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TITLE: ACTINIDE RECYCLE IN LMFBRs AS A WASTE MANAGEMENT ALTERNATIVE

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ABSTRACT

A strategy of actinide burnup in fast reactor systems has been investigated as an approach for reducing the long term hazards and storage requirements of the actinide waste elements and their decay daughters. The actinide recycle studies also included plutonium burnup studies in the event that plutonium is no longer required as a fuel. Particular emphasis was placed upon the timing of the recycle program, the requirements for separability of the waste materials, and the impact of the actinides on the reactor operations and performance. It is concluded that actinide recycle and plutonium burnout are attractive alternative waste management concepts.

1.0 SUMMARY AND CONCLUSIONS

A strategy of actinide burnup in LMFBRs has been investigated as a waste management alternative to long term storage of high level nuclear waste. This strategy has been evaluated because many of the actinides in the waste from spent-fuel reprocessing have half-lives of thousands of years and an alternative to geological storage may be desired. From a radiological viewpoint, the actinides and their daughters dominate the waste hazard for decay times beyond about 400 years. By burning the actinides in LMFBRs the long-lived isotopes can be effectively transmuted to fission products which have significantly shorter half-lives. Actinide burnup in LMFBRs rather than LWRs is preferred because the ratio of fission reaction rate to capture reaction rate for the actinides is higher in an LMFBR, and the LMFBR performance is not highly sensitive to the addition of the actinide isotopes (which would be poisons in the LWR system).

An actinide target assembly recycle scheme has been evaluated to determine the effects of the actinides on the LMFBR performance, including local power peaking, breeding ratio, and fissile material requirements. Several schemes have been evaluated to identify any major problems associated with reprocessing and fabrication of recycle actinide-containing assemblies. The overall efficiency of actinide burnout in LMFBRs is evaluated, and equilibrium cycle conditions have been determined.

The study indicates that actinide recycle in LMFBRs may offer an attractive alternative to long term storage of the actinides, and does not significantly affect the performance of the host LMFBR. Assuming a 0.1% or less actinide loss during reprocessing, a 0.1% loss or less during fabrication, and proper recycle schemes virtually all of the actinides produced by a fission reactor economy could be transmuted in fast reactors. The potential of using an alternate fast reactor system designs (U-Th, etc.) for actinide recycle has also been evaluated. It is concluded that the waste actinides from thorium fueled fast reactors could be recycled in plutonium-uranium fueled fast reactors, and vice versa, but there is no clear incentive for doing so. Also, none of the alternate fast reactor systems offers any particular advantages as a "host" reactor for the recycled actinides.

The timing of the implementation of actinide recycle has also been investigated in an effort to determine what should be done, and when, to have recycle technologies ready when needed. A number of host reactors must become available, and special actinide target assembly transportation casks must be developed. A reprocessing facility must be developed which is capable of high actinide recovery, and a remotely maintained actinide assembly fabrication facility must be developed. It is clear that the masses of actinides which can be recycled in individual LWRs and LMFBRs, without affecting reactor performance, are extremely important parameters which are at present largely unknown. Further work must be done to more accurately determine these parameters. The investigations indicate that the backlog of actinide wastes could become so large as to preclude the recycle of a large fraction of the backlog due to a lack of commercial LWR and LMFBR capacity. It may be desirable to burn the actinide wastes in special purpose, high capacity actinide burner reactors. Design strategies and limitations for several such actinide burner reactors are discussed herein.

A Pu-burner study has been undertaken to complement the actinide recycle studies. It is readily apparent that the beneficial effects of recycling the actinides in a continuous 80-year long scheme would be negated by the potential hazard of the Pu in the LMFBR from just one cycle if it were sent to waste (because it is no longer needed as a fuel). Obviously, if any actinide recycle scheme is undertaken, it must be followed by a Pu-burner scheme. A scheme which utilizes a plutonium-tungsten fuel mix has been investigated, and it was concluded that the scheme may provide a reasonable approach to burning the waste plutonium.

In summary, actinide recycle and plutonium burnout have been found to be attractive alternative waste management concepts. However, experimental programs are required if the recycle technologies are to become demonstrated waste management alternatives.

2.0 INTRODUCTION AND REVIEW

The utilization of nuclear power will result in an accumulation of solidified high-level wastes. Waste management of these isotopes may include transmutation schemes for reduction of the long-term hazards and storage requirements. In order to better evaluate the potential for transmutation of the actinides, an extensive actinide recycle study has been conducted. The results of that study are included herein.

From a radiological hazards viewpoint, the actinide wastes and their daughters dominate the waste hazard for decay times beyond about 400 years.⁽¹⁾ The actinide waste hazard is controlled by the americium and curium for decay times of up to 10,000 years. The long-lived Np^{237} and its daughters dominate for longer decay times. The remaining actinides, namely actinium, thorium, protactinium, berkelium, californium, and einsteinium do not contribute significantly to the waste hazard. In a waste management system in which at least 99.5% of the uranium and plutonium is extracted from the waste stream, removal of most of the americium, curium, and neptunium will markedly further reduce the actinide waste hazard. If these three actinides are 99.5% removed from LWR uranium fuel, the hazard becomes controlled by the uranium and plutonium and it would become beneficial (from a waste hazard viewpoint) to increase the extraction of these latter elements - especially the plutonium.

2.1 Radiological Hazards of High Level Wastes

High level wastes are, by general definition, the first cycle raffinate from the reprocessing of spent fuels. Conventional reprocessing operations would recover about 99.5% of the uranium and plutonium in the spent fuel. Thus, the high-level wastes would contain, primarily, the actinide elements (including the residual 0.5% of the U and Pu) and their decay daughters, the fission products and their decay daughters, and small amounts of structural materials. From a potential radiological hazards viewpoint, the fission products are by far the most hazardous component of the wastes for the first few hundred years. For decay periods of ~ 1000 years or longer the actinides and their daughters dominate the potential hazard of the wastes. As shown in Table 1, the actinide elements uranium, neptunium, plutonium, americium, and

TABLE 1

POTENTIAL HAZARDS OF HIGH LEVEL WASTES FROM
CONVENTIONALLY REPROCESSED LWR SPENT FUEL (a)

Contribution to the Total Hazard, %, for Various Decay Times

Component	Time (years)								
	10^2	5×10^2	10^3	10^4	5×10^4	10^5	2.5×10^5	5×10^5	10^6
U+Np+Pu+Am+Cm + Their Decay Products	0.3	94	99.51	97.90	95.76	96.73	98.25	98.94	99.4
Other Actinides + Their Decay Products	-	-	2.6×10^{-3}	0.024	0.038	0.022	4.5×10^{-3}	6.0×10^{-4}	-
Fission Products + Their Decay Products	99	6	0.54	2.11	4.26	3.28	1.69	1.00	0.60

(a) Calculated from data available in ORNL-TM-4724, (Ref. 2).

Recovery of 99.5% of the U and Pu in the spent fuel is assumed. Iodine is 99.9% removed from wastes. Values are for a LWR with uranium fuel.

Values for LMFBRs and LWRs with Pu-recycle fuel differ only slightly.

curium, and their daughter products make up at least 95% of the total hazard from high level wastes for decay periods > 1000 years. The data given in Table 1 reflect the removal of 99.9% of the fission product iodine also. The recovered iodine could be isotopically diluted and stored.

For the purposes of this work the potential radiological hazard is defined in terms of a hazard index which is the amount of water per unit volume of waste or ore required to dilute the wastes to their Radiation Concentration Guide (RCG) values for unrestricted use of the water. Two standards of comparison are used to put the relative hazards of high-level wastes into perspective. The two standards are: a) the hazard index of naturally formed high-grade pitchblende (70% U) ore, and b) the hazard index of high-grade uranium ore (0.2% U). Claiborne has considered the reduction of the potential hazards associated with the wastes from the first cycle raffinate if the waste actinides are removed.⁽²⁾ The hazard indices of wastes from various reactor types are displayed in Figure 2 for various decay periods. Hazards are plotted for wastes formed from conventional reprocessing of spent fuels (to recover 99.5% of the U and Pu) plus 99.9% iodine removal. For a uranium-fueled LWR, it is apparent from Figure 2 that the hazard index of the wastes formed by conventional reprocessing is greater than that of pitchblende for about 8,000 years. For a plutonium-fueled LWR it is apparent that the hazard is greater than that of pitchblende for about 800,000 years. The hazard for LMFBR wastes is greater than that of pitchblende for about 20,000 years.

The production and decay scheme for the major actinide isotopes is shown in Figure 1. For LWR fuels with no plutonium recycle, the actinide isotopes which contribute most to the total actinide hazard are Cm^{246} , Cm^{245} , Cm^{243} , Cm^{242} , Am^{243} , Am^{242m} , Am^{241} , Pu^{241} , Pu^{240} , Pu^{239} , Pu^{238} , and Np^{237} .⁽³⁾ Most of the hazardous daughters are located in the Pu^{238} , Pu^{239} , or Np^{237} decay chains. These actinide isotopes have half-lives so long that they present a long-term hazard, yet so short that their activities remain relatively high. Also, most of the actinides and their daughters decay by alpha emission and are biologically hazardous if they enter the body. Often these alpha emissions are followed by gamma radiation as a nucleus that has been formed in an excited state passes to a less excited state. The curium isotopes Cm^{242} and Cm^{244} are important spontaneous fission neutron sources. Am^{242m} decays by beta emission or electron capture to Cm^{242} or Pu^{242} ,

FIGURE 1 PRODUCTION AND DECAY OF ACTINIDE ISOTOPES

NOTE:
E3, E4, ETC., GIVEN IN THE HALF LIVES ARE TO BE UNDERSTOOD AS $\times 10^3, \times 10^4$,
ETC.

FIGURE 2: RELATIVE HAZARDS* OF WASTES AND NATURAL ORES
IF SECONDARY REPROCESSING IS NOT ACCOMPLISHED

(ASSUMES U AND Pu ARE 99.5% RECOVERED AT
 REPROCESSING, IODINE IS 99.9% REMOVED)

*HAZARD IS BASED UPON RECOMMENDED CONCENTRATION GUIDES FOR RADIONUCLIDES
 IN WATER. COMPARISON IS FOR EQUAL VOLUMES OF ORES AND WASTES.

respectively. Np^{237} and its daughters become the main contributors to the total hazard at long decay times.

Actinide isotopes contributing most to the total actinide hazard from LWR fuels with plutonium recycle are essentially the same as those contributing to the hazard from LWR fuels with no plutonium recycle. The only difference is the addition of Pu^{242} . Most of the hazardous daughters are included in the Pu^{238} , Pu^{239} , or Np^{237} decay chains.

Actinide isotopes contributing most to the total actinide hazard from LMFBR fuels are essentially the same as those contributing to the hazard from LWR fuels with plutonium recycle. Hazardous daughters are once again in the Pu^{238} , Pu^{239} , or Np^{237} decay chains.

The hazard indices for the various reactor types and decay times, but with secondary reprocessing to remove most of the actinides in addition to the iodine, are graphically displayed in Figure 3. The results in Figure 3 show that for all reactor types considered and for all decay times ≥ 1000 years, the hazard indices of wastes with most of the actinides and iodine removed is only 2%-5% of that of pitchblende. Secondary reprocessing to remove most of the actinides and iodine from the wastes cannot, however, eliminate the need for short-term (< 1000 years) geologic disposal. The fission products will require storage for ~ 500 years and the residual small amounts of actinides in the wastes will still remain hazardous for long periods. However, the resultant potential hazard after ~ 1000 years will be reduced to levels which occur in natural formations. Thus, the potential hazard of a breach in the disposal site integrity would be less than a breach in the integrity of a natural pitchblende formation.

2.2 Actinide Recycle in LWRs

It is accepted that the uranium and plutonium recovered by secondary processing can be used as fuel in a reactor. It is necessary to consider whether the other actinides (the Np, Am and Cm) can also be recovered and effectively "burned" in a reactor. Claiborne has performed a number of calculations concerning the recycling of the americium, curium, and neptunium in PWRs, with the recycled actinides uniformly distributed in the fuel.⁽¹⁾ Claiborne's results indicate that for a 99.9% extraction efficiency at reprocessing, the hazard of the actinides at equilibrium recycle conditions is

FIGURE 3: RELATIVE HAZARDS* OF WASTES AND NATURAL ORES IF SECONDARY**
REPROCESSING IS ACCOMPLISHED AND IODINE IS 99.9% REMOVED

*HAZARD IS BASED UPON RECOMMENDED CONCENTRATION GUIDES FOR RADIONUCLIDES IN WATER. COMPARISON IS FOR EQUAL VOLUMES OF ORES AND WASTES.

**ASSUMES THAT 99.7% OF THE U, 95% OF THE Np, 99.99% OF THE Pu, AND 99.9% OF THE Am AND Cm ARE REMOVED FROM THE WASTES. FOR THE LMFBFR THE Np REMOVAL PERCENTAGE IS 75%.

reduced to the same order as that of the long-lived fission products (I^{129} , Zr^{93} , Nb^{93M} , Tc^{99} , and Cs^{135}) for the longer decay times. The hazard due to the actinides is about twice that of the long-lived fission products at 1,000 years and drops to about one-half of the fission-product value at 1 million years. If I^{129} is removed from the waste (and treated by isotopic dilution, or separately stored), the actinides would control the total waste hazard for all decay times. An actinide extraction efficiency of 99.999+% is required before the hazard of the total waste is controlled by long-lived fission products other than I^{129} .

A recycle analysis similar to Claiborne's was performed at Battelle Pacific Northwest Laboratories (PNL) and essentially the same conclusions were reached.⁽⁴⁾ The PNL group also made a second set of calculations assuming that the actinides were recycled only in every 10th rod of the PWR, rather than in every rod. Recycling of the actinides in this way reduced the actinide inventory but not as much as when the actinides were uniformly distributed throughout all rods in the core. However, an incentive for this scheme still exists as recycling of the actinides in fewer rods will reduce the economic penalty which would occur if remote fabrication of fuel containing recycled actinides is required.

A third set of calculations was performed assuming that only the uranium was removed for storage. The plutonium was considered recycled along with the other actinides in a scheme typical of plutonium recycle strategies. Again, actinide inventories were significantly reduced.

2.3 Actinide Recycle in LMFBRs

The reaction rates in Table 2 show that the recycle of actinides in LMFBRs should produce higher actinide burnup rates than recycle in thermal reactors since the average fission reaction rate of the actinides is higher in a fast reactor than a thermal one. Also, the average capture reaction rate for the actinides is lower in a fast reactor. Thus, a primary goal of actinide recycle - to fission the actinides without an appreciable buildup of higher actinide isotopes as a consequence - is more nearly achievable in a fast reactor than in a thermal reactor.

Kubo and Rose have pointed out that recycling of the actinides in an LMFBR has additional advantage over recycling in a thermal reactor.⁽⁵⁾ Extreme separa-

TABLE 2

ACTINIDE REACTION RATES IN FAST AND THERMAL REACTORS

Reactions/sec/Atom

Isotope	Half-Life (Years)	<u>Fast Spectrum^a</u>		<u>Thermal Spectrum^b</u>	
		Fission Reaction Rate	Capture Reaction Rate	Fission Reaction Rate	Capture Reaction Rate
Np-237	2.14×10^6	2.2×10^{-9}	1.03×10^{-8}	6.18×10^{-12}	4.9×10^{-8}
Am-241	433	2.7×10^{-9}	2.35×10^{-8}	6.18×10^{-10}	1.38×10^{-7}
Am-242m	152	4.7×10^{-8}	9.69×10^{-9}	1.49×10^{-7}	1.33×10^{-7}
Am-243	7370	1.59×10^{-9}	4.5×10^{-9}	1.55×10^{-11}	3.18×10^{-8}
Cm-244	17.9	3.47×10^{-9}	2.77×10^{-9}	4.02×10^{-10}	5.9×10^{-9}

^a Average Total Flux = 6.93×10^{15} in core zone 1.

^b Average Total Flux = 3.09×10^{14} .

tions of chemical groups may not be required if recycling is done in an LMFBFR because a less pure actinide product should be recyclable without degrading the reactor's neutron economy. Also, more actinides are naturally present in an LMFBFR so the addition of more actinides affects it less.

More recently, comprehensive actinide recycle studies have been performed by Croff at ORNL.⁽⁶⁾ He has investigated actinide recycle in LMFBFRs and thermal reactors for variable nuclear electrical capacities and concludes that the LMFBFR would be the preferred actinide host reactor type. However, space limitations in LMFBFRs during the early growth period may mean that the thermal reactors operating at the time would have to be used as well if an actinide backlog of any size is to be recycled. Of the thermal reactor types considered (uranium-fueled LWRs, plutonium-fueled LWRs, and HTGRs) the uranium-fueled LWR with the actinides being recycled in target assemblies is considered most favorable.

2.4 Fuel Cycle Hazards Associated with Actinide Recycle

It is possible to define five broad areas of hazards associated with recycled actinides present in the reactor fuel cycle and waste stream processes. Three areas have been identified where the risk due to actinide recycling would be significantly greater than that which exists for the conventional nuclear fuel cycle (i.e., for LWRs with no plutonium recycle).^(1,4) These are at the reprocessing plant, during fuel fabrication, and during transportation. In addition, hazards that need to be considered in any actinide recycling study involve the long-term (greater than 1000 years) hazard of stored wastes, and the hazard involved with increasing the actinide inventory of a reactor.

If recycling is to be practiced, the actinides must first be separated from other wastes present in spent reactor fuel. Conventional chemical separation processes in use today to remove uranium and plutonium from the discharge waste stream are equipped to handle large amounts of high-level radioactive waste. If the actinides are homogeneously mixed with reactor fuel, it is believed that the increased emission of neutrons from recycled actinides should not cause an increased radiation hazard in this chemical processing since the thick concrete walls required for gamma shielding should also be adequate for the absorption of neutrons. However, the emission of alpha particles from the actinides may cause the solvents used in the chemical

separation to decompose into gases which have explosive potential if they become recombined. The utilization of organic solvents for actinide separation may increase the probability of a fire in the equipment. If the actinides are recycled in high-actinide-content target rods, chemical separation of the recycled actinides would probably be accomplished in a special small-throughput separation plant. The hazards associated with the operation of this plant remain to be investigated.

