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TRANSMUTATION OF WASTE ACTINIDES IN THERMAL REACTORS:
SURVEY CALCULATIONS OF CANDIDATE IRRADIATION SCHEMES

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by

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ABSTRACT

Actinide recycle and transmutation calculations were made for twelve specific thermal reactor environments. The calculations included H_2O-moderated reactor lattices with enriched U, recycled Pu, and $^{233,235}U$-Th. In addition two D_2O reactor cases were calculated.

When all actinides were recycled into ^{235}U-enriched fuel, about 10% of the transuranic actinides were fissioned per 3-year fuel cycle. About 9% of the actinides were fissioned per 3-year fuel cycle when waste actinides (no U or Pu) were irradiated in separate target rods in a U-fuel assembly. When actinides were recycled in separate target assemblies, the fission rate was strongly dependent on the specific loading of the target. Fission rates of 5 to 10% per 3-year fuel cycle were observed.

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TRANSMUTATION OF WASTE ACTINIDES IN THERMAL REACTORS: SURVEY CALCULATIONS OF CANDIDATE IRRADIATION SCHEMES

INTRODUCTION

Partitioning the actinides in fuel wastes from light water reactors (LWR) and transmuting them to fission products in power reactors represents a waste management concept which could reduce the long-term risk associated with geologic isolation of the wastes. The Chemical Technology Division of Oak Ridge National Laboratory (ORNL) is coordinating a program* involving several national laboratories to evaluate the feasibility and incentives that may exist for implementing the concept. Studies and tests pertaining to chemical partitioning of the actinides are being conducted at other sites, and are not discussed in this report. The portion of the process considered in the Savannah River Laboratory (SRL) study pertains to neutron-induced transmutation in thermal reactors. Specifically, computations were made to assess methods in which the waste actinides would be recycled and re-irradiated in various fuel or target forms. The transmutation results described in this report were obtained from survey studies of several recycle options; two of the more promising options were chosen for more detailed study, and these will be described in a later document.

* Contract No. W-7405-eng-26.

SUMMARY

Actinide recycle calculations were made for twelve specific situations. The calculations included H_2O moderated reactor lattices with enriched U, recycled Pu, and $^{233,235}U$-Th. In addition two D_2O reactor cases were calculated. Detailed results and plots of actinide transmutation rates are given in Tables A.1-A.16 in Appendix A and Figures 10-19, respectively.

When all actinides were recycled into ^{235}U-enriched fuel, about 10% of the transuranic actinides were fissioned per 3-year fuel cycle. After five recycles, none of the actinide concentrations had equilibrated, and the higher isotopes of Cm and Cf were increasing rapidly. In this recycle mode the Pu isotopes were always diluted by U and would be difficult to recover for weapons production.

About 9% of the actinides were fissioned per 3-year fuel cycle when waste actinides, excluding U and Pu, were irradiated in separate target rods in a U-fuel assembly. Zirconium or some other inert diluent material must be used to limit the target rod power. The diluent may introduce difficulties in chemical recovery operations on the target.

When actinides were recycled in separate target assemblies, the fission rate was strongly dependent on the specific loading of the target. Fission rates of 5 to 10% per 3-year fuel cycle were obtained in the cases studied.

Entire target assemblies are easier to handle and make a more attractive recycle mode than separate target rods in a fuel assembly. An assembly containing both target rods and fuel rods would require dismantling after irradiation, before reprocessing, if the target and fuel process streams are to be kept separate. However, the complete target assembly mode would not require any special disassembly.

BACKGROUND

The Chemical Technology Division of ORNL is coordinating a program to analyze Partitioning-Transmutation (P-T) as a waste management concept for the nuclear fuel cycle.[1]

- Partitioning is defined as the chemical process in which the level of actinides in radioactive waste is reduced to a greater extent than dictated by normal economic consideration, and where effective recovery of the actinides is achieved.

- Transmutation is defined as the irradiation process in which the actinides are converted to fission products in a reactor.

Information required to calculate the risks, costs and benefits of the P-T concept is being developed at several national laboratories under ORNL supervision. Earlier work done at other sites had little central coordination and treated some aspects of the concept incompletely. The ultimate objective of the present overall evaluation is to place the many ramifications of P-T on a common basis and to determine if implementation is feasible and cost-effective.

The responsibility of SRL was to study neutron-induced transmutation in thermal reactors. State-of-the-art computer programs such as the GLASS code[2] were utilized. These computer programs have routinely obtained good results for reactivity and depletion calculations for D_2O systems.[3] The objective of this portion of the study was to make survey calculations for several actinide recycle alternatives. The more promising cases are to be examined in greater detail in subsequent studies.

This report contains a brief description of the GLASS code, the results of verification calculations for LWR fuel with measured actinide content, and the results of calculations in which actinides were recycled in various fuel or target forms. Actinide production and depletion are described for twelve specific cases, which include a variety of possible irradiation sequences. Because waste actinide recycle is not expected to cause a major perturbation in the neutron economy of an LWR lattice, detailed neutron balance representations were not prepared for the full reactor lattices.

DESCRIPTION OF COMPUTATIONAL METHOD

The SRL GLASS code was used for all neutronic and depletion calculations in this study. GLASS performs the following general operations:

- A basic lattice physics calculation with multigroup integral transport methods. Options include 37 or 84 energy groups.

