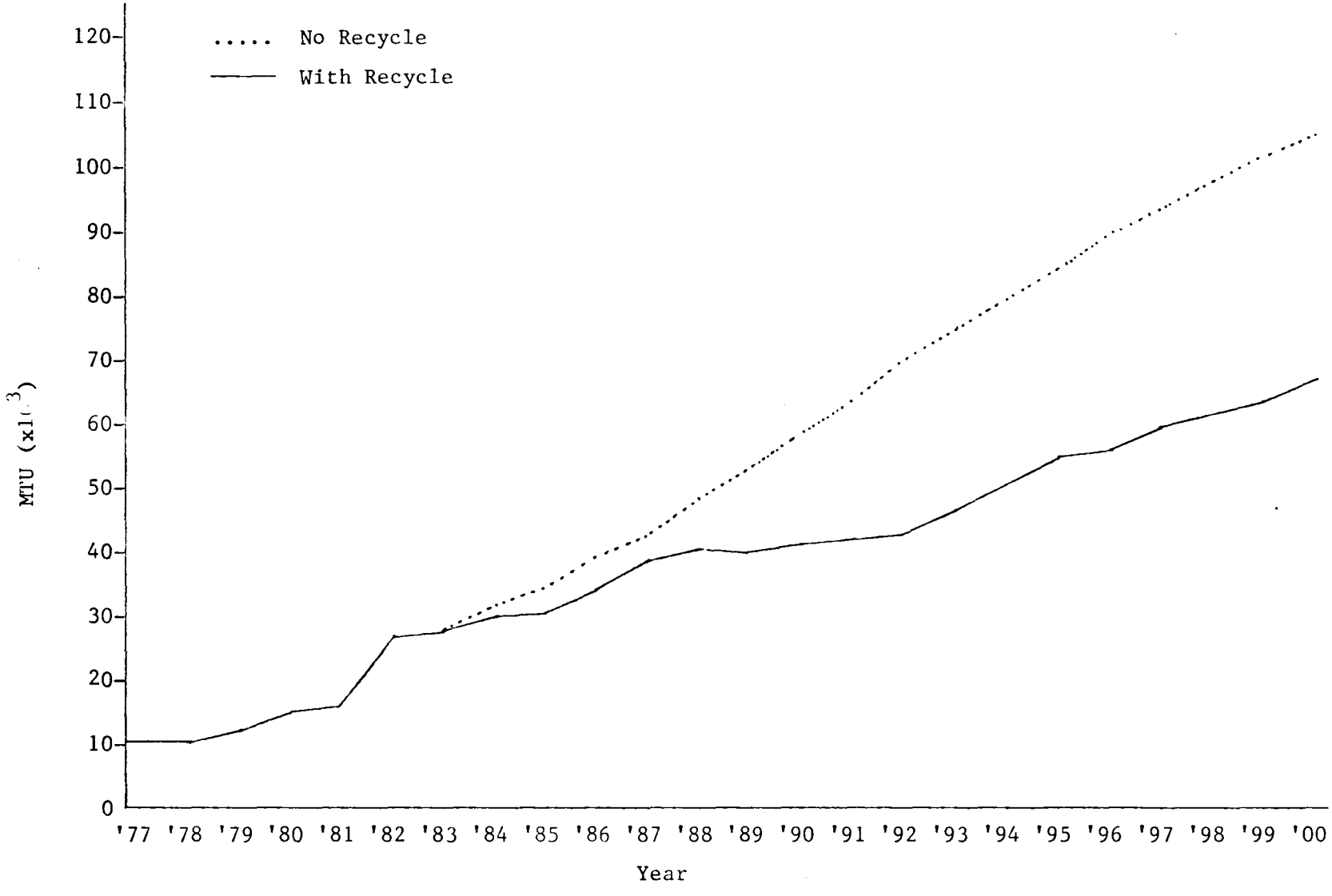

Figure 6.5. UF_6 Consumption - HIGH Case

fuel fabrication plant.

Finally, the total monetary expenditure required in producing the fuels for the no recycle case is $450.26 billion (Table A.40). The recycle option offers only a 6 percent reduction in the overall cost of the nuclear fuels (Table A.41 and Figure A.21). Results also indicate that no reactors are found to be operating as plutonium burners.

7. CONCLUSIONS

It is concluded that the scheduling of reactor fuel (UO_2 and MOX) can be modeled by linear programming. The formulation of the MOX fuel blending model and the reactor mix model specifically lead to solutions yielding optimal use of MOX fueled reactors, restricted by the availability of plutonium and the ability to produce MOX fuel (i.e. spent fuel generation, reprocessing, and MOX fuel fabrication).

Conclusions from the MOX fuel blending model indicate that gaseous diffusion tails and natural uranium are preferable to spent uranium and enriched natural uranium in the production of MOX fuel. However, as the availability of natural uranium is restricted, spent uranium exhibits a preference to enriched natural uranium in the blending process. The use of spent uranium leads to a small increase in the overall cost of the MOX fuel. If the spent uranium is further enriched, not only does the MOX fuel cost increase, but the requirements for enrichment services also increase.

From the analyses performed, the conclusions reached by this study is that the recycling of spent uranium and plutonium into the LWR fuel cycle (via self-generating reactors) is the optimal policy for conserving the natural uranium resources. This policy prevails only with the existence of plutonium and spent uranium recycle. However, controversies over reprocessing and plutonium diversion have forced the suspension of reprocessing. Thus, the absence of recycling places a higher demand on the natural uranium resources and SWU availability. The policy determined will help in specifying the types of fuel each reactor should utilize

each year upon the re-initiation of reprocessing and the recycling of uranium and plutonium.

Also to be concluded from this study is that MOX fuel fabrication and, at times, reprocessing capacities are the areas of greatest solution sensitivity. From the analyses performed, it is found that increasing the MOX fuel fabrication capacity results in a more efficient use of MOX fueled reactors. At this point, it is found that reprocessing begins to restrict the introduction of these reactors. From this, it can be concluded that by properly scheduling reprocessing and MOX fuel fabrication capacities, a significant savings in natural uranium resources and SWU can result. Not only the scheduling of these capacities, but the amount of the capacity scheduled is crucial for the effective use of MOX fueled reactors. As seen in Figure 6.3, if MOX fuel fabrication is increased, additional savings of natural uranium can be incurred. Therefore, it can be concluded that the reprocessing and MOX fuel fabrication capacities as projected by ERDA[14] are low when considered in conjunction with projected nuclear demand and the optimal reactor mix to minimize uranium consumption. Intense consideration must be given in determining these two capacity schedules. The other components of the nuclear industry have demonstrated ample capacity in order to meet required reactor demands.

The purchase of SWU is another parameter effected by recycle. From the analyses performed, it is inconclusive whether or not sufficient enrichment capability will exist for the domestic nuclear reactor program. This is due to an undefined foreign demand for U.S. enrichment services. In view of the U.S. government stance on restricting enrichment technology from foreign countries and the progressive growth of

nuclear power outside the U.S., an even greater demand for U.S. enrichment services will be required. From this it can be concluded that SWU availability is also a decisive factor when considering the possibility of spent uranium and plutonium recycle.

As reported at the 1976 Atlantic Council[5], a 21 percent savings in the cummulative demand for natural uranium and a 12 percent savings in the cummulative demand for SWU is obtained if plutonium and spent uranium are recycled. This compares favorably with the 29 to 34 percent savings in natural uranium and the 12 to 14 percent savings in SWU obtained in this study. Also reported by the Atlantic Council is that the cummulative demand for natural uranium will probably exceed the uranium resource by the mid-1990s.[5] This further substantiates the need to recycle plutonium and spent uranium in order to conserve the natural uranium resources.

8. SUMMARY AND RECOMMENDATIONS

The models developed constitute worthwhile tools for evaluating the efficiency of the use of MOX fueled reactors. In light of the present controversy over spent nuclear fuel reprocessing and plutonium diversion, the models developed should be utilized to analyze the importance of closing the nuclear fuel cycle by allowing spent nuclear fuel to be recycled. In view of the importance of the conclusions of this study, several areas of additional work have been identified. These areas could result in a more realistic treatment of the reactor mix model, and more importantly the use of MOX fueled reactors.

An important extension of this work would involve allowing each decision variable to represent reactors that are operating, under construction, or planned, coupled with actual reprocessing and fuel fabrication capacity projections. By representing actual reactors, specific fuel characteristics can be utilized, thus resulting in a more realistic solution.

Another important extension of this work would involve the assumption of a definite PuO_2 burner reactor growth schedule in order to study the effect on various components of the nuclear industry (i.e. reprocessing and MOX fuel fabrication).

Finally, in view of the cessation of the fast breeder reactor program, the model should be modified to allow for the introduction of the fast breeder reactor in order to study the effects on spent nuclear fuel and the growth of the light water reactor industry.

Specifically, as a result of this study, it is recommended that

spent uranium and plutonium be utilized in self-generating reactors, and that this strategy be adopted as a policy for minimizing the consumption of the natural uranium resource.

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10. APPENDIX

Appendix A

This section contains results of implementing the reactor mix model on the IBM-370 computer system. These graphic and tabular results represent the optimal fuel loading schedules for UO_2 and MOX fuels as established for each of the three reactor growth scenarios examined. Discussion of these results is found in Chapter 6.2.

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Table A.1. Reactor Fuel Schedule - LOW Case

Quantity - Number of Operating Reactors

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2
1976	-	-	-	-	-	-
1977	30	17	-	-	-	-
1978	35	17	-	-	-	-
1979	40	19	-	-	-	-
1980	45	21	-	-	-	-
1981	53	26	-	-	-	-
1982	59	30	-	-	-	-
1983	68	36	-	-	-	-
1984	49	40	27	-	-	-
1985	36	46	54	-	-	-
1986	51	56	54	-	-	-
1987	64	63	54	-	-	-
1988	47	67	84	-	-	-
1989	24	56	118	16	-	-
1990	24	22	129	55	-	-
1991	23	16	142	67	-	-
1992	26	32	153	58	-	-
1993	28	25	165	71	-	-
1994	27	103	179	-	-	-
1995	28	22	193	89	-	-
1996	28	13	206	103	-	-
1997	22	12	221	110	-	-
1998	18	12	234	114	-	-
1999	17	109	243	21	-	-
2000	15	11	252	122	-	-

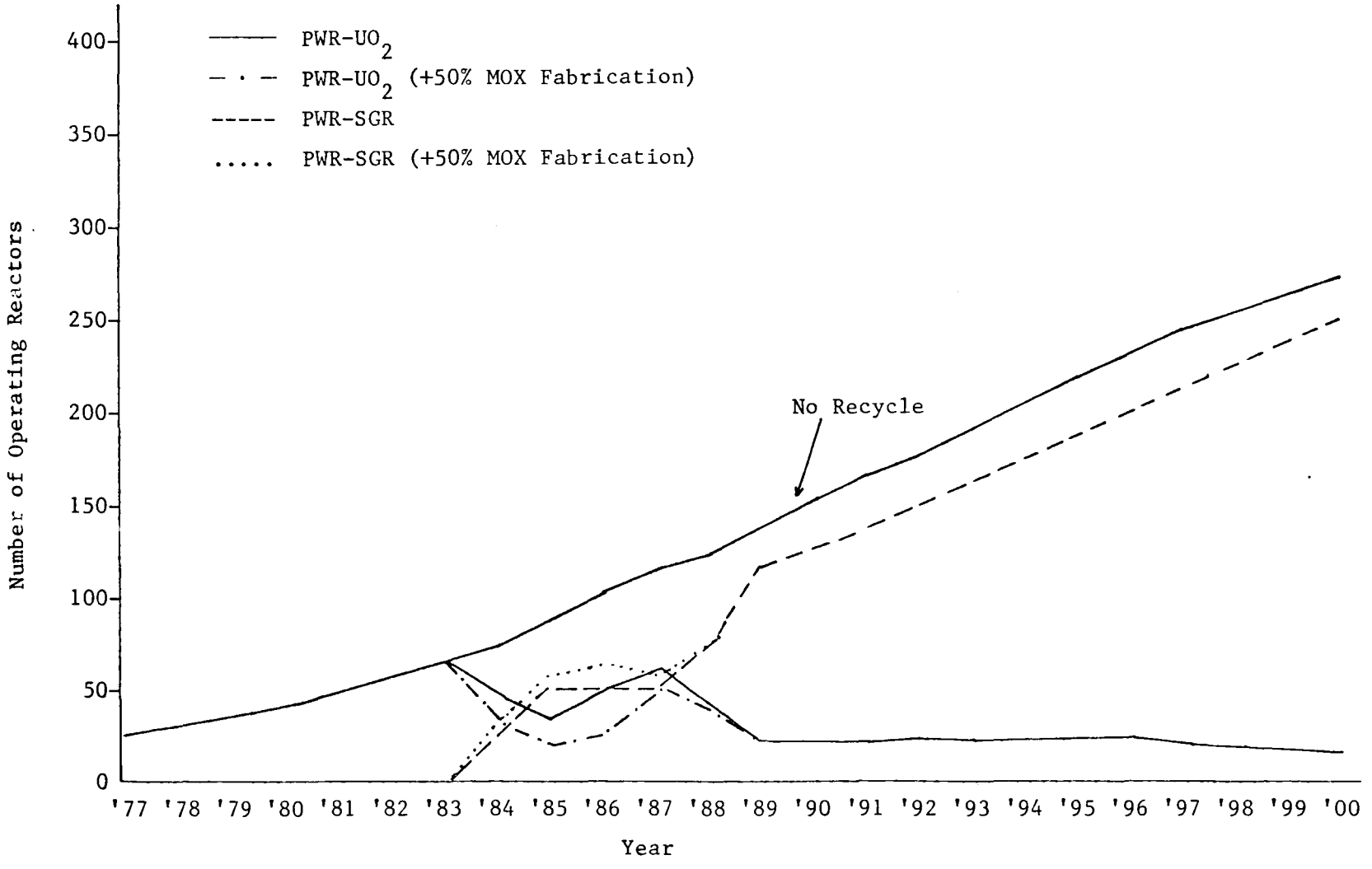

Figure A.1. PWR Fuel Schedule - LOW Case

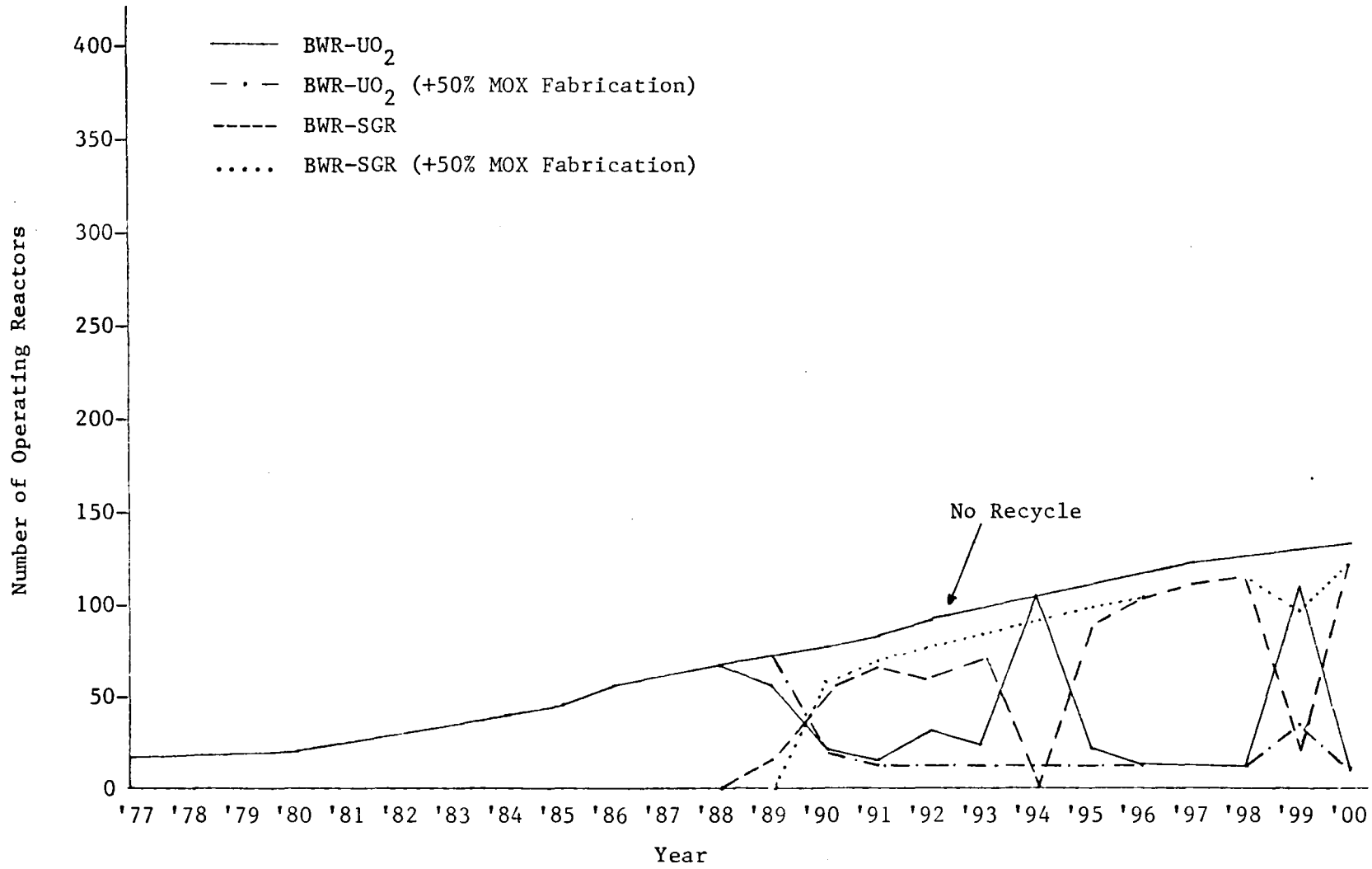

Figure A.2. BWR Fuel Schedule - LOW Case

Table A.2. MOX Fuel Fabrication - LOW Case

Quantity - MTHM

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-
1978	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-
1984	-	-	172	-	-	-	172	172
1985	-	-	344	-	-	-	344	516
1986	-	-	344	-	-	-	344	860
1987	-	-	344	-	-	-	344	1204
1988	-	-	535	-	-	-	535	1739
1989	-	-	751	117	-	-	868	2607
1990	-	-	821	403	-	-	1224	3831
1991	-	-	904	491	-	-	1395	5226
1992	-	-	974	425	-	-	1399	6625
1993	-	-	1050	520	-	-	1570	8195
1994	-	-	1139	-	-	-	1139	9334
1995	-	-	1228	652	-	-	1880	11214
1996	-	-	1311	754	-	-	2065	13279
1997	-	-	1407	806	-	-	2213	15492
1998	-	-	1489	835	-	-	2324	17816
1999	-	-	1547	154	-	-	1701	19517
2000	-	-	1604	894	-	-	2498	22015

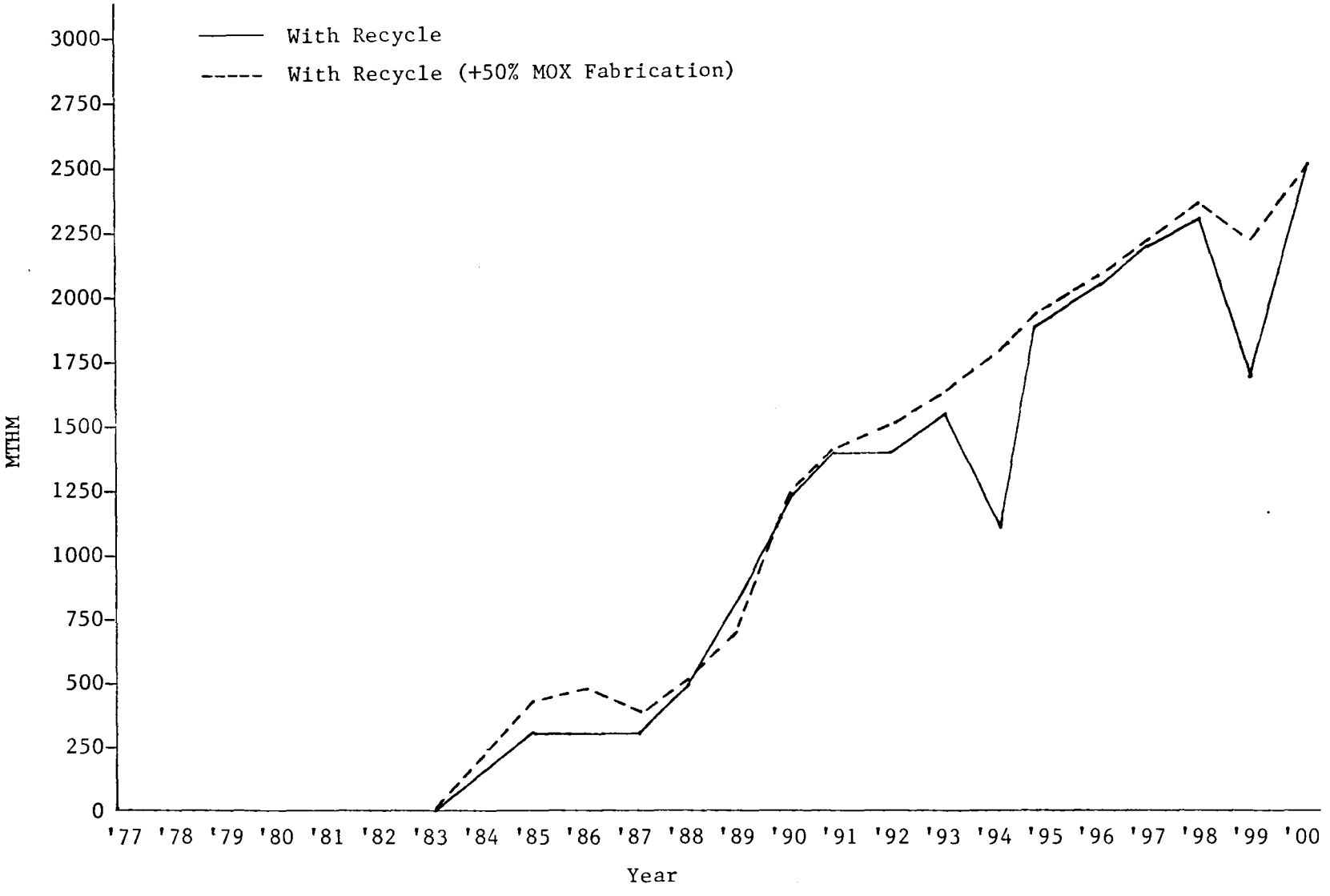

Figure A.3. MOX Fuel Fabrication - LOW Case

Table A.3. Reprocessing - LOW Case

Quantity - MTHM

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-
1978	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-
1984	-	-	663	-	-	-	663	663
1985	-	-	1325	-	-	-	1325	1988
1986	-	-	1325	-	-	-	1325	3313
1987	-	-	1325	-	-	-	1325	4638
1988	-	-	2062	-	-	-	2062	6700
1989	-	-	2896	455	-	-	3351	10051
1990	-	-	3166	1564	-	-	4730	14781
1991	-	-	3485	1905	-	-	5390	20171
1992	-	-	3755	1649	-	-	5404	25575
1993	-	-	4049	2019	-	-	6068	31643
1994	-	-	4393	-	-	-	4393	36036
1995	-	-	4737	2531	-	-	7268	43304
1996	-	-	5056	2929	-	-	7985	51289
1997	-	-	5424	3128	-	-	8552	59841
1998	-	-	5743	3242	-	-	8985	68826
1999	-	-	5964	597	-	-	6561	75387
2000	-	-	6185	3469	-	-	9564	85041

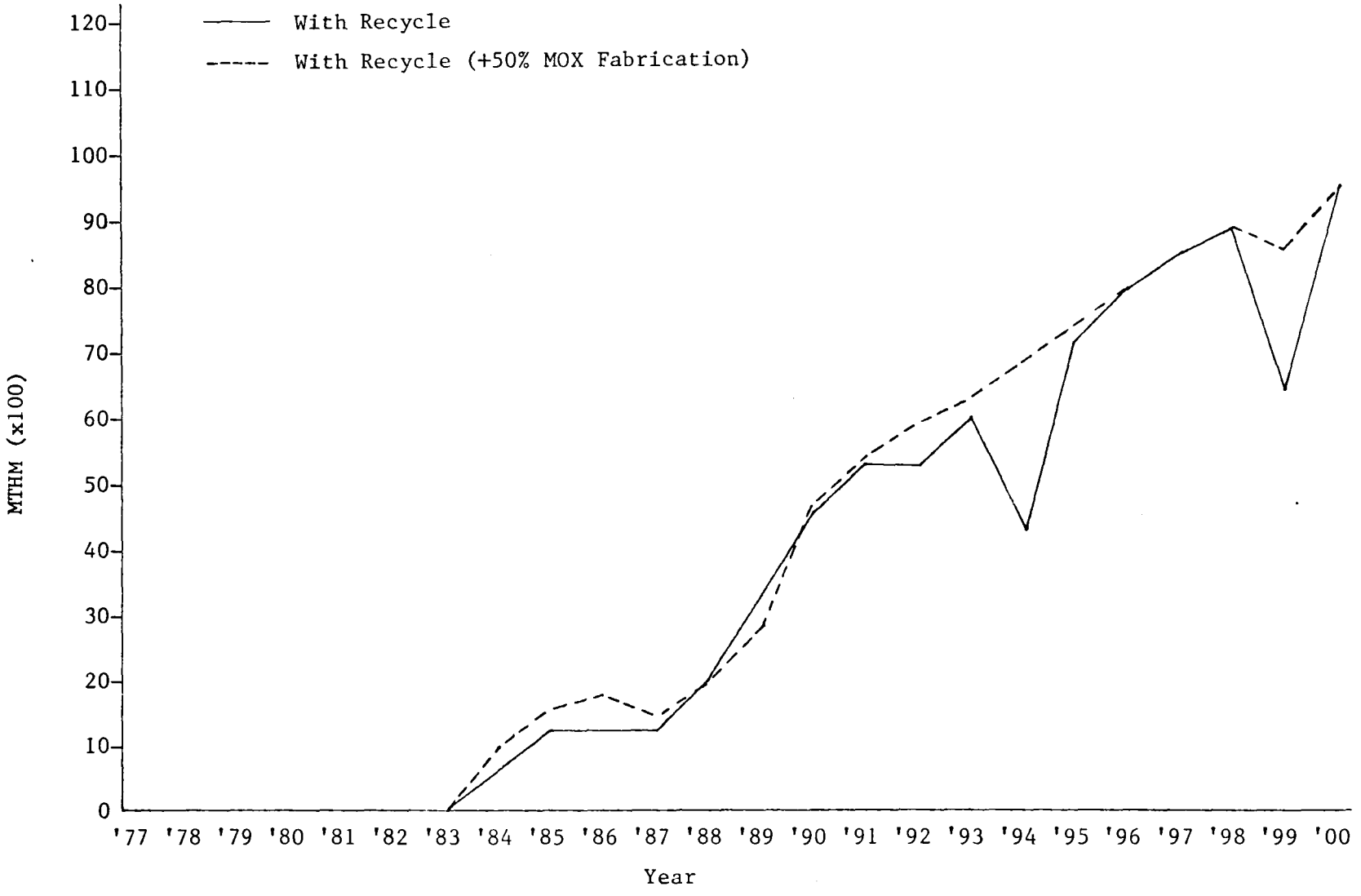

Figure A.4. Reprocessing - LOW Case

Table A.4. Enrichment Services (No Recycle) - LOW Case

Quantity - Million SWU

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	4.29	1.61	5.90	5.90
1978	4.82	1.61	6.43	12.33
1979	5.36	2.36	7.72	20.05
1980	5.89	2.55	8.44	28.49
1981	7.39	3.87	11.26	39.75
1982	7.61	3.97	11.58	51.33
1983	9.21	5.10	14.31	65.64
1984	9.86	4.91	14.77	80.41
1985	12.64	6.05	18.69	99.10
1986	14.46	8.13	22.59	121.69
1987	15.43	7.94	23.37	145.06
1988	16.18	7.47	23.65	168.71
1989	18.00	8.22	26.22	194.93
1990	18.75	8.69	27.44	222.37
1991	20.25	9.55	29.80	252.17
1992	22.18	10.49	32.67	284.84
1993	23.68	10.77	34.45	319.29
1994	24.86	11.72	36.58	355.87
1995	26.89	12.76	39.65	395.52
1996	27.86	12.38	40.24	435.76
1997	27.96	13.23	41.19	476.95
1998	28.93	13.04	41.97	518.92
1999	29.57	13.42	42.99	561.91
2000	30.11	13.42	43.53	605.44