A potential hazard also exists in the fabrication and transportation processes. Recycling will result in the buildup of nuclides that undergo spontaneous fission, and, of course, these nuclides will be present during fabrication and transportation. As the result of spontaneous fission, and of alpha-n reactions with oxide fuels, recycled actinides will generate considerably more neutrons per unit weight than plutonium. The quantities of actinides involved, however, are small when compared with the amount of plutonium which would be recycled to produce plutonium recycle fuel. Claiborne, therefore, concluded that actinide recycle material could be handled without too much change in the design of handling procedures which would be required for plutonium-recycled fuels (fuels with only the plutonium recycled as is envisioned for large scale LWR and LMFBR use). Claiborne's studies considered recycling the actinides in a homogeneous mix with the reactor fuel. A study to investigate the consequences of accidents involving actinides in reprocessing plants and plutonium fabrication plants has been initiated.⁽⁴⁾

3.0 ANALYSES OF ACTINIDE RECYCLE IN LMFBRs

Neutronics calculations have shown that actinide recycle in LMFBRs may be an attractive alternative to geological storage of these isotopes. The recycle of actinides in LMFBRs can be expected to produce higher burnup than recycle in thermal reactors since the average fission reaction rate of the actinides is higher in the fast reactor and the average capture reaction rate is lower. The higher fission rates and lower capture rates in the LMFBR system represent a more effective total removal of the actinide isotopes. Thus, a primary goal of actinide recycle - to fission the actinides without an appreciable buildup of higher actinide isotopes as a consequence - is more nearly achievable in a fast reactor than in a thermal reactor.

If recycle is accomplished in a fast reactor rather than a thermal reactor, ex-reactor shielding requirements may be reduced because penetrating radiation sources are reduced. For instance, the spontaneous fission neutron activity of the higher actinide isotopes is reduced by several orders of magnitude. This occurs because the higher actinides are not produced as much if recycle is in fast reactors. Recycling of the actinides in LMFBRs has the additional advantage that extreme partitioning of chemical groups may not be required because a less pure actinide product should be recyclable without degrading the reactors neutron economy.

The overall efficiency of actinide burnout in LMFBRs has been evaluated and equilibrium cycle conditions have been determined. An actinide target assembly recycle scheme has been evaluated to determine the effects of the actinides on the LMFBR performance. Several schemes were evaluated to identify major development requirements associated with reprocessing and fabrication. The analysis was carried out for the cycle shown in Figure 4. For the analysis all transuranium actinides, except plutonium, from three light water reactors and one LMFBR, were considered to be continuously recycled in the LMFBR. The actinides were considered to be recycled in the center core zone of the LMFBR to take advantage of the high total flux in this zone, and the favorable spectrum. The reactor model for evaluating the actinide recycle concept was based upon an advanced General Electric 1200 MWe LMFBR system.

FIGURE 4

SIMPLIFIED FUEL CYCLE FOR RECYCLE ACTINIDES

Actinide cross sections were obtained from various sources including ENDL, ENDF/B-III, ENDF/B-IV, and the multigroup cross sections compiled by Benjamin, et. al.^(7,8,9) The one-group fast neutron cross sections used for the important isotopes from U^{235} to Es^{253} are given in Table 3. These cross sections were obtained by flux-weighting the multigroup cross sections of Benjamin, et. al., with a typical 1200 MWe LMFBR center core zone flux, and collapsing. The single-level Breit-Wigner formula was used to determine the resonance cross sections.

Typical LMFBR and LWR actinide yields were determined for fuel exposures of 100,000 Mwd/MT and 25,000 Mwd/MT, respectively. These yields, shown in Tables 4 and 5, were used in all recycle calculations. The recycle burnout calculations were performed using a modified ORIGEN computer code for an LMFBR center core zone fuel exposure of 100,000 Mwd/MT.⁽¹⁰⁾

To determine the overall efficiency of actinide recycle in LMFBRs, and to determine the effects of recycle upon the performance of the LMFBR, it was necessary to first determine the conditions existing after an equilibrium cycle concentration of actinides has been achieved. The LMFBR core model assumed for the actinide recycle calculations is shown in Figure 5.

3.1 Equilibrium Cycle Conditions

To determine the equilibrium cycle conditions for a recycle scheme involving one 1200 MWe LMFBR and three LWRs of comparable power, the following recycle sequence of operations was assumed. The actinides discharged from one refueling cycle for each reactor are separated from the spent fuel at reprocessing, fabricated into actinide-target assemblies, and placed in the center core zone (the innermost 51% of the core, by volume) of the LMFBR for burnout. All reactors are then operated for their respective cycle lengths and at the end of those cycles another loading of actinides will have been produced. The original recycle actinide content of the LMFBR will have been diminished somewhat due to fission of the actinides. Newly processed and fabricated actinide target assemblies are placed, with the reduced inventory of previously recycled actinides, in the center core zone of the LMFBR and once again all reactors are operated for their respective cycle lengths. This process is repeated continually throughout the lifetimes of the reactors. Actinide recovery efficiencies at reprocessing are assumed to be such that only 0.1% of the actinides are lost to the waste stream.

TABLE 3

NUCLEAR DATA FOR THE ACTINIDES AND THEIR SOURCE OF INFORMATION

Isotope	σ_c (barns)	σ_f (barns)	$n, 2n$ (barns)	η	Source
U-235	0.612	2.04		-	ENDF/B-III
U-236	0.501	0.115		-	
U-238	0.307	0.04	2.06×10^{-3}	0.275	↓
Np-237	1.694	0.311	4.850×10^{-4}	0.457	ENDF/B-IV
Pu-238	0.471	1.150		2.099	
Pu-239	0.576	1.87		2.240	
Pu-240	0.586	0.355		1.161	
Pu-241	0.510	2.652		2.492	
Pu-242	0.395	0.270		1.232	
Am-241	1.10	0.408		0.784	↓
Am-242m	0.454	4.438		2.812	ENDL ⁽⁷⁾
Am-243	.866	0.174		0.419	Benjamin ⁽⁹⁾
Cm-244	0.513	0.517		1.654	
Cm-245	0.191	3.24		3.148	
Cm-246	0.297	0.246		1.586	
Cm-247	0.133	0.202		2.000	
Cm-248	0.250	0.302		1.948	
Bk-249	1.760	0.0		0.0	
Cf-249	0.179	3.08		3.535	
Cf-250	0.415	0.0		0.0	
Cf-251	0.186	0.627		3.194	
Cf-252	0.147	0.372		2.703	
Cf-253	0.014	2.34		4.135	
Cf-254	0.120	0.0		0.0	
Es-253	0.820	0.0		0.0	↓

Table 4
TYPICAL ACTINIDE YIELDS FROM LMFBR^a OPERATIONS

<u>Isotope</u>	<u>Half-Life</u>	<u>Total Yield, Kilograms/Cycle</u>
NP-237	2.14×10^6 y	2.11E 01
Pu-236	2.85 y	2.29E-03
Pu-238	87.8 y	1.08E 01
Pu-239	2.44×10^4 y	1.87E 03
Pu-240	6540 y	6.10E 02
Pu-241	15 y	1.05E 02
Pu-242	3.87×10^5 y	7.22E 01
Pu-244	8.30×10^7 y	9.44E-08
Am-241	433 y	1.64E 01
Am-242m	152 y	5.98E-01
Am-242	16.0 h	6.94E-03
Am-243	7370 y	1.12E 01
Cm-242	163 d	1.20E 00
Cm-243	28 y	1.39E-01
Cm-244	17.9 y	3.20E 00
Cm-245	8500 y	2.31E-01
Cm-246	4760 y	7.67E-03
Cm-247	1.54×10^7 y	3.18E-04
Cm-248	3.50×10^5 y	4.77E-06
Cm-250	1.13×10^4 y	1.03E-12
Bk-249	311 d	7.19E-08
Cf-249	352 y	2.75E-03
Cf-250	13.1 y	1.15E-08
Cf-251	~ 900 y	3.77E-10
Cf-252	2.63 y	4.50E-12
Cf-253	17.8 d	7.04E-15
Cf-254	60 d	2.72E-18
Es-253	20.47 d	6.63E-15
Total		2.72E 03
Total Without Pu		5.42E 01

^aFor a 1200 MWe LMFBR with a 472.4 day refueling interval. The plant capacity factor is 0.85 and the core average discharge burnup is 100,000 MWD/MT.

Table 5

Typical Actinide Yields from LWR^a Operations

<u>ISOTOPE</u>	<u>TOTAL YIELD, KILOGRAMS/CYCLE</u>
NP-237	1.56E 01
PU-238	4.62E 00
PU-239	1.76E 02
PU-240	8.41E 01
PU-241	3.53E 01
PU-242	1.24E 01
AM-241	8.95E-01
AM-242	3.79E-03
AM-243	2.10E 00
CM-242	6.30E-01
CM-244	<u>4.02E-01</u>
TOTAL	3.32E 02
TOTAL WITHOUT PU	1.96E 01

^aFor a 1200 MWe LWR with an average discharge burnup of 25,000 MWd/MT, and a 1 year refueling interval.

FIGURE 5

CORE MODEL ASSUMED FOR LMFBR
ACTINIDE RECYCLE CALCULATIONS*

- * Notation for LMFBR Model
- CZ1 Core zone 1 (as-loaded enrichment zone)
 - CZ2 Core zone 2 (as-loaded enrichment zone)
 - AB1 Axial blanket above and below core zone 1
 - AB2 Axial blanket above and below core zone 2
 - RB1 First ring of radial blanket fuel
 - RB2 Second ring of radial blanket fuel
 - RB3 Outer ring of radial blanket fuel
 - CB1 Corner blanket above and below radial blanket 1
 - CB2 Corner blanket above and below radial blanket 2
 - CB3 Corner blanket above and below radial blanket 3

A two year period for reprocessing and fabrication is assumed between the time any particular actinide batch is discharged from a reactor, and the time it is placed in the LMFBR. The batch stays in the LMFBR for an irradiation time of 402 days (one refueling cycle length) and then is removed for reprocessing, fabrication, and subsequent return to the LMFBR. The total weights of the actinides remaining after a specified number of recycles and the total weight which would exist if the actinides are not recycled, are given in Table 6.

The number of cycles required for a particular isotope to reach an equilibrium concentration is dependent upon the position in the actinide production chains, and the isotope half-life. The equilibrium concentration for Np^{237} is achieved after about 14 recycles, and for Cm^{244} the equilibrium concentration is achieved after about 30 recycles. Actinide isotopes heavier than Cm^{244} do not achieve equilibrium in the time period covered by Table 6, but their concentrations are low compared to the concentrations of the actinides lighter than Cm^{244} . An equilibrium concentration of the actinide mix is essentially achieved after approximately 26 recycles, and a total of about 350 kilograms of actinide waste discharged after each operating period. It is important to note that a recycle scheme could be initiated by a "near equilibrium" load of actinides from four 1200 MWe LMFBRs and twelve 1200 MWe LWRs. Succeeding recycles would begin with approximately 113 kilograms of newly produced actinides from the LMFBR and three LWRs. Thus, the LMFBR contains, at the beginning of each equilibrium cycle, about 463 kilograms of recycle actinides. At equilibrium 113 kilograms of actinides are burned up per cycle, and this is the amount of new actinides produced by the previous cycles operation of the LMFBR and three LWRs. Approximately 56.6 kilograms of plutonium, mostly Pu^{238} , are produced per recycle as a by-product of actinide recycle (the result of neutron capture in Np^{237} , and/or decay of americium and curium isotopes). It is also important to note that, for the purposes of Table 6, the plutonium produced in the target assemblies, was separated from the actinide waste. If the plutonium were recycled in the target assemblies, values reported for Am^{241} would increase slightly due to the decay of the small amounts of Pu^{241} in the assemblies. The major effect of excluding this plutonium from the recycle scheme, is to introduce conservatism to calculations of the reactors fissile inventory requirements and the breeding ratio.

The LMFBR and three LWRs will produce about 3620 kilograms of actinides during a lifetime of approximately 40 years. If the actinides are recycled,

TABLE 6

RECYCLE (a) OF Np, Am, Cm, Bk, and Cf from one 1200 MWe LMFBR and Three 1200 MWe LWRs

Cycle (b)	2	4	6	8	10	12	14	16
(Kilograms of Isotope Remaining After Indicated Number of Recycles in an LMFBR)								
(c)								
Np-237	6.49 + 1	9.29 + 1	1.05 + 2	1.10 + 2	1.12 + 2	1.13 + 2	1.14 + 2	1.14 + 2
Pu-236	3.44 - 3	4.92 - 3	5.56 - 3	5.83 - 3	5.95 - 3	6.01 - 3	6.03 - 3	6.04 - 3
Pu-238	2.72 + 1	3.91 + 1	4.44 + 1	4.68 + 1	4.79 + 1	4.84 + 1	4.86 + 1	4.87 + 1
Pu-239	1.29	1.86	2.11	2.23	2.28	2.31	2.32	2.33
Pu-240	5.13 - 1	9.98 - 1	1.39	1.69	1.91	2.06	2.16	2.23
Pu-241	2.47 - 2	4.93 - 2	6.96 - 2	8.52 - 2	9.64 - 2	1.04 - 1	1.10 - 1	1.13 - 1
Pu-242	1.43	2.17	2.56	2.77	2.87	2.93	2.96	2.97
Am-241	3.70 + 1	5.63 + 1	6.64 + 1	7.17 + 1	7.45 + 1	7.59 + 1	7.66 + 1	7.70 + 1
Am-242m	1.48	2.44	2.96	3.23	3.38	3.45	3.49	3.51
Am-243	2.54 + 1	4.20 + 1	5.28 + 1	5.98 + 1	6.43 + 1	6.73 + 1	6.92 + 1	7.04 + 1
Cm-242	3.06	4.66	5.49	5.93	6.16	6.27	6.34	6.37
Cm-243	4.61 - 1	9.40 - 1	1.34	1.65	1.88	2.04	2.15	2.22
Cm-244	1.31 + 1	2.54 + 1	3.53 + 1	4.28 + 1	4.82 + 1	5.20 + 1	5.46 + 1	5.63 + 1
Cm-245	1.43	3.19	4.81	6.13	7.12	7.84	8.34	8.68
Cm-246	1.01 - 1	3.00 - 1	5.81 - 1	9.10 - 1	1.25	1.59	1.89	2.17
Cm-247	7.43 - 3	3.16 - 2	8.11 - 2	1.60 - 1	2.69 - 1	4.02 - 1	5.56 - 1	7.23 - 1
Cm-248	1.92 - 4	1.11 - 3	3.69 - 3	8.99 - 3	1.79 - 2	3.11 - 2	4.88 - 2	7.09 - 2
Bk-249	4.14 - 6	2.65 - 5	9.47 - 5	2.42 - 4	5.01 - 4	8.92 - 4	1.43 - 3	2.10 - 3
Cf-249	2.15 - 6	1.81 - 5	7.87 - 5	2.32 - 4	5.33 - 4	1.03 - 3	1.75 - 3	2.72 - 3
Cf-250	1.01 - 6	8.11 - 6	3.59 - 5	1.10 - 4	2.64 - 4	5.32 - 4	9.45 - 4	1.52 - 3
Cf-251	6.84 - 8	5.82 - 7	3.16 - 6	1.18 - 5	3.33 - 5	7.76 - 5	1.56 - 4	2.80 - 4
Cf-252	7.11 - 9	2.07 - 8	9.41 - 8	3.71 - 7	1.14 - 6	2.84 - 6	6.03 - 6	1.13 - 5
Total Actinides	1.47 + 2	2.28 + 2	2.75 + 2	3.02 + 2	3.19 + 2	3.30 + 2	3.37 + 2	3.41 + 2
Total Pu (d)	3.05 + 1	4.42 + 1	5.05 + 1	5.36 + 1	5.51 + 1	5.58 + 1	5.62 + 1	5.63 + 1
Total Actinides + Pu	1.77 + 2	2.72 + 2	3.25 + 2	3.56 + 2	3.74 + 2	3.86 + 2	3.93 + 2	3.98 + 2
Total Actinides if not Recycled	2.26 + 2	4.52 + 2	6.78 + 2	9.04 + 2	1.13 + 3	1.36 + 3	1.58 + 3	1.81 + 3

See footnotes on page following table.

TABLE 6 (Con't)

Cycle (b)	18	20	22	24	26	28	30	32
(Kilograms of Isotope Remaining After Indicated Number of Recycles in an LMFBR)								
Np-237	1.14 + 2	1.14 + 2	1.14 + 2	1.14 + 2	1.14 + 2	1.14 + 2	1.14 + 2	1.14 + 2
Pu-236	6.04 - 3	6.04 - 3	6.05 - 3	6.05 - 3	6.05 - 3	6.05 - 3	6.05 - 3	6.05 - 3
Pu-238	4.87 + 1	4.88 + 1	4.88 + 1	4.88 + 1	4.88 + 1	4.88 + 1	4.88 + 1	4.88 + 1
Pu-239	2.33	2.33	2.33	2.33	2.33	2.33	2.33	2.33
Pu-240	2.28	2.31	2.33	2.34	2.35	2.36	2.36	2.36
Pu-241	1.16 - 1	1.18 - 1	1.19 - 1	1.91 - 1	1.20 - 1	1.20 - 1	1.20 - 1	1.21 - 1
Pu-242	2.98	2.99	2.99	2.99	2.99	2.99	2.99	2.99
Am-241	7.73 + 1	7.74 + 1	7.74 + 1	7.74 + 1	7.75 + 1	7.75 + 1	7.75 + 1	7.75 + 1
Am-242m	3.52	3.53	3.53	3.53	3.54	3.54	3.54	3.54
Am-243	7.12 + 1	7.17 + 1	7.20 + 1	7.22 + 1	7.24 + 1	7.25 + 1	7.25 + 1	7.26 + 1
Cm-242	6.39	6.40	6.40	6.40	6.40	6.40	6.40	6.41
Cm-243	2.27	2.31	2.33	2.34	2.35	2.36	2.36	2.36
Cm-244	5.75 + 1	5.83 + 1	5.88 + 1	5.91 + 1	5.93 + 1	5.95 + 1	5.96 + 1	5.96 + 1
Cm-245	8.91	9.07	9.17	9.24	9.28	9.31	9.33	9.34
Cm-246	2.40	2.61	2.78	2.92	3.03	3.13	3.20	3.27
Cm-247	8.97 - 1	1.07	1.25	1.42	1.58	1.73	1.88	2.01
Cm-248	9.70 - 2	1.27 - 1	1.59 - 1	1.93 - 1	2.28 - 1	2.64 - 1	3.00 - 1	3.35 - 1
Bk-249	2.91 - 3	3.84 - 3	4.85 - 3	5.93 - 3	7.06 - 3	8.21 - 3	9.36 - 3	1.05 - 2
Cf-249	3.92 - 3	5.34 - 3	6.95 - 3	8.70 - 3	1.06 - 2	1.25 - 2	1.45 - 2	1.64 - 2
Cf-250	2.28 - 3	3.21 - 3	4.30 - 3	5.53 - 3	6.88 - 3	8.32 - 3	9.82 - 3	1.14 - 2
Cf-251	4.61 - 4	7.05 - 4	1.02 - 3	1.40 - 3	1.85 - 3	2.36 - 3	2.93 - 3	3.54 - 3
Cf-252	1.94 - 5	3.06 - 5	4.54 - 5	6.40 - 5	8.62 - 5	1.12 - 4	1.41 - 4	1.72 - 4
Total Actinides	3.44 + 2	3.47 + 2	3.48 + 2	3.49 + 2	3.50 + 2	3.50 + 2	3.51 + 2	3.51 + 2
Total Pu ^(d)	5.64 + 1	5.66 + 1	5.66 + 1	5.66 + 1	5.66 + 1	5.66 + 1	5.66 + 1	5.66 + 1
Total Actinides + Pu	4.01 + 2	4.03 + 2	4.04 + 2	4.05 + 2	4.06 + 2	4.06 + 2	4.08 + 2	4.08 + 2
Total Actinides if not Recycled	2.03 + 3	2.26 + 3	2.49 + 3	2.71 + 3	2.94 + 3	3.17 + 3	3.39 + 3	3.62 + 3

+2.26 + 2 out
of core and 1.13 + 2 in
core of LWR and LMFBR

See footnotes on page following table.