Table A.5. Enrichment Services (With Recycle) - LOW Case

Quantity - Million SWU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	4.29	1.61	-	-	-	-	5.90	5.90
1978	4.82	1.61	-	-	-	-	6.43	12.33
1979	5.36	2.36	-	-	-	-	7.72	20.05
1980	5.89	2.55	-	-	-	-	8.44	28.49
1981	7.39	3.87	-	-	-	-	11.26	39.75
1982	7.61	3.97	-	-	-	-	11.58	51.33
1983	9.21	5.10	-	-	-	-	14.31	65.64
1984	6.96	4.91	2.22	-	-	-	14.09	79.73
1985	6.86	6.05	4.43	-	-	-	17.34	97.07
1986	8.68	8.13	4.43	-	-	-	21.24	118.31
1987	9.64	7.94	4.43	-	-	-	22.01	140.32
1988	7.39	7.47	6.90	-	-	-	21.76	162.08
1989	5.36	6.71	9.69	1.10	-	-	22.86	184.94
1990	4.93	3.50	10.59	3.79	-	-	22.81	207.75
1991	5.04	3.21	11.66	4.61	-	-	24.52	232.27
1992	5.79	5.01	12.56	3.99	-	-	27.35	259.62
1993	6.00	4.06	13.55	4.89	-	-	28.50	288.12
1994	5.68	11.72	14.70	-	-	-	32.10	320.22
1995	6.21	4.35	15.84	6.13	-	-	32.53	352.75
1996	5.79	2.65	16.91	7.09	-	-	32.44	385.19
1997	4.29	2.84	18.14	7.57	-	-	32.84	418.03
1998	3.86	2.27	19.21	7.85	-	-	33.19	451.22
1999	3.54	11.44	19.95	1.45	-	-	36.38	487.60
2000	3.11	1.89	20.69	8.40	-	-	34.09	521.69

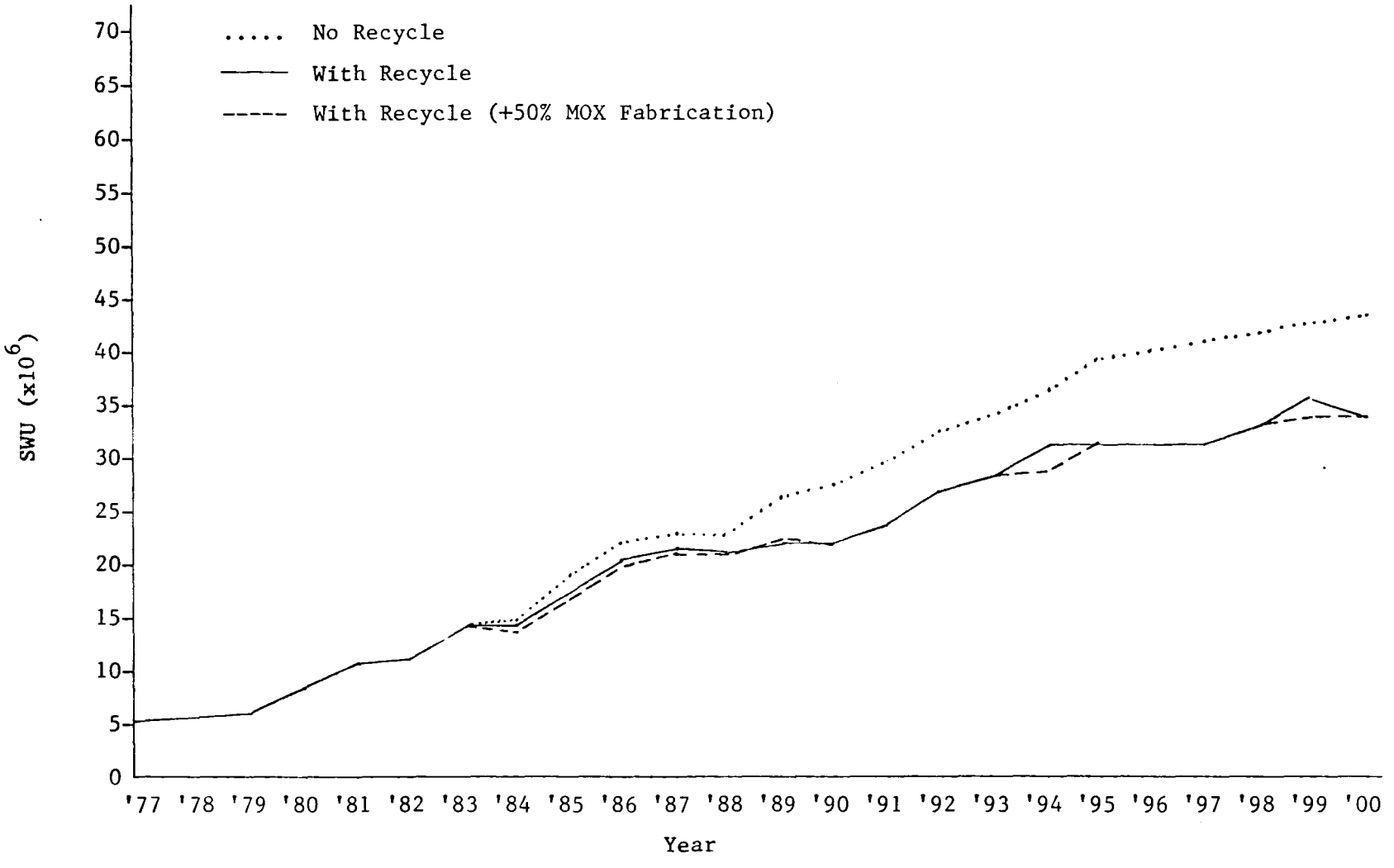

Figure A.5. Enrichment Services - LOW Case

Table A.6. UO_2 Fuel Fabrication (With Recycle) - LOW Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	1018	498	-	-	-	-	1516	1516
1978	1146	498	-	-	-	-	1644	3160
1979	1273	733	-	-	-	-	2006	5166
1980	1400	791	-	-	-	-	2191	7357
1981	1757	1201	-	-	-	-	2958	10315
1982	1808	1231	-	-	-	-	3039	13354
1983	2190	1582	-	-	-	-	3772	17126
1984	1655	1524	516	-	-	-	3695	20821
1985	1629	1875	1031	-	-	-	4535	25356
1986	2062	2520	1031	-	-	-	5613	30969
1987	2291	2461	1031	-	-	-	5783	36752
1988	1757	2315	1604	-	-	-	5676	42428
1989	1273	2080	2253	352	-	-	5958	48386
1990	1171	1084	2463	1209	-	-	5927	54313
1991	1197	996	2711	1472	-	-	6376	60689
1992	1375	1553	2922	1275	-	-	7125	67814
1993	1426	1260	3151	1560	-	-	7397	75211
1994	1349	3633	3418	-	-	-	8400	83611
1995	1477	1348	3685	1956	-	-	8466	92077
1996	1375	820	3934	2263	-	-	8392	100469
1997	1018	879	4220	2417	-	-	8534	109003
1998	917	703	4468	2505	-	-	8593	117596
1999	840	3545	4640	461	-	-	9486	127082
2000	738	586	4812	2681	-	-	8817	135899

Table A.7. UO_2 Fuel Fabrication (No Recycle) - LOW Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	1018	498	1516	1516
1978	1146	498	1644	3160
1979	1273	733	2006	5166
1980	1400	791	2191	7357
1981	1757	1201	2958	10315
1982	1808	1231	3039	13354
1983	2190	1582	3772	17126
1984	2342	1524	3866	20992
1985	3004	1875	4879	25871
1986	3437	2520	5957	31828
1987	3666	2461	6127	37955
1988	3844	2315	6159	44114
1989	4277	2549	6826	50940
1990	4456	2696	7152	58092
1991	4812	2959	7771	65863
1992	5270	3252	8522	74385
1993	5627	3340	8967	83352
1994	5907	3633	9540	92892
1995	6390	3956	10346	103238
1996	6620	3838	10458	113696
1997	6645	4102	10747	124443
1998	6874	4043	10917	135360
1999	7027	4161	11188	146548
2000	7154	4161	11315	157863

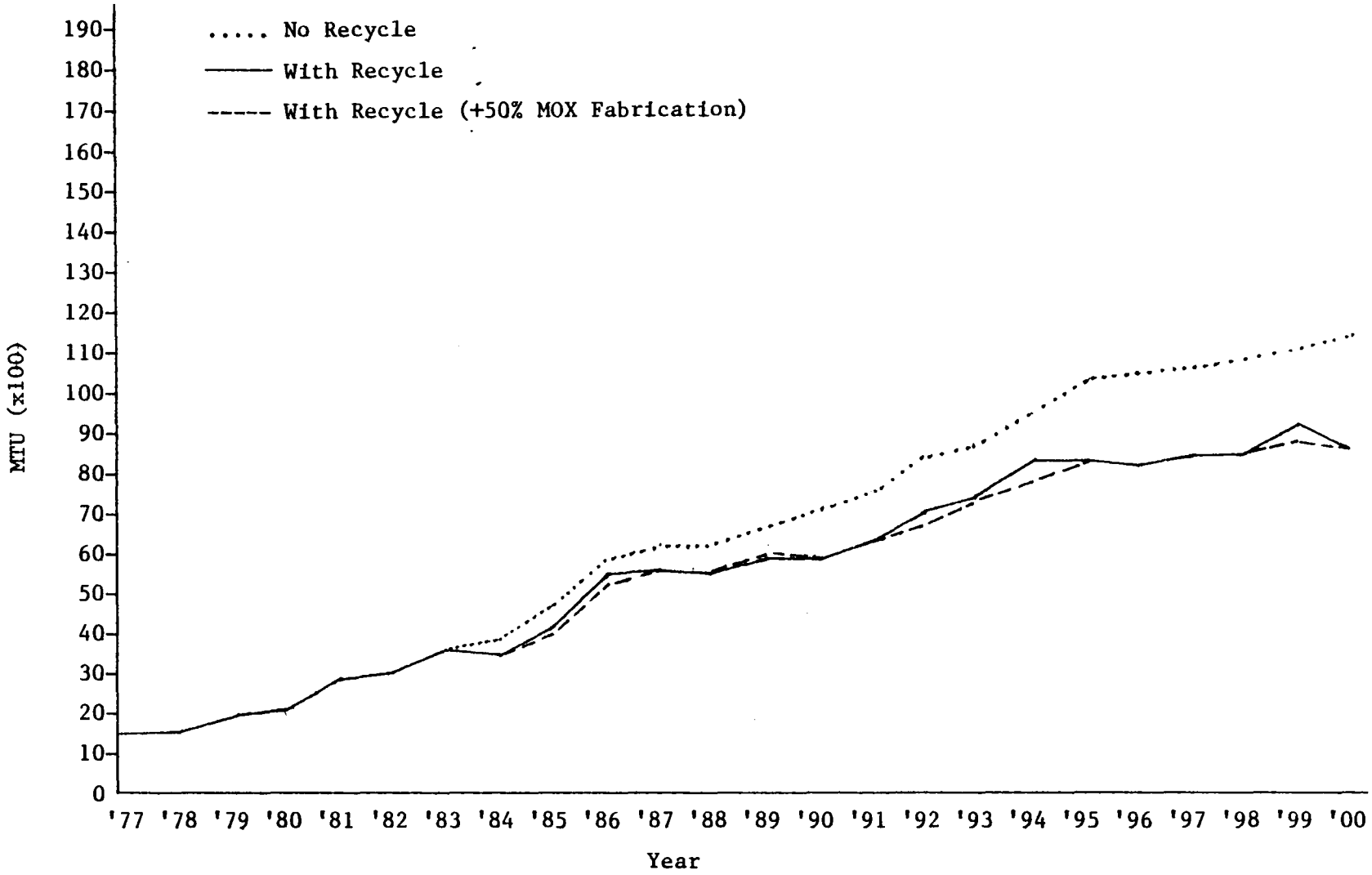

Figure A.6. UO_2 Fuel Fabrication - LOW Case

Table A.8. Fuel Cost (No Recycle) - LOW Case

Quantity - Billions of Dollars

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	0.88	0.36	1.24	1.24
1978	1.05	0.39	1.44	2.68
1979	1.25	0.60	1.85	4.53
1980	1.47	0.69	2.16	6.69
1981	1.97	1.11	3.08	9.77
1982	2.22	1.25	3.47	13.24
1983	2.92	1.74	4.66	17.90
1984	3.33	1.78	5.11	23.01
1985	4.53	2.32	6.85	29.86
1986	5.38	3.24	8.62	38.48
1987	5.88	3.24	9.12	47.60
1988	6.48	3.21	9.69	57.29
1989	7.62	3.74	11.36	68.65
1990	8.45	4.21	12.66	81.31
1991	9.87	5.00	14.87	96.18
1992	11.68	5.95	17.63	113.81
1993	13.29	6.51	19.80	133.61
1994	14.59	7.41	22.00	155.61
1995	16.31	8.34	24.65	180.26
1996	17.47	8.37	25.84	206.10
1997	18.10	9.22	27.32	233.42
1998	19.31	9.38	28.69	262.11
1999	20.48	10.02	30.50	292.61
2000	21.54	10.35	31.89	324.50

Table A.9. Fuel Cost (With Recycle) - LOW Case

Quantity- Billions of Dollars

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	0.88	0.36	-	-	-	-	1.24	1.24
1978	1.05	0.39	-	-	-	-	1.44	2.68
1979	1.25	0.60	-	-	-	-	1.85	4.53
1980	1.47	0.69	-	-	-	-	2.16	6.69
1981	1.97	1.12	-	-	-	-	3.09	9.78
1982	2.22	1.25	-	-	-	-	3.47	13.25
1983	2.92	1.74	-	-	-	-	4.66	17.91
1984	2.35	1.78	0.86	-	-	-	4.99	22.90
1985	2.46	2.32	1.84	-	-	-	6.62	29.52
1986	3.23	3.24	1.91	-	-	-	8.38	37.90
1987	3.67	3.24	1.95	-	-	-	8.86	46.76
1988	2.96	3.21	3.19	-	-	-	9.36	56.12
1989	2.27	3.05	4.73	0.62	-	-	10.67	66.79
1990	2.22	1.69	5.49	2.26	-	-	11.66	78.45
1991	2.45	1.68	6.52	2.97	-	-	13.62	92.07
1992	3.05	2.84	7.58	2.78	-	-	16.25	108.32
1993	3.37	2.45	8.70	3.62	-	-	18.14	126.46
1994	3.33	7.41	9.86	-	-	-	20.60	147.06
1995	3.77	2.84	10.99	4.90	-	-	22.50	169.56
1996	3.63	1.79	12.12	5.87	-	-	23.41	192.97
1997	2.77	1.98	13.41	6.46	-	-	24.62	217.59
1998	2.57	1.63	14.64	6.91	-	-	25.75	243.34
1999	2.45	8.54	15.77	1.32	-	-	28.08	271.42
2000	2.22	1.46	16.88	7.91	-	-	28.47	299.89

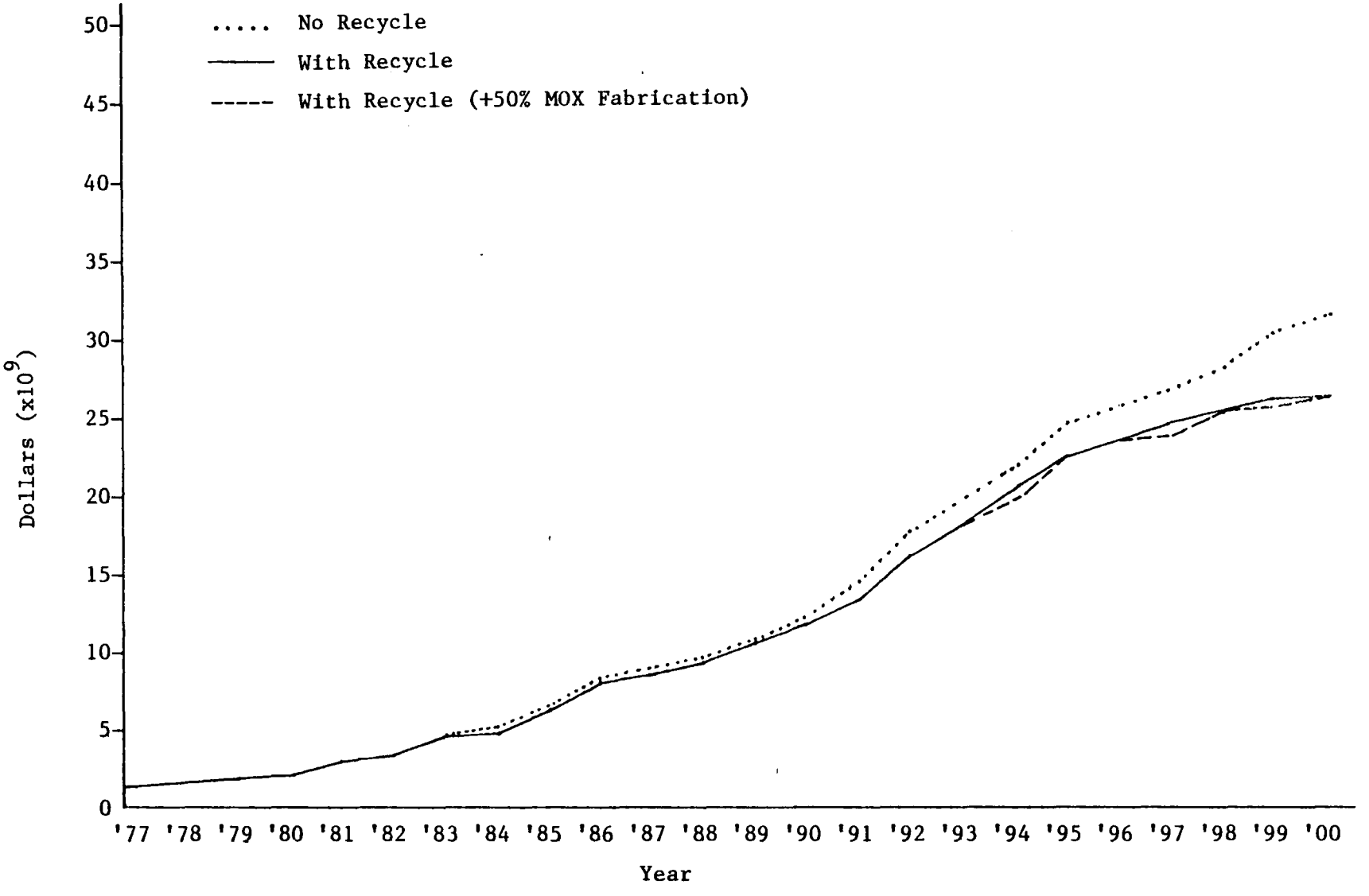

Figure A.7. Fuel Cost - LOW Case

Table A.10. UF_6 Consumption (+50% MOX Fuel Fabrication Capacity)

LOW Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	6517	2647	-	-	-	-	9164	9164
1978	7331	2647	-	-	-	-	9978	19142
1979	8146	3893	-	-	-	-	12039	31181
1980	8961	4204	-	-	-	-	13165	44346
1981	11242	6384	-	-	-	-	17626	61972
1982	11567	6540	-	-	-	-	18107	80079
1983	14011	8409	-	-	-	-	22420	102499
1984	8309	8097	2926	-	-	-	19332	121831
1985	8146	9966	4853	-	-	-	22965	144796
1986	9612	13392	5423	-	-	-	28427	173223
1987	13197	13080	4496	-	-	-	30773	203996
1988	10753	12302	6066	-	-	-	29121	233117
1989	8146	13547	8421	-	-	-	30114	263231
1990	7494	5450	9206	3924	-	-	26074	289305
1991	7657	4827	10133	4819	-	-	27436	316741
1992	8798	5294	10918	5301	-	-	30311	347052
1993	9124	5761	11775	5714	-	-	32374	379426
1994	8635	4827	12774	6196	-	-	32432	411858
1995	9449	6073	13773	6609	-	-	35904	447762
1996	8798	4360	14700	7091	-	-	34949	482711
1997	6517	4516	15771	7641	-	-	34445	517156
1998	5865	3426	16698	7986	-	-	33975	551131
1999	5376	5450	17341	6540	-	-	34707	585838
2000	4725	3114	17983	8399	-	-	34221	620059

Table A.11. Reactor Fuel Schedule (+50% MOX Fuel Fabrication Capacity)

LOW Case

Quantity - Number of Operating Reactors

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2
1976	-	-	-	-	-	-
1977	30	17	-	-	-	-
1978	35	17	-	-	-	-
1979	40	19	-	-	-	-
1980	45	21	-	-	-	-
1981	53	26	-	-	-	-
1982	59	30	-	-	-	-
1983	68	36	-	-	-	-
1984	35	40	41	-	-	-
1985	22	46	68	-	-	-
1986	29	56	76	-	-	-
1987	55	63	63	-	-	-
1988	44	67	85	-	-	-
1989	24	72	118	-	-	-
1990	24	20	129	57	-	-
1991	23	13	142	70	-	-
1992	26	13	153	77	-	-
1993	28	13	165	83	-	-
1994	27	13	179	90	-	-
1995	28	15	193	96	-	-
1996	28	13	206	103	-	-
1997	22	11	221	111	-	-
1998	18	10	234	116	-	-
1999	17	35	243	95	-	-
2000	15	11	252	122	-	-

Table A.12. MOX Fuel Fabrication (+50% MOX Fuel Fabrication Capacity)

LOW Case

Quantity - MTHM

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-
1978	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-
1984	-	-	261	-	-	-	261	261
1985	-	-	433	-	-	-	433	694
1986	-	-	484	-	-	-	484	1178
1987	-	-	401	-	-	-	401	1579
1988	-	-	541	-	-	-	541	2120
1989	-	-	751	-	-	-	751	2871
1990	-	-	821	418	-	-	1239	4110
1991	-	-	904	513	-	-	1417	5527
1992	-	-	974	564	-	-	1538	7065
1993	-	-	1050	608	-	-	1658	8723
1994	-	-	1139	659	-	-	1798	10521
1995	-	-	1228	703	-	-	1931	12452
1996	-	-	1311	754	-	-	2065	14517
1997	-	-	1407	813	-	-	2220	16737
1998	-	-	1489	850	-	-	2339	19076
1999	-	-	1547	696	-	-	2243	21319
2000	-	-	1604	894	-	-	2498	23817

Table A.13. Reprocessing (+50% MOX Fuel Fabrication Capacity)

LOW Case

Quantity - MTHM

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-
1978	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-
1984	-	-	1006	-	-	-	1006	1006
1985	-	-	1669	-	-	-	1669	2675
1986	-	-	1865	-	-	-	1865	4540
1987	-	-	1546	-	-	-	1546	6086
1988	-	-	2086	-	-	-	2086	8172
1989	-	-	2896	-	-	-	2896	11068
1990	-	-	3166	1621	-	-	4787	15855
1991	-	-	3485	1991	-	-	5476	21331
1992	-	-	3755	2190	-	-	5945	27276
1993	-	-	4049	2360	-	-	6409	33685
1994	-	-	4393	2559	-	-	6952	40637
1995	-	-	4737	2730	-	-	7467	48104
1996	-	-	5056	2929	-	-	7985	56089
1997	-	-	5424	3157	-	-	8581	64670
1998	-	-	5743	3299	-	-	9042	73712
1999	-	-	5964	2702	-	-	8666	82378
2000	-	-	6185	3469	-	-	9654	92032

Table A.14. Enrichment Services (+50% MOX Fuel Fabrication Capacity)

LOW Case

Quantity - Million SWU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	4.29	1.61	-	-	-	-	5.90	5.90
1978	4.82	1.61	-	-	-	-	6.43	12.33
1979	5.36	2.36	-	-	-	-	7.72	20.05
1980	5.89	2.55	-	-	-	-	8.44	28.49
1981	7.39	3.88	-	-	-	-	11.27	39.76
1982	7.61	3.97	-	-	-	-	11.58	51.34
1983	9.21	5.11	-	-	-	-	14.32	65.66
1984	5.46	4.91	3.37	-	-	-	13.74	79.40
1985	5.36	6.05	5.58	-	-	-	16.99	96.39
1986	6.32	8.13	6.24	-	-	-	20.69	117.08
1987	8.68	7.94	5.17	-	-	-	21.79	138.87
1988	7.07	7.47	6.98	-	-	-	21.52	160.39
1989	5.36	8.22	9.69	-	-	-	23.27	183.66
1990	4.93	3.31	10.60	3.92	-	-	22.76	206.42
1991	5.04	2.93	11.66	4.82	-	-	24.45	230.87
1992	5.79	3.21	12.56	5.30	-	-	26.86	257.73
1993	6.00	2.93	13.55	5.71	-	-	28.19	285.92
1994	5.68	3.21	14.70	6.20	-	-	29.79	315.71
1995	6.21	3.69	15.84	6.61	-	-	32.35	348.06
1996	5.79	2.65	16.91	7.09	-	-	32.44	380.50
1997	4.29	2.74	18.14	7.64	-	-	32.81	413.31
1998	3.86	2.08	19.21	7.99	-	-	33.14	446.45
1999	3.54	4.44	19.95	6.54	-	-	34.47	480.92
2000	3.11	1.89	20.69	8.40	-	-	34.09	515.01

Table A.15. UO_2 Fuel Fabrication (+50% MOX Fuel Fabrication Capacity)

LOW Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	1018	498	-	-	-	-	1516	1516
1978	1146	498	-	-	-	-	1644	3160
1979	1273	733	-	-	-	-	2006	5166
1980	1400	791	-	-	-	-	2191	7357
1981	1757	1201	-	-	-	-	2958	10315
1982	1808	1231	-	-	-	-	3039	13354
1983	2190	1582	-	-	-	-	3772	17126
1984	1299	1524	783	-	-	-	3606	20732
1985	1273	1875	1298	-	-	-	4446	25178
1986	1502	2520	1451	-	-	-	5473	30651
1987	2062	2461	1203	-	-	-	5726	36377
1988	1680	2315	1623	-	-	-	5618	41995
1989	1273	2549	2253	-	-	-	6075	48070
1990	1171	1026	2463	1253	-	-	5913	53983
1991	1197	908	2711	1538	-	-	6354	60337
1992	1375	996	2922	1692	-	-	6985	67322
1993	1426	908	3151	1824	-	-	7309	74631
1994	1349	996	3418	1978	-	-	7741	82372
1995	1477	1143	3685	2110	-	-	8415	90787
1996	1375	820	3934	2263	-	-	8392	99179
1997	1018	850	4220	2439	-	-	8527	107706
1998	917	645	4468	2549	-	-	8579	116285
1999	840	1377	4640	2088	-	-	8945	125230
2000	738	586	4812	2681	-	-	8817	134047

Table A.16. Fuel Cost (+50% MOX Fuel Fabrication Capacity)

LOW Case

Quantity - Billions of Dollars

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	0.88	0.36	-	-	-	-	1.24	1.24
1978	1.05	0.39	-	-	-	-	1.44	2.68
1979	1.25	0.60	-	-	-	-	1.85	4.53
1980	1.47	0.69	-	-	-	-	2.16	6.69
1981	1.97	1.12	-	-	-	-	3.09	9.78
1982	2.22	1.25	-	-	-	-	3.47	13.25
1983	2.92	1.74	-	-	-	-	4.66	17.91
1984	1.84	1.78	1.31	-	-	-	4.93	22.84
1985	1.92	2.32	2.31	-	-	-	6.55	29.39
1986	2.35	3.24	2.68	-	-	-	8.27	37.66
1987	3.31	3.24	2.28	-	-	-	8.83	46.49
1988	2.83	3.21	3.23	-	-	-	9.27	55.76
1989	2.27	3.74	4.73	-	-	-	10.74	66.50
1990	2.22	1.60	5.49	2.35	-	-	11.66	78.16
1991	2.45	1.53	6.52	3.11	-	-	13.61	91.77
1992	3.05	1.82	7.58	3.69	-	-	16.14	107.91
1993	3.37	1.77	8.70	4.23	-	-	18.07	125.98
1994	3.33	2.03	9.86	4.80	-	-	20.02	146.00
1995	3.77	2.41	10.99	5.29	-	-	22.46	168.46
1996	3.63	1.79	12.12	5.86	-	-	23.40	191.86
1997	2.77	1.91	13.41	5.87	-	-	23.96	215.82
1998	2.57	1.50	14.64	7.03	-	-	25.74	241.56
1999	2.45	3.03	15.77	5.97	-	-	27.22	268.78
2000	2.22	1.46	16.88	7.91	-	-	28.47	297.25

Table A.17. Reactor Fuel Schedule - MID Case

Quantity - Number of Operating Reactors

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2
1976	-	-	-	-	-	-
1977	33	18	-	-	-	-
1978	39	18	-	-	-	-
1979	43	19	-	-	-	-
1980	48	22	-	-	-	-
1981	54	26	-	-	-	-
1982	66	34	-	-	-	-
1983	77	40	-	-	-	-
1984	51	47	27	-	-	-
1985	51	53	52	-	-	-
1986	69	62	48	-	-	-
1987	70	70	61	-	-	-
1988	60	76	86	-	-	-
1989	32	77	131	5	-	-
1990	32	50	146	40	-	-
1991	32	25	163	73	-	-
1992	35	17	178	90	-	-
1993	35	17	195	98	-	-
1994	35	17	213	107	-	-
1995	36	18	230	115	-	-
1996	35	134	248	7	-	-
1997	32	62	266	87	-	-
1998	29	33	283	123	-	-
1999	27	14	298	149	-	-
2000	26	106	312	63	-	-

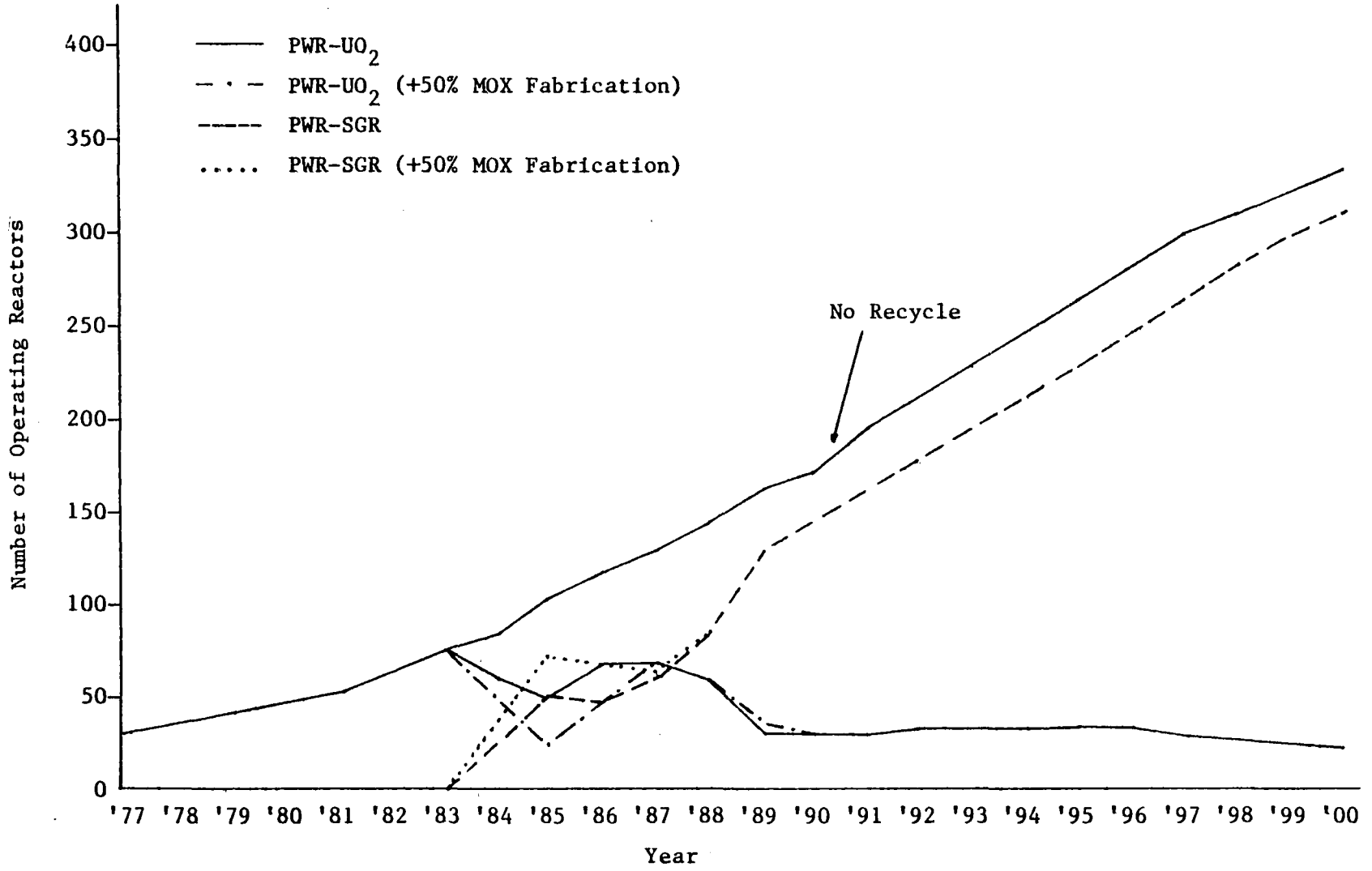

Figure A.8. PWR Fuel Schedule - MID Case

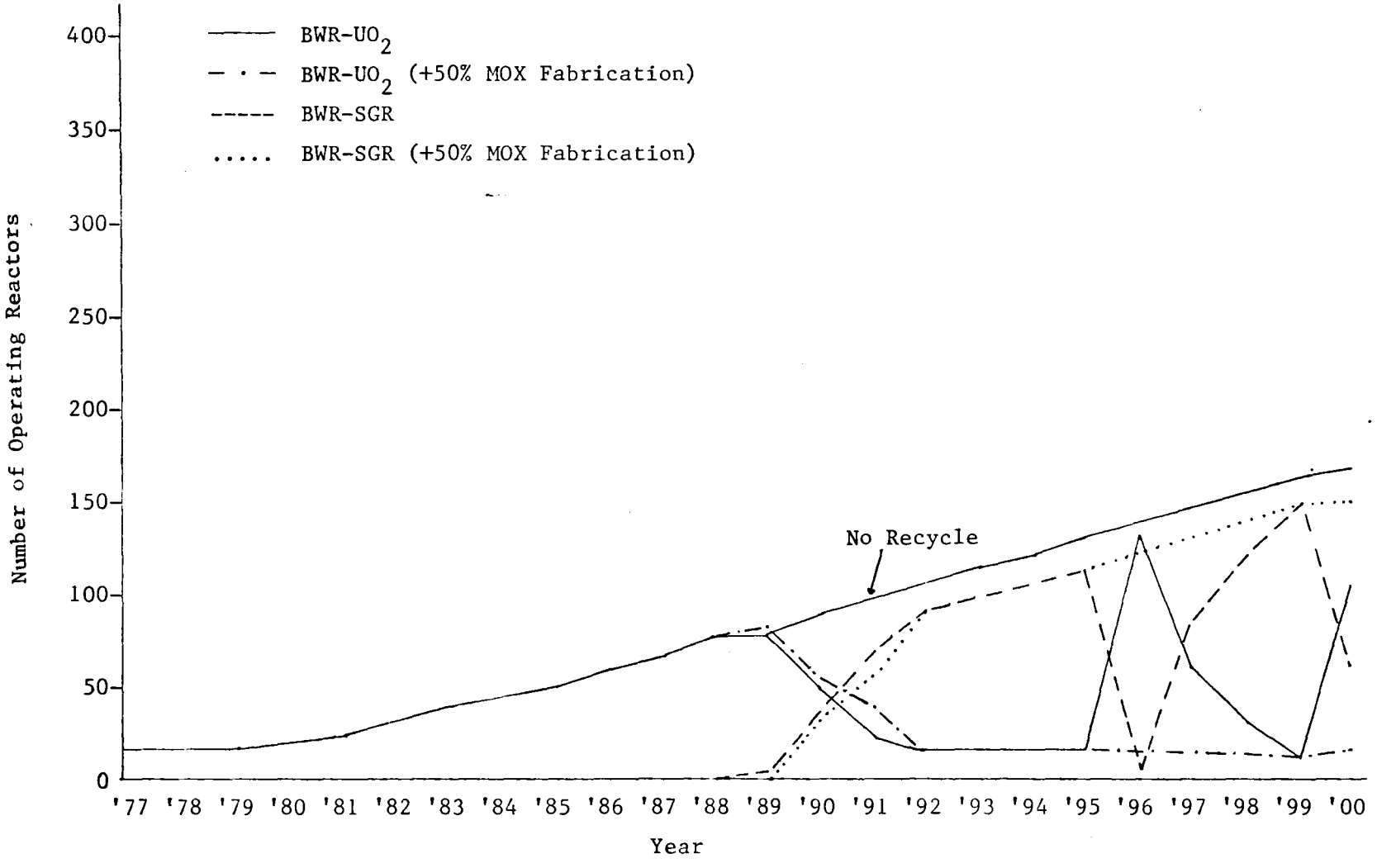

Figure A.9. BWR Fuel Schedule - MID Case

Table A.18. MOX Fuel Fabrication - MID Case

Quantity - MTHM

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-
1978	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-
1984	-	-	172	-	-	-	172	172
1985	-	-	331	-	-	-	331	503
1986	-	-	306	-	-	-	306	809
1987	-	-	388	-	-	-	388	1197
1988	-	-	547	-	-	-	547	1744
1989	-	-	834	36	-	-	870	2614
1990	-	-	929	293	-	-	1222	3836
1991	-	-	1037	535	-	-	1572	5408
1992	-	-	1133	659	-	-	1792	7200
1993	-	-	1241	718	-	-	1959	9159
1994	-	-	1356	784	-	-	2140	11299
1995	-	-	1464	842	-	-	2306	13605
1996	-	-	1579	51	-	-	1630	15235
1997	-	-	1693	637	-	-	2330	17565
1998	-	-	1801	901	-	-	2702	20267
1999	-	-	1897	1091	-	-	2988	23255
2000	-	-	1986	461	-	-	2447	25702

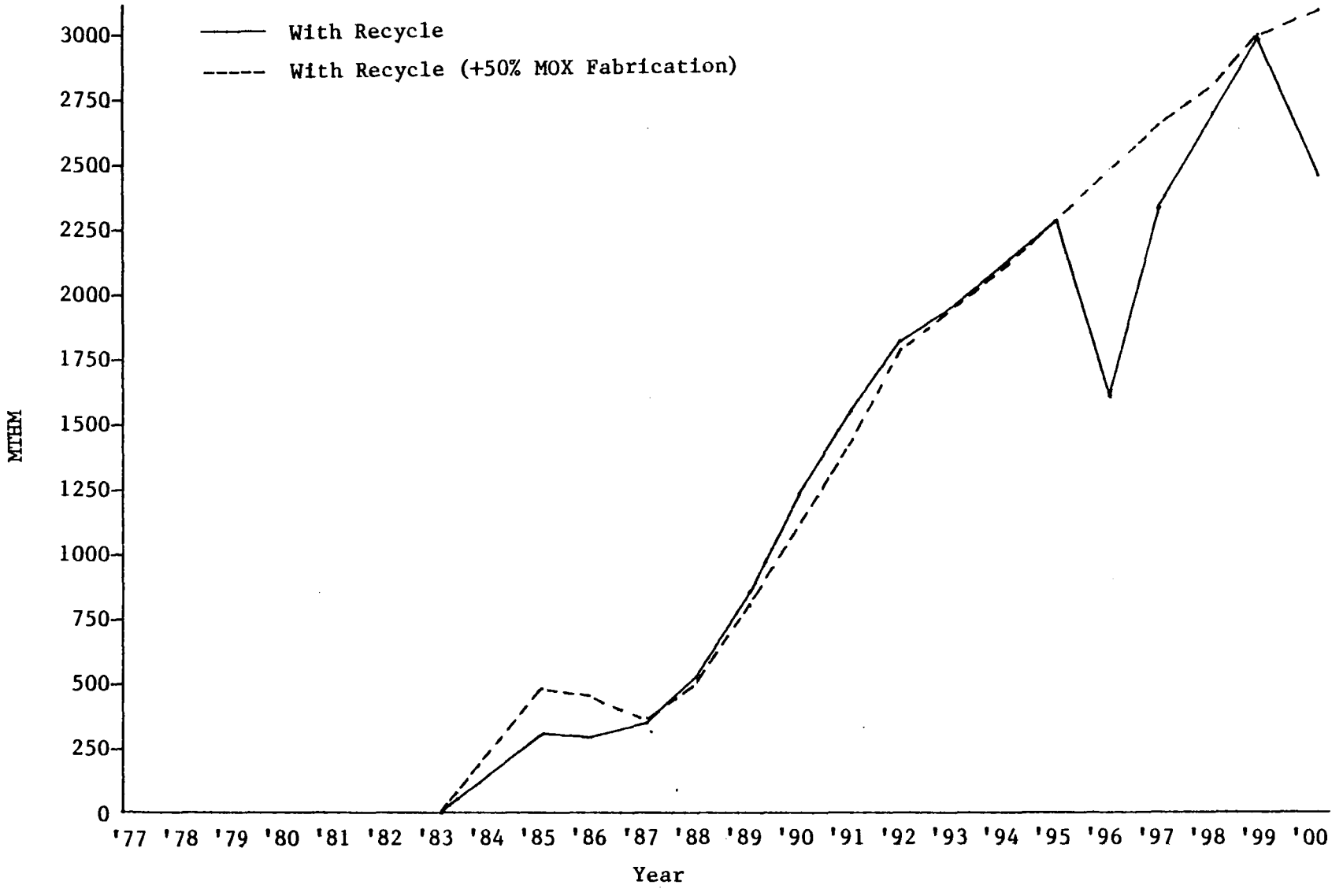

Figure A.10. MOX Fuel Fabrication - MID Case

Table A.19. Reprocessing - MID Case

Quantity - MTHM

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-
1978	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-
1984	-	-	663	-	-	-	663	663
1985	-	-	1276	-	-	-	1276	1939
1986	-	-	1178	-	-	-	1178	3117
1987	-	-	1497	-	-	-	1497	4614
1988	-	-	2111	-	-	-	2111	6725
1989	-	-	3215	142	-	-	3357	10082
1990	-	-	3583	1137	-	-	4720	14802
1991	-	-	4000	2076	-	-	6076	20878
1992	-	-	4368	2559	-	-	6927	27805
1993	-	-	4786	2787	-	-	7573	35378
1994	-	-	5227	3043	-	-	8270	43648
1995	-	-	5645	3270	-	-	8915	52563
1996	-	-	6086	199	-	-	6285	58848
1997	-	-	6528	2474	-	-	9002	67850
1998	-	-	6945	3498	-	-	10443	78293
1999	-	-	7314	4237	-	-	11551	89844
2000	-	-	7657	1792	-	-	9449	99293

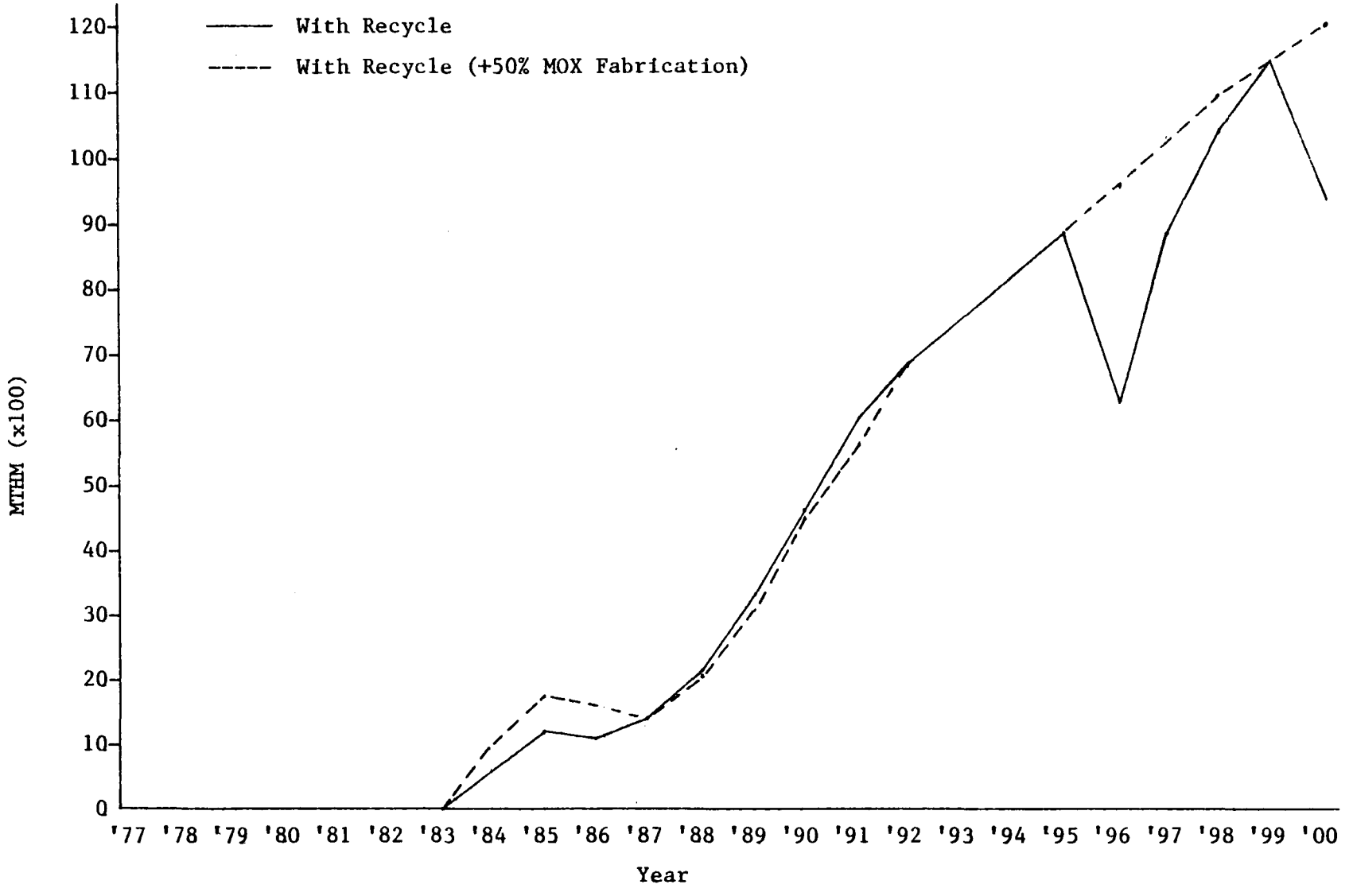

Figure A.11. Reprocessing - MID Case

Table A.20. Enrichment Services (No Recycle) - MID Case

Quantity - Million SWU

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	5.04	1.98	7.02	7.02
1978	5.46	1.70	7.16	14.18
1979	5.46	2.08	7.54	21.72
1980	6.21	2.93	9.14	30.86
1981	7.07	3.59	10.66	41.52
1982	9.64	5.48	15.12	56.64
1983	10.61	5.48	16.09	72.73
1984	11.79	6.43	18.22	90.95
1985	14.25	6.71	20.96	111.91
1986	15.54	8.41	23.95	135.86
1987	17.04	8.88	25.92	161.78
1988	18.86	8.88	27.74	189.52
1989	21.11	9.45	30.56	220.08
1990	22.29	10.96	33.25	253.33
1991	24.54	11.72	36.26	289.59
1992	26.68	12.85	39.53	329.12
1993	28.28	13.14	41.42	370.54
1994	30.43	14.27	44.70	415.24
1995	32.36	15.12	47.48	462.72
1996	33.96	15.59	49.55	512.27
1997	35.14	16.34	51.48	563.75
1998	36.43	16.73	53.16	616.91
1999	37.61	17.39	55.00	671.91
2000	39.00	17.62	56.62	728.53

Table A.21. Enrichment Services (With Recycle) - MID Case

Quantity - Million SWU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	5.04	1.98	-	-	-	-	7.02	7.02
1978	5.46	1.70	-	-	-	-	7.16	14.18
1979	5.46	2.08	-	-	-	-	7.54	21.72
1980	6.21	2.93	-	-	-	-	9.14	30.86
1981	7.07	3.59	-	-	-	-	10.66	41.52
1982	9.64	5.48	-	-	-	-	15.12	56.64
1983	10.61	5.48	-	-	-	-	16.09	72.73
1984	7.82	6.43	2.22	-	-	-	16.47	89.20
1985	8.68	6.71	4.27	-	-	-	19.66	108.86
1986	10.39	8.41	3.94	-	-	-	22.74	131.60
1987	10.50	8.88	5.01	-	-	-	24.39	155.99
1988	9.64	8.88	7.06	-	-	-	25.58	181.57
1989	7.07	8.98	10.75	0.34	-	-	27.14	208.71
1990	6.64	6.99	11.99	2.75	-	-	28.37	237.08
1991	7.07	4.63	13.38	5.03	-	-	30.11	267.19
1992	7.18	4.16	14.61	6.20	-	-	32.15	299.34
1993	6.96	3.87	16.01	6.75	-	-	33.59	332.88
1994	7.18	4.16	17.49	7.37	-	-	36.20	369.08
1995	7.29	4.25	18.88	7.92	-	-	38.34	407.42
1996	6.96	14.93	20.36	0.48	-	-	42.73	450.15
1997	6.64	8.13	21.84	5.99	-	-	42.60	492.75
1998	6.11	5.10	23.23	8.47	-	-	42.91	535.66
1999	5.68	3.31	24.47	10.26	-	-	43.72	579.38
2000	5.57	11.72	25.61	4.34	-	-	47.24	626.62

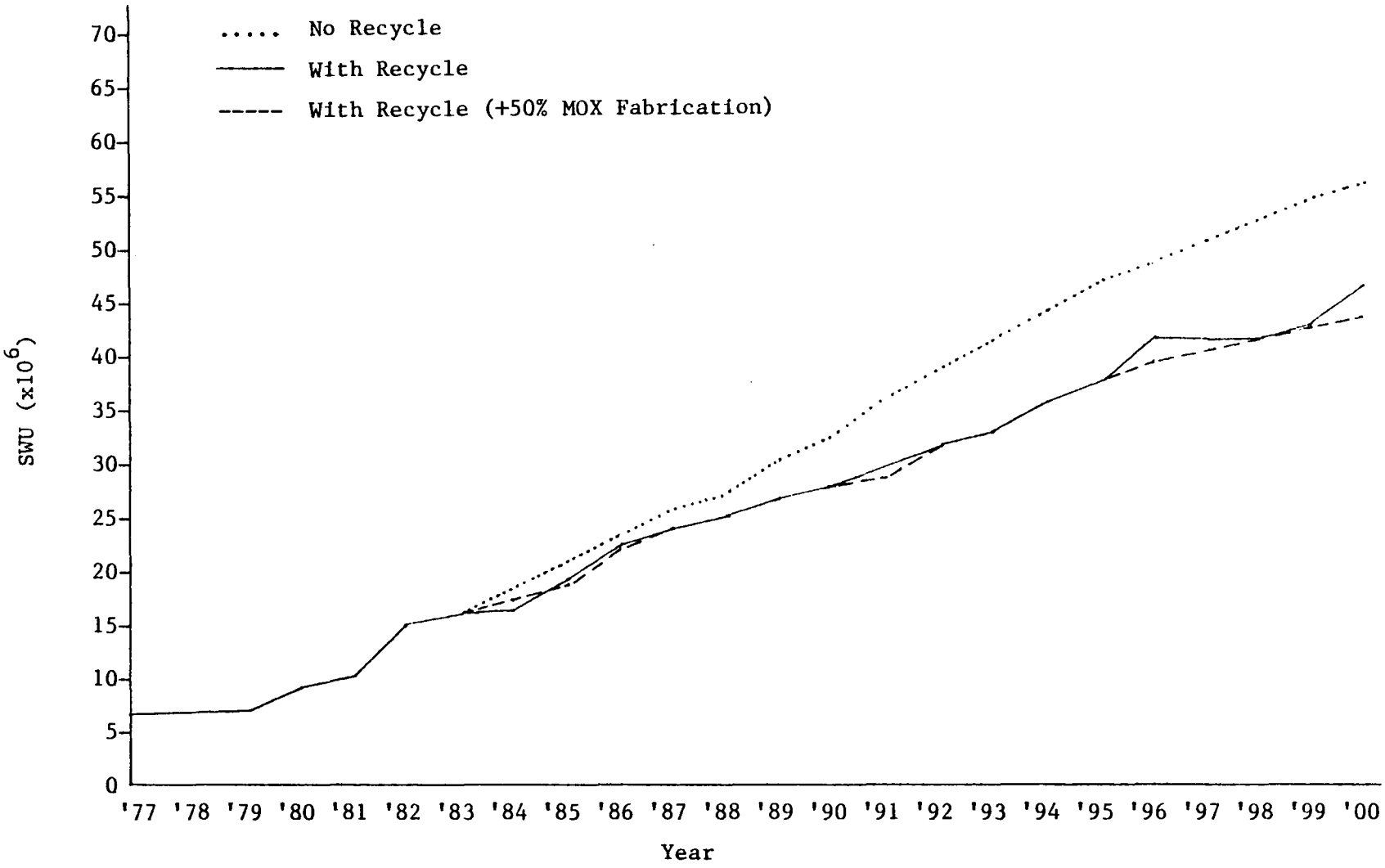

Figure A.12. Enrichment Services - MID Case

Table A.22. UO_2 Fuel Fabrication (With Recycle) - MID Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	1197	615	-	-	-	-	1812	1812
1978	1298	527	-	-	-	-	1825	3637
1979	1298	645	-	-	-	-	1943	5580
1980	1477	908	-	-	-	-	2385	7965
1981	1680	1113	-	-	-	-	2793	10758
1982	2291	1699	-	-	-	-	3990	14748
1983	2521	1699	-	-	-	-	4220	18968
1984	1859	2285	516	-	-	-	4660	23628
1985	2062	2080	993	-	-	-	5135	28763
1986	2470	2608	917	-	-	-	5995	34758
1987	2495	2754	1165	-	-	-	6414	41172
1988	2291	2754	1642	-	-	-	6687	47859
1989	1680	2784	2501	110	-	-	7075	54934
1990	1579	2168	2788	879	-	-	7414	62348
1991	1680	1436	3112	1604	-	-	7832	70180
1992	1808	1289	3399	1978	-	-	8474	78654
1993	1757	1201	3724	2154	-	-	8836	87490
1994	1808	1289	4067	2351	-	-	9515	97005
1995	1833	1319	4392	2527	-	-	10071	107076
1996	1757	4629	4736	154	-	-	11276	118352
1997	1579	2520	5079	1912	-	-	11090	129442
1998	1451	1582	5404	2703	-	-	11140	140582
1999	1349	1026	5690	3274	-	-	11339	151921
2000	1324	3633	5958	1384	-	-	12299	164220