FOOTNOTES FOR TABLE 6

- (a) Recycle is done in a 1200 MWe LMFBR. At the beginning of each cycle approximately 113 kilograms of newly produced actinides go into the LMFBR (54.2 kilograms from the LMFBR, and 19.6 kilograms from each of three LWR's).
- (b) 1 cycle = 472.4 days. Plant capacity factor = 0.85.
- (c) Read as 6.49×10^1
- (d) This plutonium is produced as the result of actinide recycle operations and results from neutron capture in Np^{237} and from decay of americium and curium isotopes. If recycle is in target pins and material from the target pins is combined with material from plutonium fuel pins for chemical separation at the reprocessor, this plutonium will not be included in the next recycle target pins. It will instead be in the plutonium that makes up plutonium fuel, and may impose remote maintenance of the $\text{PuO}_2\text{-UO}_2$ fuel fabrication facility. The isotopic composition of this plutonium can be obtained from Table 6 for the indicated times.

the amount remaining at the end of this period is 690 kilograms (113 kilograms of newly produced actinides in the four reactors, 351 kilograms of "equilibrium concentration" actinides remaining in the LMFBFR, and 226 kilograms at the reprocessor or fabrication facility, assuming two years of ex-reactor time between recycles). Thus, actinide recycle can reduce the total weight and volume of the actinides by a factor of about five over the lifetimes of the reactors. If the reactors are replaced by another generation of comparably powered reactors and recycle is continued, the equilibrium concentrations will remain essentially the same, but the total weight of actinides produced will double. Thus, the total weight of the actinide waste produced during two generations of reactor operations will be reduced by an order of magnitude. It is important to note that most of the remaining waste remains stored in the reactor system.

Of course, not all of the difference between actinide weights with and without recycle will be found in the LMFBFR at the end of the scheme. Reprocessing inefficiencies and fabrication inefficiencies will result in small amounts of the actinides going to waste at each cycle. If recovery efficiencies of 99.9% are assumed at reprocessing, 0.113 kilograms of actinides will be lost during initial reprocessing of each cycle's spent fuel inventory from the four reactors (which amounts to 7.2 kilograms for two generations of reactors). About 21.4 kilograms of actinides will be lost during reprocessing of the first two generations (80 years) of recycle assemblies, and assuming a 0.1% loss during fabrication of recycle actinide-containing assemblies, another 28.6 kilograms of actinides will be lost. Thus, the total loss, after two generations of recycle operations, is 57.2 kilograms of actinides. This contrasts sharply with the 7240 kilograms that would eventually go to waste if the recycle scheme was not undertaken. Even if the actinides should someday be found commercially useful, they, or their daughter products, would eventually have to be treated as a hazardous waste unless it could be proved that their usefulness remained for the long time periods required for them to decay to innocuous levels.

In summary, two generations of recycling the actinides from one LMFBFR and three LWRs can be thought of as being 99.2% efficient if the 690 kilograms of actinides remaining at the end of the scheme are recycled in a third generation of LMFBFRs, or if they are transmuted in the blanket of a CTR, or by a spallation reactor. These 690 kilograms represent only about 12.6% of the inventory of plutonium remaining in the LMFBFR at the end of the scheme. Assuming that the

recycle scheme eventually comes to an end because fission reactors are no longer required, it may be possible to further transmute the actinides in the LMFBR if it is converted to a plutonium burner mode of operation (see Section 5).

3.2 Possible Recycle Schemes

The favorable burnout efficiencies reported in the section above encourage further study to evaluate various possible recycle schemes, and their effects on the fuel cycle. Five actinide recycle schemes, identified in Table 7, may be considered as possible waste management alternatives. Schemes 1 and 2 recycle the actinides in a homogeneous mix with the $\text{PuO}_2\text{-UO}_2$ that fuels the center core zone of the LMFBR. Scheme 1 was considered because of its apparent simplicity. Scheme 2 was considered as a possible alternative to scheme 1 if the intense radiation from curium is deemed undesirable. Both schemes were found to be unattractive from the standpoint of hands-on maintenance in the fuel fabrication plant.

Neutron and gamma radiation sources have been determined for the recycle scheme which was described in Section 3.1. The sources are given in Tables 8 and 9 for recycle Schemes 1 and 2. If curium is removed from the recycle scheme, neutron sources from alpha-n reactions with oxide fuel are reduced by about a factor of 18.5, and spontaneous fission neutron sources are reduced by a factor of 3100. Gamma sources are not greatly reduced, however, if curium is removed. Hands-on maintenance of a fabrication facility assembly line that contains only one gram of residual actinide-containing fuel material would be prohibited. A maintenance worker coming into direct physical contact with the gram of material would receive an entire quarters maximum allowable dose to hands and forearms from gammas alone in just over six minutes. Major contributors to this gamma dose rate are Am^{243} and Np^{239} . This large dose rate will provide impetus for actinide recycle in target assemblies manufactured in a special small-throughput, remotely maintained fabrication facility, rather than in a homogeneous mix with the fuel material.

If the actinide target assemblies are reprocessed concurrently with the $\text{PuO}_2\text{-UO}_2$ discharged fuel assemblies, the Pu^{238} produced in the target assemblies (about 49 kilograms per equilibrium cycle at discharge, building to 54 kilograms after two years of precursor decay) will find its way

Table 7

Actinide Recycle Schemes

Scheme	Initial Reprocessing	Fabrication	Actinide Irradiation	Reprocessing of Pins Containing Recycle Actinides
1	Remove U, Pu, Np, Am, Cm, Bk, and Cf from spent fuel	Fabricate pins containing U, Pu, Np, Am, Cm, Bk, and Cf	In all fuel pins of a LMFR	Similar to initial reprocessing
2	Reprocess as in 1 above and further remove curium for storage	Fabricate as in 1 above without curium	Curium allowed to decay; irradiate after radiation levels have fallen	Similar to initial reprocessing
3	Reprocess spent fuel such that the U and Pu are separate from the Np, Am, Cm, Bk, and Cf	Fabricate fuel pins containing U, and Pu; fabricate target pins containing Np, Am, Cm, Bk, and Cf, and a possible diluent	In target pins initially containing only Np, Am, Cm, Bk, Cf, and a possible diluent	<p>i) Reprocess target pins separately from fuel pins</p> <p>ii) Mix material from target pins with material from spent fuel; reprocess in a manner similar to initial reprocessing</p>
4	Reprocess spent fuel such that U, Pu, and Np are separate from the Am, Cm, Bk, and Cf	Fabricate fuel pins containing U, Pu, and Np; fabricate target pins containing Am, Cm, Bk, Cf, and a possible diluent	Np irradiated in fuel pins; Am, Cm, Bk, and Cf irradiated in target pins	<p>i) Reprocess target pins separately from fuel pins</p> <p>ii) Mix material from target pins with material from spent fuel; reprocess in a manner similar to initial reprocessing</p>
5	Reprocess as in 3 or 4 above, carrying some of the lanthanide fission products with the Am, Cm, Bk, and Cf	Fabricate as in 3 or 4	Irradiate as in 3 or 4	Reprocess recycle pins as in 3 or 4

TABLE 8

ACTINIDE RADIATION SOURCES AT FABRICATION - 33rd RECYCLE
OF MATERIAL FROM ONE LMFBR AND THREE LWRs

Isotope	α, n Neutron Source in Oxide Fuel, Neutrons/sec/MT of Fuel Fabricated ^a		Spontaneous Fission Neutrons, Neutrons/sec/Mt of Fuel Fabricated ^a	
	With Curium	Without Curium	With Curium	Without Curium
Np-237	2.48 + 4	2.48 + 4	-	-
Np-239	-	-	-	-
Am-241	1.18 + 4	1.18 + 8	-	-
Am-242	-	-	-	-
Am-243	7.72 + 6	7.72 + 6	-	-
Cm-242	7.55 + 8	2.42 + 7 ^b	1.53 + 9	4.91 + 7 ^b
Cm-243	5.07 + 7	-	-	-
Cm-244	1.87 + 9	-	1.09 + 11	-
Cm-245	4.41 + 5	-	-	-
Cm-246	3.07 + 5	-	4.80 + 9	-
Cm-247	4.58 + 1	-	-	-
Cm-248	5.31 + 4	-	2.24 + 9	-
Cm-250	-	-	3.17 + 5	-
Bk-249	2.90 - 7	1.14 - 11	-	-
Cf-249	5.93 + 4	9.62 - 1	-	-
Cf-250	5.35 + 5	1.71 + 1	1.86 + 10	5.92 + 5
Cf-251	2.33 + 3	1.56 - 1	-	6.32 + 6
Cf-252	<u>2.92 + 5</u>	<u>4.86 + 1</u>	<u>3.81 + 10</u>	<u>6.32 + 6</u>
Total	2.80 + 9	1.50 + 8	1.74 + 11	5.60 + 7

^aApproximately 6.304 MT of LMFBR center core zone fuel is fabricated for each refueling interval.

^bProduced by decay chain: Am-242m $\xrightarrow[152 \text{ yr}]{\text{e.c.}}$ Am-242 $\xrightarrow[16.0 \text{ h}]{80.85\%}$ Cm-242.

1 year decay assumed between Cm separation at the reprocessor, and fabrication.

TABLE 9

APPROXIMATE ACTINIDE PHOTON RELEASE RATES AT
FABRICATION - 33rd RECYCLE OF MATERIAL FROM ONE
LMFBR AND THREE LWRs

E_{mean} (MeV)	RELEASE RATES (PHOTONS/SEC/MT OF FUEL FABRICATED ^a)	
	With Curium	Without Curium ^b
3.00 - 2	4.52 + 13	4.51 + 13
4.00 - 2	4.47 + 14	4.17 + 14
6.00 - 2	6.81 + 14	6.42 + 14
1.00 - 1	2.19 + 12	1.62 + 12
1.50 - 1	3.98 + 13	3.76 + 13
2.00 - 1	1.26 + 14	3.17 + 13
3.00 - 1	9.15 + 13	2.28 + 13
6.30 - 1	6.79 + 13	6.71 + 13
1.10	1.71 + 13	1.68 + 13
1.55	2.28 + 11	3.32 + 10
1.99	1.23 + 11	1.78 + 10
2.38	7.77 + 10	1.08 + 10
2.75	1.21 + 11	5.81 + 10
3.25	3.63 + 10	5.04 + 9
3.70	2.14 + 10	2.97 + 9
4.22	1.19 + 10	1.65 + 9
4.70	6.84 + 9	9.49 + 8
5.25	<u>3.71 + 9</u>	<u>5.16 + 8</u>
Total	1.52 + 15	1.28 + 15
MeV/sec	1.82 + 14	1.37 + 14

^a Approximately 6.304 MT of LMFBR center core zone fuel is fabricated for each refueling interval.

^b Major contributors to the photon release rates are Am-243 and Np-239, thus little difference in release rates is observed if curium is removed.

into the main plutonium stream. This Pu^{238} will thus be present during fabrication of $\text{PuO}_2\text{-UO}_2$ fuel assemblies and may itself dictate remote maintenance of the fabrication facility. To avoid this potentially economically unattractive consequence of actinide recycle, it may be necessary to reprocess the target assemblies in a batch completely separate from the other fuel assemblies. Or, if this procedure is unacceptable, actinide recycle may dictate, in addition to the special target fabrication facility, a special small-throughput target assembly reprocessing facility. The underlying assumption, of course, is that decisions to keep the dose received "as low as reasonably achievable" during maintenance of Pu-recycle fuel fabrication facilities, does not impose remote maintenance regardless of whether the other actinides are recycled.

Schemes 3, 4 and 5 are target assembly schemes, one of which would be utilized to possibly eliminate the need for remote maintenance of the $\text{PuO}_2\text{-UO}_2$ fuel fabrication facility. All the important actinides would be recycled in target assemblies, and fabrication would take place in a small-throughput, remotely maintained facility. Scheme 4 may be more attractive than scheme 3 due to chemical reprocessing considerations. Scheme 5, similar to schemes 3 and 4 would relax lanthanide fission product separations requirements during reprocessing.

3.3 Effects of Actinide Recycle on the Host Reactor and Its Fuel Cycle

This investigation has considered the effects of waste actinide target assemblies in the center core zone of the LMFBR. The effects have been found to be minimal, except for the cases of decay heat removal, reprocessing, and fabrication. The actinides were lumped into target assemblies because of fabrication and reprocessing considerations, and because it is easier to select the location of the actinides in the reactor if they are in target assemblies. Effects considered were:

1. Power output of actinide target assemblies and variation with time.
2. Reactivity of a core with and without recycle actinides.
3. Increase in fissile inventory requirements.
4. Breeding ratio changes.
5. Shutdown decay heat removal.

6. Reprocessing to perform actinide - lanthanide separations.
7. Fabrication of target assemblies - remote maintenance.
8. Target assembly reprocessing.

3.3.1 Power

To avoid power peaking problems and yet maintain full LMFBR power, the power output of actinide-containing target assemblies was "tailored" to be similar to the power output of the standard center core zone fuel assemblies. Assemblies were assumed to be hexagonal LMFBR assemblies, with a fuel length of approximately 107.7 cm, and a fuel weight of about 70 kilograms. An assembly completely loaded with recycle actinides was found to produce approximately twice as much power as a standard fuel assembly, so a 50% actinide - 50% diluent mix was chosen for further study. About 14 center core zone assemblies or approximately 4% of the total core) are required for equilibrium cycles.

Uranium-238 was chosen as the diluent because it is a fertile material, heat transfer effects are minimized, and it is obvious that more reactor experience has been gained for this isotope than for any other. Also, U^{238} will contribute about 10% of the power output of the target assemblies. Power output of the target assemblies varies from about 7.0 MW_t per assembly at the beginning of a cycle to about 9.2 MW_t per assembly at the end of a cycle for cycles leading up to the equilibrium cycle. Power output for the cycles after equilibrium has been achieved varies from about 8.2 MW_t to 9.5 MW_t per assembly. The standard center core zone assembly produces, for the same flux, between 8.2 and 8.5 MW_t per assembly. This match of power outputs between target assemblies and standard fuel assemblies is judged to be reasonable. However, tailoring of the power outputs can be accomplished, if required, by adjusting the content of the target pins. Power output increases could be made possible by the addition of initial plutonium to the target assemblies. Power output decreases could be accomplished by placement of some neptunium in the standard assemblies rather than in the target assemblies, thus decreasing the buildup of Pu^{238} in the target assemblies.

3.3.2 Reactivity and Fissile Inventory

The effects of recycle upon the LMFBR neutronics, the breeding ratio, and the fissile inventory requirements were explored by comparing the reactivity worths of standard fuel assemblies and target recycle assemblies. Worth is defined for the purposes of this work as:

$$\text{Worth} = \sum_{i=1}^n N_i (\nu_i \sigma_{if} - \sigma_{ia})$$

where n is the number of reactive materials in the assemblies, N_i is the atom density of the i th isotope, σ_{if} and σ_{ia} are the one-group microscopic fission and absorption cross sections, and ν is the average number of neutrons per fission. Leakage is assumed to be the same for the standard assemblies and recycle assemblies. The actinides, while in general having values of ν exceeding that of U^{238} , have a greater negative center core zone worth than U^{238} . This is true mainly because the absorption cross sections of the actinides are significantly higher than that of U^{238} . Fortunately, $\nu\sigma_f$ for the actinides is also relatively large so that the actinides do not overly degrade the center core zone LMFBR flux. If actinide recycle target assemblies containing a 50-50 actinide- U^{238} mix are assumed to replace an equal number of standard fuel assemblies, the worth of the core is only slightly decreased. For equilibrium cycles, the "worst" condition because the greatest number of recycle assemblies are required, the worth of the core can be brought back to that of a "standard" non-recycle core by the addition of about another 56 kilograms of plutonium to the center core zone. This represents a total core plutonium mass increase of only about 1.7% (assuming that the make-up plutonium has a BWR discharge plutonium composition).

3.3.3 Breeding Ratio

As a result of reducing the total U^{238} content of the core (by about 1%) and increasing the overall core plutonium by 1.4%, the breeding ratio of the reactor will decrease slightly. The effect of actinide recycle on the breeding

ratio was investigated using neutron balance data, and the simplified definition of the breeding ratio:

$$\text{Breeding Ratio} = \frac{C^{238\text{U}} + C^{240\text{Pu}}}{A^{239\text{Pu}} + A^{241\text{Pu}} + A^{235\text{U}}}$$

where: C^i = number of captures in material i ,
and

A^i = number of absorption in material i ,

The difference between the breeding ratio for the standard, non-recycle core, and the core containing 14 recycle assemblies (an equilibrium cycle load) was only 1% to 2%, a modest decrease.

The above calculations, concerning the fissile inventory requirements of the reactor and the breeding ratio, are conservative because no credit is given for the plutonium generated as a result of actinide recycle. This plutonium, if recycled in the target assemblies, would add to the worth and power output of the assemblies. The increased power output of the target assemblies would allow further dilution with U^{238} , thus decreasing, slightly, the effects of recycle on the breeding ratio. The increased worth of the assemblies would alleviate the requirements for additional plutonium enrichment of the rest of the core.

3.3.4 Shutdown Decay Heat

A fuel assembly containing actinide waste instead of fuel would produce more alpha particle decay heat than a standard mixed oxide fuel assembly. Calculations indicate that the actinides would produce almost half as much decay power as the fission products from a standard assembly immediately after reactor shutdown. Assuming that the fission product decay heat from a recycle

assembly is essentially the same as the fission product decay heat from a standard assembly, the total shutdown decay heat in the recycle assembly was estimated to be about 43% greater than that from a standard assembly.

3.3.5 Reprocessing to Perform Actinide - Lanthanide Separations

Reprocessing operations to separate the actinides from spent fuel will be carried out in the presence of lanthanide fission products. Due to the large quantity of lanthanides and their possible impact on reactor operations, it is necessary to at least partially separate the actinides from the lanthanides before the actinides can be recycled. Many of the lanthanides are trivalent (as are the actinides), and the ionic radii of the transplutonium actinides overlap those of the major lanthanide fission products.⁽¹¹⁾ Because the valence and ionic radii of the lanthanides and actinides are alike, chemical separation of the two is difficult. Thus, ordinary reprocessing operations to separate the actinides from spent fuel will most likely result in the actinides and lanthanides separating from the fuel together.