Table A.23. UO_2 Fuel Fabrication (No Recycle) - MID Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	1197	615	1812	1812
1978	1298	527	1825	3637
1979	1298	645	1943	5580
1980	1477	908	2385	7965
1981	1680	1113	2793	10758
1982	2291	1699	3990	14748
1983	2521	1699	4220	18968
1984	2801	1992	4793	23761
1985	3386	2080	5466	29227
1986	3692	2608	6300	35527
1987	4048	2754	6802	42329
1988	4481	2754	7235	49564
1989	5016	2930	7946	57510
1990	5296	3340	8636	66146
1991	5830	3575	9405	75551
1992	6340	3926	10266	85817
1993	6721	4073	10794	96611
1994	7231	4395	11626	108237
1995	7689	4659	12348	120585
1996	8071	4805	12876	133461
1997	8351	5040	13391	146852
1998	8656	5157	13813	160665
1999	8936	5362	14298	174963
2000	9267	5450	14717	189680

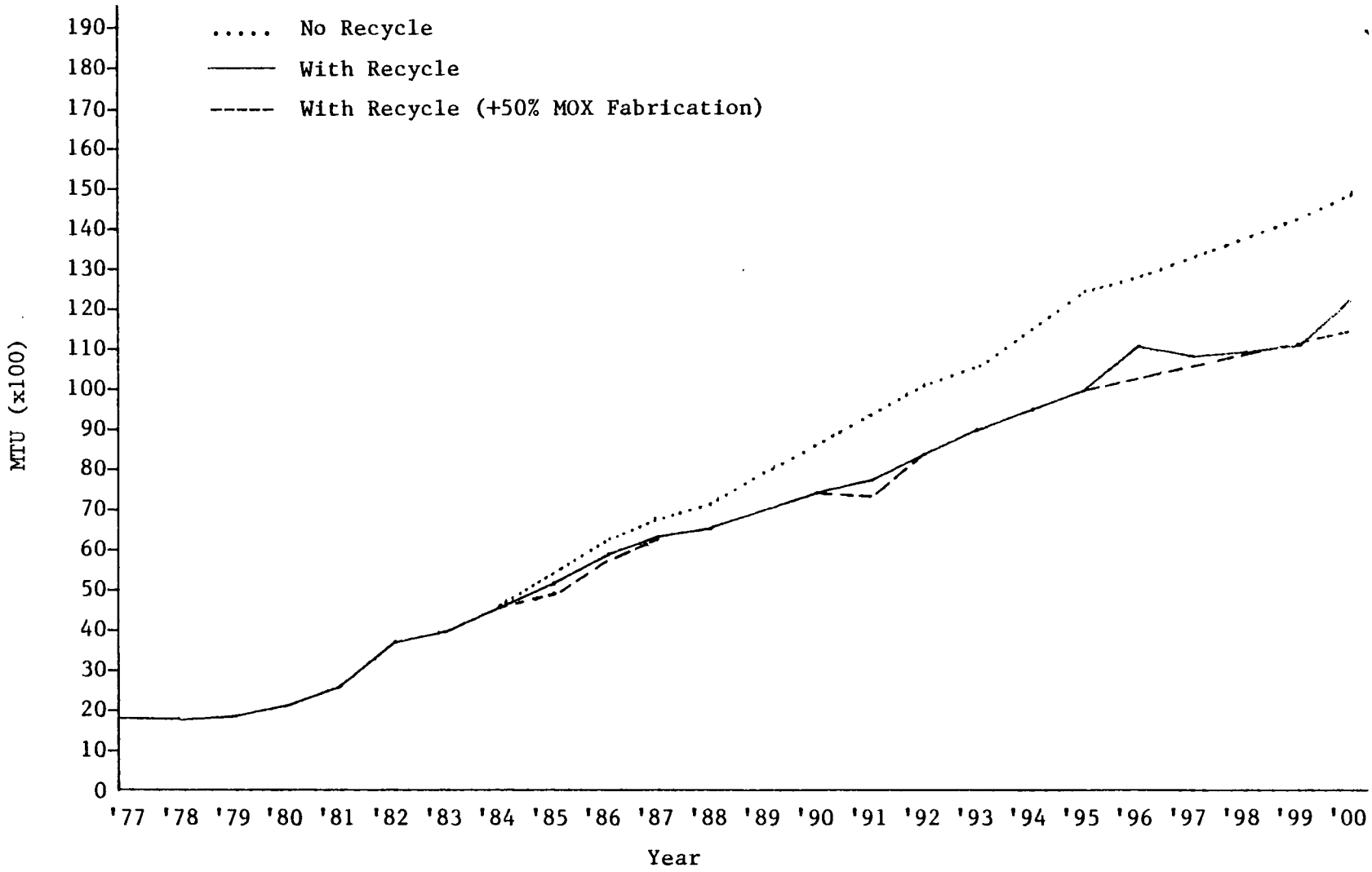

Figure A.13. UO_2 Fuel Fabrication - MID Case

Table A.24. Fuel Cost (No Recycle) - MID Case

Quantity - Billions of Dollars

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	1.03	0.45	1.48	1.48
1978	1.19	0.41	1.60	3.08
1979	1.27	0.53	1.80	4.88
1980	1.55	0.80	2.35	7.23
1981	1.88	1.04	2.92	10.15
1982	2.82	1.73	4.55	14.70
1983	3.36	1.87	5.23	19.93
1984	3.98	2.33	6.31	26.24
1985	5.11	2.58	7.69	33.93
1986	5.78	3.35	9.13	43.06
1987	6.49	3.63	10.12	53.18
1988	7.56	3.82	11.38	64.56
1989	8.94	4.30	13.24	77.80
1990	10.05	5.22	15.27	93.07
1991	11.95	6.04	17.99	111.06
1992	14.05	7.18	21.23	132.29
1993	15.87	7.93	23.80	156.09
1994	17.86	9.02	26.88	182.97
1995	19.63	9.88	29.51	212.48
1996	21.30	10.54	31.84	244.32
1997	22.73	11.40	34.13	278.45
1998	24.32	12.03	36.35	314.80
1999	26.05	12.98	39.03	353.83
2000	27.90	13.63	41.53	395.36

Table A.25. Fuel Cost (With Recycle) - MID Case

Quantity - Billions of Dollars

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	1.03	0.45	-	-	-	-	1.48	1.48
1978	1.19	0.41	-	-	-	-	1.60	3.08
1979	1.27	0.53	-	-	-	-	1.80	4.88
1980	1.55	0.80	-	-	-	-	2.35	7.23
1981	1.88	1.04	-	-	-	-	2.92	10.15
1982	2.82	1.73	-	-	-	-	4.55	14.70
1983	3.36	1.87	-	-	-	-	5.23	19.93
1984	2.64	2.33	0.86	-	-	-	5.83	25.76
1985	3.11	2.58	1.77	-	-	-	7.46	33.22
1986	3.87	3.35	1.69	-	-	-	8.91	42.13
1987	4.00	3.63	2.20	-	-	-	9.83	51.96
1988	3.86	3.82	3.26	-	-	-	10.94	62.90
1989	2.99	4.08	5.25	0.19	-	-	12.51	75.41
1990	2.99	3.39	6.22	1.65	-	-	14.25	89.66
1991	3.45	2.43	7.49	3.24	-	-	16.61	106.27
1992	4.01	2.36	8.82	4.31	-	-	19.50	125.77
1993	4.15	2.34	10.28	5.00	-	-	21.77	147.54
1994	4.46	2.63	11.74	5.71	-	-	24.54	172.08
1995	4.68	2.78	13.09	6.34	-	-	26.89	198.97
1996	4.64	10.09	14.59	0.40	-	-	29.72	228.69
1997	4.30	5.67	16.14	5.11	-	-	31.22	259.91
1998	4.08	3.67	17.71	7.45	-	-	32.91	292.82
1999	3.93	2.27	19.34	9.36	-	-	34.90	327.72
2000	3.99	8.31	20.90	4.09	-	-	37.29	365.01

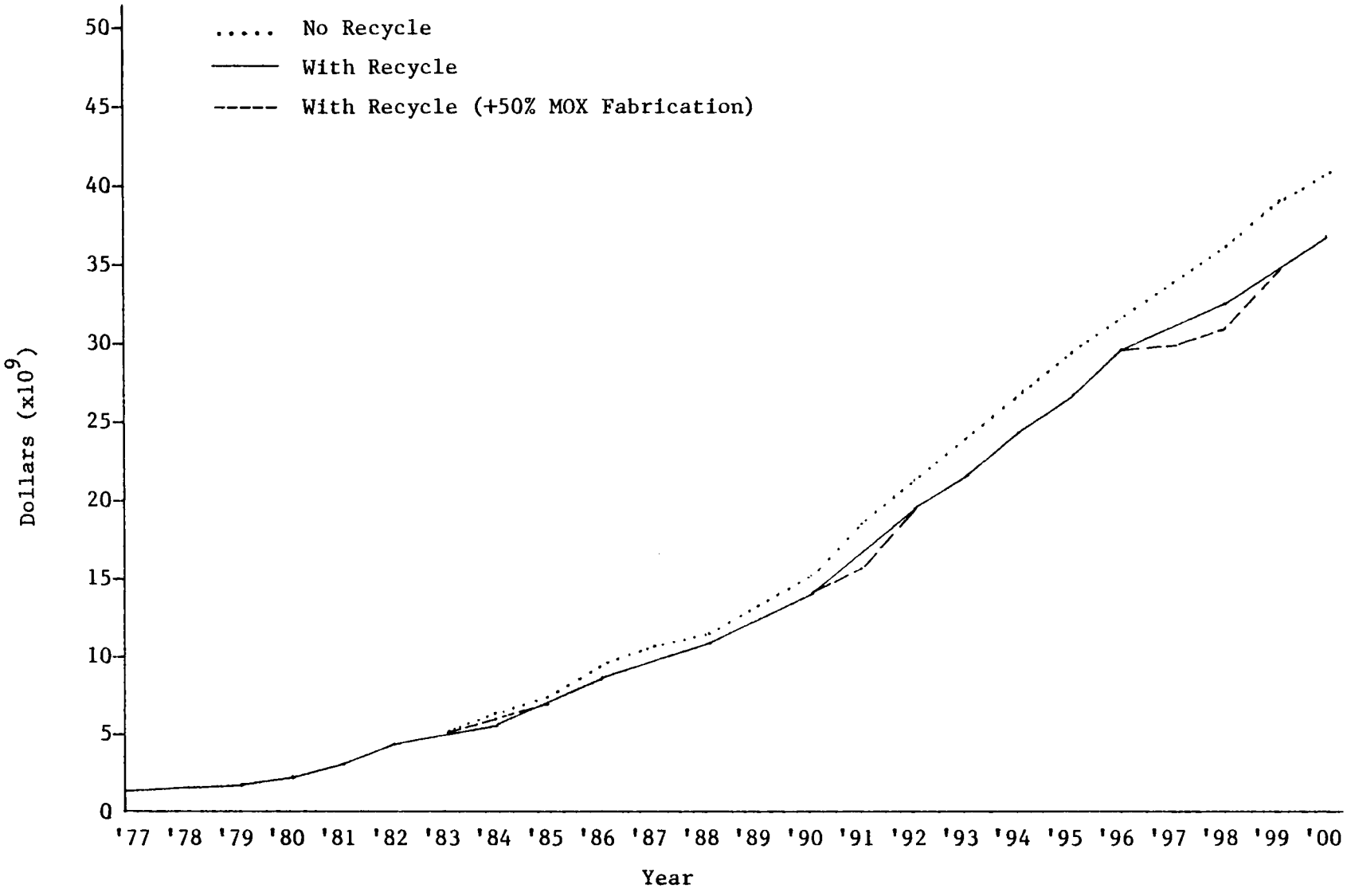

Figure A.14. Fuel Cost - MID Case

Table A.26. UF_6 Consumption (+50% MOX Fuel Fabrication Capacity)

MID Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	7657	3270	-	-	-	-	10927	10927
1978	8309	2803	-	-	-	-	11112	22039
1979	8309	3426	-	-	-	-	11735	33774
1980	9449	4827	-	-	-	-	14276	48050
1981	10753	5917	-	-	-	-	16670	64720
1982	14663	9032	-	-	-	-	26395	88415
1983	16129	9032	-	-	-	-	25161	113576
1984	11242	12146	2926	-	-	-	26314	139890
1985	9124	11056	5495	-	-	-	25675	165565
1986	12382	13859	4924	-	-	-	31165	196730
1987	15966	14637	4353	-	-	-	34956	231686
1988	14826	14637	6066	-	-	-	35529	267215
1989	11567	15572	8991	-	-	-	36130	303345
1990	10101	12302	10419	2409	-	-	35231	338576
1991	10753	7630	11632	3924	-	-	33939	372515
1992	11567	6852	12702	6196	-	-	37317	409832
1993	11242	6384	13915	6747	-	-	38288	448120
1994	11567	6852	15200	7366	-	-	40985	489105
1995	11730	7007	16413	7917	-	-	43067	532172
1996	11242	6384	17698	8536	-	-	43860	576032
1997	10753	6229	18982	9156	-	-	45120	621152
1998	9287	5606	20195	9707	-	-	44795	665947
1999	8635	5450	21266	10257	-	-	45608	711555
2000	8472	5450	22265	10464	-	-	46641	758196

Table A.27. Reactor Fuel Schedule (+50% MOX Fuel Fabrication Capacity)

MID Case

Quantity - Number of Operating Reactors

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2
1976	-	-	-	-	-	-
1977	33	18	-	-	-	-
1978	39	18	-	-	-	-
1979	43	19	-	-	-	-
1980	48	22	-	-	-	-
1981	54	26	-	-	-	-
1982	66	34	-	-	-	-
1983	77	40	-	-	-	-
1984	47	47	41	-	-	-
1985	26	53	77	-	-	-
1986	48	62	69	-	-	-
1987	70	70	61	-	-	-
1988	61	76	85	-	-	-
1989	37	82	126	-	-	-
1990	32	55	146	35	-	-
1991	32	25	163	57	-	-
1992	35	17	178	90	-	-
1993	35	17	195	98	-	-
1994	35	17	213	107	-	-
1995	36	18	230	115	-	-
1996	35	17	248	124	-	-
1997	32	16	266	133	-	-
1998	29	15	283	141	-	-
1999	27	14	298	149	-	-
2000	26	17	312	152	-	-

Table A.28. MOX Fuel Fabrication (+50% MOX Fuel Fabrication Capacity)

MID Case

Quantity - MTHM

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-
1978	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-
1984	-	-	261	-	-	-	261	261
1985	-	-	490	-	-	-	490	751
1986	-	-	439	-	-	-	439	1190
1987	-	-	388	-	-	-	388	1578
1988	-	-	541	-	-	-	541	2119
1989	-	-	802	-	-	-	802	2921
1990	-	-	929	256	-	-	1185	4106
1991	-	-	1037	418	-	-	1455	5561
1992	-	-	1133	659	-	-	1792	7353
1993	-	-	1241	718	-	-	1959	9312
1994	-	-	1356	784	-	-	2140	11452
1995	-	-	1464	842	-	-	2306	13758
1996	-	-	1579	908	-	-	2487	16245
1997	-	-	1693	974	-	-	2667	18912
1998	-	-	1801	1033	-	-	2834	21746
1999	-	-	1897	1091	-	-	2988	24734
2000	-	-	1986	1113	-	-	3099	27833

Table A.29. Reprocessing (+50% MOX Fuel Fabrication Capacity)

MID Case

Quantity - MTHM

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-
1978	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-
1984	-	-	1006	-	-	-	1006	1006
1985	-	-	1890	-	-	-	1890	2896
1986	-	-	1693	-	-	-	1693	4589
1987	-	-	1497	-	-	-	1497	6086
1988	-	-	2086	-	-	-	2086	8172
1989	-	-	3092	-	-	-	3092	11264
1990	-	-	3583	995	-	-	4578	15842
1991	-	-	4000	1621	-	-	5621	21463
1992	-	-	4368	2559	-	-	6927	28390
1993	-	-	4786	2787	-	-	7573	35963
1994	-	-	5227	3043	-	-	8270	44233
1995	-	-	5645	3270	-	-	8915	53148
1996	-	-	6086	3526	-	-	9612	62760
1997	-	-	6528	3782	-	-	10310	73070
1998	-	-	6945	4010	-	-	10955	84025
1999	-	-	7314	4237	-	-	11551	95576
2000	-	-	7657	4322	-	-	11979	107555

Table A.30. Enrichment Services (+50% MOX Fuel Fabrication Capacity)

MID Case

Quantity - Million SWU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	5.04	1.98	-	-	-	-	7.02	7.02
1978	5.46	1.70	-	-	-	-	7.16	14.18
1979	5.46	2.08	-	-	-	-	7.54	21.72
1980	6.21	2.93	-	-	-	-	9.14	30.86
1981	7.07	3.59	-	-	-	-	10.66	41.52
1982	9.64	5.48	-	-	-	-	15.12	56.64
1983	10.61	5.48	-	-	-	-	16.09	72.73
1984	7.39	6.43	3.37	-	-	-	17.19	89.92
1985	6.00	6.71	6.32	-	-	-	19.03	108.95
1986	8.14	8.41	5.66	-	-	-	22.21	131.16
1987	10.50	8.88	5.01	-	-	-	24.39	155.55
1988	9.75	8.88	6.98	-	-	-	25.61	181.16
1989	7.61	9.45	10.34	-	-	-	27.40	208.56
1990	6.64	7.47	11.99	2.41	-	-	28.51	237.07
1991	7.07	4.63	13.38	3.92	-	-	29.00	266.07
1992	7.18	4.16	14.61	6.20	-	-	32.15	298.22
1993	6.96	3.87	16.01	6.75	-	-	33.59	331.81
1994	7.18	4.16	17.49	7.37	-	-	36.20	368.01
1995	7.29	4.25	18.88	7.92	-	-	38.34	406.35
1996	6.96	3.87	20.36	8.54	-	-	39.73	446.08
1997	6.64	3.78	21.84	9.16	-	-	41.42	487.50
1998	6.11	3.40	23.23	9.71	-	-	42.45	529.95
1999	5.68	3.31	24.47	10.26	-	-	43.72	573.67
2000	5.57	3.31	25.61	10.46	-	-	44.96	618.62

Table A.31. UO_2 Fuel Fabrication (+50% MOX Fuel Fabrication Capacity)

MID Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	1197	615	-	-	-	-	1812	1812
1978	1298	527	-	-	-	-	1825	3637
1979	1298	645	-	-	-	-	1943	5580
1980	1477	908	-	-	-	-	2385	7965
1981	1680	1113	-	-	-	-	2793	10758
1982	2291	1699	-	-	-	-	3990	14748
1983	2521	1699	-	-	-	-	4220	18968
1984	1757	2285	783	-	-	-	4825	23793
1985	1426	2080	1470	-	-	-	4976	28769
1986	1935	2608	1318	-	-	-	5861	34630
1987	2495	2754	1165	-	-	-	6414	41044
1988	2317	2754	1623	-	-	-	6694	47738
1989	1808	2930	2406	-	-	-	7144	54882
1990	1579	2315	2788	769	-	-	7451	62333
1991	1680	1436	3112	1253	-	-	7481	69814
1992	1808	1289	3399	1978	-	-	8474	78288
1993	1757	1201	3724	2154	-	-	8836	87124
1994	1808	1289	4067	2351	-	-	9515	96639
1995	1833	1319	4392	2527	-	-	10071	106710
1996	1757	1201	4736	2725	-	-	10419	117129
1997	1579	1172	5079	2923	-	-	10753	127882
1998	1451	1055	5404	3098	-	-	11008	138890
1999	1349	1026	5690	3274	-	-	11339	150229
2000	1324	1026	5958	3340	-	-	11648	161877

Table A.32. Fuel Cost (+50% MOX Fuel Fabrication Capacity)

MID Case

Quantity - Billions of Dollars

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	1.03	0.45	-	-	-	-	1.48	1.48
1978	1.19	0.41	-	-	-	-	1.60	3.08
1979	1.27	0.53	-	-	-	-	1.80	4.88
1980	1.55	0.80	-	-	-	-	2.35	7.23
1981	1.88	1.04	-	-	-	-	2.92	10.15
1982	2.82	1.73	-	-	-	-	4.55	14.70
1983	3.36	1.87	-	-	-	-	5.23	19.93
1984	2.49	2.33	1.31	-	-	-	6.13	26.06
1985	2.15	2.58	2.62	-	-	-	7.35	33.41
1986	3.03	3.35	2.43	-	-	-	8.81	42.22
1987	4.00	3.63	2.20	-	-	-	9.83	52.05
1988	3.91	3.82	3.23	-	-	-	10.96	63.01
1989	3.22	4.30	5.05	-	-	-	12.57	75.58
1990	2.99	3.62	6.22	1.44	-	-	14.27	89.85
1991	3.45	2.43	7.49	2.53	-	-	15.90	105.75
1992	4.01	2.36	8.82	4.31	-	-	19.50	125.25
1993	4.15	2.34	10.28	5.00	-	-	21.77	147.02
1994	4.46	2.63	11.74	5.71	-	-	24.54	171.56
1995	4.68	2.78	13.09	6.34	-	-	26.89	198.45
1996	4.64	2.62	14.59	7.06	-	-	28.91	227.36
1997	4.30	2.64	16.14	7.81	-	-	30.89	258.25
1998	4.08	2.45	17.71	8.54	-	-	32.78	291.03
1999	3.93	2.27	19.34	9.36	-	-	34.90	325.93
2000	3.99	2.55	20.90	9.86	-	-	37.30	363.23

Table A.33. Reactor Fuel Schedule - HIGH Case

Quantity - Number of Operating Reactors

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2
1976	-	-	-	-	-	-
1977	33	18	-	-	-	-
1978	39	18	-	-	-	-
1979	44	20	-	-	-	-
1980	51	23	-	-	-	-
1981	55	27	-	-	-	-
1982	72	37	-	-	-	-
1983	85	44	-	-	-	-
1984	72	52	27	-	-	-
1985	60	58	54	-	-	-
1986	74	67	54	-	-	-
1987	88	76	54	-	-	-
1988	79	84	82	-	-	-
1989	45	91	137	-	-	-
1990	40	73	161	27	-	-
1991	40	45	182	56	-	-
1992	41	34	201	88	-	-
1993	42	39	222	93	-	-
1994	43	55	242	88	-	-
1995	42	85	264	68	-	-
1996	41	77	285	86	-	-
1997	39	104	306	68	-	-
1998	39	107	326	75	-	-
1999	37	110	345	82	-	-
2000	35	135	365	65	-	-

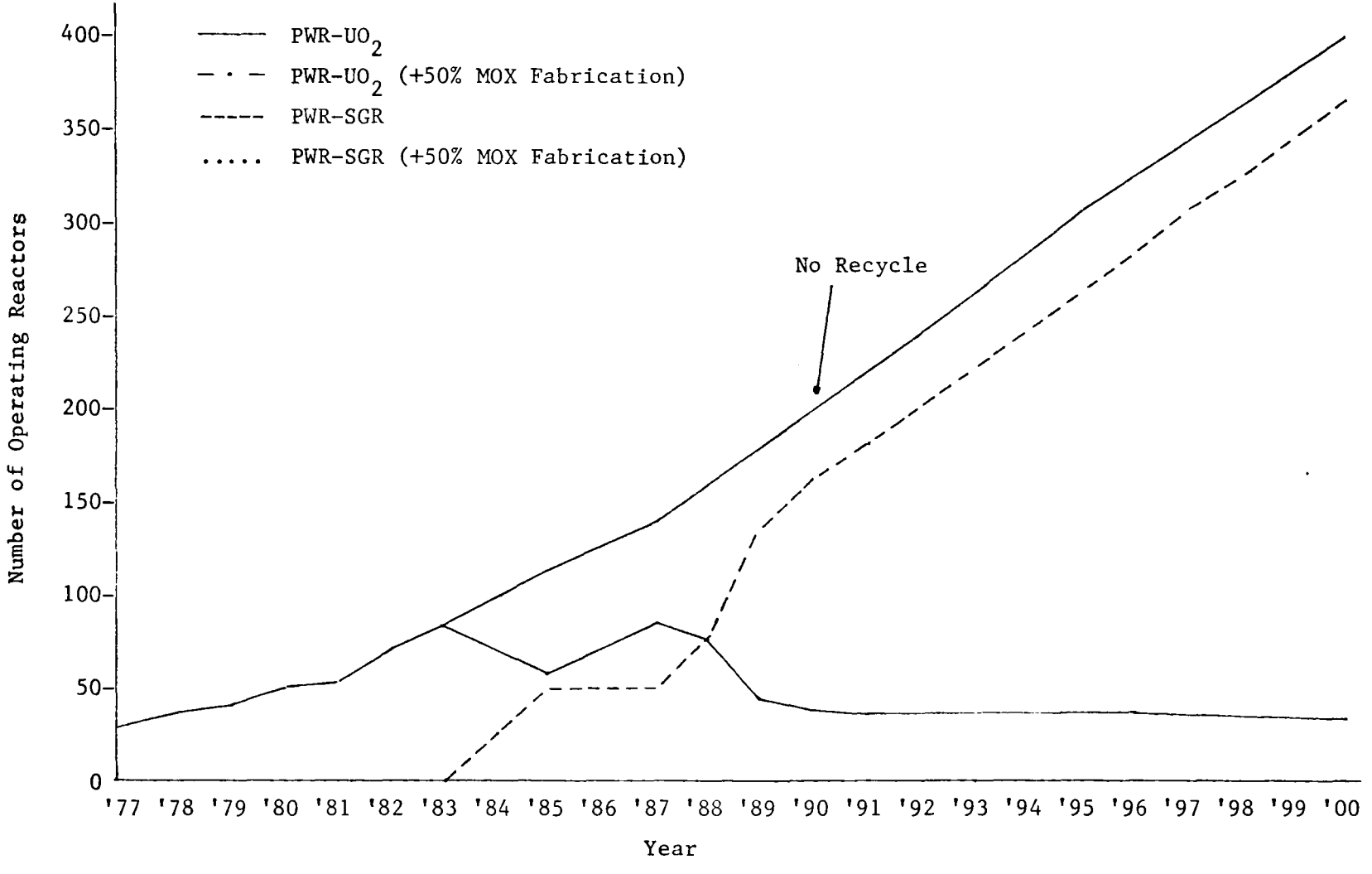

Figure A.15. PWR Fuel Schedule - HIGH Case

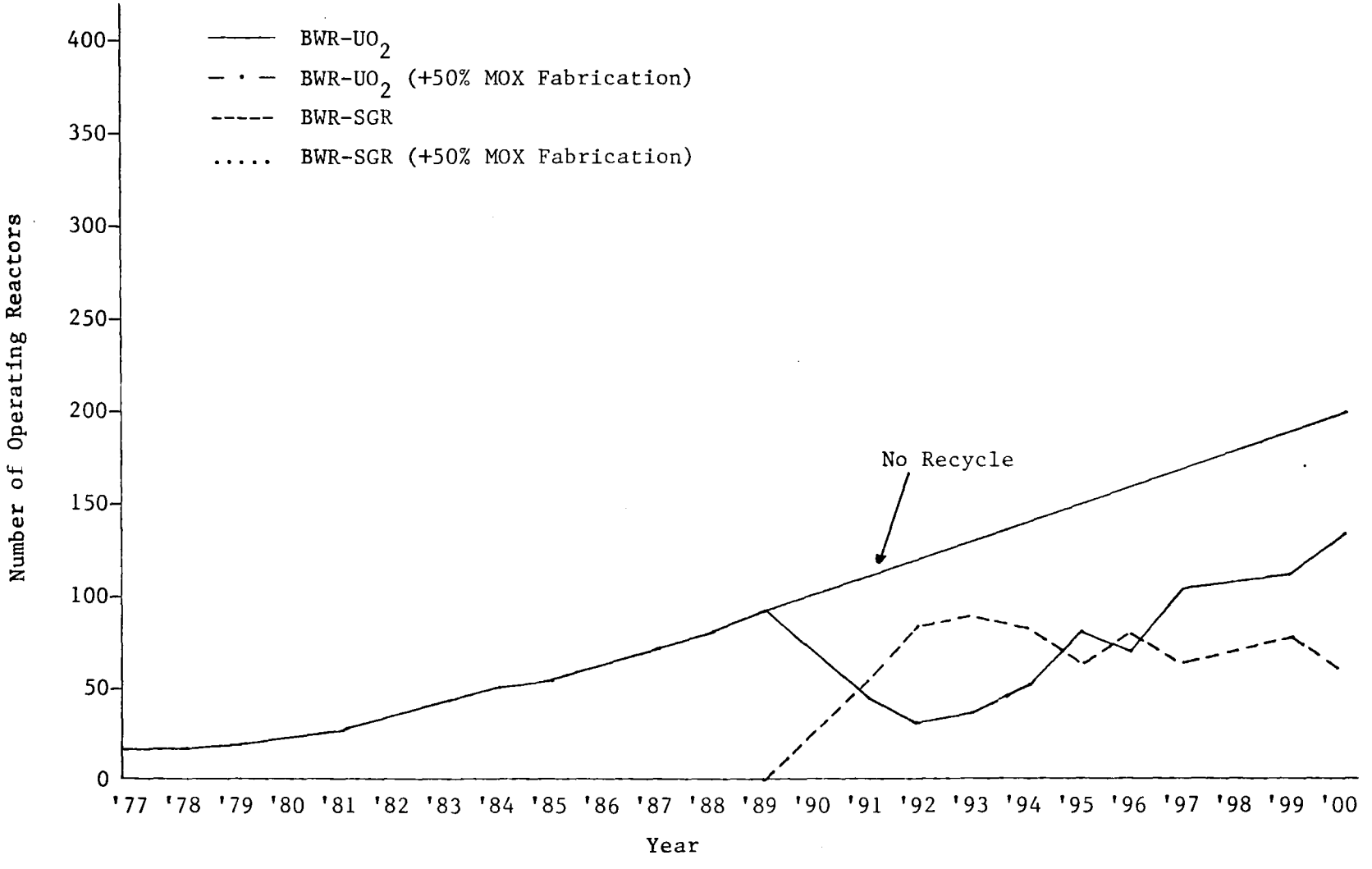

Figure A.16. BWR Fuel Schedule - HIGH Case

Table A.34. MOX Fuel Fabrication - HIGH Case

Quantity - MTHM

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-
1978	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-
1984	-	-	172	-	-	-	172	172
1985	-	-	344	-	-	-	344	516
1986	-	-	344	-	-	-	344	860
1987	-	-	344	-	-	-	344	1204
1988	-	-	522	-	-	-	522	1726
1989	-	-	872	-	-	-	872	2598
1990	-	-	1025	198	-	-	1223	3821
1991	-	-	1158	410	-	-	1568	5389
1992	-	-	1279	645	-	-	1924	7313
1993	-	-	1413	681	-	-	2094	9407
1994	-	-	1540	645	-	-	2185	11592
1995	-	-	1680	498	-	-	2178	13770
1996	-	-	1814	630	-	-	2444	16214
1997	-	-	1948	498	-	-	2446	18660
1998	-	-	2075	549	-	-	2624	21284
1999	-	-	2196	601	-	-	2797	24081
2000	-	-	2323	476	-	-	2799	26880

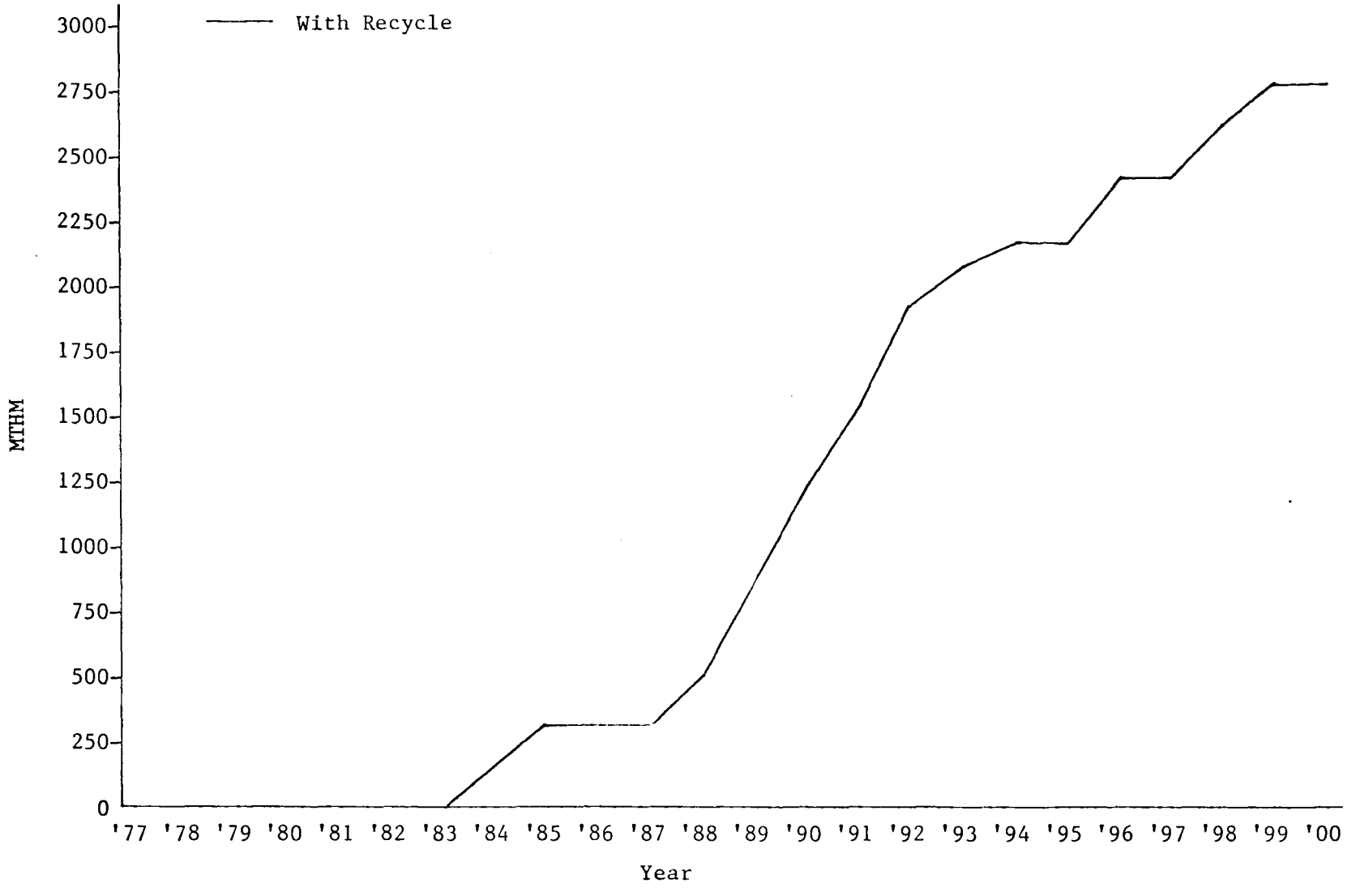

Figure A.17. MOX Fuel Fabrication - HIGH Case

Table A.35. Reprocessing - HIGH Case

Quantity - MTHM

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	-	-	-	-	-	-	-	-
1978	-	-	-	-	-	-	-	-
1979	-	-	-	-	-	-	-	-
1980	-	-	-	-	-	-	-	-
1981	-	-	-	-	-	-	-	-
1982	-	-	-	-	-	-	-	-
1983	-	-	-	-	-	-	-	-
1984	-	-	663	-	-	-	663	663
1985	-	-	1325	-	-	-	1325	1988
1986	-	-	1325	-	-	-	1325	3313
1987	-	-	1325	-	-	-	1325	4638
1988	-	-	2012	-	-	-	2012	6650
1989	-	-	3363	-	-	-	3363	10013
1990	-	-	3951	768	-	-	4719	14732
1991	-	-	4467	1592	-	-	6059	20791
1992	-	-	4933	2502	-	-	7435	28226
1993	-	-	5448	2645	-	-	8093	36319
1994	-	-	5939	2502	-	-	8441	44760
1995	-	-	6479	1934	-	-	8413	53173
1996	-	-	6994	2446	-	-	9440	62613
1997	-	-	7510	1934	-	-	9444	72057
1998	-	-	8001	2133	-	-	10134	82191
1999	-	-	8467	2332	-	-	10799	92990
2000	-	-	8958	1848	-	-	10806	103796

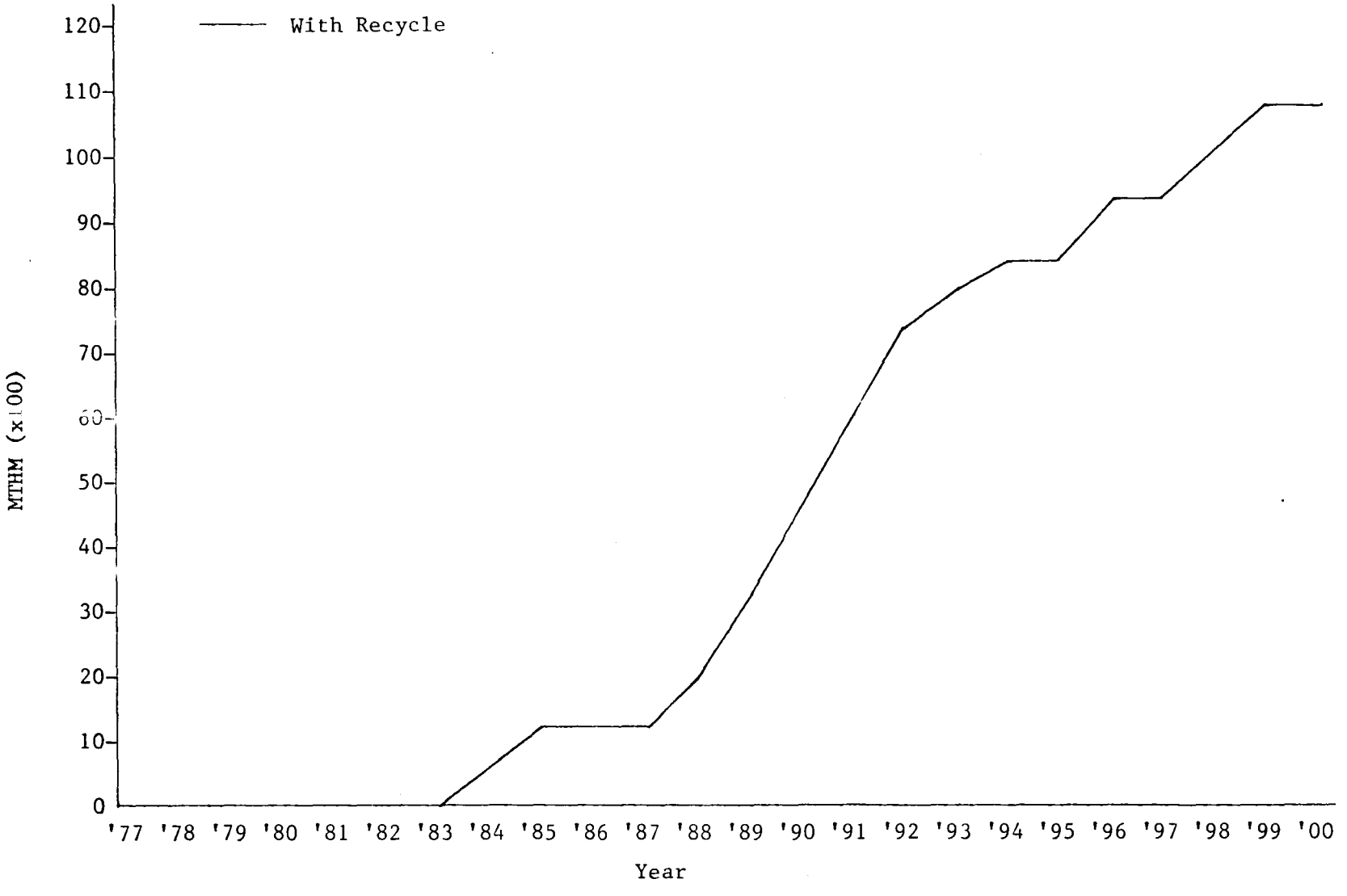

Figure A.18. Reprocessing - HIGH Case

Table A.36. Enrichment Services (No Recycle) - HIGH Case

Quantity - Million SWU

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	4.82	1.70	6.52	6.52
1978	5.46	1.70	7.16	13.68
1979	5.79	2.46	8.25	21.93
1980	6.96	3.02	9.98	31.91
1981	6.75	3.69	10.44	42.35
1982	11.36	6.33	17.69	60.04
1983	11.89	6.14	18.03	78.07
1984	13.61	7.18	20.79	98.86
1985	15.43	7.18	22.61	121.47
1986	16.71	8.88	25.59	147.06
1987	18.21	9.73	27.94	175.00
1988	21.32	10.21	31.53	206.53
1989	24.00	10.58	34.58	241.11
1990	25.61	12.29	37.90	279.01
1991	28.28	13.23	41.51	320.52
1992	30.21	14.65	44.86	365.38
1993	33.00	15.31	48.31	413.69
1994	35.03	16.63	51.66	465.35
1995	37.28	17.29	54.57	519.92
1996	39.21	18.24	57.45	577.37
1997	41.03	19.09	60.12	637.49
1998	43.39	19.75	63.14	700.63
1999	44.57	20.98	65.55	766.18
2000	46.71	21.17	67.88	834.06

Table A.37. Enrichment Services (With Recycle) - HIGH Case

Quantity - Million SWU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	4.82	1.70	-	-	-	-	6.52	6.52
1978	5.46	1.70	-	-	-	-	7.16	13.68
1979	5.79	2.46	-	-	-	-	8.25	21.93
1980	6.96	3.02	-	-	-	-	9.98	31.91
1981	6.75	3.69	-	-	-	-	10.44	42.35
1982	11.36	6.33	-	-	-	-	17.69	60.04
1983	11.89	6.14	-	-	-	-	18.03	78.07
1984	10.71	7.18	2.22	-	-	-	20.11	98.18
1985	9.64	7.18	4.43	-	-	-	21.25	119.43
1986	10.93	8.88	4.43	-	-	-	24.24	143.67
1987	12.43	9.73	4.43	-	-	-	26.59	170.26
1988	12.54	10.21	6.73	-	-	-	29.48	199.74
1989	9.32	10.58	11.25	-	-	-	31.15	230.89
1990	8.36	9.73	13.22	1.86	-	-	33.17	264.06
1991	8.79	8.03	14.94	3.86	-	-	35.62	299.68
1992	8.69	6.33	16.50	6.06	-	-	37.58	337.26
1993	9.21	6.52	18.23	6.40	-	-	40.36	377.62
1994	9.11	8.32	19.87	6.06	-	-	43.36	420.98
1995	9.00	10.87	21.67	4.68	-	-	46.22	467.20
1996	8.68	10.11	23.40	5.92	-	-	48.11	515.31
1997	8.25	12.66	25.12	4.68	-	-	50.71	566.02
1998	8.46	12.66	26.76	5.16	-	-	53.04	619.06
1999	7.61	13.23	28.32	5.65	-	-	54.81	673.87
2000	7.61	15.03	29.97	4.48	-	-	57.09	730.96

Figure A.19. Enrichment Services - HIGH Case

Table A.38. UO_2 Fuel Fabrication (With Recycle) - HIGH Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	1146	527	-	-	-	-	1673	1673
1978	1298	527	-	-	-	-	1825	3498
1979	1375	762	-	-	-	-	2137	5635
1980	1655	938	-	-	-	-	2593	8228
1981	1604	1143	-	-	-	-	2747	10975
1982	2699	1963	-	-	-	-	4662	15637
1983	2826	1905	-	-	-	-	4731	20368
1984	2546	2227	516	-	-	-	5289	25657
1985	2291	2227	1031	-	-	-	5549	31206
1986	2597	2754	1031	-	-	-	6382	37588
1987	2953	3018	1031	-	-	-	7002	44590
1988	2979	3164	1566	-	-	-	7709	52299
1989	2215	3282	2616	-	-	-	8113	60412
1990	1986	3018	3074	593	-	-	8671	69083
1991	2088	2491	3475	1231	-	-	9285	78368
1992	2062	1963	3838	1934	-	-	9797	88165
1993	2190	2022	4239	2044	-	-	10495	98660
1994	2164	2578	4621	1934	-	-	11297	109957
1995	2139	3370	5041	1494	-	-	12044	122001
1996	2062	3135	5442	1890	-	-	12529	134530
1997	1960	3926	5843	1494	-	-	13223	147753
1998	2011	3926	6225	1648	-	-	13810	161563
1999	1808	4102	6588	1802	-	-	14300	175863
2000	1808	4659	6970	1428	-	-	14865	190728

Table A.39. UO_2 Fuel Fabrication (No Recycle) - HIGH Case

Quantity - MTU

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	1146	527	1673	1673
1978	1298	527	1825	3498
1979	1375	762	2137	5635
1980	1655	938	2593	8228
1981	1604	1143	2747	10975
1982	2699	1963	4662	15637
1983	2826	1905	4731	20368
1984	3233	2227	5460	25828
1985	3666	2227	5893	31721
1986	3972	2754	6726	38447
1987	4328	3018	7346	45793
1988	5067	3164	8231	54024
1989	5703	3282	8985	63009
1990	6085	3809	9894	72903
1991	6721	4102	10823	83726
1992	7180	4542	11722	95448
1993	7842	4767	12609	108057
1994	8325	5157	13482	121539
1995	8860	5362	14222	135761
1996	9318	5655	14973	150734
1997	9751	5919	15670	166404
1998	10311	6124	16435	182839
1999	10591	6505	17096	199935
2000	11101	6563	17664	217599

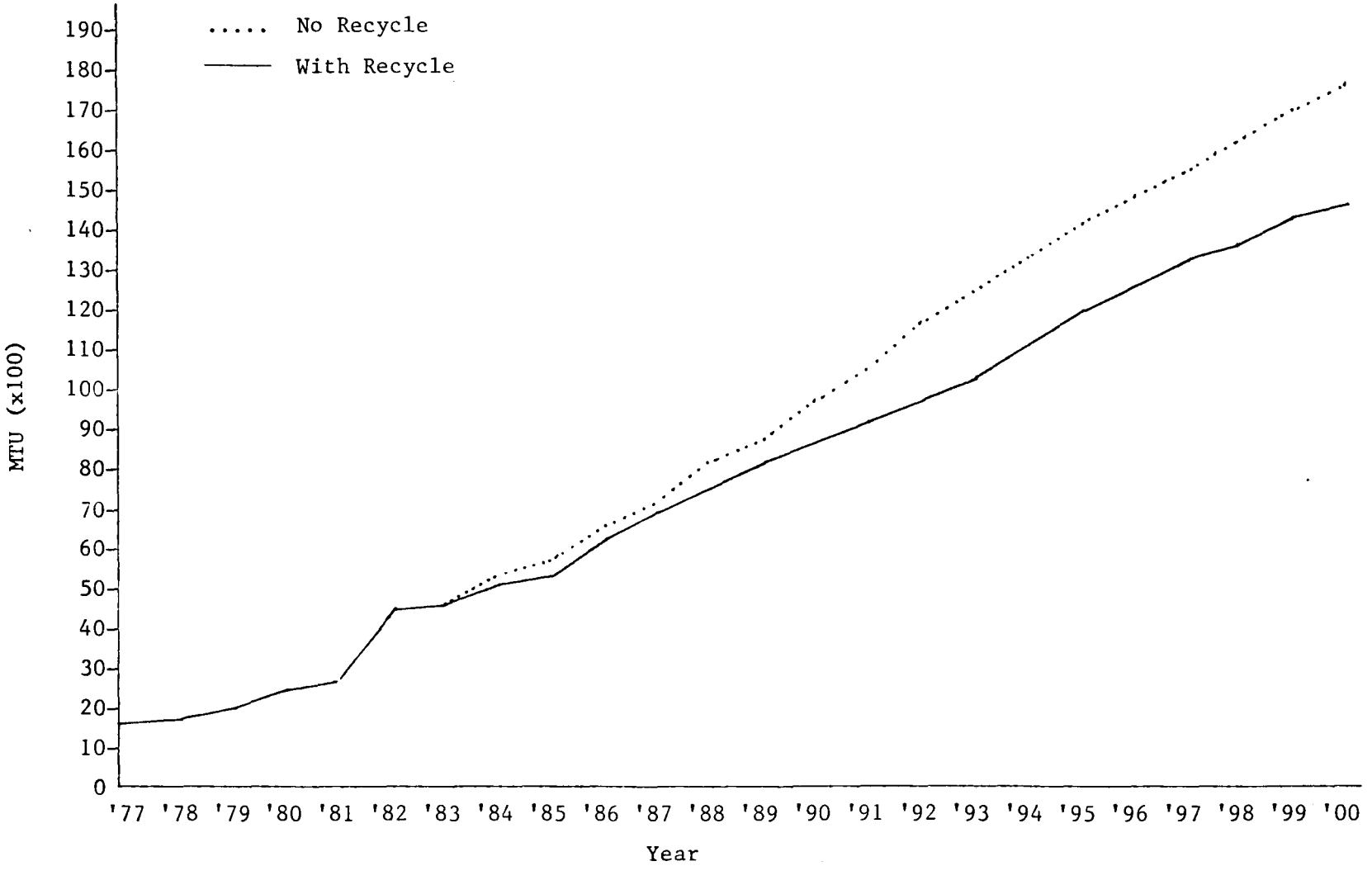

Figure A.20. UO_2 Fuel Fabrication - HIGH Case

Table A.40. Fuel Cost (No Recycle) - HIGH Case

Quantity - Billions of Dollars

Year	PWR UO_2	BWR UO_2	Annual Total	Cumm. Total
1976	-	-	-	-
1977	0.99	0.39	1.38	1.38
1978	1.19	0.41	1.60	2.98
1979	1.35	0.63	1.98	4.96
1980	1.74	0.82	2.56	7.52
1981	1.80	1.06	2.86	10.38
1982	2.25	2.00	4.25	14.63
1983	3.77	2.10	5.87	20.50
1984	4.59	2.60	7.19	27.69
1985	5.53	2.76	8.29	35.98
1986	6.22	3.54	9.76	45.74
1987	6.94	3.98	10.92	56.66
1988	8.54	4.39	12.93	69.59
1989	10.16	4.81	14.97	84.56
1990	11.54	5.95	17.49	102.05
1991	13.78	6.93	20.71	122.76
1992	15.91	8.30	24.21	146.97
1993	18.52	9.25	27.77	174.74
1994	20.56	10.51	31.07	205.81
1995	22.62	11.30	33.92	239.73
1996	24.60	11.36	35.96	275.69
1997	26.55	12.26	38.81	314.50
1998	28.97	13.08	42.05	356.55
1999	30.87	14.41	45.28	401.83
2000	33.42	15.01	48.43	450.26