The masses of the lanthanides in actinide recycle assemblies, and their relative macroscopic reactivity worths in the center core zone of an LMFBR have been calculated in an attempt to provide an estimate of the required actinide-lanthanide separations requirements. The masses were calculated for an actinide recycle scheme in which the actinides from one 1200 MWe LMFBR and three 1200 MWe LWRs are recycled in the LMFBR. The LMFBR core fuel management is a two-batch scheme with an operating cycle of 402 full-power days and an average discharge fuel burnup of about 100,000 MWd/MT. The LWR is based on a four-batch scheme with a 4-year fuel residence time and a burnup of about 20,000 MWd/MT. Due to the long time required to reach equilibrium, such a scheme would most likely be initiated by a "near equilibrium" load of actinides from four 1200 MWe LMFBRs and twelve 1200 MWe LWRs. The initial "near equilibrium" load of lanthanides would then be the discharge lanthanides from four LMFBRs and twelve LWRs if no actinide-lanthanide separations were made. The mass of this initial load of lanthanides has been calculated using ORIGEN, and is shown in Table 10. These masses were calculated for a decay time of 16 months after

Table 10
Equilibrium Cycle Lanthanide Masses and Relative Macroscopic Reactivity
Worths In The Center Core Zone of an LMFBR

Isotope	Weight ^b (gm)	σ_a (b)	Relative Macroscopic Reactivity Worth ^c
La-139	3.74×10^5	1.81×10^{-2}	-8.27×10^{-6}
Nd-143	2.86×10^5	3.47×10^{-1}	-1.18×10^{-4}
Nd-144	1.98×10^5	8.36×10^{-2}	-1.95×10^{-5}
Nd-145	1.96×10^5	4.93×10^{-1}	-1.13×10^{-4}
Nd-146	1.98×10^5	1.16×10^{-1}	-2.68×10^{-5}
Nd-148	1.19×10^5	1.48×10^{-1}	-2.02×10^{-5}
Nd-150	7.16×10^4	1.64×10^{-1}	-1.33×10^{-5}
Pm-147	6.98×10^4	7.90×10^{-1}	-6.35×10^{-5}
Sm-147	6.10×10^4	4.55×10^{-1}	-3.21×10^{-5}
Sm-148	1.88×10^4	1.11×10^{-1}	-2.39×10^{-6}
Sm-149	8.87×10	6.32×10^{-1}	-6.40×10^{-5}
Sm-150	1.22×10^4	1.46×10^{-1}	-2.01×10^{-6}
Sm-151	5.04×10^4	7.71×10^{-1}	-4.37×10^{-5}
Sm-152	5.23×10^4	1.62×10^{-1}	-9.48×10^{-6}
Sm-154	2.08×10^4	1.50×10^{-1}	-3.44×10^{-6}
Eu-151	8.87×10^4	1.42	-1.41×10^{-6}
Eu-152	3.22×10^1	5.38	-1.94×10^{-7}
Eu-153	2.49×10^4	1.06	-2.92×10^{-5}
Eu-154	3.03×10^3	4.04	-1.35×10^{-5}
Eu-155	1.07×10^4	8.11×10^{-1}	-9.48×10^{-6}
Gd-155	4.25×10^3	8.91×10^{-1}	-4.15×10^{-6}
Gd-156	1.13×10^4	2.16×10^{-1}	-2.66×10^{-6}
Gd-157	6.35×10^3	1.04	-7.14×10^{-6}
Gd-158	5.56×10^3	2.38×10^{-1}	-1.42×10^{-6}
Gd-160	1.51×10^3	1.92×10^{-1}	-3.08×10^{-7}
Tb-159	2.34×10^3	8.73×10^{-1}	-2.18×10^{-6}
Dy-160	3.82×10^2	8.54×10^{-2}	-3.46×10^{-8}
Dy-161	7.50×10^2	4.37×10^{-1}	-3.46×10^{-7}
Dy-162	4.58×10^2	9.53×10^{-2}	-4.58×10^{-8}
Dy-163	1.63×10^2	4.96×10^{-1}	-8.41×10^{-8}
Dy-164	1.23×10^2	1.21×10^{-1}	-1.54×10^{-8}
Total	1.86×10^6		-6.12×10^{-4}

^aLanthanides are from four 1200 MWe LMFBRs and twelve 1200 MWe LWRs.

^bEach LMFBR produces ~217 kilograms of lanthanides/refueling interval, and each LWR produces ~84.8 kilograms of lanthanides/refueling interval.

^cRelative macroscopic reactivity worth is defined as:

$$\text{Worth} = -N_i \sigma_{ai}$$

where N_i is the atom density of the i th isotope and σ_{ai} is its microscopic absorption cross section.

discharge from the reactor. Spent fuel reprocessing (which would remove some of the lanthanide's precursors) was assumed to occur 11 months after discharge from the reactor.

The relative macroscopic reactivity worths of the lanthanides in the center core zone of the LMFBR are also shown in Table 10. The relative macroscopic worth of each isotope is defined using the equation in Section 3.3.2. The one-group lanthanide cross sections were obtained from the LMFBR nuclear data library of ORIGEN. The masses and relative macroscopic reactivity worths of the recycle actinides are shown in Table 11 for comparison purposes. The combined lanthanides and actinides would have a center core zone worth which could be approximately compensated by an additional 39 kilograms of Pu^{239} (or about 1.3% of the total core fissile mass), assuming that the lanthanides and actinides replace U^{238} . Thus, if only the relative macroscopic reactivity worth is considered, the presence of the lanthanides should not significantly penalize the LMFBR physics.

The lanthanide mass shown in Table 10 would, however, occupy a significant fraction of the core volume. Assuming a lanthanide elements density of about 6 gm/cm^3 , the total lanthanide mass would occupy about 24% of the center zone assemblies of a typical 1200 MWe LMFBR (or about 12% of the entire core) and the actinides would occupy an additional 7.5% of the center core zone. A potential solution to this problem may be to partially separate the lanthanides from the actinides and replace the U^{238} diluent with the remaining lanthanides. Approximately 291 kilograms of remaining lanthanides could be recycled with the recycle actinides if all the U^{238} diluent in the recycle assemblies were replaced by the lanthanides. Therefore, an actinide/lanthanide initially loaded mass ratio of 452 kg/291 kg is tentatively judged acceptable, and will be used as a target figure for actinide-lanthanide operations requirements.

The lanthanide mass will not "burn up" appreciably in the LMFBR (as will the actinides), but may increase due to fissioning of the actinides. The lanthanide mass in the target assemblies would, over a period of several recycles, steadily increase unless the appropriate actinide-lanthanide separation requirements could be met during reprocessing of both the spent fuel and the recycle assemblies. For preliminary purposes, these separations requirements will be considered to be met if the actinide/lanthanide mass ratio is less than about 1.5 at the beginning of any recycle irradiation period.

Table 11

Equilibrium Cycle^a Actinide Masses and Relative Macroscopic
Reactivity Worths in the Center Core Zone of an LMFBFR

Isotope	Mass ^b (gm)	ν	σ_f (b)	σ_c (b)	Relative Macroscopic Reactivity Worth: $N(\sigma_f \nu - \sigma_a)$ (cm^{-1})
Np-237	2.39E 05	2.950	0.311	1.694	-1.86E-04
Am-241	1.18E 05	3.275	0.408	1.10	-1.43E-05
Am-242m	2.36E 03	3.300	4.438	0.454	1.61E-05
Am-243	6.96E 04	3.342	0.174	0.866	-2.23E-05
Cm-242	7.84E 02	3.400	0.420	0.380	3.45E-07
Cm-243	5.64E 02	3.338	0.320	0.400	1.37E-07
Cm-244	2.02E 04	3.400	0.517	0.513	1.02E-05
Cm-245	1.44E 03	3.338	3.240	0.191	7.37E-06
Cm-246	8.80E 01	3.578	0.246	0.297	2.05E-08
Cm-247	1.96	3.31?	0.207	0.133	4.66E-10
Cm-248	6.96E-02	3.566	0.302	0.250	2.58E-11
Bk-249	6.16E-04	0.0	0.0	1.760	-7.39E-13
Cf-249	4.08E-04	3.751	3.080	0.179	2.31E-12
Cf-250	1.33E-04	0.0	0.0	0.415	-3.75E-14
Cf-251	4.76E-05	4.141	0.627	0.186	5.74E-14
Cf-252	2.32E-05	3.771	0.372	0.147	1.38E-14
Total	4.52E 05				-1.88E-04

^a An equilibrium cycle loading for a scheme in which the actinides from one LMFBFR and three LWRs is recycled in the LMFBFR. The scheme is started at $\sim$ equilibrium conditions by using an initial loading composed of the actinides from four LMFBFRs and twelve LWRs.

^b Each LMFBFR produces $\sim$ 54.2 kilograms of recycle actinides, and each LWR produces $\sim$ 19.6 kilograms of recycle actinides.

3.3.6 Fabrication of Recycle Actinides - Remote Maintenance

Calculations have been performed using ORIGEN and the shielding code ISOSHL⁽¹²⁾ to determine the fabrication facility handling requirements for the actinides. The results of the calculations indicate that remote maintenance facilities are required regardless of whether the actinides are recycled in target assemblies or in a homogeneous mix with the rest of the fuel. This is especially true if the lanthanide fission products cannot be completely removed.

3.3.7 Reprocessing Aspects of Actinide Recycle in Target Assemblies

Due to the likelihood that radiation sources from the actinides will require the utilization of target assemblies, it is necessary to address the reprocessing problems associated with such a scheme. The basic techniques for separating individual actinides from each other and from fission products are known. The problem is in the selection of an appropriate set of techniques which can be utilized at high concentrations and at high throughputs. This type of technology is not well developed and where such has been used, the emphasis was on a reasonable recovery of the actinides.

Actinide recycle introduces a new approach. Instead of a high D.F. (decontamination factor) of the fission products from the actinide product, and a low D.F. of the actinides from aqueous raffinate, we require the inverse, relatively high D.F. of actinides from raffinate and low D.F. of the actinide product.

In the separation of actinides from the spent fuel, the concentration of neptunium and the transplutonium isotopes will build up over many cycles so that separations requirements will change. Spent fuels from LWRs and LMFBRs will contain relatively small quantities of these actinides. But in the reprocessing of the target actinide fuels, their concentration will be almost half of the bulk. It would seem that these distinctions in the processing behavior could be dealt with best by considering two fuel cycles: one for the target actinides and one for the conventional mixed oxide fuel assemblies. The conventional processing cycle of LWR and LMFBR fuels would not be perturbed

by the buildup of recycled neptunium, americium, and curium, and would carry about 93% of the fuel cycle capacity for LMFBR reloads. The actinide processing cycle would account for 7% of the LMFBR reprocessing load. Such an arrangement would not impede development of the conventional fuel cycle, except by adding on separation steps for removal of neptunium, and the transplutonium isotopes. A possible scheme for parallel actinide target and conventional reprocessing lines is shown in Figure 6. The schematic layout shows the two separation lines where uranium, neptunium, and plutonium are extracted by similar methods in each line but at different throughput rates. The transplutonium isotopes are extracted with the rare earth isotopes and then separated at a later stage. This leaves a waste stream contaminated with traces of alpha active constituents. These traces should be removed, but probably by a different technique than that which is used for extraction of higher concentrations of the actinides upstream. The dashed lines show the combination of separated elements which describe the actinide target. This combination includes the neptunium, americium, curium, berkelium, and californium from both reprocessing lines. The plutonium and uranium from the conventional processing line are recovered separately as feed to a conventional plutonium fabrication facility. The plutonium recovered from the actinide targets (high in Pu^{238} content) could be recycled back to the actinide targets, or isotopically diluted so that the aforementioned remote maintenance problems in a conventional plutonium fabrication facility could be avoided.

After extraction of the plutonium from the two parallel lines it may be possible to combine the raffinates from the two lines instead of keeping them separate as shown in the figure. The concentrations of transplutonium isotopes in the two streams are small. The subsequent treatment of the raffinate to remove traces of actinides including uranium, plutonium, and neptunium could be combined also. Some carry-over of fission products such as rare earth isotopes may be tolerated also to allow better decontamination of actinides from the high activity beta-gamma waste which would be buried.

The specified separation techniques for removal of individual elements shown in Figure 6 is well established for uranium and plutonium. These are usually removed by solvent extraction. Extraction of neptunium is also readily adaptable to solvent extraction methods used for uranium and plutonium. Americium and curium behave similarly to rare earths and could be coextracted

A POSSIBLE PARALLEL REPROCESSING SCHEME FOR ACTINIDE TARGET ASSEMBLIES AND CONVENTIONAL FUEL ASSEMBLIES

with the conditions set for extraction of the transplutonium isotopes. A second separation from rare earths may be necessary if transplutonium isotopes and rare earths are coextracted. The actinide target fuel could possibly allow a rare earth content of up to 5% of the total actinides without affecting solvent extraction, ion exchange, or precipitation. Considerable development would be required before a particular method can be selected.

A final reprocessing step to clean up traces of actinides remaining in the high activity waste is expected. The appropriate method here would be ion exchange or precipitation. One of the major problems expected is that residual plutonium and other actinides may be present in colloidal form and may therefore be difficult to separate by chemical methods. Considerable development will be needed to surmount this situation if the beta-gamma waste is to be suitably free of all actinides, particularly plutonium.

A survey of recent actinide partitioning work at Argonne National Laboratory (ANL), Idaho Chemical Processing Plant (ICCP), Sandia Laboratories, and Oak Ridge National Laboratory (ORNL) has been carried out as part of a program to monitor the actinide partitioning efforts.⁽¹³⁾

The partitioning program at ANL is directed toward the recovery of large amounts of uranium, neptunium, plutonium, americium, and curium from high level liquid wastes. Flowsheets have been developed and tested to determine the feasibility of removing the neptunium, plutonium, americium, and curium from synthetically exhaustively extracted waste solution. The first flowsheet involves the use of dihexoxyethyl phosphoric acid in diethylbenzene (HDHOEP in DEB) to extract 99.5% of the uranium, neptunium, and plutonium, from the feed solution. The raffinate from this process is then diluted with water and a second extraction is performed with HDHOEP in DEB to recover about 94% of the remaining americium and curium.

A second flowsheet has been developed which is a simple modification of the two-step-extraction process discussed above. By properly adjusting the solution temperature, acidity, and mass flow ratios, a one-step-extraction process has been developed and tested. This process can remove 99.9% of the neptunium, 99.99% of the plutonium, and 99.7% of the americium and curium from the wastes. Back extraction of 99% of the americium and curium is accomplished

by using a 6 molar HNO_3 strip and HDHOEP in DEB. A tricaprylmethyl ammonium nitrate strip and HDHEOP in DEB is used to back extract 99.8% of the neptunium and 99.99% of the plutonium. The tests demonstrate the feasibility of recovering large fractions of actinide elements from the wastes.

The extractants used in processes 1 and 2 have favorable physical properties (phase disengagement is good and no formation of emulsions or interfacial precipitates are observed in the dihexoxyethyl phosphoric acid, and the extractant densities are about .87 gm/ml), and their stability to high radiation is good. However, difficulties in stripping yttrium and uranium could complicate the extractant cleanup. Continuing work at ANL will address this problem, and examine alternatives for separating the actinides from the actinide-lanthanide mix obtained in step one. The extraction processes are expected to remove large quantities of lanthanides as well as actinides, and additional work at ANL will address actinide-lanthanide separation techniques.

Efforts at ICPP are directed toward a study of the effectiveness of neutral bidentate extractants in recovering the transplutonium actinides from high level waste. A commercially available bidentate extractant, DHDECMP has been shown capable of selectively removing the actinides and lanthanides from acidic waste solutions. An actinide partitioning flowsheet has not yet been developed, however, because of a number of uncertainties involving the DHDECMP. For example, the chemical and physical properties of the DHDECMP will not be determined until pure (99%) samples of DHDECMP are obtained by use of preparative liquid chromatography. Also, the recovery of americium has been shown to be highly dependent upon the type of solvent used to dilute the DHDECMP, and an investigation of different solvents is under way.

Actinide partitioning work at Sandia has focused on the use of inorganic ion exchange media to separate americium and curium from the lanthanides. This is necessary because of the large mass of lanthanides which accompanies the actinides in most recovery schemes. Chromatography on an inorganic bed rather than on an organic resin should result in less radiation damage to the exchanger materials. The studies indicate that the degree of actinide-lanthanide separation on a niobate, titanate, or zirconate ion exchange column may be controlled by controlling the pH. After separation by ion exchange, the actinides and lanthanides would be desorbed from the exchanger materials for

recycle or disposal. The possibility also exists of using inorganic ion exchangers to retrieve the actinides and lanthanides from low level wastes.

Experimental work indicates that curium can be separated from the lanthanides on a niobate ion exchange column. The discrimination between the curium and the lanthanides is determined by controlling the pH of the solution. The experiment suggests that for a solution pH of 3, the mixture of actinides and lanthanides can be separated into two parts in the ion exchange column. The two segments of the column can then be separated, and the actinides and lanthanides desorbed from the exchanger material. Additional work will be required to determine the degree of actinide-lanthanide separation on the column, and to investigate the desorption of the actinides from the column.

The experimental program at ORNL to recover and purify americium and curium is based upon the use of exhaustive extraction with tributyl phosphate (TBP), oxalate precipitation, and cation exchange chromatography or talspeak solvent extraction as "add-ons" to a modified Purex process.⁽⁶⁾ The ability of TBP to extract hexavalent uranium, and tetravalent neptunium and plutonium is well known and it has been used extensively in industry. Thus, there are incentives for the use of a TBP solvent to co-extract the neptunium, uranium, and plutonium from the high level liquid wastes. Experimental work is needed, however, to verify the practical extraction limits, and to determine the magnitude of effects on downstream purification and extraction of uranium and plutonium. Next, the bulk of the trivalent actinides and lanthanides would be precipitated from the Purex process raffinate by dilution with oxalic acid. Oxalate precipitation and ion exchange cleanup of high level liquid wastes has been performed on a small scale (200 g of UO_2) for fuel irradiated to 31,000 MWd/MT and cooled for two years. About 99% of the U and Pu were removed by repeated 30% TBP extractions; the americium and curium were 99.9% removed from the raffinate by ion exchange. Conceptually, actinide-lanthanide separations would then be performed using either cation exchange chromatography or talspeak solvent extraction. Cation exchange is the most well known of all the actinide-lanthanide separation processes, but to determine the overall americium and curium recoveries additional experimental work is required. The talspeak process shows promise (early results indicate 99% recovery) but it has not been demonstrated as completely as cation exchange and additional work is required. A third actinide-lanthanide separation technique under investigation at ORNL is the tramex process used at the transuranium processing plant.

Specially constructed equipment with resistance to chloride reagents would be required, however, so this process is probably unsuitable for commercial application.