Table A.41. Fuel Cost (With Recycle) - HIGH Case

Quantity - Billions of Dollars

Year	PWR UO_2	BWR UO_2	PWR SGR	BWR SGR	PWR PuO_2	BWR PuO_2	Annual Total	Cumm. Total
1976	-	-	-	-	-	-	-	-
1977	0.99	0.39	-	-	-	-	1.38	1.38
1978	1.19	0.41	-	-	-	-	1.60	2.98
1979	1.35	0.63	-	-	-	-	1.98	4.96
1980	1.74	0.82	-	-	-	-	2.56	7.52
1981	1.80	1.06	-	-	-	-	2.86	10.38
1982	2.25	2.00	-	-	-	-	4.25	14.63
1983	3.77	2.10	-	-	-	-	5.87	20.50
1984	3.62	2.60	0.86	-	-	-	7.08	27.58
1985	3.46	2.76	1.84	-	-	-	8.06	35.64
1986	4.07	3.54	1.91	-	-	-	9.52	45.16
1987	4.74	3.98	1.95	-	-	-	10.67	55.83
1988	5.02	4.39	3.11	-	-	-	12.52	68.35
1989	3.95	4.81	5.49	-	-	-	14.25	82.60
1990	3.77	4.72	6.86	1.11	-	-	16.46	99.06
1991	4.28	4.21	8.36	2.49	-	-	19.34	118.40
1992	4.57	3.59	9.62	4.22	-	-	22.00	140.40
1993	5.17	3.94	11.71	4.74	-	-	25.56	165.96
1994	5.35	5.26	13.34	4.69	-	-	28.64	194.60
1995	5.46	7.10	15.03	3.75	-	-	31.34	225.94
1996	5.44	6.83	16.77	4.90	-	-	33.94	259.88
1997	5.34	8.83	18.56	3.99	-	-	36.72	296.60
1998	5.65	9.11	20.40	4.54	-	-	39.70	336.30
1999	5.27	9.88	22.39	5.15	-	-	42.63	378.93
2000	5.44	11.59	24.45	4.22	-	-	45.70	424.63