A flowsheet has been developed which consists of two solvent extraction cycles for separating the actinides and lanthanides, and an HNO_3 stripping cycle to recover the actinides from the organic extractant. The first cycle uses a solution of DI(2-ethylhexyl) phosphoric acid (HDHEHP) in diisopropylbenzene to extract the trivalent lanthanides from an aqueous solution of the actinides and lanthanides in glycolic acid. The actinides are then extracted from the first cycle raffinate by using HDHEHP in normal dodecane. It is expected that if approximately six extraction stages and four stripping stages are used, more than 99.9% of the americium could be recovered, and the americium would be accompanied by only a few tenths of a percent of the lanthanides. This degree of actinide-lanthanide separation could very well meet the partitioning requirements for an actinide recycle scheme.

3.4 Actinide Production and Recycle in Alternate Fast Reactor Designs

A number of alternate fast reactor system designs have been proposed (for non-proliferation purposes). The actinide waste production of these systems is of interest to any waste management scheme. The potential of using one of these systems for actinide recycle is especially pertinent to any actinide recycle study.

The actinide discharge masses were calculated for the following fast reactor systems:

1. $(\text{Pu-U})\text{O}_2$ Core - UO_2 Blankets (Homogeneous System)
2. $(\text{Pu-U})\text{O}_2$ Core - ThO_2 Blankets
3. $(\text{Pu-Th})\text{O}_2$ Core - ThO_2 Blankets
4. UO_2 (Denatured) Core - ThO_2 Blankets
5. $(\text{U-Th})\text{O}_2$ (Denatured) Core - ThO_2 Blankets
6. $(\text{Pu-C})\text{C}$ Core - UC Blankets
7. $(\text{Pu-U})\text{O}_2$ Core - UO_2 Blankets (Heterogeneous System).

The discharge masses were considered to be the masses discharged at the time of reactor refueling plus a 16 month decay period.

The actinide discharge calculations were carried out using the ORIGEN code and the data which has been generated for a series of advanced core design studies.⁽¹⁴⁾ The design data for the alternate fast reactor systems is given in Table 12, and the actinide discharge quantities are given in Tables 13 - 19.

3.4.1 Hazards of Actinide Wastes from Alternate Fast Reactor Systems

The radiological ingestion hazards due to the actinide waste discharge from the alternate fast reactor systems have been determined for decay times of from 1000 to 1,000,000 years. The hazard calculations were performed using the ORIGEN code, and the radiation concentration guide (RCG) values specified in the Code of Federal Regulations (10CFR20). Reprocessing losses were assumed to be 0.5% for the thorium, uranium, and plutonium for all cases. It should be noted that the Purex process is technologically more developed than the thorex process. The results in Figures 7 and 8 correspond to the total hazard from the actinide wastes for each design case. The results in Figure 7 show the hazard in terms of the volume of water required to dilute a cubic meter of solidified wastes to acceptable levels as defined by the RCG values. The spent fuel from the plutonium-uranium systems (design Cases 1, 6 and 7) would most likely be processed using the Purex process, and would produce about one cubic meter of solidified waste per 11.8 metric tons of fuel processed.⁽¹⁵⁾ The spent fuel from the uranium-thorium systems (design cases 4 and 5) would most likely be processed using the thorex process, and would produce one cubic meter of solidified waste per 5.89 metric tons of fuel processed.⁽¹⁵⁾ The spent fuel from the mixed plutonium-thorium systems (design cases 2 and 3) would be processed, most likely, by combined Purex and thorex processes or a modified process; it was assumed to produce one cubic meter of solidified waste per 5.89 metric tons of fuel processed. The radiological ingestion hazards from one cubic meter of high-grade pitchblende ore are also shown in Figure 7 for comparison purposes. The results in Figure 8 indicate the hazard in terms of the volume of water required to dilute the wastes produced during the generation of one GW_e electric to acceptable levels as defined by the RCG values.

The plots in Figures 7 and 8 show that the waste ingestion hazard from the plutonium waste is at least an order of magnitude less than the total

Table 12
Design Data for Alternate Fast Reactor Systems

	Design Case						
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>
Reactor Thermal Power, MWt	2740	2740	2740	2740	2740	2758	3738
Reactor Electric Power, MWe	1000	1000	1000	1000	1000	900	1200
Fuel Type	Oxide	Oxide	Oxide	Oxide	Oxide	Carbide	Oxide
Structural Material	Improved 20% CW 316SS	Improved 20% CW 316SS	Improved 20% CW 316SS	Improved 20% CW 316SS	Improved 20% CW 316SS	SS316	20% CW SS316
Core Fuel	Pu-U _t **	Pu-U _t	Pu-Th	U ₃ -U _t ***	U-Th	P-U	Pu-U
Internal Blanket Fuel (Heterogeneous Design)	---	---	---	---	---	---	U
Radial Blanket Fuel	U _t	Th	Th	Th	Th	U	U
Axial Blanket Fuel	U _t	Th	Th	Th	Th	U	U
Capacity Factor	70%	70%	70%	70%	70%	70%	70%
Refueling Interval, days	450	450	450	550	365	434	365
Core Fuel Residence Time, days	900	900	900	1100	1095	868	1095
Internal Blanket Residence Time, days	---	---	---	---	---	---	730
Radial Blanket Residence Time, days	Row 1 1350 Row 2 1800 Row 3 2250	1350 1800 2250	1350 1800 2250	1650 2200 2750	1095 1095 1095	1302 1736 2170	1095 2190 3285
Core Fuel Smear Density	90%	90%	90%	90%	88%	83%	85.5%
Blanket Fuel Smear Density	90%	90%	90%	90%	93.7%	92%	93.7%

** U_t = Uranium tails

*** U₃ = Uranium 233 fissile isotope

Table 13

Design Case 1:

Actinide Production in a Typical1000 MWe LMFBR with (Pu-U)O₂ Core and UO₂ Blankets

<u>ISOTOPE</u>	<u>TOTAL GRAMS</u>
TH229	-----
TH230	-----
TH232	-----
PA231	-----
U232	6.08E-02
U233	7.33E-02
U234	3.26E 01
U235	4.16E 04
U236	3.98E 03
U238	2.79E 07
NP237	6.13E 03
PU236	9.55E-02
PU238	1.87E 03
PU239	1.74E 06
PU240	4.71E 05
PU241	1.19E 05
PU242	5.81E 04
AM241	2.32E 04
AM242M	2.29E 02
AM243	4.05E 03
CM242	6.33E 01
CM243	1.88E 01
CM244	2.71E 02
CM245	6.38E 00
CM246	5.56E-02
CM247	5.72E-04
CM248	1.91E-06
CF249	8.71E-09
CF250	2.69E-10
CF252	<u>2.74E-15</u>
TOTAL	3.04E 07
TOTAL WITHOUT Th, U, AND Pu	3.40E 04

Table 14

Design Case 2:

Actinide Production in a Typical1000 MWe LMFBR with (Pu-U)₂ Core and ThO₂ Blankets

<u>ISOTOPE</u>	<u>TOTAL GRAMS</u>
TH229	4.63E 00
TH230	1.29E 01
TH232	1.61E 07
PA231	9.28E 02
U232	2.45E 01
U233	3.67E 05
U234	5.63E 03
U235	1.22E 04
U236	2.34E 03
U238	1.02E 07
NP237	4.83E 03
PU236	9.34E-02
PU238	1.84E 03
PU239	1.35E 06
PU240	4.62E 05
PU241	1.19E 05
PU242	5.85E 04
AM241	2.32E 04
AM242M	2.32E 02
AM243	4.12E 03
CM242	6.42E 01
CM243	1.93E 01
CM244	2.78E 02
CM245	6.54E 00
CM246	5.68E-02
CM247	5.83E-04
CM248	1.93E-06
CF249	8.77E-09
CF250	2.69E-10
CF252	<u>2.73E-15</u>
TOTAL	2.87E 07
TOTAL WITHOUT Th, U, AND Pu	3.37E 04

Table 15

Design Case 3:

Actinide Production in a Typical

1000 MWe LMFBF with (Pu-Th) O_2 and Th O_2 Blankets

<u>ISOTOPE</u>	<u>TOTAL GRAMS</u>
TH229	9.74E 00
TH230	4.72E 01
TH232	2.87E 07
PA231	3.32E 03
U232	2.32E 02
U233	9.02E 05
U234	2.48E 04
U235	1.05E 03
U236	2.22E 02
U238	4.55E-01
NP237	9.72E 01
PU236	6.28E-04
PU238	1.53E 03
PU239	1.08E 06
PU240	5.23E 05
PU241	1.54E 05
PU242	7.06E 04
AM241	2.99E 04
AM242M	3.01E 02
AM243	3.99E 03
CM242	8.19E 01
CM243	2.05E 01
CM244	3.18E 02
CM245	8.68E 00
CM246	7.91E-02
CM247	8.91E-04
CM248	3.63E-06
CF249	1.78E-08
CF250	7.50E-10
CF252	1.46E-14
TOTAL	3.15E 07
TOTAL WITHOUT Th, U AND Pu	3.80E 04

Table 16

Design Case 4:

Actinide Production in a Typical
1000 MWe LMFBR with UO₂ Core and ThO₂ Blankets

<u>ISOTOPE</u>	<u>TOTAL GRAMS</u>
TH229	2.14E 01
TH230	1.72E 01
TH232	2.17E 07
PA231	8.31E 02
U232	6.41E 01
U233	1.28E 06
U234	4.63E 05
U235	1.02E 05
U236	2.48E 04
U238	1.44E 07
NP237	5.76E 03
PU236	6.62E-02
PU238	9.40E 02
PU239	6.59E 05
PU240	3.93E 04
PU241	1.32E 03
PU242	4.07E 01
AM241	1.34E 02
AM242M	4.36E-01
AM243	7.22E-01
CM242	1.50E-01
CM243	1.71E-02
CM244	3.35E-02
CM245	6.48E-04
CM246	3.80E-06
CM247	3.21E-08
CM248	1.10E-10
CF249	4.44E-13
CF250	2.01E-14
CF252	4.73E-19
TOTAL	3.86E 07
TOTAL WITHOUT Th, U, AND Pu	6.72E 03

Table 17

Design Case 5:

Actinide Production in a Typical1000 MWe LMFBR with (U-Th)₂O₂ Core and ThO₂ Blankets

<u>ISOTOPE</u>	<u>TOTAL GRAMS</u>
TH229	1.88E 01
TH230	2.56E 01
TH232	2.62E 07
PA231	1.77E 03
U232	1.36E 02
U233	1.25E 06
U234	5.23E 04
U235	3.46E 04
U236	3.48E 03
U238	5.14E 06
NP237	1.85E 03
PU236	2.50E-02
PU238	2.45E 02
PU239	2.33E 05
PU240	1.20E 04
PU241	3.53E 02
PU242	1.01E 01
AM241	3.60E 01
AM242M	9.97E-02
AM243	1.59E-01
CM242	3.44E-02
CM243	4.13E-03
CM244	5.29E-03
CM245	7.46E-05
CM246	3.68E-07
CM247	2.41E-09
CM248	2.42E-09
CF249	2.00E-14
CF250	5.93E-21
CF252	5.21E-21
TOTAL	3.29E 07
TOTAL WITHOUT Th, U, AND Pu	3.65E 03

Table 18

Design Case 6:

Actinide Production in a Typical900 MWe LMFBR with (Pu-U)C Core and UC Blankets

<u>ISOTOPE</u>	<u>TOTAL GRAMS</u>
TH229	-----
TH230	-----
TH232	-----
PA231	-----
U232	4.76E-02
U233	6.70E-02
U234	2.93E 01
U235	3.92E 04
U236	4.43E 03
U238	2.72E 07
NP237	5.62E 03
PU236	7.62E-03
PU238	1.73E 03
PU239	1.61E 06
PU240	5.60E 05
PU241	1.47E 05
PU242	7.28E 04
AM241	2.80E 04
AM242M	2.38E 02
AM243	5.00E 03
CM242	3.96E 03
CM243	1.73E 01
CM244	2.87E 02
CM245	5.98E 00
CM246	4.62E-02
CM247	4.22E-04
CM248	1.21E-06
CF249	4.91E-09
CF250	1.29E-10
CF252	<u>9.44E-16</u>
TOTAL	2.97E 07
TOTAL WITHOUT Th, U AND Pu	4.31E 04

Table 19
Design Case 7:
Actinide Production in a Typical
1200 MWe Heterogeneous LMFBF with (Pu-U)₂O₃ Core,
UO₂ Internal Blankets, and UO₂ External Blankets

<u>ISOTOPE</u>	<u>TOTAL GRAMS</u>
TH229	-----
TH230	-----
TH232	-----
PA231	-----
U232	4.36E-02
U233	6.70E-02
U234	3.68E 01
U235	5.21E 04
U236	4.16E 03
U238	3.34E 07
NP237	5.30E 03
PU236	6.78E-02
PU238	2.12E 03
PU239	1.90E 06
PU240	5.24E 05
PU241	1.30E 05
PU242	6.44E 04
AM241	2.97E 04
AM242M	3.08E 02
AM243	4.28E 03
CM242	7.35E 01
CM243	2.18E 01
CM244	2.71E 02
CM245	6.09E 00
CM246	5.06E-02
CM247	5.04E-04
CM248	1.61E-06
CF249	7.32E-09
CF250	2.09E-10
CF252	<u>2.02E-15</u>
TOTAL	3.61E 07
TOTAL WITHOUT Th, U AND Pu	3.99E 04

FIGURE 7
ACTINIDE WASTE HAZARD VS TIME

AUGUST 31, 1978

SEPTEMBER 05, 1978

FIGURE 8
ACTINIDE WASTE HAZARD VS TIME

hazard for all decay times considered. The waste ingestion hazard from the plutonium-uranium systems (design cases 1, 6, and 7) decreases steadily for all decay times considered, except for a minor increase in hazard at about 1.2×10^5 years. The primary sources of hazard from these systems are the isotopes of americium and plutonium for decay times to about 1.2×10^5 years, and isotopes in the Np^{237} decay chain for longer decay times. The wastes from the mixed plutonium-thorium systems have the short-term (less than 10,000 years) characteristics of the plutonium-uranium systems and the long-term (greater than 10,000 years) characteristics of the uranium-thorium systems.

None of the alternate fast reactor systems investigated were found to be particularly advantageous from a waste management viewpoint. The advantages of the comparatively low hazards of the wastes from the uranium-thorium systems for decay times less than approximately 8000 years may be negated by the comparatively high hazards from these systems for longer decay times.

3.4.2 Actinide Waste Recycle in Alternate Fast Reactor Systems

Qualitative neutron flux and cross section comparisons are useful in assessing the relative merits of actinide recycle in the alternate fast reactor systems discussed above. The neutron flux and cross section values determine the actinide burnup rate in the reactor. These parameters, however, are design dependent and consequently designs may be optimized to satisfy various desirable criteria.

The cross sections for the actinides in the alternate fast reactor systems are not significantly different from those used for the actinide recycle study and presented earlier in this report. It is also noted that the actinide wastes from thorium fueled reactors (mainly thorium, protactinium, uranium, neptunium, and plutonium) have cross sections which are not significantly different from those of the actinide wastes from plutonium-uranium fueled reactors (uranium, neptunium, plutonium, americium, and curium). The center core zone average total fluxes for the alternate fast reactor systems do not differ significantly from those used for the actinide recycle studies reported earlier. The comparison of cross sections and fluxes for the alternate systems leads to the following qualitative conclusions:

1. The waste actinides from thorium fueled fast reactors could be recycled in plutonium-uranium fueled fast reactors, and vice versa, but there is no clear incentive for doing so.
2. None of the alternate fast reactor systems offers any particular advantage as a "host" reactor for the recycled actinides. Further studies of the alternate fast reactor systems as "host" reactors would most likely yield results similar to the results of the actinide recycle studies reported herein.

3.5 Economic Aspects of Actinide Recycle

A parametric estimate has been made of the incremental fuel cycle costs for LWRs and LMFBRs for a scheme in which the actinides from LWRs and LMFBRs are recycled in LMFBRs. Such a scheme perturbs the LWR fuel cycle only at the reprocessor, but perturbs the LMFBR fuel cycle at both the reprocessor and the fabricator. All costs are viewed from the perspective of the utility purchasing either a LWR or a LMFBR and the associated fuel and fuel cycle services, and the costs are levelized over the plant lifetimes. These costs can be categorized as being, mainly, reactor capital costs and fuel cycle costs. In the case of the LWR the fuel cycle cost can be further categorized as costs of U_3O_8 ore, enrichment, fabrication, reprocessing, and a Pu credit. For the LMFBR the fuel cycle costs can be broken down into costs of fabrication, reprocessing, net Pu created (negative costs), and the Pu constant lifetime inventory. In both cases the reprocessing costs include transportation from the reactor to the reprocessor, recovery of reusable materials, and waste management costs.

The capital costs of an LMFBR are not expected to be affected significantly by actinide recycle. Actinide recycle would require that assemblies containing recycle actinides be handled as strong radiation sources during arrival, storage, inspection, and loading into the reactor. However, the incremental addition to the LMFBR capital costs to accommodate these "hot" assemblies is estimated to be less than 1% of the total LMFBR capital expenditure.⁽¹⁶⁾ Thus, the estimation of actinide recycle costs is focused upon the incremental fuel cycle costs mentioned above.

Actinide recycle schemes would require the reprocessing facility to produce a highly actinide-free waste stream and an actinide-lanthanide feed

stream with the recycle actinide/lanthanide mass ratio loaded to the LMFBF of less than approximately 1.5. It is also desirable that these recovery techniques do not generate large additional waste streams as a result of actinide recycle. Reprocessing flow sheets to accomplish this have not yet been fully developed and analyzed. Thus, at the present time the effects of actinide recycle on the reprocessing portion of the fuel cycle can only be done parametrically. For the purposes of this work the reprocessing portion of the LWR and LMFBF fuel cycles have each been arbitrarily increased by 50% and 200% to determine the effect on total fuel cycle costs.