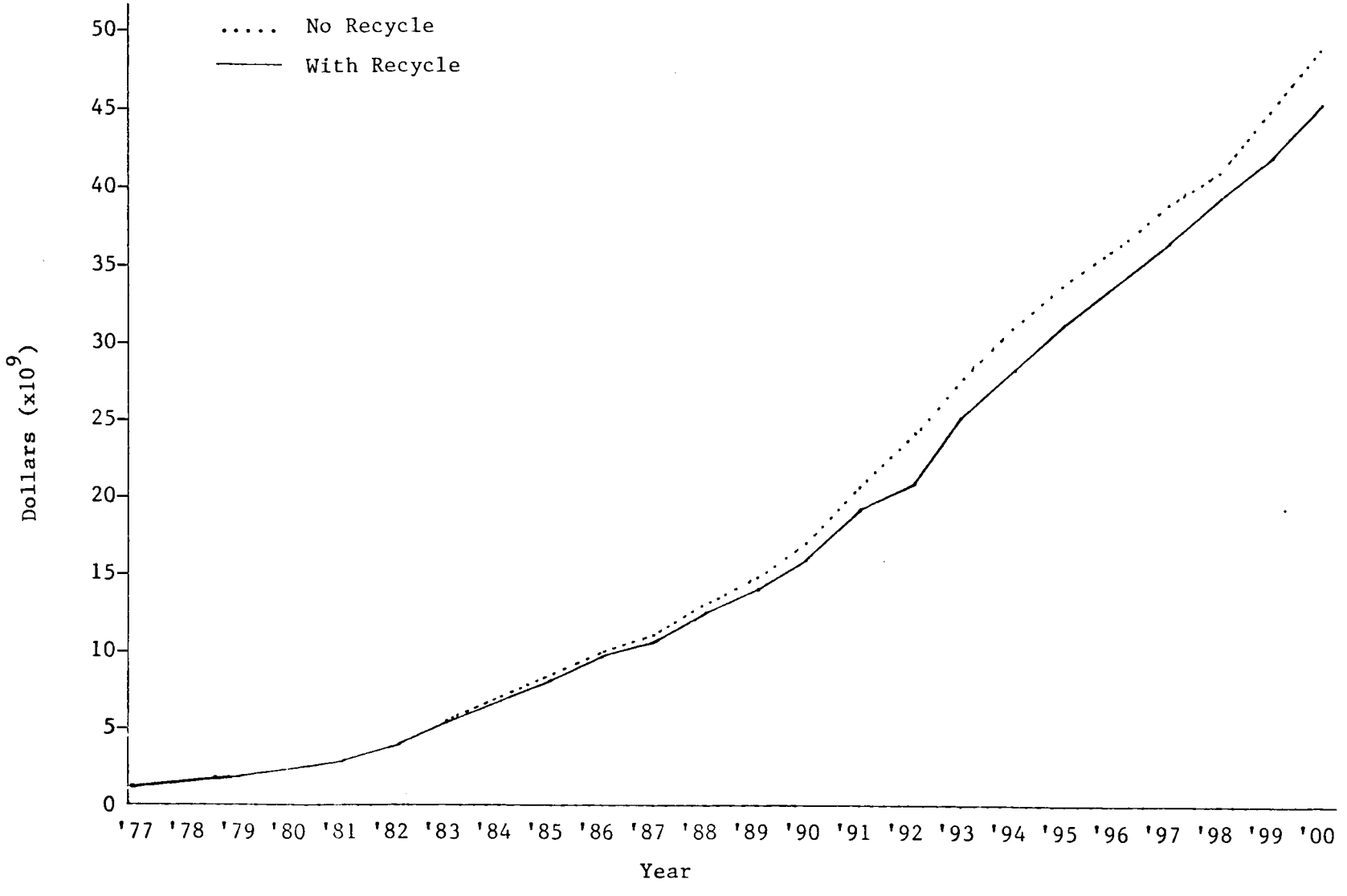

Figure A.21. Fuel Cost - HIGH Case

Appendix B

Fortran Computer Program for MPS-III Data Generation

```
C       MAIN PROGRAM                                                    MPS00010
C*****************************************************************MPS00020
C**                                                              **MPS00030
C**     THIS PROGRAM CALCULATES THE INPUT DATA FOR THE MPS PROGRAM  **MPS00040
C**                                                              **MPS00050
C*****************************************************************MPS00060
C                                                                       MPS00070
      IMPLICIT REAL*4(A-H,M,O-Z)                                        MPS00080
      DIMENSION IYEAR(25), CMOX(25), NRX(25), NPUR(25), NRUF(25), CREP(2MPS00090
     15)                                                                MPS00100
      DIMENSION FMOX(25), FUO2(25), SWU(25), REP(25)                    MPS00110
      DIMENSION MP(6,3), MOX(6,3), MO2(6,3), MSF(6)                     MPS00120
      DIMENSION B(6), E(6), G(6), H(6)                                  MPS00130
      DIMENSION XPU(6), PU(6)                                           MPS00140
      COMMON XU(6),CS(25),CF(25),CC(25),CUO2(25),XOU(6),CDT(25),M(6,3)  MPS00150
      COMMON DU(6),MU(6,3)                                              MPS00160
      READ (5,45) NYEAR,NTF,NPUF,IREP,IFMOX                             MPS00170
C                                                                       MPS00180
C*****************************************************************MPS00190
C**                                                              **MPS00200
C**   NYEAR  = NUMBER OF YEARS IN PLANNING HORIZON                  **MPS00210
C**   NTF    = NUMBER OF FUEL TYPES                                 **MPS00220
C**   NPUF   = NUMBER OF FUEL TYPES UTILIZING PLUTONIUM             **MPS00230
C**   IREP   = YEAR REPROCESSING BEGINS                             **MPS00240
C**   NUF    = NUMBER OF FUEL TYPES UTILIZING URANIUM ONLY          **MPS00250
C**   IFMOX  = YEAR MOX FUEL FABRICATION BEGINS                     **MPS00260
C**                                                              **MPS00270
C*****************************************************************MPS00280
C                                                                       MPS00290
      NUF=NTF-NPUF                                                      MPS00300
      XW=.0025                                                          MPS00310
      DO 1 I=1,NYEAR                                                    MPS00320
```

```
      READ (5,44) IYEAR(I),CS(I),CF(I),CMOX(I),CUO2(I),NRX(I),NPWR(I)    MPS00330
      READ (5,45) FMOX(I),FUO2(I),SWU(I),REP(I),CC(I),COT(I),CREP(I)     MPS00340
C                                                                        MPS00350
C*****************************************************************MPS00360
C*                                                                     **MPS00370
C**   IYEAR(I) = SPECIFIC YEAR IN PLANNING HORIZON                     **MPS00380
C*    CS(I)    = UNIT COST OF SWU IN YEAR I                             **MPS00390
C**   CF(I)    = UNIT COST OF NATURAL URANIUM IN YEAR I                 **MPS00400
C**   CMOX(I)  = UNIT COST OF MOX FUEL FABRICATION IN YEAR I            **MPS00410
C**   CUO2(I)  = UNIT COST OF UO2 FUEL FABRICATION IN YEAR I            **MPS00420
C*    NRX(I)   = NUMBER OF REACTORS IN YEAR I                           **MPS00430
C**   NPWR(I)  = NUMBER OF PWR REACTORS IN YEAR I                       **MPS00440
C*    FMOX(I)  = MOX FUEL FABRICATION CAPACITY IN YEAR I                **MPS00450
C**   FUO2(I)  = UO2 FUEL FABRICATION IN YEAR I                         **MPS00460
C*    SWU(I)   = SWU CAPACITY IN YEAR I                                 **MPS00470
C**   REP(I)   = REPROCESSING CAPACITY IN YEAR I                        **MPS00480
C**   CC(I)    = UNIT COST OF U3O8 TO UF6 CONVERSION IN YEAR I          **MPS00490
C**   COT(I)   = UNIT COST OF GASEOUS DIFFUSION TAILS IN YEAR I         **MPS00500
C*    CREP(I)  = UNIT COST OF REPROCESSING IN YEAR I                    **MPS00510
C**   NBWR(I)  = NUMBER OF BWR REACTORS IN YEAR I                       **MPS00520
C*                                                                     **MPS00530
C*****************************************************************MPS00540
C                                                                        MPS00550
      NBWR(I)=NRX(I)-NPWR(I)                                             MPS00560
1     CONTINUE                                                           MPS00570
      DO 2 L=1,NTF                                                       MPS00580
      READ (5,46) (M(L,K),K=1,3)                                         MPS00590
      READ (5,46) (MP(L,K),K=1,3)                                        MPS00600
      READ (5,46) (MU(L,K),K=1,3)                                        MPS00610
      READ (5,46) (MMX(L,K),K=1,3)                                       MPS00620
      READ (5,46) (MO2(L,K),K=1,3)                                       MPS00630
      READ (5,47) XDU(L),XU(L),XPU(L),DU(L),PU(L)                        MPS00640
```

```
C                                                                       MPS00650
C*****************************************************************MPS00660
C**                                                                   **MPS00670
C**    M(L,K)    = TOTAL QUANTITY OF FRESH FUEL REQUIRED FOR INITIAL AND*MPS00680
C**                RELOAD CORES                                        **MPS00690
C**    MP(L,K)   = TOTAL QUANTITY OF PLUTONIUM REQUIRED FOR INITIAL AND **MPS00700
C**                RELOAD CORES (KG)                                   **MPS00710
C**    MU(L,K)   = TOTAL QUANTITY OF URANIUM REQUIRED FOR INITIAL AND   **MPS00720
C**                RELOAD CORES (KG)                                   **MPS00730
C**    MOX(L,K)  = TOTAL QUANTITY OF MOX FUEL FABRICATION REQUIRED FOR  **MPS00740
C**                INITIAL AND RELOAD CORES (KG)                       **MPS00750
C**    UO2(L,K)  = TOTAL QUANTITY OF UO2 FUEL FABRICATION REQUIRED FOR  **MPS00760
C**                INITIAL AND RELOAD CORES (KG)                       **MPS00770
C**    XDU(L)    = % U-235 IN SPENT FUEL                               **MPS00780
C**    XU(L)     = % U-235 REQUIRED IN FRESH FUEL                      **MPS00790
C**    XPU(L)    = FISSILE CONTENT OF PLUTONIUM                        **MPS00800
C**    DU(L)     = QUANTITY OF URANIUM IN SPENT FUEL (KG)              **MPS00810
C**    PU(L)     = QUANTITY OF PLUTONIUM IN SPENT FUEL (KG)            **MPS00820
C**                                                                    **MPS00830
C*****************************************************************MPS00840
C                                                                       MPS00850
      MSF(L)=DU(L)+PU(L)                                                MPS00860
      H(L)=DU(L)/MSF(L)                                                 MPS00870
      F(L)=PU(L)/MSF(L)                                                 MPS00880
      B(L)=MP(L,3)/M(L,3)                                               MPS00890
      G(L)=DU(L)/M(L,3)                                                 MPS00900
2     CONTINUE                                                          MPS00910
      READ (5,43) ITFC,IITFC,ITUF6,IITUF6                               MPS00920
C                                                                       MPS00930
C     ITFC + IITFC = TOTAL FUEL COST ALLOWED (*)                        MPS00940
C     ITUF6 + IITUF6 = TOTAL UF6 ALLOWED FOR CONSUMPTION (KG)           MPS00950
C                                                                       MPS00960
```

```
C                                                                       MPS00970
C     INPUT DATA NAME                                                   MPS00980
C                                                                       MPS00990
      WRITE (3,49)                                                      MPS01000
C                                                                       MPS01010
C     ROWS SECTION OF INPUT DATA                                        MPS01020
C                                                                       MPS01030
      WRITE (3,50)                                                      MPS01040
C                                                                       MPS01050
C     OBJECTIVE FUNCTION NAME                                           MPS01060
C                                                                       MPS01070
      WRITE (3,51)                                                      MPS01080
      DO 3 J=2,NYEAR                                                    MPS01090
      JJ=J+75                                                           MPS01100
      NR=NRX(J)                                                         MPS01110
C                                                                       MPS01120
C     DEFINES FIRST CONSTRAINT TYPE AS AN EQUALITY CONSTRAINT           MPS01130
C                                                                       MPS01140
      DO 3 K=1,NR                                                       MPS01150
      IF (K.LE.9) WRITE (3,52) K,JJ                                     MPS01160
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,53) K,JJ                    MPS01170
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,54) K,JJ                   MPS01180
3     CONTINUE                                                          MPS01190
      IOX=IFNOX-74                                                      MPS01200
C                                                                       MPS01210
C     DEFINES SECOND CONSTRAINT TYPE AS A LESS-THAN-OR-EQUAL-TO         MPS01220
C        CONSTRAINT                                                     MPS01230
C                                                                       MPS01240
      DO 4 J=IOX,NYEAR                                                  MPS01250
      JJ=J+75                                                           MPS01260
      WRITE (3,55) JJ                                                   MPS01270
4     CONTINUE                                                          MPS01280
```

```
C                                                                       MPS01290
C     DEFINES THE THIRD CONSTRAINT TYPE AS A LESS-THAN-OR-EQUAL-TO      MPS01300
C     CONSTRAINT                                                        MPS01310
C                                                                       MPS01320
      DO 5 J=2,NYEAR                                                    MPS01330
      JJ=J+75                                                           MPS01340
      WRITE (3,56) JJ                                                   MPS01350
5     CONTINUE                                                          MPS01360
C                                                                       MPS01370
C     DEFINES THE FOURTH CONSTRAINT TYPE AS A LESS-THAN-OR-EQUAL-TO     MPS01380
C        CONSTRAINT                                                     MPS01390
C                                                                       MPS01400
      DO 6 J=2,NYEAR                                                    MPS01410
      JJ=J+75                                                           MPS01420
      WRITE (3,57) JJ                                                   MPS01430
6     CONTINUE                                                          MPS01440
C                                                                       MPS01450
C     DEFINES THE FIFTH CONSTRAINT TYPE AS A LESS-THAN-OR-EQUAL-TO      MPS01460
C        CONSTRAINT                                                     MPS01470
C                                                                       MPS01480
      DO 7 J=IOX,NYEAR                                                  MPS01490
      JJ=J+75                                                           MPS01500
      WRITE (3,58) JJ                                                   MPS01510
7     CONTINUE                                                          MPS01520
C                                                                       MPS01530
C     DEFINES THE SIXTH CONSTRAINT TYPE AS A LESS-THAN-OR-EQUAL-TO      MPS01540
C        CONSTRAINT                                                     MPS01550
C                                                                       MPS01560
      DO 8 J=IOX,NYEAR                                                  MPS01570
      JJ=J+75                                                           MPS01580
      WRITE (3,59) JJ                                                   MPS01590
8     CONTINUE                                                          MPS01600
```

```
C
C     DEFINES THE SEVENTH CONSTRAINT TYPE AS A LESS-THAN-OR-EQUAL-TO
C        CONSTRAINT
C
      DO 9 J=IOX,NYEAR
      JJ=J+75
      WRITE (3,60) JJ
9     CONTINUE
C
C     DEFINES THE EIGHTH CONSTRAINT TYPE AS A LESS-THAN-OR-EQUAL-TO
C        CONSTRAINT
C
      WRITE (3,61)
C
C     COLUMNS SECTION OF INPUT DATA
C
      WRITE (3,62)
      DO 32 J=2,NYEAR
      JJ=J+75
      NR=NRX(J)
      DO 32 I=1,NTF
      DO 32 K=1,N
      IF ((JJ.LE.IF40X).AND.(I.LE.NUF)) GO TO 10
      IF ((JJ.LE.IF40X).AND.(I.GT.NUF)) GO TO 32
      IF ((JJ.GT.IF40X)) GO TO 16
C
C     FOR NUCLEAR INDUSTRY PRIOR TO IMPLEMENTATION OF R-CYCLE
C
10    CONTINUE
C
C     IF:    KK = 0  -  NO URANIUM RECYCLE
C            KK = 1  -  URANIUM RECYCLE
```

```
C
      KK=0
      CALL COST (J,K,I,KK,TC,DUC,PUC,SWP,FP)
      GO TO (11,12), I
C
C     PROCESSES COLUMN DATA FOR UO2-PWR PRIOR TO YEAR OF RECYCLE
C
11    IF (K.GT.NPWR(J)) GO TO 32
      IF (K.LE.NPWR(J-1)) TUF6=MU(I,3)*FP
      IF (K.LE.NPWR(J-1)) TFC=TC*M(I,3)
      IF (K.GT.NPWR(J-1)) TUF6=MU(I,1)*FP
      IF (K.GT.NPWR(J-1)) TFC=TC*M(I,1)
      AA=1.0
      IF (K.LE.9) WRITE (3,63) I,K,JJ,TUF6,K,JJ,AA
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,64) I,K,JJ,TUF6,K,JJ,AA
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,65) I,K,JJ,TUF6,K,JJ,AA
      IF (K.LE.NPWR(J-1)) MM=M(I,3)
      IF (K.GT.NPWR(J-1)) MM=M(I,1)
      IF (K.LE.NPWR(J-1)) DD=SWP*M(I,3)
      IF (K.GT.NPWR(J-1)) DD=SWP*M(I,1)
      IF (K.LE.9) WRITE (3,66) I,K,JJ,JJ,MM,JJ,DD
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,67) I,K,JJ,JJ,MM,JJ,DD
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,68) I,K,JJ,JJ,MM,JJ,DD
      GO TO 13
C
C     PROCESSES COLUMN DATA FOR UO2-BWR PRIOR TO YEAR OF RECYCLE
C
12    KJ=NPWR(J)+K
      IF (K.GT.NBWR(J)) GO TO 32
      IF (K.LE.NBWR(J-1)) TUF6=MU(I,3)*FP
      IF (K.LE.NBWR(J-1)) TFC=TC*M(I,3)
      IF (K.GT.NBWR(J-1)) TUF6=MU(I,1)*FP
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```
      IF (K.GT.NBWR(J-1)) TFC=TC*M(I,1)                                 MPS02250
      AA=1.0                                                            MPS02260
      IF (K.LE.9) WRITE (3,71) I,K,JJ,TUF6,KJ,JJ,AA                     MPS02270
      IF ((K.GE.10).AND.(K.LE.99).AND.(KJ.GE.10).AND.(KJ.LE.99)) WRITE (MPS02280
     13,72) I,K,JJ,TUF6,KJ,JJ,AA                                        MPS02290
      IF ((K.GE.100).AND.(K.LE.NR).AND.(KJ.LE.99)) WRITE (3,73) I,K,JJ,TMPS02300
     1UF6,KJ,JJ,AA                                                      MPS02310
      IF ((K.GE.10).AND.(K.LE.99).AND.(KJ.GE.100)) WRITE (3,69) I,K,JJ,TMPS02320
     1UF6,KJ,JJ,AA                                                      MPS02330
      IF ((K.GE.100).AND.(K.LE.NR).AND.(KJ.GE.100)) WRITE (3,70) I,K,JJ,MPS02340
     1TUF6,KJ,JJ,AA                                                     MPS02350
      IF (K.LE.NBWR(J-1)) MM=M(I,3)                                     MPS02360
      IF (K.LE.NBWR(J-1)) DQ=SWP*M(I,3)                                 MPS02370
      IF (K.GT.NBWR(J-1)) MM=M(I,1)                                     MPS02380
      IF (K.GT.NBWR(J-1)) DQ=SWP*M(I,1)                                 MPS02390
      IF (K.LE.9) WRITE (3,66) I,K,JJ,JJ,MM,JJ,DQ                       MPS02400
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,67) I,K,JJ,JJ,MM,JJ,DQ      MPS02410
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,68) I,K,JJ,JJ,MM,JJ,DQ     MPS02420
C                                                                       MPS02430
C     PROCESSES COLUMN DATA FOR BOTH UO2-PWR & BWR FOR                  MPS02440
C        CONSTRAINT TYPES 5 & 6.                                        MPS02450
C                                                                       MPS02460
13    DO 14 II=IDX,NYEAR                                                MPS02470
      IQ=II+75                                                          MPS02480
      IF (J.EQ.IDX-1) IQ=II+76                                          MPS02490
      IF ((K.GT.NPWR(J-1)).AND.(I.EQ.1).AND.(JJ.GE.IPMOX)) IQ=II+77     MPS02500
      IF ((K.GT.NBWR(J-1)).AND.(I.EQ.2).AND.(JJ.GE.IBMOX)) IQ=II+77     MPS02510
      HQ=-H(I)*MSF(I)                                                   MPS02520
      EQ=-E(I)*MSF(I)                                                   MPS02530
      IF (IQ.GT.NYEAR+75) GO TO 14                                      MPS02540
      IF (K.LE.9) WRITE (3,74) I,K,JJ,IQ,EQ,IQ,HQ                       MPS02550
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,75) I,K,JJ,IQ,EQ,IQ,HQ      MPS02560
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      IF ((K.GE.100).AND.(K.LE.NP)) WRITE (3,76) I,K,JJ,IC,FC,IC,MW      MPS02570
14    CONTINUE                                                          MPS02580
C                                                                       MPS02590
C     PROCESSES COLUMN DATA FOR BOTH UO2-PWR & BWR FOR                  MPS02600
C        CONSTRAINT TYPE 2.                                             MPS02610
C                                                                       MPS02620
      JK=J+1                                                            MPS02630
      DO 15 III=JK,NYEAR                                                MPS02640
      JI=I I+75                                                         MPS02650
      IF (JI.GT.NYEAR+75) GO TO 15                                      MPS02660
      MM=M(I,3)                                                         MPS02670
      IF ((I.EQ.1).AND.(K.GT.NPWR(J-1))) MM=M(I,1)                      MPS02680
      IF ((I.EQ.2).AND.(K.GT.NBWR(J-1))) MM=M(I,1)                      MPS02690
      IF (K.LE.9) WRITE (3,77) I,K,JJ,JI,MM                             MPS02700
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,78) I,K,JJ,JI,MM            MPS02710
      IF (K.GE.100) WRITE (3,79) I,K,JJ,JI,MM                           MPS02720
15    CONTINUE                                                          MPS02730
C                                                                       MPS02740
C     PROCESSES COLUMN DATA FOR BOTH UO2-PWR & BWR FOR                  MPS02750
C        CONSTRAINT TYPE 3.                                             MPS02760
C                                                                       MPS02770
      IF (K.LE.9) WRITE (3,118) I,K,JJ,TFC                              MPS02780
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,119) I,K,JJ,TFC             MPS02790
      IF (K.GE.100) WRITE (3,120) I,K,JJ,TFC                            MPS02800
      GO TO 32                                                          MPS02810
C                                                                       MPS02820
C     FOR NUCLEAR INDUSTRY WITH RECYCLE AVAILABLE                       MPS02830
C                                                                       MPS02840
16    CONTINUE                                                          MPS02850
      KK=1                                                              MPS02860
      IF ((K.GT.NPWR(J-2)).AND.((I.EQ.1).OR.(I.EQ.3).OR.(I.EQ.5))) KK=0 MPS02870
      IF ((K.GT.NBWR(J-2)).AND.((I.EQ.2).OR.(I.EQ.4).OR.(I.EQ.6))) KK=0 MPS02880
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```
      IF (I.LE.NUF) KK=0                                                MPS02890
      CALL COST (J,K,I,KK,TC,DUC,PUC,SWP,FP)                            MPS02900
      GO TO (17,18,19,20,21,22), I                                      MPS02910
C                                                                       MPS02920
C     PROCESSES COLUMN DATA FOR UB2-PWR                                 MPS02930
C                                                                       MPS02940
17    IF (K.GT.NPWR(J)) GO TO 32                                        MPS02950
      IF (K.LE.NPWR(J-1)) TUF6=M(I,3)*FP                                MPS02960
      IF (K.LE.NPWR(J-1)) TFC=TC*M(I,3)                                 MPS02970
      IF (K.GT.NPWR(J-1)) TUF6=M(I,1)*FP                                MPS02980
      IF (K.GT.NPWR(J-1)) TFC=TC*M(I,1)                                 MPS02990
      AA=1.0                                                            MPS03000
      IF (K.LE.9) WRITE (3,83) I,K,JJ,TUF6,K,JJ,AA                      MPS03010
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,84) I,K,JJ,TUF6,K,JJ,AA     MPS03020
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,85) I,K,JJ,TUF6,K,JJ,AA    MPS03030
      IF (K.LE.NPWR(J-1)) AA=M(I,3)                                     MPS03040
      IF (K.LE.NPWR(J-1)) DQ=SWP*M(I,3)                                 MPS03050
      IF (K.GT.NPWR(J-1)) AA=M(I,1)                                     MPS03060
      IF (K.GT.NPWR(J-1)) DQ=SWP*M(I,1)                                 MPS03070
      IF (K.LE.9) WRITE (3,86) I,K,JJ,JJ,AA,JJ,DQ                       MPS03080
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,87) I,K,JJ,JJ,AA,JJ,DQ      MPS03090
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,88) I,K,JJ,JJ,AA,JJ,DQ     MPS03100
      GO TO 23                                                          MPS03110
C                                                                       MPS03120
C     PROCESSES COLUMN DATA FOR UB2-BWR                                 MPS03130
C                                                                       MPS03140
18    KJ=NPWR(J)+K                                                      MPS03150
      IF (K.GT.NBWR(J)) GO TO 32                                        MPS03160
      IF (K.LE.NBWR(J-1)) TUF6=M(I,3)*FP                                MPS03170
      IF (K.LE.NBWR(J-1)) TFC=TC*M(I,3)                                 MPS03180
      IF (K.GT.NBWR(J-1)) TUF6=M(I,1)*FP                                MPS03190
      IF (K.GT.NBWR(J-1)) TFC=TC*M(I,1)                                 MPS03200
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```
      AA=1.0                                                            MPS03210
      IF ((K.LE.9).AND.(KJ.GE.10).AND.(KJ.LE.99)) WRITE (3,89) I,K,JJ,TUMPS03220
     1F6,KJ,JJ,AA                                                       MPS03230
      IF ((K.LE.9).AND.(KJ.GE.100)) WRITE (3,93) I,K,JJ,TUF6,KJ,JJ,AA   MPS03240
      IF ((K.GE.10).AND.(K.LE.99).AND.(KJ.GE.10).AND.(KJ.LE.99)) WRITE (MPS03250
     13,90) I,K,JJ,TUF6,KJ,JJ,AA                                        MPS03260
      IF ((K.GE.10).AND.(K.LE.99).AND.(KJ.GE.100)) WRITE (3,92) I,K,JJ,TMPS03270
     1UF6,KJ,JJ,AA                                                      MPS03280
      IF ((K.GE.100).AND.(K.LE.NR).AND.(KJ.GE.100).AND.(KJ.LE.NR)) WRITEMPS03290
     1 (3,91) I,K,JJ,TUF6,KJ,JJ,AA                                      MPS03300
      IF (K.LE.NBWR(J-1)) MM=M(I,3)                                     MPS03310
      IF (K.LE.NBWR(J-1)) DD=SWP*M(I,3)                                 MPS03320
      IF (K.GT.NBWR(J-1)) MM=M(I,1)                                     MPS03330
      IF (K.GT.NBWR(J-1)) DD=SWP*M(I,1)                                 MPS03340
      IF (K.LE.9) WRITE (3,86) I,K,JJ,JJ,MM,JJ,DD                       MPS03350
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,87) I,K,JJ,JJ,MM,JJ,DD      MPS03360
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,88) I,K,JJ,JJ,MM,JJ,DD     MPS03370
      GO TO 23                                                          MPS03380
C                                                                       MPS03390
C     PROCESSES COLUMN DATA FOR SGR-PWR                                 MPS03400
C                                                                       MPS03410
19    IF (K.GT.NPWR(J-1)) GO TO 32                                      MPS03420
      TPUC=PUC-(CMOX(J-1)-CUO2(J-1))/(WP(I,3)*1000.*XPU(I)/MOX(I,3))    MPS03430
      TFC=TPUC*1000.*WP(I,3)*XPU(I)+TC*MU(I,3)+PU(I)*PUC+MOX(I,3)*CMOX(JMPS03440
     1-1)                                                               MPS03450
      TUF6=MU(I,3)*FP                                                   MPS03460
      AA=1.0                                                            MPS03470
      IF (K.LE.9) WRITE (3,83) I,K,JJ,TUF6,K,JJ,AA                      MPS03480
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,84) I,K,JJ,TUF6,K,JJ,AA     MPS03490
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,85) I,K,JJ,TUF6,K,JJ,AA    MPS03500
      MUO2=UO2(I,3)                                                     MPS03510
      MMOX=MOX(I,3)                                                     MPS03520
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```
      DQ=SWP*M(I,3)                                                     MPS03530
      IF (K.LE.9) WRITE (3,94) I,K,JJ,JJ,MMOX,JJ,MUO2                   MPS03540
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,95) I,K,JJ,JJ,MMOX,JJ,MUO2  MPS03550
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,96) I,K,JJ,JJ,MMOX,JJ,MUO2 MPS03560
      IF (K.LE.9) WRITE (3,97) I,K,JJ,JJ,DQ                             MPS03570
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,98) I,K,JJ,JJ,DQ            MPS03580
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,99) I,K,JJ,JJ,DQ           MPS03590
      GO TO 23                                                          MPS03600
C                                                                       MPS03610
C     PROCESSES COLUMN DATA FOR SGR-MWR                                 MPS03620
C                                                                       MPS03630
20    KJ=NPWR(J)+K                                                      MPS03640
      IF (K.GT.N3WR(J-2)) GO TO 32                                      MPS03650
      TPUC=PUC-(CMOX(J-1)-CUO2(J-1))/(MP(I,3)*1000.*XPU(I)/MOX(I,3))    MPS03660
      TFC=TPUC*1000.*XPU(I)*MP(I,3)+TC*MU(I,3)+DU(I)*DUC+MOX(I,3)*CMOX(JMPS03670
     1-1)                                                               MPS03680
      TUF6=MU(I,3)*FP                                                   MPS03690
      AA=1.0                                                            MPS03700
      IF ( K.LE.9).AND.(KJ.GE.10).AND.(KJ.LE.99)) WRITE (3,89) I,K,JJ,TUMPS03710
     1F6,KJ,JJ,AA                                                       MPS03720
      IF ((K.LE.9).AND.(KJ.GE.100)) WRITE (3,93) I,K,JJ,TUF6,KJ,JJ,AA   MPS03730
      IF ((K.GE.10).AND.(K.LE.99).AND.(KJ.GE.10).AND.(KJ.LE.99)) WRITE (MPS03740
     13,90) I,K,JJ,TUF6,KJ,JJ,AA                                        MPS03750
      IF ((K.GE.100).AND.(K.LE.NR).AND.(KJ.GE.100)) WRITE (3,91) I,K,JJ,MPS03760
     1TUF6,KJ,JJ,AA                                                     MPS03770
      IF ((K.GE.10).AND.(K.LE.99).AND.(KJ.GE.100)) WRITE (3,92) I,K,JJ,TMPS03780
     1UF6,KJ,JJ,AA                                                      MPS03790
      MUO2=MUO2(I,3)                                                    MPS03800
      MMOX=MOX(I,3)                                                     MPS03810
      DQ=SWP*M(I,3)                                                     MPS03820
      IF (K.LE.9) WRITE (3,94) I,K,JJ,JJ,MMOX,JJ,MUO2                   MPS03830
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,95) I,K,JJ,JJ,MMOX,JJ,MUO2  MPS03840
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      IF ((K.GE.100).AND.(K.LE.99)) WRITE (3,96) I,K,JJ,JJ,MMOX,JJ,MUO2 MPS03850
      IF (K.LE.9) WRITE (3,97) I,K,JJ,JJ,DQ                            MPS03860
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,98) I,K,JJ,JJ,DQ           MPS03870
      IF (K.GE.100) WRITE (3,99) I,K,JJ,JJ,DQ                          MPS03880
      GO TO 23                                                         MPS03890
C                                                                      MPS03900
C     PROCESSES COLUMN DATA FOR PUO2-PUP                               MPS03910
C                                                                      MPS03920
21    IF ((K.GT.NPWR(J)).OR.(K.LE.NPUP(IFMOX-75))) GO TO 32            MPS03930
      IF (K.GT.NPWR(J-1)) TPUC=PUC-(CMOX(J-1)-CUO2(J-1))/(MP(I,1)*1000.*MPS03940
     1XPU(I)/M(I,1))                                                   MPS03950
      IF (K.GT.NPWR(J-1)) TFC=TPUC*MP(I,1)*1000.+CF(J-1)*MU(I,1)+MOX(I,1MPS03960
     1)*CMOX(J-1)                                                      MPS03970
      IF (K.GT.NPWR(J-1)) TUF6=MU(I,1)                                 MPS03980
      IF (K.LE.NPWR(J-1)) TPUC=PUC-(CMOX(J-1)-CUO2(J-1))/(MP(I,3)*1000.*MPS03990
     1XPU(I)/M(I,3))                                                   MPS04000
      IF (K.LE.NPWR(J-1)) TFC=TPUC*MP(I,3)*1000.+CF(J-1)*MU(I,3)+MOX(I,3MPS04010
     1)*CMOX(J-1)                                                      MPS04020
      IF (K.LE.NPWR(J-1)) TUF6=MU(I,3)                                 MPS04030
      AA=1.0                                                           MPS04040
      IF (K.LE.9) WRITE (3,83) I,K,JJ,TUF6,K,JJ,AA                     MPS04050
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,84) I,K,JJ,TUF6,K,JJ,AA    MPS04060
      IF ((K.GE.100).AND.(K.LE.99)) WRITE (3,85) I,K,JJ,TUF6,K,JJ,AA   MPS04070
      IF (K.GT.NPWR(J-1)) MMOX=M(I,1)                                  MPS04080
      IF (K.LE.NPWR(J-1)) MMOX=M(I,3)                                  MPS04090
      IF (K.LE.9) WRITE (3,100) I,K,JJ,JJ,MMOX                         MPS04100
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,101) I,K,JJ,JJ,MMOX        MPS04110
      IF ((K.GE.100).AND.(K.LE.99)) WRITE (3,102) I,K,JJ,JJ,MMOX       MPS04120
      GO TO 23                                                         MPS04130
C                                                                      MPS04140
C     PROCESSES COLUMN DATA FOR PUO2-BWR                               MPS04150
C                                                                      MPS04160
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22    KJ=NPWR(J)+K                                                      MPS04170
      IF ((K.GT.NBWR(J)).OR.(K.LE.NBWR(IPMOX-75))) GO TO 32             MPS04180
      IF (K.GT.NBWR(J-1)) TPUC=PUC-(CMOX(J-1)-CMO2(J-1))/(MP(I,1)*1000.*MPS04190
     1XPU(I)/M(I,1))                                                    MPS04200
      IF (K.GT.NBWR(J-1)) TFC=TPUC*MP(I,1)*1000.+CDT(J-1)*MU(I,1)+MOX(I,MPS04210
     11)*CMOX(J-1)                                                      MPS04220
      IF (K.GT.NBWR(J-1)) TUF6=1.0                                      MPS04230
      IF (K.LE.NBWR(J-1)) TPUC=PUC-((CMOX(J-1)-CMO2(J-1))/(MP(I,3)*1000.*MPS04240
     1XPU(I)/M(I,3))                                                    MPS04250
      IF (K.LE.NBWR(J-1)) TFC=TPUC*MP(I,3)*1000.+CDT(J-1)*MU(I,3)+MOX(I,MPS04260
     13)*CMOX(J-1)                                                      MPS04270
      IF (K.LE.NBWR(J-1)) TUF6=1.0                                      MPS04280
      AA=1.0                                                            MPS04290
      IF ((K.LE.9).AND.(KJ.GE.10).AND.(KJ.LE.99)) WRITE (3,89) I,K,JJ,TUMPS04300
     1U6,KJ,JJ,AA                                                       MPS04310
      IF ((K.GE.10).AND.(K.LE.99).AND.(KJ.GE.10).AND.(KJ.LE.99)) WRITE (MPS04320
     13,90) I,K,JJ,TUF6,KJ,JJ,AA                                        MPS04330
      IF ((K.GE.100).AND.(K.LE.N8).AND.(KJ.GE.100)) WRITE (3,91) I,K,JJ,MPS04340
     1TUF6,KJ,JJ,AA                                                     MPS04350
      IF ((K.GE.10).AND.(K.LE.99).AND.(KJ.GE.100)) WRITE (3,92) I,K,JJ,TMPS04360
     1UF6,KJ,JJ,AA                                                      MPS04370
      IF (K.GT.NBWR(J-1)) MMOX=M(I,1)                                   MPS04380
      IF (K.LE.NBWR(J-1)) MMOX=M(I,3)                                   MPS04390
      IF (K.LE.9) WRITE (3,100) I,K,JJ,JJ,MMOX                          MPS04400
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,101) I,K,JJ,JJ,MMOX         MPS04410
      IF ((K.GE.100).AND.(K.LE.N8)) WRITE (3,102) I,K,JJ,JJ,MMOX        MPS04420
23    DO 26 II=J,NYEAR                                                  MPS04430
      IO=II+75                                                          MPS04440
      IF ((I.LE.2).AND.(IO.LE.NYEAR+75)) IO=II+77                       MPS04450
      IF ((I.EQ.1).AND.(K.GT.NPWR(J-1))) IO=II+73                       MPS04460
      IF ((I.EQ.2).AND.(K.GT.NBWR(J-1))) IO=II+73                       MPS04470
      IF (IO.GT.NYEAR+75) GO TO 26                                      MPS04480
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      EQ=-E(I)*MSF(I)                                                   MPS04490
      HQ=-H(I)*MSF(I)                                                   MPS04500
      BQ=B(I)*M(I,3)                                                    MPS04510
      GQ=G(I)*M(I,3)                                                    MPS04520
      IF (I.GT.NUF) GO TO 24                                            MPS04530
      IF (K.LE.9) WRITE (3,103) I,K,JJ,IQ,EQ,IQ,HQ                      MPS04540
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,104) I,K,JJ,IQ,EQ,IQ,HQ     MPS04550
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,105) I,K,JJ,IQ,EQ,IQ,HQ    MPS04560
      GO TO 25                                                          MPS04570
24    IF (I.GT.4) GO TO 25                                              MPS04580
      BE=BQ+EQ                                                          MPS04590
      HG=HQ+GQ                                                          MPS04600
      IF ((JJ+2.GE.IQ).AND.(K.LE.9)) WRITE (3,106) I,K,JJ,IQ,BQ,IQ,GQ   MPS04610
      IF ((JJ+2.GE.IQ).AND.(K.GE.10).AND.(K.LE.99)) WRITE (3,107) I,K,JJMPS04620
     1,IQ,BQ,IQ,GQ                                                      MPS04630
      IF ((JJ+2.GE.IQ).AND.(K.GE.100).AND.(K.LE.NR)) WRITE (3,108) I,K,JMPS04640
     1J,IQ,BQ,IQ,GQ                                                     MPS04650
      IF ((JJ+2.LT.IQ).AND.(K.LE.9)) WRITE (3,106) I,K,JJ,IQ,BE,IQ,HG   MPS04660
      IF ((JJ+2.LT.IQ).AND.(K.GE.10).AND.(K.LE.99)) WRITE (3,107) I,K,JJMPS04670
     1,IQ,BE,IQ,HG                                                      MPS04680
      IF ((JJ+2.LT.IQ).AND.(K.GE.100).AND.(K.LE.NR)) WRITE (3,108) I,K,JMPS04690
     1J,IQ,BE,IQ,HG                                                     MPS04700
      GO TO 25                                                          MPS04710
25    BE=BQ+EQ                                                          MPS04720
      BQ=B(I)*M(I,1)                                                    MPS04730
      IF (IQ.GT.JJ) BQ=B(I)*M(I,3)                                      MPS04740
      IF ((I.EQ.5).AND.(K.LE.NPR(J-1))) BQ=B(I)*M(I,3)                  MPS04750
      IF ((I.EQ.6).AND.(K.LE.NPR(J-1))) BQ=B(I)*M(I,3)                  MPS04760
      IF ((JJ+2.GE.IQ).AND.(K.LE.9)) WRITE (3,109) I,K,JJ,IQ,BQ         MPS04770
      IF ((JJ+2.GE.IQ).AND.(K.GE.10).AND.(K.LE.99)) WRITE (3,110) I,K,JJMPS04780
     1,IQ,BQ                                                            MPS04790
      IF ((JJ+2.GE.IQ).AND.(K.GE.100).AND.(K.LE.NR)) WRITE (3,111) I,K,JMPS04800
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     1J,IQ,BQ                                                           MPS04810
      IF ((JJ+2.LT.IQ).AND.(K.LE.9)) WRITE (3,109) I,K,JJ,IQ,BQ         MPS04820
      IF ((JJ+2.LT.IQ).AND.(K.GE.10).AND.(K.LE.99)) WRITE (3,110) I,K,JJMPS04830
     1,IQ,BE                                                            MPS04840
      IF ((JJ+2.LT.IQ).AND.(K.GE.100)) WRITE (3,111) I,K,JJ,IQ,BE       MPS04850
26    CONTINUE                                                          MPS04860
      JK=J+1                                                            MPS04870
      DO 29 IV=JK,NYEAR                                                 MPS04880
      JI=IV+75                                                          MPS04890
      IF (JI.GT.NYEAR+75) GO TO 29                                      MPS04900
      IF (I.GT.NUF) GO TO 27                                            MPS04910
      MM=M(I,3)                                                         MPS04920
      IF ((I.EQ.1).AND.(K.GT.NPWR(J-1))) MM=M(I,1)                      MPS04930
      IF ((I.EQ.2).AND.(K.GT.NBWR(J-1))) MM=M(I,1)                      MPS04940
      IF (K.LE.9) WRITE (3,77) I,K,JJ,JI,MM                             MPS04950
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,78) I,K,JJ,JI,MM            MPS04960
      IF (K.GE.100) WRITE (3,79) I,K,JJ,JI,MM                           MPS04970
      GO TO 29                                                          MPS04980
27    IF (I.GE.5) GO TO 28                                              MPS04990
      IF (K.LE.9) WRITE (3,112) I,K,JJ,JI,MUD2,JI,MMOX                  MPS05000
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,113) I,K,JJ,JI,MUD2,JI,MMOX MPS05010
      IF (K.GE.100) WRITE (3,114) I,K,JJ,JI,MUD2,JI,MMOX                MPS05020
      GO TO 29                                                          MPS05030
28    MMOX=MOX(I,3)                                                     MPS05040
      IF ((I.EQ.5).AND.(K.GT.NPWR(J-1))) MMOX=MOX(I,1)                  MPS05050
      IF ((I.EQ.6).AND.(K.GT.NBWR(J-1))) MMOX=MOX(I,1)                  MPS05060
      IF (K.LE.9) WRITE (3,115) I,K,JJ,JI,MMOX                          MPS05070
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,116) I,K,JJ,JI,MMOX         MPS05080
      IF (K.GE.100) WRITE (3,117) I,K,JJ,JI,MMOX                        MPS05090
29    CONTINUE                                                          MPS05100
      DO 31 II=J,NYEAR                                                  MPS05110
      IF (I.LE.NUF) GO TO 31                                            MPS05120
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      IO=II+75                                                          MPS05130
      IF (IO.GT.NYEAR+75) GO TO 31                                      MPS05140
      S=MSF(I)                                                          MPS05150
      IF (I.GT.4) GO TO 30                                              MPS05160
      IF (K.LE.9) WRITE (3,80) I,K,JJ,IO,S                              MPS05170
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,81) I,K,JJ,IO,S             MPS05180
      IF (K.GE.100) WRITE (3,82) I,K,JJ,IO,S                            MPS05190
      GO TO 31                                                          MPS05200
30    IF (I.EQ.5) S=MSF(5)+8.0*MSF(1)                                   MPS05210
      IF (I.EQ.6) S=MSF(6)+5.0*MSF(2)                                   MPS05220
      IF ((I.EQ.5).AND.(K.GT.NBWR(J-1))) S=31.0*MSF(1)                  MPS05230
      IF ((I.EQ.6).AND.(K.GT.NBWR(J-1))) S=30.0*MSF(2)                  MPS05240
      IF (K.LE.9) WRITE (3,80) I,K,JJ,IO,S                              MPS05250
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,81) I,K,JJ,IO,S             MPS05260
      IF (K.GE.100) WRITE (3,82) I,K,JJ,IO,S                            MPS05270
31    CONTINUE                                                          MPS05280
      IF (K.LE.9) WRITE (3,118) I,K,JJ,TFC                              MPS05290
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,119) I,K,JJ,TFC             MPS05300
      IF (K.GE.100) WRITE (3,120) I,K,JJ,TFC                            MPS05310
32    CONTINUE                                                          MPS05320
C                                                                       MPS05330
C     END SECTION OF INPUT DATA                                         MPS05340
C                                                                       MPS05350
      WRITE (3,121)                                                     MPS05360
C                                                                       MPS05370
C     DEFINES THE RHS FOR THE FIRST CONSTRAINT TYPE                     MPS05380
C                                                                       MPS05390
      AA=1.0                                                            MPS05400
      DO 33 J=2,NYEAR                                                   MPS05410
      JJ=J+75                                                           MPS05420
      NR=NRX(J)                                                         MPS05430
      DO 33 K=1,NR                                                      MPS05440
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      IF (K.LE.9) WRITE (3,123) K,JJ,AA                                 MPS05450
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,124) K,JJ,AA                MPS05460
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,122) K,JJ,AA               MPS05470
33    CONTINUE                                                          MPS05480
C                                                                       MPS05490
C     DEFINES THE RHS FOR THE SECOND CONSTRAINT TYPE                    MPS05500
C        (MAX FABRICATION CAPACITY)                                     MPS05510
C                                                                       MPS05520
      DO 34 J=IOX,NYEAR                                                 MPS05530
      JJ=J+75                                                           MPS05540
      FMO=FMOX(J-1)*1000.                                               MPS05550
      WRITE (3,125) JJ,FMO                                              MPS05560
34    CONTINUE                                                          MPS05570
C                                                                       MPS05580
C     DEFINES THE RHS FOR THE THIRD CONSTRAINT TYPE                     MPS05590
C        ( O2 FABRICATION CAPACITY)                                     MPS05600
C                                                                       MPS05610
      DO 35 J=2,NYEAR                                                   MPS05620
      JJ=J+75                                                           MPS05630
      FUO=FUO2(J-1)*1500.                                               MPS05640
      WRITE (3,126) JJ,FUO                                              MPS05650
35    CONTINUE                                                          MPS05660
C                                                                       MPS05670
C     DEFINES THE RHS FOR THE FOURTH CONSTRAINT TYPE                    MPS05680
C        (SWU CAPACITY)                                                 MPS05690
C                                                                       MPS05700
      DO 36 J=2,NYEAR                                                   MPS05710
      SU=SWU(J-1)*1000.                                                 MPS05720
      JJ=J+75                                                           MPS05730
      WRITE (3,127) JJ,SU                                               MPS05740
36    CONTINUE                                                          MPS05750
C                                                                       MPS05760
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C     DEFINES THE RHS FOR THE FIFTH CONSTRAINT TYPE                     MPS05770
C        (PLUTONIUM - SUPPLY VS. DEMAND)                                MPS05780
C                                                                       MPS05790
      AE=0.0                                                            MPS05800
      DO 37 J=IOX,NYEAR                                                 MPS05810
      JJ=J+75                                                           MPS05820
      WRITE (3,128) JJ,AE                                               MPS05830
37    CONTINUE                                                          MPS05840
C                                                                       MPS05850
C     DEFINES THE RHS FOR THE SIXTH CONSTRAINT TYPE                     MPS05860
C        (SPENT URANIUM - SUPPLY VS. DEMAND)                            MPS05870
C                                                                       MPS05880
      AF=0.0                                                            MPS05890
      DO 38 J=IOX,NYEAR                                                 MPS05900
      JJ=J+75                                                           MPS05910
      WRITE (3,129) JJ,AF                                               MPS05920
38    CONTINUE                                                          MPS05930
C                                                                       MPS05940
C      DEFINES THE RHS FOR THE SEVENTH CONSTRAINT TYPE                  MPS05950
C        (REPROCESSING CAPACITY)                                        MPS05960
C                                                                       MPS05970
      DO 39 J=IOX,NYEAR                                                 MPS05980
      JJ=J+75                                                           MPS05990
      RP=REP(J-2)*1000.                                                 MPS06000
      WRITE (3,130) JJ,RP                                               MPS06010
39    CONTINUE                                                          MPS06020
C                                                                       MPS06030
C     DEFINES THE RHS FOR THE EIGHTH CONSTRAINT TYPE                    MPS06040
C        (COST)                                                         MPS06050
C                                                                       MPS06060
      WRITE (3,131) ITFC,IITFC                                          MPS06070
C                                                                       MPS06080
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C     BOUNDS SECTION OF INPUT DATA                                      MPS06090
C        SETS UPPER LIMIT ON ALL DECISION VARIABLES TO 1.0              MPS06100
C                                                                       MPS06110
      WRITE (3,132)                                                     MPS06120
      DO 42 J=2,NYEAR                                                   MPS06130
      NR=NBX(J)                                                         MPS06140
      JJ=J+75                                                           MPS06150
      AA=1.0                                                            MPS06160
      DO 42 I=1,NTF                                                     MPS06170
      DO 42 K=1,NR                                                      MPS06180
      IF (J.EQ.2) GO TO 40                                              MPS06190
      IF ((I.EQ.3).AND.(K.GT.NPWR(J-2))) GO TO 42                       MPS06200
      IF ((I.EQ.4).AND.(K.GT.NBWR(J-2))) GO TO 42                       MPS06210
40    IF ((K.GT.NPWR(J)).AND.((I.EQ.1).OR.(I.EQ.3).OR.(I.EQ.5))) GO TO 4MPS06220
     12                                                                 MPS06230
      IF ((K.GT.NBWR(J)).AND.((I.EQ.2).OR.(I.EQ.4).OR.(I.EQ.6))) GO TO 4MPS06240
     12                                                                 MPS06250
      IF ((JJ.LE.IFMOX).AND.(I.GT.NTF)) GO TO 42                        MPS06260
      IF (JJ.GE.IFMOX+1) GO TO 41                                       MPS06270
      IF (K.LE.9) WRITE (3,134) I,K,JJ,AA                               MPS06280
      IF ((K.GE.10).AND.(K.LE.99)) WRITE (3,135) I,K,JJ,AA              MPS06290
      IF ((K.GE.100).AND.(K.LE.NR)) WRITE (3,133) I,K,JJ,AA             MPS06300
      GO TO 42                                                          MPS06310
41    IF ((I.LE.4).AND.(K.LE.9)) WRITE (3,134) I,K,JJ,AA                MPS06320
      IF ((I.LE.4).AND.(K.GE.10).AND.(K.LE.99)) WRITE (3,135) I,K,JJ,AA MPS06330
      IF ((I.LE.4).AND.(K.GE.100).AND.(K.LE.NR)) WRITE (3,133) I,K,JJ,AAMPS06340
      IFMO=IFMOX-75                                                     MPS06350
      IF ((I.EQ.5).AND.(K.GT.NPWR(IFMO)).AND.(K.LE.9)) WRITE (3,134) I,KMPS06360
     1,JJ,AA                                                            MPS06370
      IF ((I.EQ.5).AND.(K.GT.NPWR(IFMO)).AND.(K.GE.10).AND.(K.LE.99)) WRMPS06380
     1ITE (3,135) I,K,JJ,AA                                             MPS06390
      IF ((I.EQ.5).AND.(K.GT.NPWR(IFMO)).AND.(K.GE.100).AND.(K.LE.NR)) WMPS06400
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      IRITE (3,133) I,K,JJ,IA                                           MPS06410
       IF ((I.EQ.6).AND.(K.GT.NBWR(IF40)).AND.(K.LE.9)) WRITE (3,134) I,KMPS06420
      I,JJ,AA                                                           MPS06430
       IF ((I.EQ.6).AND.(K.GT.NBWR(IF40)).AND.(K.GE.10).AND.(K.LE.99)) WRMPS06440
      IITE (3,135) I,K,JJ,AA                                            MPS06450
       IF ((I.EQ.6).AND.(K.GT.NBWR(IF40)).AND.(K.GE.100).AND.(K.LE.99)) WMPS06460
      IRITE (3,133) I,K,JJ,IA                                           MPS06470
42     CONTINUE                                                         MPS06480
C                                                                       MPS06490
C      END OF INPUT DATA                                                MPS06500
C                                                                       MPS06510
       WRITE (3,136)                                                    MPS06520
       STOP                                                             MPS06530
C                                                                       MPS06540
43     FORMAT (5I2)                                                     MPS06550
44     FORMAT (I2,4F6.2,2F3)                                            MPS06560
45     FORMAT (F7.1,F6.1,F9.1,F8.1,F4.2,F5.2,F6.2)                      MPS06570
46     FORMAT (3F8.1)                                                   MPS06580
47     FORMAT (3F5.3,2F7.1)                                             MPS06590
48     FORMAT (4I6)                                                     MPS06600
49     FORMAT (4HNAME,10X,4HFUEL)                                       MPS06610
50     FORMAT (4HNOWS)                                                  MPS06620
51     FORMAT (1X,1HN,2X,4HTUF6)                                        MPS06630
52     FORMAT (1X,1HE,2X,4HAA..,I1,I2)                                  MPS06640
53     FORMAT (1X,1HE,2X,3HAA.,I2,I2)                                   MPS06650
54     FORMAT (1X,1HE,2X,2HAA,I3,I2)                                    MPS06660
55     FORMAT (1X,1HL,2X,2HAB,I2)                                       MPS06670
56     FORMAT (1X,1HL,2X,2HAC,I2)                                       MPS06680
57     FORMAT (1X,1HL,2X,2HAD,I2)                                       MPS06690
58     FORMAT (1X,1HL,2X,2HAE,I2)                                       MPS06700
59     FORMAT (1X,1HL,2X,2HAF,I2)                                       MPS06710
60     FORMAT (1X,1HL,2X,2HAG,I2)                                       MPS06720
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61    FORMAT (1X,1HL,2X,4HAH..)                                          MPS06730
62    FORMAT (7HCOLUMNS)                                                 MPS06740
63    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,4HTUF6,6X,F12.0,3X,4HAA..,I1,I2,3X MPS06750
     1,F12.0)                                                            MPS06760
64    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,4HTUF6,6X,F12.0,3X,3HAA..,I2,I2,3X,FMPS06770
     112.0)                                                              MPS06780
65    FORMAT (4X,1HX,I1,I3,I2,3X,4HTUF6,6X,F12.0,3X,2HAA,I3,I2,3X,F12.0)MPS06790
66    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAC,I2,6X,F12.0,3X,2HAD,I2,6X,F12MPS06800
     1.0)                                                                MPS06810
67    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAC,I2,6X,F12.0,3X,2HAD,I2,6X,F12.MPS06820
     10)                                                                 MPS06830
68    FORMAT (4X,1HX,I1,I3,I2,3X,2HAC,I2,6X,F12.0,3X,2HAD,I2,6X,F12.0)  MPS06840
69    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,4HTUF6,6X,F12.0,3X,2HAA,I3,I2,3X,F1MPS06850
     12.0)                                                               MPS06860
70    FORMAT (4X,1HX,I1,I3,I2,3X,4HTUF6,6X,F12.0,3X,2HAA,I3,I2,3X,F12.0)MPS06870
71    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,4HTUF6,6X,F12.0,3X,3HAA.,I2,I2,3X,MPS06880
     1F12.0)                                                             MPS06890
72    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,4HTUF6,6X,F12.0,3X,2HAA.,I2,I2,3X,FMPS06900
     112.0)                                                              MPS06910
73    FORMAT (4X,1HX,I1,I3,I2,3X,4HTUF6,6X,F12.0,3X,3HAA.,I2,I2,3X,F12.0MPS06920
     1)                                                                  MPS06930
74    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAE,I2,6X,F12.0,3X,2HAF,I2,6X,F12MPS06940
     1.0)                                                                MPS06950
75    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAE,I2,6X,F12.0,3X,2HAF,I2,6X,F12.MPS06960
     10)                                                                 MPS06970
76    FORMAT (4X,1HX,I1,I3,I2,3X,2HAE,I2,6X,F12.0,3X,2HAF,I2,6X,F12.0)  MPS06980
77    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAC,I2,6X,F12.0)                 MPS06990
78    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAC,I2,6X,F12.0)                  MPS07000
79    FORMAT (4X,1HX,I1,I3,I2,3X,2HAC,I2,6X,F12.0)                      MPS07010
80    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAG,I2,6X,F12.0)                 MPS07020
81    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAG,I2,6X,F12.0)                  MPS07030
82    FORMAT (4X,1HX,I1,I3,I2,3X,2HAG,I2,6X,F12.0)                      MPS07040
```

```
83    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,4HTUF6,6X,F12.0,3X,4HAA..,I1,I2,3XMPS07050
     1,F12.0)                                                          MPS07060
84    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,4HTUF6,6X,F12.0,3X,3HAA.,I2,I2,3X,FMPS07070
     112.0)                                                            MPS07080
85    FORMAT (4X,1HX,I1,I3,I2,3X,4HTUF6,6X,F12.0,3X,2HAA,I3,I2,3X,F12.0)MPS07090
86    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAC,I2,6X,F12.0,3X,2HAD,I2,6X,F12MPS07100
     1.0)                                                              MPS07110
87    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAC,I2,6X,F12.0,3X,2HAD,I2,6X,F12.MPS07120
     10)                                                               MPS07130
88    FORMAT (4X,1HX,I1,I3,I2,3X,2HAC,I2,6X,F12.0,3X,2HAD,I2,6X,F12.0)  MPS07140
89    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,4HTUF6,6X,F12.0,3X,3HAA.,I2,I2,3X,MPS07150
     1F12.0)                                                           MPS07160
90    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,4HTUF6,6X,F12.0,3X,3HAA.,I2,I2,3X,FMPS07170
     112.0)                                                            MPS07180
91    FORMAT (4X,1HX,I1,I3,I2,3X,4HTUF6,6X,F12.0,3X,2HAA,I3,I2,3X,F12.0)MPS07190
92    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,4HTUF6,6X,F12.0,3X,2HAA,I3,I2,3X,F1MPS07200
     12.0)                                                             MPS07210
93    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,4HTUF6,6X,F12.0,3X,2HAA,I3,I2,3X,FMPS07220
     112.0)                                                            MPS07230
94    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAB,I2,6X,F12.0,3X,2HAC,I2,6X,F12MPS07240
     1.0)                                                              MPS07250
95    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAB,I2,6X,F12.0,3X,2HAC,I2,6X,F12.MPS07260
     10)                                                               MPS07270
96    FORMAT (4X,1HX,I1,I3,I2,3X,2HAB,I2,6X,F12.0,3X,2HAC,I2,6X,F12.0)  MPS07280
97    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAD,I2,6X,F12.0)                 MPS07290
98    FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAD,I2,6X,F12.0)                  MPS07300
99    FORMAT (4X,1HX,I1,I3,I2,3X,2HAD,I2,6X,F12.0)                      MPS07310
100   FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAB,I2,6X,F12.0)                 MPS07320
101   FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAB,I2,6X,F12.0)                  MPS07330
102   FORMAT (4X,1HX,I1,I3,I2,3X,2HAB,I2,6X,F12.0)                      MPS07340
103   FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAE,I2,6X,F12.0,3X,2HAF,I2,6X,F12MPS07350
     1.0)                                                              MPS07360
```

```
104   FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAE,I2,6X,F12.0,3X,2HAF,I2,6X,F12.MPS07370
     10)                                                                MPS07380
105   FORMAT (4X,1HX,I1,I3,I2,3X,2HAC,I2,6X,F12.0,3X,2HAF,I2,6X,F12.0)  MPS07390
106   FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAE,I2,6X,F12.0,3X,2HAF,I2,6X,F12MPS07400
     1.0)                                                               MPS07410
107   FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAE,I2,6X,F12.0,3X,2HAF,I2,6X,F12.MPS07420
     10)                                                                MPS07430
108   FORMAT (4X,1HX,I1,I3,I2,3X,2HAE,I2,6X,F12.0,3X,2HAF,I2,6X,F12.0)  MPS07440
109   FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAE,I2,6X,F12.0)                 MPS07450
110   FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAE,I2,6X,F12.0)                  MPS07460
111   FORMAT (4X,1HX,I1,I3,I2,3X,2HAE,I2,6X,F12.0)                      MPS07470
11    FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAC,I2,6X,F12.0,3X,2HAD,I2,6X,F12MPS07480
     1.0)                                                               MPS07490
113   FORMAT (4X,1HX,I1,1H.,I2,I2,3X,[illegible] 6X,F12.0,3X,2HAD,I2,6X,F12.MPS07500
     10)                                                                MPS07510
114   FORMAT (4X,1HX,I1,I3,I2,3X,2HAC,I2,6X,F12.0,3X,2HAD,I2,6X,F12.0)  MPS07520
115   FORMAT (4X,1HX,I1,2H..,I1,I2,3X,2HAD,I2,6X,F12.0)                 MPS07530
116   FORMAT (4X,1HX,I1,1H.,I2,I2,3X,2HAD,I2,6X,F12.0)                  MPS07540
117   FORMAT (4X,1HX,I1,I3,I2,3X,2HAD,I2,6X,F12.0)                      MPS07550
118   FORMAT (4X,1HX,I1,2H..,I1,I2,3X,4HAH..,6X,F12.0)                  MPS07560
119   FORMAT (4X,1HX,I1,1H.,I2,I2,3X,4HAH..,6X,F12.0)                   MPS07570
120   FORMAT (4X,1HX,I1,I3,I2,3X,4HAH..,6X,F12.0)                       MPS07580
12[illegible]  FORMAT (3HRHS)                                           MPS07590
122   FORMAT (4X,3HZZ1,7X,2HAA,I3,I2,3X,F12.0)                          MPS07600
123   FORMAT (4X,3HZZ1,7X,4HAA..,I1,I2,3X,F12.0)                        MPS07610
124   FORMAT (4X,3HZZ1,7X,3HAA..,I2,I2,3X,F12.0)                        MPS07620
125   FORMAT (4X,3HZZ1,7X,2HAB,I2,6X,F12.0)                             MPS07630
126   FORMAT (4X,3HZZ1,7X,2HAC,I2,6X,F12.0)                             MPS07640
127   FORMAT (4X,3HZZ1,7X,2HAD,I2,6X,F12.0)                             MPS07650
128   FORMAT (4X,3HZZ1,7X,2HAE,I2,6X,F12.0)                             MPS07660
129   FORMAT (4X,3HZZ1,7X,2HAF,I2,6X,F12.0)                             MPS07670
130   FORMAT (4X,3HZZ1,7X,2HAG,I2,6X,F12.0)                             MPS07680
```

```
131   FORMAT (4X,3HZZ1,7X,4HAH..,6X,2I5)                                MPS07690
132   FORMAT (6HBOUNDS)                                                 MPS07700
133   FORMAT (1X,2HUP,1X,2HB1,8X,1HX,I1,I3,I2,3X,F12.0)                 MPS07710
134   FORMAT (1X,2HUP,1X,2HB1,8X,1HX,I1,2H..,I1,I2,3X,F12.0)            MPS07720
135   FORMAT (1X,2HUP,1X,2HB1,8X,1HX,I1,1H.,I2,I2,3X,F12.0)             MPS07730
136   FORMAT (6HENDATA)                                                 MPS07740
      END                                                               MPS07750
```

```
C       SUBROUTINE COST                                                 MPS07760
C*****************************************************************MPS07770
C**                                                              **MPS07780
C**     SUBROUTINE COST                                          **MPS07790
C**                                                              **MPS07800
C*****************************************************************MPS07810
C**                                                              **MPS07820
C**     THIS SUBROUTINE CALCULATES THE UNIT COST OF FRESH FUEL   **MPS07830
C**     REQUIRED BY THE SIX REACTOR-FUEL TYPES                   **MPS07840
C**                                                              **MPS07850
C*****************************************************************MPS07860
C**                                                              **MPS07870
C**     J = YEAR OF COST CALCULATION                             **MPS07880
C**     K = REACTOR NUMBER                                       **MPS07890
C**     I = FUEL TYPE                                            **MPS07900
C**     KK = 1 - SPENT FUEL RECYCLE                              **MPS07910
C**     KK = 0 - NO SPENT FUEL RECYCLE                           **MPS07920
C**     TC = TOTAL UNIT COST OF FRESH FUEL (\$/KG)               **MPS07930
C**     DUC = UNIT COST OF SPENT URANIUM (\$/KG)                 **MPS07940
C**     PUC = UNIT COST OF PLUTONIUM (\$/GM FISSILE)             **MPS07950
C**     SWP = SWU REQUIRED TO PRODUCE 1 KG OF FUEL               **MPS07960
C**     FP = AMOUNT OF NATURAL URANIUM REQUIRED TO PRODUCE 1 KG OF FUEL **MPS07970
C**                                                              **MPS07980
C*****************************************************************MPS07990
C                                                                       MPS08000
      SUBROUTINE COST (J,K,I,KK,TC,DUC,PUC,SWP,FP)                      MPS08010
      IMPLICIT REAL*4(A-H,J,O-Z)                                        MPS08020
      REAL N1,N2,N3                                                     MPS08030
      COMMON XU(6),CS(25),CF(25),CC(25),CUO2(25),XNU(6),CPT(25),T(6,3)  MPS08040
      COMMON DU(6),MU(6,3)                                              MPS08050
      V(X)=(2.*X-1.)*ALOG(X/(1.-X))                                     MPS08060
      XW=.0025                                                          MPS08070
```

```
      XNF=.00711                                                        MPS08080
      N1=.005                                                           MPS08090
      N2=.003                                                           MPS08100
      N3=.01                                                            MPS08110
      GO TO (1,1,5,6,5,6), I                                            MPS08120
1     IF (KK.EQ.1) GO TO 2                                              MPS08130
      FP=(XU(I)-XW)/(XNF-XW)                                            MPS08140
      SWP=(V(XU(I))-V(XW))-FP*(V(XNF)-V(XW))                            MPS08150
      TC=SWP*CS(J-1)+FP*CF(J-1)+CUD2(J-1)                               MPS08160
      GO TO 7                                                           MPS08170
2     FPT=(XU(I)-XW)/(XNF-XW)                                           MPS08180
      FDU=(XU(I)-XW)/(XDU(I)-XW)                                        MPS08190
      FP=((MU(I,3)-(DU(I)/FDU))*FPT)/MU(I,3)                            MPS08200
      FD=(XDU(I)-XW)/(XNF-XW)                                           MPS08210
      SWUT=(V(XU(I))-V(XW))-FPT*(V(XNF)-V(XW))                          MPS08220
      SWDU=(V(XDU(I))-V(XW))-FD*(V(XNF)-V(XW))                          MPS08230
      SWP=SWUT-SWDU                                                     MPS08240
      TC=SWP*CS(J-1)+FP*CF(J-1)+CUD2(J-1)                               MPS08250
      IF ((I.EQ.1).OR.(I.EQ.3)) GO TO 3                                 MPS08260
      IF ((I.EQ.2).OR.(I.EQ.4)) GO TO 4                                 MPS08270
3     DUC=(0.19491*CS(J-1)+1.40998*CF(J-1)-CC(J-1))*(1.0-N1-N2)         MPS08280
      GO TO 7                                                           MPS08290
4     DUC=(0.1271*CS(J-1)+1.27983*CF(J-1)-CC(J-1))*(1.0-N1-N2)          MPS08300
      GO TO 7                                                           MPS08310
5     PUC=(0.1906*CS(J-1)+0.2037*CF(J-1))*(1.0-N1-N2-N3)                MPS08320
      IF (I.EQ.5) GO TO 7                                               MPS08330
      GO TO 1                                                           MPS08340
6     PUC=(0.180*CS(J-1)+0.1870*CF(J-1))*(1.0-N1-N2-N3)                 MPS08350
      IF (I.EQ.6) GO TO 7                                               MPS08360
      GO TO 1                                                           MPS08370
7     CONTINUE                                                          MPS08380
      RETURN                                                            MPS08390
```