Fuel cycle costs will also increase due to the need for remote maintenance of the LMFBF target assembly fabrication facility. Recent cost estimates⁽¹⁶⁾ suggest that the cost of a full scale, remotely maintained LMFBF fuel fabricator would range from a factor of 2 to a factor of 5 higher than the cost of a hands-on maintained facility. Proper scaling factors have not been developed; however, it should be noted that target assembly fabricators would be required to produce only about 13 target assemblies per LMFBF per fuel interval whereas the full scale LMFBF fuel fabricators would be required to produce about 243 fuel + blanket assemblies per LMFBF per fuel interval. Thus, for the purposes of this work the fabrication portion of the LMFBF fuel cycle has been arbitrarily increased by 50% and 200% to determine the effect on total LMFBF fuel cycle costs. Shown in Table 20 is a breakdown of the fuel cycle costs for LWRs and LMFBFs. The "base-case" or nonactinide recycle case costs are taken from Reference 17, and assume U_3O_8 and Pu costs of \$60.00/lb and \$42.47/gm, respectively, and a 6% annual rate of inflation. The costs of actinide recycle are then estimated by assuming that the costs of reprocessing and fabrication are increased. In one case, it is assumed that the cost increases in each fuel cycle are borne by the reactor associated with that cycle. That is, the utility owning a LWR would be liable only for those additional costs of actinide recycle which directly affect the LWR fuel cycle, and the utility owning a LMFBF would be liable only for those costs which directly affect the LMFBF. For the second case shown in Table 20, it is assumed that actinide recycle is viewed as a waste management "service" to the entire industry and that the costs should be divided proportionately among all reactors involved according to the mass of actinides recycled from each reactor. This report suggests that the actinides from three LWRs and one comparably sized LMFBF could be recycled in the LMFBF, and this "mix" of reactors is used for the

Table 20

Fuel Cycle Costs for LWRs and LMFBRs
(Levelized Over Plant Lifetime)

Cost of U_3O_8 = \$60.00/lb

6% Annual Rate of Inflation

Cost of Pu = \$42.47/gm

	<u>Base Case Costs^a</u> <u>mills/kWh(e)</u>	<u>Case 1 Costs^b</u> <u>mills/kWh(e)</u>		<u>Case 2 Costs^c</u> <u>mills/kWh(e)</u>	
		+50%	+200%	+50%	+200%
<u>LWR</u>					
U_3O_8	8.97	8.97	8.97	8.97	8.97
Enrichment	1.89	1.89	1.89	1.89	1.89
Fabrication	0.66	0.66	0.66	0.66	0.66
Reprocessing	0.64	0.96	1.28	0.64	0.64
Pu Credit	-1.54	-1.54	-1.54	-1.54	-1.54
Recycle "Services"	<u>0.00</u>	<u>0.00</u>	<u>0.00</u>	<u>0.36</u>	<u>0.73</u>
Total	10.62	10.94	11.26	10.98	11.35
<u>LMFBR</u>					
Fabrication	1.24	1.86	2.48	1.24	1.24
Reprocessing	1.04	1.56	2.08	1.04	1.04
Pu Net Created	-1.67	-1.67	-1.67	-1.67	-1.67
Pu, Plant Constant					
Lifetime Inventory	3.55	3.55	3.55	3.55	3.55
Recycle "Services"	<u>0.00</u>	<u>0.00</u>	<u>0.00</u>	<u>1.01</u>	<u>2.01</u>
Total	4.16	5.30	6.44	5.17	6.17
Fuel Cycle Cost Differential	6.46	5.64	4.82	5.81	5.18

^aBase case costs are taken from Reference 17.

^bCase 1 costs are calculated by assuming that each reactor owner is liable only for those actinide recycle costs which directly affect the fuel cycle of his particular reactor type.

^cCase 2 costs are calculated by assuming that actinide recycle is viewed as a waste management "service", and each reactor owner pays a fraction of the total actinide recycle cost which is proportionate to the mass of actinides recycled from his reactor. Thus, for the +50% case, each LWR owner pays:

$$[(3 \text{ LWRs})(10.94 - 10.62) + (1 \text{ LMFBR})(5.30 - 4.16)] \left(\frac{19.6}{(3)(19.6) + 54.2} \right) \text{mills/kWh(e)}$$

second case. Thus, in a scheme wherein each LWR (of three providing actinides to the LMFBR) produces 19.6kg of new actinides per recycle loading and the LMFBR produces 54.2 kg of new actinides per loading, each LWR owner would be liable for approximately 17.4% of the total cost of actinide recycle. The LMFBR owner would be liable for approximately 48% of the total cost of actinide recycle. In each case the reprocessing and fabrication costs are first increased by 50% and then 200%.

The fuel cycle cost differential is also shown in Table 20. This is the extra cost, in mills/kWh_e, which a utility could afford to invest in LMFBR capital over that of an LWR. From Table 20 it is apparent that in the worst case from the viewpoint of the LMFBR owner (Case 1, 200%), the fuel cycle costs are such that a 4.82 mills/kWh_e cost differential still exists. A cost incentive remains which allows a utility to invest 4.82 mills/kWh_e more in LMFBR capital than LWR capital and still sell electricity to the customer at the same rates. Thus, actinide recycle in LMFBRs cannot be ruled out on the basis of cost alone, and the LMFBR would still remain attractive to the utility contemplating purchasing a reactor. In the worst case as viewed from the perspective of the LWR owner (Case 2 + 200%), the LWR fuel cycle costs only increased by about 7.3%. The above conclusions are based on 1975 forecast figures, and with increases in the price of U₃O₈ the LMFBR would be further favored.

3.6 Reactor Capacity Requirements Associated with Actinide Recycle

After the need for actinide recycle as a waste management alternative has been determined and the technology demonstrated, the next logical step would be implementation on an industry-wide scale. It is possible to specify limits on the timing of this implementation by considering the backlog of actinides produced prior to any given time, and the capacity of the nuclear industry to recycle this backlog. The DOE-projected growth of the light water reactor (LWR) electrical generating capacity is shown in Table 21 for the years 1975 to 2000.⁽¹⁸⁾ This generating capacity in GW_e, has been translated into an equivalent number of 1200 MWe LWRs, all operating at 80% capacity. Each of these reactors would then produce about 20 kilograms per year of waste actinides. For the purpose of this work the waste actinides are considered to be Np, Am,

Table 21

Growth of Nuclear Power Capacity and the Resultant Production
Of The Actinides^a For the Years 1975 to 2000
(Scenario No. 1)

Year	ERDA Projected ^b LWR Capacity (GWe)	Equivalent Number of 1200 MWe LWRs ^c	Yearly Production of Actinide Wastes (Kgms) ^d	Accumulation of Actinide Wastes if Not Recycled ^d (Kgms)
1974 and Prior Years				
1975	38.0	39.5	791.5	1341.4
1976	44.3	46.1	922.8	2132.6
1977	51.3	53.4	1068.6	3055.6
1978	58.4	60.7	1216.5	4124.2
1979	65.5	68.1	1364.4	5340.7
1980	75.5	78.5	1572.7	6705.0
1981	92.3	96.0	1922.6	8277.7
1982	112.7	117.2	2347.5	10200.3
1983	133.9	139.3	2789.1	12547.9
1984	157.4	163.7	3278.6	15337.0
1985	179.4	186.6	3736.9	18615.6
1986	202.0	210.1	4207.7	22352.5
1987	225.6	234.6	4699.2	26560.2
1988	254.0	264.2	5290.8	31259.4
1989	284.0	295.4	5915.7	36550.3
1990	315.6	328.2	6627.0	42466.0
1991	348.7	362.6	7316.5	49093.0
1992	382.7	398.0	8077.8	56409.5
1993	416.6	433.3	8784.0	64487.3
1994	450.7	468.7	9494.3	73271.4
1995	483.9	503.3	10238.9	84765.7
1996	516.2	536.8	10911.7	93004.7
1997	547.6	569.5	11619.0	103916.4
1998	579.1	602.3	12381.4	115535.4
1999	609.7	634.1	13125.0	127916.8
2000	638.6	664.1	13939.4	141041.8
				154981.2

^aFor the purposes of this work, the actinide wastes are considered to be all the isotopes of Np, Am, and Cm.

^bBased upon ERDA projections of the growth of LWR generating capacity in the U.S. See Reference 3.

^cA capacity factor of 80% is assumed for all LWRs.

^dIncludes the wastes from LMFBRs introduced between 1990 and the year 2000, assuming pessimistic projections.

and Cm. The U and Pu were not included because they would not be considered waste. If recovered during reprocessing operations, the U and Pu would be considered fuel. The yearly production of the waste actinides from LWRs and LMFBRs and their accumulation is also shown in Table 21.

Clearly, if the projections are assumed for the growth of the nuclear capacity, by the year 2000 there will be an accumulated inventory of about 155 metric tons of waste actinides if recycle is not accomplished. If actinide recycle is initiated at this time, it will be necessary to consider whether there will be a sufficient number of reactors operating to allow the recycle of this backlog of actinides. Two scenarios are explored wherein LWRs and LMFBRs are assumed capable of accommodating various masses of actinides without overly affecting reactor performance.

The first scenario is probably overly conservative because the capacities of LWRs and LMFBRs to recycle the backlog actinides are conservatively estimated. For the first scenario, it is assumed that it is possible for a 1200 MWe LWR to accommodate as much as 195 kilograms of recycle-actinide wastes without affecting the performance of the reactor⁽¹⁾. Similarly, it is assumed that a 1200 MWe LMFBR could accommodate about 464 kilograms of recycle-actinide wastes at equilibrium conditions without overly affecting the reactor performance (see Section 3.3). At the end of each refueling cycle (assumed to be 1 year for the LWR and approximately 470 days for the LMFBR) each reactor would have burned enough of the actinide wastes that it could accommodate additional actinides. The LWR would be capable of accommodating, for the first cycle, a backlog of 195 kilograms of actinide wastes. Assuming that the backlog wastes burn out at the same rate as the equilibrium cycle wastes, the reactor would be capable of recycling its own wastes (about 20 kilograms) for all succeeding cycles.

If the same assumptions are made for the LMFBR, the LMFBR would be capable of accommodating, for the first recycle, a backlog of about 464 kilograms of actinide wastes. For each succeeding recycle the LMFBR would be capable of recycling the actinide wastes generated (during the previous cycle) by itself and by three comparably powered LWRs (a total of about 113 kilograms).

Table 22 shows that by the year 1996, the projected LWR capacity is the equivalent of 537 large (1200 MWe) LWRs, and that of these, 533 LWRs would be required to initiate recycle of the backlog of actinide wastes present at that time. Clearly, enough reactor capacity would be available to accommodate the wastes. However, if recycle begins in the year 2000, the equivalent of 664 LWRs would be available - but the equivalent of 795 LWRs would be required to initiate recycle. The remaining backlog, enough to initiate recycle in an additional 131 LWRs, would have to be deferred for a few years while additional reactors are being built. If the growth of the LWR capacity were to continue in the years between 2001 and 2005 at the same rate as during the previous decade (the equivalent of about 30 new LWRs per year), this backlog would be accommodated by LWRs by the end of the year 2005. At that time, all the actinide wastes ever generated by commercial LWRs would be in LWRs being recycled. The only actinide wastes outside reactors would be those at the reprocessor or fabricator, in between recycles.

Table 22 also demonstrates that if recycle does not begin by about the year 1998 and new reactor capacity (LWR or LMFBFR) is not introduced after the year 2000, the backlog of actinide wastes eventually would be so large as to preclude the recycle of a large fraction of the backlog. For each year of operating the 664 LWRs after the year 2000, another 13.28 metric tons of actinide waste from LWRs would be added to the backlog if recycle is not initiated. Thus, each year's actinide waste production would be large enough to initiate recycle in no fewer than 68 additional LWRs. Without the additional capacity, an alternative to actinide recycle as a waste management concept would have to be found for the backlog actinides.

The introduction of the LMFBFR, with its greater capacity for the actinide wastes (assumed for this scenario to be 464 kilograms), would help to an extent - but by itself the LMFBFR would probably not be capable of initiating the burnout of the backlog of actinide wastes. Projections show that there may be the equivalent of only 12 large (1200 MWe) LMFBFRs operating in the year 2000. To initiate recycle of the backlog of actinide wastes in LMFBFRs alone (no recycle in LWRs), 334 LMFBFRs would have to be available (see Table 23). Even if optimistic projections of the growth of the LMFBFR operating capacity are used, by the year 2000 only 115 LMFBFRs would be available.

Table 22

The Capacity of LWRs to Initiate Recycle
of the Backlog of Actinide Wastes

(Scenario No. 1^a)

<u>Year</u>	<u>Equivalent Number of 1200 MWe LWRs On-Line</u>	<u>Equivalent Number of 1200 MWe LWRs Required to Initiate Recycle of Backlog of Actinide Wastes</u>
1975	39.5	10.9
1976	46.1	15.7
1977	53.4	21.1
1978	60.7	27.4
1979	68.1	34.4
1980	78.5	42.4
1981	96.0	52.3
1982	117.2	64.3
1983	139.3	78.7
1984	163.7	95.5
1985	186.6	114.6
1986	210.1	136.2
1987	234.6	160.3
1988	264.2	187.4
1989	295.4	217.8
1990	328.2	251.8
1991	362.6	289.3
1992	398.0	330.7
1993	433.3	375.8
1994	468.7	434.7
1995	503.3	476.9
1996	536.8	532.9
1997	569.5	592.5
1998	602.3	656.0
1999	634.1	723.3
2000	664.1	794.8

^aBased on the following estimate of reactor capacity for actinides:

464 kgms in LMFBR
195 kgms in LWR

Table 23

The Capacity of LMFBRs to Initiate Recycle
of the Backlog of Actinide Wastes

(Scenario No. 1^a)

Year	Equivalent Number of LMFBRs On-Line ^b	Equivalent Number of 1200 MWe LMFBRs Required to Initiate Recycle of Backlog of Actinide Wastes
1975	--	4.6
1976	--	6.6
1977	--	8.9
1978	--	11.5
1979	--	14.5
1980	--	17.8
1981	--	22.0
1982	--	27.0
1983	--	33.1
1984	--	40.1
1985	--	48.2
1986	--	57.2
1987	--	67.4
1988	--	78.8
1989	--	91.5
1990	0.98	105.8
1991	0.98	121.6
1992	1.96	139.0
1993	1.96	157.9
1994	1.96	182.7
1995	2.94	200.4
1996	2.94	224.0
1997	3.92	249.0
1998	5.88	275.7
1999	7.84	304.0
2000	11.76	334.0

^aBased on the following estimate of reactor capacity for actinides 464 kgms in LMFBR
195 kgms in LWR

^bProjections for a "pessimistic" LMFBR growth. The capacity factor of each reactor is assumed to be 85%.

If recycle is carried out in both LWRs and LMFBRs, fewer LWRs would be required than if recycle is performed only in LWRs. For instance, after the year 2000, each year's actinide waste production (large enough to initiate recycle in 68 additional LWRs) could be accommodated in only 30 LMFBRs.

Thus, using DOE projections for the growth of the LWR and LMFBR generating capacity, it is clear that if recycle begins in the year 2000, it should be carried out in LWRs primarily, as well as in the few LMFBRs available. If recycle is not introduced by about the year 1998, and the number of LWRs and LMFBRs does not increase after the year 2000, the capability to recycle the backlog of actinide wastes will decrease rapidly with time, as the backlog itself increases rapidly with time.

Of course, if the growth of the reactor capacity is slower than that projected by Table 21, actinide recycle could proceed at a later date when (and if) the growth rate accelerates, providing more capability. The limit to this is, of course, the no-growth case. From Tables 21 and 22 it is possible to determine that if in the year 1980 a nationwide moratorium on new reactors is enforced, but existing reactors are allowed to continue operating, and if scenario 1 recycling capacities are assumed, the backlog of actinides would be too large to accommodate in the reactors by the year 1985. Thus, there is incentive to study potential designs for special purpose, high capacity, actinide burner reactors (see Section 4.0).

The second scenario is probably overly optimistic because the capacities of LWRs and LMFBRs are liberally estimated, and optimistic projections for the introduction of the LMFBR are assumed. The LWR is assumed capable of accommodating 1950 kilograms of recycle-actinide wastes without affecting the performance of the reactor (1950 kilograms is approximately 80% of the mass of U^{235} supplied to the entire core). The LMFBR is assumed capable of accommodating 4640 kilograms of recycle-actinide wastes without affecting the performance of the reactor (4640 kilograms is approximately 1.15 times the mass of Pu supplied to the entire LMFBR core). These LWR and LMFBR capacities are 10 times those assumed in the first scenario.

An increased number of LMFBRs is assumed on-line, and the yearly production of actinide wastes and the inventory of wastes accumulated at any time will increase slightly from the values shown in Table 22. The new values are shown

in Table 24. The number of equivalent 1200 MWe LWRs required to initiate recycle in any particular year (recycle only in LWRs) is shown in Table 25, along with the number of equivalent 1200 MWe LWRs assumed to be on-line. Clearly, for all times considered, there will be a sufficient number of LWRs available to initiate recycle of the backlog of actinides. Even if there were no growth in the number of reactors on-line after the year 2000, the backlog of actinides produced would not grow to be so large as to preclude recycle in LWRs alone until at least the year 2052. The number of equivalent 1200 MWe LMFBRs required to initiate recycle in any particular year (recycle only in LMFBRs) is shown in Table 26, along with the number of equivalent 1200 MWe LMFBRs expected to be on-line. It is evident that, using the assumptions of scenario 2, LMFBRs could easily accommodate the actinide backlog for any year shown beyond 1994. Even if there were no growth in the number of reactors on-line after the year 2000, the backlog of actinides would not grow to be so large as to preclude recycle in LMFBRs alone until at least the year 2021.

In conclusion, if long-term geological storage is undesirable because of scientific or sociopolitical concerns, a demonstrated alternative waste management concept may be desirable. Actinide recycle could prove to be such an alternative. However, to recycle the backlog of wastes generated up to the time recycle begins, the proper reactor capacity is required. Assuming scenario 1 conditions, recycle could begin as late as the year 1998. If the reactor growth rates assumed for scenario 1 continue for the years 2001-2005, recycle could begin as late as the year 2000. However, assuming a moratorium on the growth of reactor capacity in the year 1980, recycle must begin before the year 1985. If not, the reactors existing in 1980 will produce, by about the year 1990, a backlog of actinides that could not be accommodated without significantly detracting from the reactor performance. It is paradoxical that if sociopolitical concerns should force an early moratorium on reactor growth, such a moratorium could hinder the solution to one of the problems that it would supposedly "solve."

Table 24

Growth of Nuclear Power Capacity and the Resultant Production
of the Actinides^a for the Years 1975 to 2000
(Scenario No. 2)

Year	ERDA Projected ^b LWR Capacity (GWe)	Equivalent Number of 1200 MWe LWRs ^c	Yearly Production of Actinide Wastes (Kgms) ^d	Accumulation of Actinide Wastes if Not Recycled ^d (Kgms)
1974 and Prior Years				
1975	38.0	39.5	791.5	1341.4
1976	44.3	46.1	922.8	2132.6
1977	51.3	53.4	1068.6	3055.6
1978	58.4	60.7	1216.5	4124.2
1979	65.5	68.1	1364.4	5340.7
1980	75.5	78.5	1572.7	6705.0
1981	92.3	96.0	1922.6	8277.7
1982	112.7	117.2	2347.5	10200.3
1983	133.9	139.3	2789.1	12547.9
1984	157.4	163.7	3278.6	15337.0
1985	179.4	186.6	3736.9	18615.6
1986	202.0	210.1	4207.7	22352.5
1987	225.6	234.6	4699.2	26560.2
1988	254.0	264.2	5290.8	31259.4
1989	284.0	295.4	5915.7	36550.3
1990	315.6	327.2	6597.0	42466.0
1991	348.7	359.6	7351.0	49063.0
1992	382.7	391.0	8191.0	56414.0
1993	416.6	419.3	9128.0	64605.0
1994	450.7	445.7	10186.0	73733.0
1995	483.9	469.3	11188.0	83919.0
1996	516.2	489.8	12287.0	95107.0
1997	547.6	508.5	13403.0	107344.0
1998	579.1	525.3	14587.0	120797.0
1999	609.7	539.1	15817.0	135334.0
2000	638.6	549.1	17077.0	151151.0
				168228.0

^aFor the purposes of this work, the actinide wastes are considered to be all the isotopes of Np, Am, and Cm.

^bBased upon ERDA projections of the growth of LWR generating capacity in the U.S. See Reference 3.

^cA capacity factor of 80% is assumed for all LWRs and LMFBRs. For some years, the number of LWRs on-line is less than that of Table 4 because it is assumed that some 1200 MWe LWRs are replaced by an equal number of 1200 MWe LMFBRs.

^dIncludes the wastes from LMFBRs introduced between 1990 and the year 2000, assuming optimistic projections.

Table 25

The Capacity of LWRs to Initiate Recycle
of the Backlog of Actinide Wastes
(Scenario No. 2^a)

<u>Year</u>	<u>Equivalent Number of 1200 MWe LWRs On-Line</u>	<u>Equivalent Number of 1200 MWe LWRs Required to Initiate Recycle of Backlog of Actinide Wastes</u>
1975	39.5	1.09
1976	46.1	1.57
1977	53.4	2.11
1978	60.7	2.74
1979	68.1	3.44
1980	78.5	4.24
1981	96.0	5.23
1982	117.2	6.43
1983	139.3	7.87
1984	163.7	9.55
1985	186.6	11.46
1986	210.1	13.62
1987	234.6	16.03
1988	264.2	18.74
1989	295.4	21.78
1990	327.2	25.16
1991	359.6	28.93
1992	391.0	33.13
1993	419.3	37.81
1994	445.7	43.04
1995	469.3	48.77
1996	489.8	55.05
1997	508.5	61.95
1998	525.3	69.40
1999	539.1	77.51
2000	549.1	86.27

^aEach LWR is assumed capable of recycling 1950 kilograms of actinides. This is about one-half of the mass of U-235 supplied to the core.

Table 26

The Capacity of LMFBRs to Initiate Recycle
of the Backlog of Actinide Wastes
(Scenario No. 2^a)

Year	Equivalent Number of 1200 MWe LMFBRs On-Line ^b	Equivalent Number of 1200 MWe LMFBRs Required to Initiate Recycle of Backlog of Actinide Wastes
1990	1	10.57
1991	3	12.16
1992	7	13.92
1993	14	15.89
1994	23	18.09
1995	34	20.50
1996	47	23.13
1997	61	26.03
1998	77	29.17
1999	95	32.58
2000	115	36.26

^aEach LMFBR is assumed capable of recycling 4940 kilograms of actinides

^bProjections for an "optimistic" LMFBR growth. The capacity factor of each reactor is assumed to be 85%.

Assuming scenario 2 conditions, large scale recycle in LWRs alone could begin as late as the year 2052, even if no new reactor capacity were added after the year 2000. Recycle in LMFBRs alone could begin as late as the year 2021, even if no new reactor capacity were added after the year 2000. A moratorium on the growth of reactor capacity in the year 1980 would have little affect on the future capability of initiating recycle. Reactors on-line in the year 1980 could continue to produce actinide wastes for 92 years without the backlog becoming too large to accommodate.

It is clear that the masses of actinides which can be recycled in individual LWRs and LMFBRs, without affecting reactor performance, are extremely important parameters. To determine which scenario most closely represents the actual capacities of reactors to recycle the actinides, further work must be done.

3.7 Demonstration and Implementation of Actinide Recycle

The following technological developments must take place if actinide recycle is to become a demonstrated alternative to geological storage:

- a. A number of host reactors must become available.
- b. A transportation cask must be developed to transport target assemblies from the reactor to the processor and must be capable of providing adequate shielding against $\sim 1.14 \times 10^{11}$ n/sec/target assembly (mainly from spontaneous fission neutrons), and $\sim 5.31 \times 10^{17}$ photons/sec/target assembly, in addition to the sources normally encountered from the fission products. By comparison, the neutron activity from an equal mass of Pu-recycle fuel discharged from a LWR would be about 10^9 n/sec.⁽¹⁸⁾ The transportation cask must also be capable of dissipating a combined $\alpha+\beta+\gamma$ thermal load of $\sim 1.21 \times 10^5$ watts/assembly. This thermal loading is in addition to the heat generated in the shielding of neutrons, and in addition to the loading normally encountered from the fission products. By comparison, the $\alpha+\beta+\gamma$ actinide thermal power from a typical LMFBR center core zone assembly is $\sim 2.5 \times 10^4$ watts at discharge from the reactor, and $\sim 1.43 \times 10^2$ watts after a decay period of 2 years.

- c. A transportation cask must be developed to transport the target assemblies from the fabrication facility to the reactor and must be capable of providing adequate shielding against $\sim 8.17 \times 10^{10}$ n/sec/target assembly (mainly from spontaneous fission), and $\sim 7.1 \times 10^{14}$ photons/sec/target assembly. There is probably no reason why the same cask used for transportation from the reactor to the reprocessor cannot be used, although the possibilities of an accidental criticality should be further investigated. This is of particular interest because a single fresh target assembly will contain ~ 35 Kg. of fissionable isotopes and many spontaneous fission neutron sources will be present.
- d. A reprocessing facility must be capable of recovering the actinides from spent fuels and spent target assemblies to the following decontamination percentages:

<u>Element:</u>	<u>% Recovery</u> ⁽¹⁹⁾
U	99.7
Np	93.0
Pu	99.99
Am	99.9
Cm	99.9

- e. The facility that fabricates the target assemblies must be remotely operated, and remotely maintained.
- f. Recovery of uranium and transuranium elements at the fuel fabricator and target assembly fabricator must be essentially total, in keeping with proposed 10 n/Ci/g limits on low-level wastes. It is conceivable that high recoveries of U and Pu will be required regardless of actinide recycle. Recovery of the other actinides will add to the complexity of the chemistry used, as methods of recovering the U and Pu would not necessarily recover the other actinides.
- g. Target fabrication problems and materials incompatibilities must be explored.

Of course, development (a) need not occur if recycle were in LWRs, and realistically the initiation of an actinide recycle scheme may very well take place in LWRs because a sufficient number of LMFBRs may not be available. If recycle is in LWRs, and the actinides are mixed homogeneously with the fuel, the neutron sources mentioned in (b) and (c) can be expected to increase by 1 to 4 orders of magnitude.⁽¹⁸⁾

Development (d) requires the most work at the present time.

4.0 ACTINIDE BURNER REACTORS

The use of special actinide burner reactors has been investigated as one approach to actinide recycle as a waste management alternative. Previous studies have indicated that the actinide wastes can be burned out in commercial LWRs or LMFBRs, but that the LMFBR is preferred because of the higher flux available in an LMFBR and because of the favorable actinide fission to capture cross section ratios. Further investigations have indicated that the backlog of actinide wastes could become so large as to preclude the recycle of a large fraction of this backlog in LMFBRs due to a lack of reactor capacity. Thus, it may be desirable to burn the actinide wastes in special purpose high capacity actinide burner reactors.

The goal of any actinide recycle scheme is to provide a high actinide burnout rate. The burnout rate is proportional to the actinide atom densities, the neutron flux, and the neutron fission and capture cross sections. The effects of the flux level and the flux spectra (and thus the effective reaction rates) on the actinide burnout rate are shown in Table 27. The actinide burnout rates shown in Table 27 would result if the actinides were placed in target assemblies and exposed to various neutron fluxes in typical LWR and LMFBR spectra.

TABLE 27

Actinide Burnup Rates, % Per Year

<u>Flux</u>	<u>LWR Spectra</u>	<u>LMFBR Spectra</u>
5×10^{13}	4	Very Low
1×10^{15}	84	2
5×10^{16}	Very High	70

The data in Table 27 show that for a given flux level the actinide burnup rate is greatest if the special burner reactor is capable of providing a thermal neutron flux. The burnout rate is higher for a thermal flux because of the following:

1. The thermal capture cross section of Np^{237} is large.
2. The plutonium isotopes resulting from capture in Np^{237} have very large thermal fission cross sections.
3. Am^{241} has a very large thermal capture cross section.
4. The Am^{242} and Am^{242} resulting from neutron capture in Am^{241} have very large thermal fission cross sections (in the thousand of barns).

The neutron flux level of commercial LWRs (typically $5.0 \pm 13 \text{ n/cm}^2/\text{sec}$) is not sufficient to effectively utilize the high thermal capture and fission cross sections of the actinide isotopes. Commercial LMFBRs, on the other hand, would provide a high flux level, but the actinide burnout rate (shown in Table 27) is only a few percent per year for a typical LMFBR flux spectra. A fast flux of $5.0 \pm 16 \text{ n/cm}^2/\text{sec}$ would provide a satisfactory actinide burnout rate, but this flux is approximately an order of magnitude higher than that of a typical LMFBR center core zone.

The data in Table 27 suggests that it may be attractive to use one of the following types of actinide burner reactors:

4.1 Liquid Fuel Actinide Burner Reactor

A small metal-fueled spherical reactor with very little structure or other moderating material may be of interest. The spectrum should be very hard, and the power density should be very high. The reactor would not necessarily be "driven" by external uranium or plutonium fuel because it is possible to achieve a critical mass with metallic Np^{237} , Am^{241} , Cm^{244} , and many of the higher actinide isotopes if the spectrum is sufficiently hard. It has been estimated that an unreflected critical sphere of Np^{237} metal would weigh only about 68.6 kilograms, and an unreflected critical sphere of Am^{241} metal would weigh only about 113.5 kilograms.⁽²⁰⁾

Diffusion theory scoping calculations have been performed using the one-dimensional flux solution code SN1D to determine the critical mass of a sphere of LWR discharge actinides. The critical mass is only about 120 kilograms. The calculated spectrum is very hard and the actinide fission to capture cross section ratios are significantly more favorable than those which would exist in a commercial LMFBR. The spectrum is shown graphically in Figure 9, and a typical spectrum for the center core zone of a large commercial

FIGURE 9 NEUTRON FLUX VS. ENERGY, SPHERICAL ACTINIDE BURNER REACTOR

LMFBR is shown in Figure 10 for comparison purposes. The neutron fission and capture cross sections for the actinide burner reactor are shown in Table 28. The combination of the favorable neutron cross sections, and a high flux would result in a high actinide burnout rate.

Heat removal system design studies have not been performed for this reactor. However, the reactor would almost certainly be a fluid-fueled reactor because the major actinide waste elements have significantly low melting points. Metallic americium melts at 994°C and boils about 2607°C⁽²¹⁾. Neptunium metal melts at 640°C and boils at about 3902°C. A high flux (and therefore a high power density) would very likely be incompatible with the low melting temperature of the metal fuel. The heat removal system for this reactor would very likely involve pumping of liquid metal fuel and would require special design consideration. Fluid-fueled reactors may be advantageous for the following reasons:

1. Fuel fabrication costs may be eliminated.
2. Radiation damage to fuel elements (both the structure and the fuel itself) may be eliminated.
3. The continuous removal of fission products and the addition of fresh makeup fuel during operation would be possible.
4. The excess reactivity normally built into solid-fueled reactors may not necessarily need to be large and may be easier to regulate.
5. A fluid-fueled reactor should have a negative temperature coefficient of reactivity due to thermal expansion.

A fluid fuel may be very highly corrosive, however, and may require the use of special construction materials. The reactor power and flux level would be limited mainly by heat removal and structural materials irradiation damage considerations. Diluent materials would probably be required and these materials could significantly effect the flux spectrum and the actinide neutron cross sections.

4.2 Actinide Fueled Fast Reactor Similar to LMFBR

A large, sodium-cooled, oxide-fueled fast reactor (or reactors) with the material volume fractions, geometry, and heat removal system similar to that

FIGURE 10 NEUTRON FLUX VS. ENERGY, ZPR6-7 FAST REACTOR BENCHMARK

Table 28

Neutron Cross Sections* For the Major Transuranium Isotopes
In a 2700 MW_t Spherical, Metal-Fueled Actinide Burner Reactor

<u>Isotope</u>	<u>Capture, Barns</u>	<u>Fission, Barns</u>
²³⁷ Np	4.35-1	8.43-1
²³⁸ Pu	9.06-2	1.58
²³⁹ Pu	1.12-1	1.68
²⁴⁰ Pu	1.48-1	8.45-1
²⁴¹ Pu	1.68-1	1.72
²⁴¹ Am	1.99-1	7.05-1
²⁴³ Am	1.81-1	5.61-1
²⁴⁴ Cm	1.22-1	1.12

*Neutron cross section data from ENDF/B-IV were used.

of a large commercial LMFBR design may be attractive. The data in Table 27 suggest that the actinide burnout rate may be relatively low, but if the reactor (or reactors) were properly sized, it may be possible to burn out the actinide wastes at the same rate at which they are being produced in commercial power reactors. Ideally, an actinide burner reactor should have a large capacity to recycle the waste actinide isotopes. The reactor should be capable of burning the backlog of actinide wastes that have been produced to date in addition to the waste actinide isotopes produced in future LWRs and LMFBRs. To gain an appreciation for the sizing of an actinide burner reactor, it is noted that the waste neptunium, americium, and curium produced by commercial reactors in the U.S. during the year 1979 alone (about 1400 kilograms) would produce about 3660 Mwt/year if fissioned. Thus, it is not unrealistic to consider the use of large (a few thousand Mwt) actinide burner reactors fueled initially by the waste backlog, and capable of burning the wastes at the same rate at which they are being produced.

Diffusion theory scoping calculations have been performed using SN1D to determine the size and neutron flux level of a 2700 Mwt sodium-cooled fast actinide burner reactor. The reactor was assumed to be fueled with a LWR discharge composition of the actinide wastes neptunium, americium, and curium and had approximately the same fuel, sodium, and structure volume fractions as a large commercial LMFBR. The core was designed as a cylinder with a 100 cm height, and the critical radius was determined to be about 87 cm. The critical mass of the reactor was calculated to be about 10,000 kilograms, and the average total neutron flux was about $6.5 \pm 1.5 \text{ N/cm}^2/\text{sec}$. The flux spectrum shown in Figure 11 is significantly harder than that of the center core zone of a large commercial LMFBR. The resulting actinide fission and capture cross sections are shown in Table 29. Calculations performed with the isotope production and depletion code ORIGEN indicate that the reactor would be capable of burning out about 870 kilograms of waste actinides per year. This is almost two-thirds of the amount of waste actinides that will be produced by all the operating commercial LWRs in the U.S. in the year 1979. The initial 10,000 kilograms of actinides required to start up the reactor could come from the backlog of commercial actinide wastes which now resides in fuel storage pools, and would utilize about half of the existing backlog.

FIGURE 11 NEUTRON FLUX VS. ENERGY, 2700 MWe ACTINIDE BURNER REACTOR

Table 29

Neutron Cross Sections* For the Major Transuranium Isotopes
In a 2700 MW_t Sodium Cooled Fast Actinide Burner Reactor

<u>Isotope</u>	<u>Capture, Barns</u>	<u>Fission, Barns</u>
²³⁷ Np	8.71-1	5.24-1
²³⁸ Pu	1.74-1	1.23
²³⁹ Pu	2.25-1	1.65
²⁴⁰ Pu	2.58-1	5.45-1
²⁴¹ Pu	2.67-1	1.94
²⁴¹ Am	4.85-1	4.53-1
²⁴³ Am	3.62-1	3.22-1
²⁴⁴ Cm	2.35-1	7.43-1

*Neutron cross section data from ENDF/B-IV were used.

Special precautions would have to be taken to ensure that the reactivity of the system would not become too positive as a function of burnup. Calculations indicate that as the actinide waste (mostly Np^{237}) is irradiated, a large fraction of ^{238}Pu is built up due to neutron capture in the Np^{237} . Succeeding capture reactions lead to Pu^{239} , Pu^{240} , and Pu^{241} . The buildup of the plutonium isotopes as a function of time leads to a strong positive reactivity worth of the fuel and may be difficult to control. The buildup of Pu^{238} and Pu^{239} is such that k_{eff} increases from a control-out value of 1.05 at the beginning-of-cycle to a value of 1.12 after only 120 days of burnup operations. The magnitude of the reactivity swing indicates that the control requirements are significant. Two possible solutions to this problem may be readily available. One solution involves starting the reactor up with an initial inventory of plutonium which, as it is burned out, would help smooth out the reactivity increase from new plutonium being bred from neptunium. Calculations indicate that an initial plutonium enrichment of about 20% to 25% would be satisfactory, assuming the plutonium has the LWR discharge isotopic composition. This solution is not particularly attractive, however, because of the large plutonium mass required. The fuel volume occupied by the plutonium could otherwise be occupied by the waste actinides. Also, the initial plutonium in the core would increase the power density of the core considerably unless the flux level was substantially reduced. The actinide waste burnout rate would also be reduced correspondingly. A better solution to the problem of reactivity increases as a function to time may be to simply remove some of the fuel assemblies at regular intervals. The core fuel volume fraction would thus be decreased, the core sodium volume fraction would increase, and the magnitude of the reactivity increase would be reduced. The long-term (2 years or more) problem of reactivity increases due to plutonium buildup could be overcome by simply reprocessing every few years to remove the plutonium. This plutonium (rich in Pu^{238}) may be useful as a denaturant fuel for proliferation-resistant LMFBR fuel cycles. If a future energy source were to replace the need for nuclear fission, the fuel in the actinide burner reactors could eventually be burned out using a scheme similar to that used for plutonium burnout (see Section 5).

Another major disadvantage of an actinide burner reactor is the low Doppler coefficient. Calculations for the burner reactor indicate that the negative Doppler coefficient ($T \frac{dk}{dT}$) is never more negative than $\sim -1.0 \times 10^{-4}$.

Thus, one of the important safety characteristics of the LMFBR is lost in going to the actinide burner.

The reactor discussed above was fueled by the actinide waste isotopes neptunium, americium, and curium only. No initial uranium or plutonium was used. However, to explore the potential of using U^{238} as a fuel diluent for possible materials compatibility purposes, an attempt was made to determine the critical mass of a system with a 50%-50% mix of actinide wastes and U^{238} . It was found that this reactor would not go critical.

4.3 Thermal Actinide Burner Zone in a LMFBR

It may be attractive to consider a reactor with a sodium cooled "commercial" LMFBR center core zone which contains a special thermal actinide burner section. Thus, the actinides would be irradiated in a thermal flux and at a flux level similar to that of an LMFBR center core zone (about 1.0×10^{15} n/cm²/sec). The actinide burner section could be composed of waste actinide isotopes surrounded by a sufficient moderator⁽²²⁾, e.g., approximately 19 cm of graphite, 10 cm of beryllium oxide, or a few cm of zirconium hydride. A burnout rate of about 84% per year would result (see Table 27). The average neutron flux energy could be expected to be significantly less than that of a commercial LMFBR center core zone. Thus, the Doppler coefficient of the driver fuel should increase and the positive sodium void reactivity worth should decrease.