END

MPS03400

Appendix C

MPS-III Computer Program

The following is an example of typical IBM Control Language (JCL) necessary when large linear programs are involved. The JCL consists of two steps. The first step involves the implementation of an IBM Utility Program, IEBCOPY. The purpose of this step is to compress the partitioned data set, A99999.MAPSFILE, in place and catalog the data set. This is utilized to reduce the amount of storage space necessary while computing the LP solution. This step is not used in the first program and can only be used if the data set, preserved on MAPSFILE by the MPS program, is on a magnetic tape or an off-line disk. The second step executes the MPS linear program.

```
//    JOB CARD
//STEP1  EXEC  PGM=IEBCOPY,TIME=1,REGION=200K
//SYSPRINT DD  SYSOUT=A
//INOUT5   DD  DSNAME=A99999.MAPSFILE,UNIT=SYSDA,
//             VOL=SER=USR305,DISP=(OLD,CATLG)
//SYSUT3   DD  DSNAME=&&TEMP1,UNIT=SYSDA,
//             DISP=(NEW,DELETE),SPACE=(TRK,(5))
//SYSUT4   DD  DSNAME=&&TEMP2,UNIT=SYSDA,
//             DISP=(NEW,DELETE),SPACE=(TRK,(5))
//SYSIN    DD  *
     COPY OUTDD=INOUT5,INDD=INOUT5
/*
//STEP2  EXEC  LP,TIME=30,REGION=990K,ETA=2000,MATRIX=1500
//LP.SYSIN DD  *

        (Insert MPS program here)

/*
//GO.SCRATCH1  DD  DSNAME=A99999.SCRATCH1,UNIT=SYSDA,
//                 VOL=SER=USR305,
//                 SPACE=(3120,(400),,CONTIG,ROUND),
//                 DISP=(NEW,CATLG)
//GO.SCRATCH2  DD  DSNAME=A99999.SCRATCH2,UNIT=SYSDA,
//                 VOL=SER=USR305,
//                 SPACE=(3120,(400),,CONTIG,ROUND),
//                 DISP=(NEW,CATLG)
//GO.PROBFILE  DD  DSNAME=A99999.PROBFILE,UNIT=SYSDA,
//                 VOL=SER=USR305,
//                 SPACE=(3120,(160),,CONTIG,ROUND),
//                 DISP=(NEW,CATLG)
```

```
//GO.MAPSFILE  DD  DSNAME=A99999.MAPSFILE,UNIT=SYSDA,
//                 VOL=SER=USR305,
//                 SPACE=(TRK,(15,10,10)),
//                 DISP=(NEW,CATLG)
//GO.SYSIN     DD  DSNAME=MPS,DISP=(OLD,KEEP),
//                 UNIT=TAPE9,VOL=SER=DH62Z,
//                 LABEL=(1,SL),
//                 DCB=(LRECL=80,RECFM=FB,BLKSIZE=8000)
/*
//
```

Note that an off-line disk, USR305, is utilized to store information for SCRATCH1, SCRATCH2, PROBFILE, and MAPSFILE. The use of a magnetic tape, DH62Z, is used to store necessary input data for the MPS program.

```
*****************************************************************
*****************************************************************
***                                                           ***
***          MPS   -   MATHEMATICAL PROGRAMMING SYSTEM        ***
***                                                           ***
*****************************************************************
*****************************************************************
***                                                           ***
***     The MP system is composed of a set of procedures for  ***
***     dealing with Linear Programming (LP).  The LP procedures ***
***     of the MP system use the bounded variable/product form ***
***     of the inverse/revised simplex method.  For further infor- ***
***     mation on the simplex method and the MP system, see   ***
***     reference 32.                                         ***
***                                                           ***
*****************************************************************
*****************************************************************
***                                                           ***
***     The system Program Control Language (PCL) consists of a ***
***     series of statements that are specifically designed for ***
***     the solution of mathematical programming problems.  The ***
***     following is a listing of the PCL statements used in  ***
***     solving LP problems.                                  ***
***                                                           ***
*****************************************************************
*****************************************************************
***                                                           ***
        PROGRAM('ND')
***                                                           ***
*****************************************************************
***                                                           ***
***     This must be the first statement in the PCL.  It identifies ***
***     the beginning of the control program.  The ND parameter ***
***     indicates that no diagnostics are to be generated if an ***
***     unknown procedure is encountered.                     ***
***                                                           ***
*****************************************************************
***                                                           ***
        INITIALZ
***                                                           ***
*****************************************************************
***                                                           ***
***     INITIALZ is used to establish initial settings for    ***
***     tolerances, frequencies, and demands.                 ***
***                                                           ***
*****************************************************************
***                                                           ***
        TITLE('  TOTAL UF6 CONSUMPTION FOR 507 REACTORS  ')
***                                                           ***
*****************************************************************
***                                                           ***
```

```
***     The TITLE statement defines a title that is to appear at     ***
***     the top of each page of the printed output.                  ***
***                                                                  ***
**********************************************************************
***                                                                  ***
        XFREQ1 = 100
        MVADR(XDOFREQ1,SAVIT)
***                                                                  ***
**********************************************************************
***                                                                  ***
***     The XFREQ1 statement defines a storage region as 100.        ***
***     When the current iteration number is a multiple of the       ***
***     integer contained in XFREQ1, XDOFREQ1 demands that SAVIT     ***
***     be implemented.  In this case, at every 100th iteration,     ***
***     the current solution produced by VARIFORM will be            ***
***     PRESERVEd.                                                   ***
***                                                                  ***
**********************************************************************
***                                                                  ***
CASE    DC('SAVE507')
***                                                                  ***
**********************************************************************
***                                                                  ***
***     The DC (Define Constant) statement allocates storage space   ***
***     for SAVE507.  SAVE507 is the name used when the current      ***
***     solution is PRESERVEd or RESET.                              ***
***                                                                  ***
**********************************************************************
***                                                                  ***
        MOVE(XDATA,'FUEL')
        MOVE(XPBNAME,'M507')
        MOVE(XOBJ,'TUF6')
        MOVE(XRHS,'ZZ1')
***                                                                  ***
**********************************************************************
***                                                                  ***
***     These four insructions (MOVE) move specific information      ***
***     into designated storage regions, i.e., the input data name,  ***
***     FUEL, is moved into the XDATA storage region.  The problem   ***
***     file name, M507, is moved into the XPBNAME region.  TUF6     ***
***     is the name of the objective function row and ZZ1 is the     ***
***     name of the right-hand side.  They are moved into the XOBJ   ***
***     and XRHS regions, respectively.  This information is         ***
***     required by SETUP and CONVERT.                               ***
***                                                                  ***
**********************************************************************
***                                                                  ***
        CONVERT('SUMMARY')
***                                                                  ***
**********************************************************************
***                                                                  ***
```

```
***     CONVERT is called to read and check the input data.  It      ***
***     then converts the input data to packed binary format and     ***
***     writes it on PROBFILE.  The parameter SUMMARY is included    ***
***     to produce a report of the number of elements in each row    ***
***     and column.                                                  ***
***                                                                  ***
*********************************************************************
***                                                                  ***
        SETUP('MIN','BOUND','B1')
***                                                                  ***
*********************************************************************
***                                                                  ***
***     SETUP takes the problem named in XPBNAME from PROBFILE and   ***
***     prepares it for processing by allocating storage, initializ- ***
***     ing I/O, creating the work matrix, and establishing an       ***
***     initial solution.  The parameter MIN sets XSSCALE to +1,     ***
***     which signifies that the objective function is to be mini-   ***
***     mized.  The parameters BOUND and B1 indicate that vectors    ***
***     being bounded will be specified in the BOUNDS section of     ***
***     the input data.                                              ***
***                                                                  ***
*********************************************************************
***                                                                  ***
        RESET('NAME',CASE)
***                                                                  ***
*********************************************************************
***                                                                  ***
***     RESET is employed to reinstate the K-map, B-map, and H-re-   ***
***     gion previously PRESERVEd on MAPSFILE under the NAME,        ***
***     SAVE507.  This utilizes several short computer runs for      ***
***     solving a large LP problem rather than using one long        ***
***     computer run.  Programs utilizing the RESET statement are    ***
***     not to be CONVERTed.                                         ***
***                                                                  ***
*********************************************************************
***                                                                  ***
        VARIFORM
***                                                                  ***
*********************************************************************
***                                                                  ***
***     VARIFORM is the main optimization procedure that utilizes    ***
***     a PRIMAL algorithm.  Upon completion, a feasible-optimal     ***
***     solution will have been attained.                            ***
***                                                                  ***
*********************************************************************
***                                                                  ***
        PRESERVE('NAME',CASE)
***                                                                  ***
*********************************************************************
***                                                                  ***
***     PRESERVE saves the K-map, B-map, and H-region on MAPSFILE    ***
```

```
***     upon obtaining a feasible-optimal solution.                    ***
***                                                                    ***
**********************************************************************
***                                                                    ***
        SOLUTION
***                                                                    ***
**********************************************************************
***                                                                    ***
***     SOLUTION prints out the current feasible-optimal solution      ***
***     of the problem on SYSPRINT.                                    ***
***                                                                    ***
**********************************************************************
***                                                                    ***
        EXIT
***                                                                    ***
**********************************************************************
***                                                                    ***
***     EXIT transfers control from the MP system to the Operating     ***
***     System.                                                        ***
***                                                                    ***
**********************************************************************
***                                                                    ***
SAVIT   PRESERVE('NAME',CASE)
***                                                                    ***
**********************************************************************
***                                                                    ***
***     This statement is implemented when the current iteration       ***
***     number is a multiple of the integer contained in XFREQ1.       ***
***     PRESERVE is defined above.                                     ***
***                                                                    ***
**********************************************************************
***                                                                    ***
        CONTINUE
***                                                                    ***
**********************************************************************
***                                                                    ***
***     CONTINUE transfers control back to the most recent execute     ***
***     statement (VARIFORM) once PRESERVE has been implemented.       ***
***                                                                    ***
**********************************************************************
***                                                                    ***
        PEND
***                                                                    ***
**********************************************************************
***                                                                    ***
***     PEND indicates the end of the PCL program and causes           ***
***     control to return to the operating system.                     ***
***                                                                    ***
**********************************************************************
**********************************************************************
**********************************************************************
```

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CONSUMPTION MINIMIZATION OF THE URANIUM RESOURCES

BY THE USE OF MIXED-OXIDE FUELED REACTORS

by

Bruce Loren Johnson

(ABSTRACT)

The need to conserve the limited natural uranium resources necessitates the determination of the optimal use of MOX fueled reactors under various reactor growth scenarios. The reactor growth scenarios include an industry that attains 400, 507, and 600 operating reactors by the year 2000. The reactor-fuel types under consideration include a PWR and a BWR, each of which can utilize an all UO_2 core, a self-generating recycle core, or a plutonium burner core. Results from developing, analyzing, and solving the reactor mix model are used to recommend specific fuel loading strategies.

The reactor mix problem involves the interaction between reactor fuel demand and the availability of SWU, fuel fabrication (UO_2 and MOX), reprocessing, and spent fuel generation. The cost of each type of nuclear fuel is based upon projected costs of uranium, separative work, conversion, reprocessing, and fuel fabrication, as well as plutonium and spent uranium values. Application of the reactor mix model is done on an annual basis for a twenty-five year planning horizon.

The model application is developed through a linear program. The

analyses of the linear program problem is done by the use of the proprietary mathematical MPS-III system.

Specific results indicate that spent uranium and plutonium should be utilized in self-generating reactors in order to minimize the consumption of the natural uranium resources. The ability to reprocess spent fuel and to fabricate MOX fuel assemblies are the parameters which restrict the effective introduction of these reactors.