It has been noted that the actinide burnout rate is high in thermal systems due to the relatively high thermal capture cross sections of neptunium and americium. Most of the actinide waste isotopes are not directly burned out, but instead are first transmuted into plutonium or more fissionable americium isotopes. A fast reactor design with a thermal actinide burner section would, therefore, be expected to exhibit a strong positive reactivity increase as a function of burnup. This may lead to problems of control of the reactor. Scoping studies have not been performed for this type of actinide burner reactor.

5.0 PLUTONIUM BURNER STUDY

The computer code ORIGEN has been used to compute the potential hazard from the non-plutonium transuranics and their radioactive daughters relative to the hazard from plutonium and its radioactive daughters. The total production of neptunium, americum, curium, berkelium, and californium from 80 years of operation of one 1200 MWe LMFBR and three uranium-fueled 1200 MWe LWRs has been determined and the potential hazard from these materials is shown in Figure 12. The potential hazard, a function of the decay time, is simply a measure of the volume of water required to dilute a given isotope to the extent that the water could be safely consumed for 50 years. The radiation concentration guides from 10CFR20 were used.

The potential hazard from all the plutonium in the 1200 MWe LMFBR at the end of a cycle is also shown in Figure 12. These results show that for decay periods from 1000 to 50,000 years the potential hazard from the actinides produced by operating one LMFBR and three LWRs for 80 years is of the same order of magnitude as that from the plutonium in the LMFBR at the end of any cycle. It is readily apparent that the beneficial effects of recycling the actinides in a continuous 80-year long scheme would be negated by the potential hazard of the Pu in the LMFBR from just one cycle if it were sent to waste. This of course assumes that the plutonium is no longer needed as a fuel due to the introduction of a new means of energy generation which does not require plutonium. The results in Figure 12 show that if any actinide recycle scheme is undertaken, it must be followed by a plutonium-burner scheme. Thus, a plutonium burner reactor study has been undertaken to complement the actinide recycle studies.

Two basic options which represent extremes of the plutonium burner reactor operation have been explored. The options are:

1. Operation with no initial U^{238} in the core.
2. Operation with an initial Pu^{239}/U^{238} atom ratio of 0.2 at the beginning of each refueling interval.

Figure 12: Comparison of the Potential Hazards of Pu- and Non Pu-Transuranic Nuclei and Their Daughters

Both options consider irradiation of plutonium discharged from LMFBRs at the end of equilibrium cycles. The discharge plutonium composition is assumed to be:

$$\begin{aligned} \text{Pu}^{239} &= 67\%, \\ \text{Pu}^{240} &= 24\%, \\ \text{Pu}^{241} &= 6\%, \\ \text{Pu}^{242} &= 3\%. \end{aligned}$$

A center core zone average total flux of about 6.02×10^{15} n/cm²/sec was assumed to be maintained throughout all irradiation times, and each refueling interval was assumed to be comprised of 402 days of irradiation followed by 70 days of decay (during refueling) followed by another 402 days of irradiation followed by 16 months of decay (during reprocessing and fabrication). The plutonium is then returned to a Pu-burner reactor for another refueling interval. Staggered startup times for several burner reactors are assumed so that an incompatibility does not exist between reactor startup times and fuel availability. To ensure criticality as the mass of plutonium decreases, plutonium from several burners will need to be combined in fewer reactors.

Option 1, given above, was considered to determine the minimum amount of time required to burn the plutonium to 1% of its initial mass. For a given flux, Option 1 minimizes the burning time required because plutonium breeding via U^{238} is minimized. Option 2 was considered to determine the effect of leaving U^{238} in the burner for possible safety and materials compatibility reasons. The presence of initial U^{238} , however, increases the time required to burn out the plutonium.

Option 1 is characterized by a rapid burnout of Pu^{239} . At the end of five cycles (a total of about 17 calendar years), equilibrium conditions are nearly achieved and the isotopic composition of the plutonium is:

$$\begin{aligned} \text{Pu}^{238} &= 2.6\%, \\ \text{Pu}^{239} &= 3.8\%, \\ \text{Pu}^{240} &= 58.6\%, \\ \text{Pu}^{241} &= 13.0\%, \\ \text{and Pu}^{242} &= 22.0\%. \end{aligned}$$

The Pu^{238} buildup is caused by the production and decay of other actinide isotopes in the plutonium burner reactor. These isotopes are assumed to be recycled along with the plutonium.

The total mass of plutonium remaining after five cycles is about 14% of the initial mass of plutonium. A total of about 14 cycles (51.9 calendar years) will be required to reduce the plutonium mass to 1% of its initial value. Curium and other transplutonium actinides produced by the burner reactor operation would make up only about 50% of the transuranium mass remaining at that time.

If Option 2 is utilized, the length of time required to reduce just the Pu^{239} mass to 1% of its initial value is increased from 17 years (for Option 1) to about 39 years. The length of time required to burn the rest of the plutonium isotopes is accordingly increased and is judged to be undesirably long.

The two options briefly discussed here represent extremes of plutonium burner operation. Option 1 probably represents an optimistically fast burnout rate because no U^{238} was allowed. Thus, no Doppler contribution from U^{238} was present. Option 2, while surely having a U^{238} Doppler contribution, did not give a favorable plutonium burnout rate.

The plutonium burnout rate is limited by the maximum allowable burnup and power density, as well as the reactor's U^{238} content. Thus, the burnup rate limiting effects of the presence of U^{238} cannot necessarily be overcome by simply increasing the flux or the plutonium atom density.

Ideally, to minimize the rate limiting effects of U^{238} , Option 1 should be used with a nonfertile diluent replacing the UO_2 . Possible candidate diluents considered include yttrium, zirconium, rare earth compounds, titanium, tungsten, and tantalum. From the viewpoint of ease of fabrication with PuO_2 , the yttrium, zirconium, rare earths, and titanium are favored. Reactivity calculations indicate that replacing all the UO_2 with yttria, Y_2O_3 , would be unacceptable because of the small absorption cross section of the yttrium. Qualitative cross section comparisons suggest that zirconium and titanium would be unacceptable for the same reason. Neutronically,

tungsten and tantalum are more favorable and tungsten may even exhibit significant Doppler contributions. To increase the melting temperatures of the fuel, carbides or nitrides of these elements may be considered. Also, the tungsten and tantalum compounds should have higher thermal conductivities than UO_2 ⁽²³⁾. If so, it may be interesting to consider the use of carbides or nitrides of tungsten or tantalum in an attempt to increase the maximum allowable burnup and power density which would result in an increased plutonium burnup rate.

5.1 PuO_2 -W Plutonium Burner Reactors

Successive iterations using SN2D and the fuel management code FUMBLE II have been completed for two series of plutonium-burner reactors. The first series of reactors are fueled by a PuO_2 -W mix containing PuO_2 volume fractions of up to 0.4 in the fuel. These reactors are characterized by the core geometry shown in Figure 13 and the core volume fractions shown in Table 30. The reactors are all rated at 1200 MWe, assuming that 1200 MWe LMFBRs are on line when the switch to the plutonium-burner concept is made. The original steam supply systems would then be used by the plutonium-burners. The basic core geometry and volume fractions are also typical of 1200 MWe LMFBRs.

As the plutonium isotopics change (i.e., as fissile plutonium is burnt), the volume fraction of the PuO_2 is steadily increased to insure a critical mass. The core geometries are preserved, however by keeping the total fuel volume fraction constant. This is done by replacing the W with PuO_2 as the mass of the Pu increases. Each reactor is single batched, and has a burnup reactivity [$(k_{\text{eff}}(\text{end-of-cycle}) - k_{\text{eff}}(\text{beginning-of-cycle}))$] of -0.05. The first reactor of the series initially has a PuO_2 volume fraction of 0.23 in the fuel. A second series of reactors are fueled by a PuC-WC mix and immediately follows the PuO_2 -W reactor series. The switch from PuO_2 -W fuel to PuC-WC fuel is made due to concern that tungsten oxidation problems would occur if the PuO_2 volume in the fuel were to become greater than about 0.4. The total number of Pu-burner reactors decreases with time because the total plutonium mass available decreases with time, and also because the plutonium mass required by each reactor to achieve a no-control k_{eff} of 1.05 increases as the Pu isotopics change.

FIGURE 13

TABLE 30

Pu-BURNER REACTOR MATERIAL SPECIFICATIONS AND OPERATING PARAMETERS

1. Core and Reflector Material Volume Fractions:

Core Fuel Assembly		Radial Reflector Assembly	
Fuel	0.4575	PE-16 Structure	0.7275
Structure	0.1768	Sodium	0.2725
Sodium	0.3657		
	1.0000		1.0000

2. PE-16 Reflector Composition
(Material/Weight Percent)

	"PE-16"
Chromium	18.0
Iron	42.0
Nickel	40.0
	100.0

3. Thermal Power = 3000 MW

4. Reactor Capacity Factor = 0.85

Tungsten was chosen as the non-fertile diluent because of its high melting point (3410°C), its high thermal conductivity (69.7 Btu/H-ft F at 1000°F), and its potentially favorable Doppler properties. Also, limited experience has been gained with fabrication⁽²⁴⁾ and irradiation⁽²⁵⁾ of $\text{UO}_2\text{-W}$ fuel materials.

The $\text{PuO}_2\text{-W}$ series of reactors begins with refueling intervals of about 106 days and reactors near the end of the series have refueling intervals of about 190 days. The Doppler coefficient ($-\text{T dK/dT}$) is about 0.0090 for reactors at the beginning of the series and about 0.0095 for reactors at the end of the series. Most of the Doppler contribution is due to the presence of the tungsten, although as the plutonium isotopics change, the plutonium eventually makes a contribution to the Doppler. A total of 24 cycles of $\text{PuO}_2\text{-W}$ reactors could be operated before the switch to PuC-WC would have to be made. A cycle is considered to be comprised of all those reactors which start with the same mass of plutonium and the same isotopics, and is assumed to include 16 months for reprocessing and fabrication.

The PuC-WC series of reactors begin immediately following reprocessing and fabrication of the discharge from the 14th cycle of $\text{PuO}_2\text{-W}$ reactors. The beginning-of-cycle plutonium isotopics for the 1st cycle of PuC-WC reactors are thus the same as the discharge isotopics for the 24th cycle of $\text{PuO}_2\text{-W}$ reactors. The PuC-WC reactors begin with refueling intervals of about 196 days and reactors near the end of the series have refueling intervals of about 404 to about 445 days depending upon the number of cycles operated. The number of PuC-WC cycles operated depends, of course, upon how completely the Pu mass is to be reduced and the total mass present at the beginning of the Pu-burner scheme. The Doppler coefficient for cycles near the beginning of the PuC-WC series is approximately 0.0076 and after about 30 cycles of PuC-WC reactors is approximately 0.0059. The Doppler for this series is less than that of the $\text{PuO}_2\text{-W}$ series because the tungsten total mass in the core is less for the WC diluent than for the W diluent, and the negative Pu contribution is not sufficient to make up the difference. The Doppler coefficients of both series are considered to be adequate, as a comparably sized $\text{PuO}_2\text{-UO}_2$ LMFBR would have a Doppler coefficient of about 0.008. Sodium void calculations have not been performed for the plutonium-burner reactors.

The plutonium mass is shown in Table 31 as a function of the number of operating cycles and the time elapsed since the beginning of the plutonium burner operations. Three cases are shown for different numbers of 1200 MWe LMFBRs on line just prior to initiating the plutonium-burner scheme. The cases are for 1000, 200, and 50 initial LMFBRs. The table shows that for the case of 1000 initial LMFBRs, the plutonium mass can be burned from approximately four million kilograms to only a little over 1% of this mass in less than 110 years. Additional cycles of plutonium burner reactors could be operated, if desired, because enough mass is left to make four more critical masses in the 1200 MWe geometry. For the 200 initial LMFBRs and 50 initial LMFBRs cases, the plutonium mass becomes less than that required for a 1200 MWe geometry critical mass after 28 PuC-WC cycles and 17 PuC-WC cycles, respectively. Additional cycles of plutonium-burner reactors could be operated, if desired, by utilizing a reactor design which would allow criticality with the smaller mass of plutonium. Alternatively, schemes can be envisioned wherein the remaining plutonium could be further burned in U^{235} -W systems, accelerators, or possibly CTRs.

In addition to decreasing the mass of the plutonium left after plutonium is no longer needed as a fissile fuel, the plutonium-burner concept alters the plutonium isotopics. This change of isotopics is shown in Figure 14 for various Pu-burner operating generations and times. The Pu^{239} isotopic percentage is steadily decreased as the plutonium-burners are operated, until it is virtually gone. After 30 cycles of Pu-WC reactors, Pu^{239} makes up only 0.04% of the plutonium. The Pu^{239} feedback path via Cm-242 ($Pu-241 \xrightarrow{\beta} Am-241 \xrightarrow{n,\gamma} Am-242 \xrightarrow{\beta} Cm-242 \xrightarrow{\alpha} Pu^{238}$) has been ignored for this study as it is considered to be only a minor producer of Pu^{238} . All isotopes in this path are capable of being "burned" in a reactor, as an actinide recycle analysis has shown. The rest of the plutonium is primarily Pu^{240} and Pu^{242} , with isotopic percentages of 48% and 44%, respectively.

In conclusion, the above proposed scheme provides a reasonable approach to burning up the excess plutonium created by present and future fission power reactors when it may no longer be needed as an energy resource.

Table 31

The Pu Mass Decrease as a Function of Reactor Cycles Operated:

Cases are for 1000, 200, and 50 Initial LMFBRS

Cycle ^a	Time EOC Years ^{b,c}	Number of Reactors per Cycle and Total Mass of Plutonium Remaining at EOC					
		Reactors	Kilograms	Reactors	Kilograms	Reactors	Kilograms
	0	1000	4.076+6	200	8.152+5	50	2.038+5
PuO ₂ -W Reactors	1	697	3.863+6	139	7.725+5	34	1.931+5
	5	535	3.104+6	107	6.208+5	26	1.552+5
	10	366	2.365+6	73	4.731+5	18	1.183+5
	15	248	1.801+6	49	3.602+5	12	9.005+4
	20	167	1.354+6	33	2.709+5	8	6.772+4
	24	119	1.061+6	23	2.122+5	5	5.304+4
PuC-WC Reactors	1	110	9.945+5	22	1.989+5	5	4.973+4
	5	74	7.461+5	14	1.492+5	3	3.731+4
	10	44	4.879+5	8	9.758+4	2	2.439+4
	15	25	2.946+5	5	5.892+4	1	1.473+4
	20	13	1.695+5	2	3.389+4	0	1.185+4 ^d
	25	7	9.519+4	1	1.904+4	0	--
	30	4	5.282+4	0	1.339+4 ^e	0	--

^aA generation of Pu-burner reactors is considered to be all those reactors which start with the same mass of plutonium and the same isotopics.

^bTime t=0 is the BOC of the first cycle of Pu-burner reactors.

^cTotal out-of-core time for each cycle is assumed to be 16 months for reprocessing and fabrication and all reactors are single batched.

^dThis mass is discharged from the 17th cycle of the PuC-WC reactors.

^eThis mass is discharged from the 28th cycle of PuC-WC reactors

*Assuming each cycle includes 16 months for reprocessing and fabrication and single batched reactors.

5.2 Pu-Th, Pu-Burner-U-Breeder Reactor

A number of different LMFBR core configurations have been suggested for use in a proliferation-resistant nuclear strategy. One of the favored options for use within a secure area consists of a reactor with plutonium and thorium in the core and thorium in the blankets. Such a reactor would burn fissile plutonium and produce fissile U^{233} and as such might be considered as a plutonium-burner option. A series of calculations were performed to determine the mass flow of such a plutonium-burner based on the PLBR Phase I reference core. The reactor composition is specified in Table 32. The supplied fuel for the core is plutonium discharged from a U^{235}/U^{238} fueled LWR. The fuel management for the core consists of a two-batch operation with a 2-year cycle length. In the radial blanket, the residence time for each of the rows is respectively 2, 4, and 6 years. A plant capacity factor of 0.85 is assumed. The mass flow was determined using FUMBLE, and the results are summarized in Table 33. With each batch, about 760 kg of Pu are destroyed while about 1000 kg of fissile U are created. The above reactor is thus a very effective burner-breeder reactor. The average discharge burnup is about 70,000 MWd/Mt and the burnup Δk_{eff} is about 0.2%. The above reactor appears to be a feasible option both as a Pu-burner and as a breeder of U^{233} .

For comparison purposes, a PuO_2 -W reactor of the type described by Figure 13 and Table 30 was designed. The reactor was designed to have a cycle length equal to that of the reactor described above so that mass flow comparisons could be made. Because new fissile uranium was not being bred in this reactor, the PuO_2 volume fraction in the fuel was increased to about 0.26. The resulting average discharge burnup was 145.5 MWd/kg, and the burnup Δk_{eff} was -0.15. The plutonium mass flow results are shown in Table 34.

Table 32

Pu-Th Pu-Burner - U-Breeder ReactorMaterial Specifications and Operating Parameters

1. Core and Blanket Material Fractions

<u>Core Fuel Assembly</u>		<u>Radial Blanket Fuel Assembly</u>	
Fuel	0.44	Fuel	0.58
Structure	0.16	Structure	0.12
Sodium	0.40	Sodium	0.30

2. Thermal Power 3000 MW_{th}

3. % Fissile Pu/(Pu + Th) (CZ1/CZ2) 10.4/15.4

4. Core Fuel Average Discharge Exposure 69.9 MWd/kg

5. Burnup Δk_{eff} (k_{eff} (EOEC) -

k_{eff} (BOEC)) -0.002

Table 33

Mass Flow of Heavy Metal in Pu-Burner U-Breeder

	<u>Supplied Fuel by Batch (kg)</u>	<u>Discharged Fuel by Batch (kg)</u>	<u>Net Fuel Change by Batch (kg)</u>
Total Pu	2528	1769	-759
Fissile Pu	1959	1167	-792
Fissile U	0	996	996
Th	30760	29468	1292
EOEC Heavy Metal Inventory (kg)			
Total Fuel	85197		
Total Pu	3888		
Fissile Pu	2684		
Fissile U	1716		
Th	78030		

Table 34

Mass Flow of Pu in PuO₂-W Pu-Burner Reactor

	<u>Supplied Pu by Batch (kg)</u>	<u>Discharged Pu by Batch (kg)</u>	<u>Net Change by Batch (kg)</u>
Total Pu	6668.6	5605.9	-1062.7
Fissile Pu	4487.3	3447.7	-1039.6

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C. L. Cowan
E. Kujawski
R. Protsik

END

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