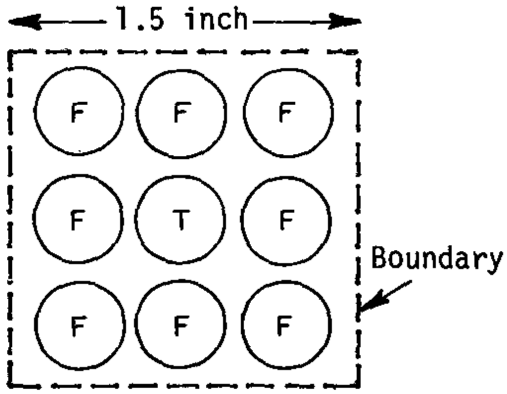
- A Nordheim calculation of self-shielded resonance integrals.

- An isotope depletion and decay calculation for all actinides and for selected fission products that is based on reaction rates from the physics calculation. The neutron energy spectrum calculation is repeated at regular intervals during the depletion calculation.

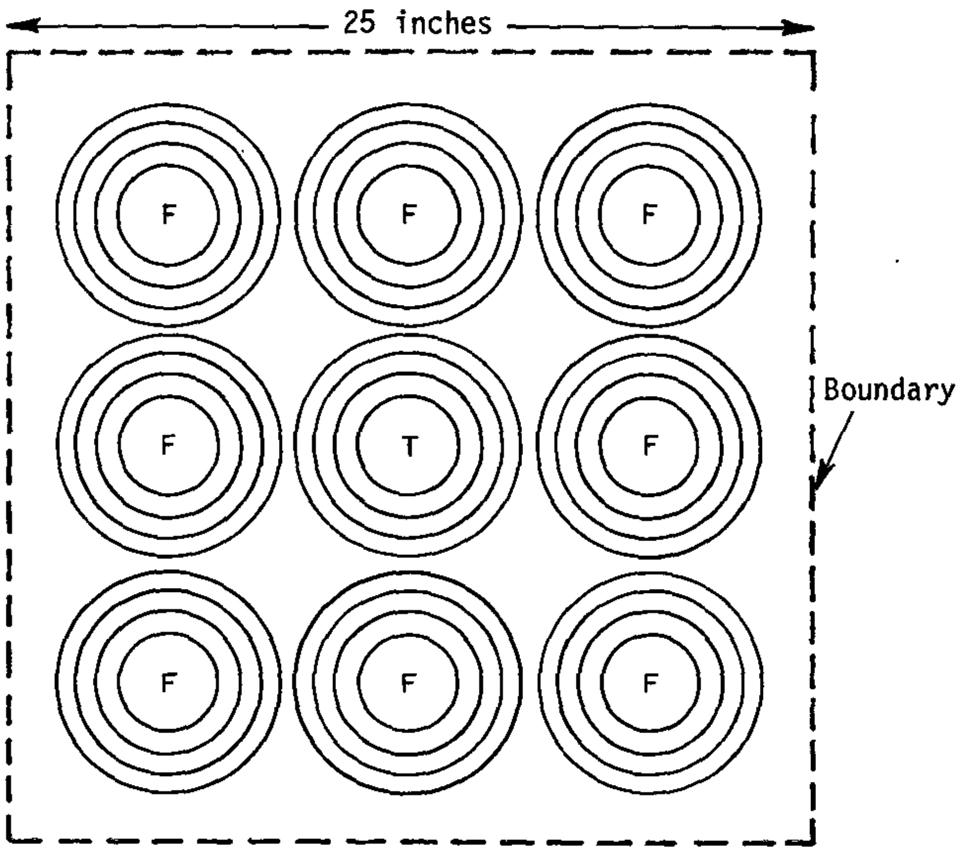
Input parameters include isotopic compositions, temperatures, and spatial dimensions in annular, square, or hexagonal geometry. A standard cross section data base is part of the SRL library, which is regularly updated to provide good results for thermal and near-thermal reactors; it currently includes the Phase I ENDF/B-V data for the transplutonium actinides.

GLASS is not limited to the simple "pin cell" geometry, with zero-current boundary conditions. It may be used to simulate multi-region annular geometry within a cell, and different cells may be linked to form "supercells". A supercell is defined as a connected group of cells which form an array which repeats by translation in a lattice. The neutron currents at cell boundaries are not zero, but the total neutron current around the supercell normally is zero.

Examples of supercells are shown in Figure 1. Figure 1-a is a target rod surrounded by eight fuel rods to form a repeating array (e.g., within an LWR fuel assembly). In Figure 1-b entire LWR fuel or target assemblies have been represented by annular mockups. These assemblies may have different properties. This feature is important because it permits a realistic calculation of resonance self-shielding in target assemblies while also obtaining a realistic multigroup spectrum that is dominated by the fuel environment.



1-a. 9-Pin Supercell



1-b. 9-Assembly Supercell

FIGURE 1. Examples of LWR Fuel Supercells

VERIFICATION OF LWR CALCULATIONS

To verify that the GLASS code is appropriate for use in LWR systems, comparisons were made between calculated and measured actinide contents of H. B. Robinson and Yankee fuel pins. These fuel pins were assumed to be in regions of asymptotic flux. Total fissions and total exposure[4] were deduced from measured ^{148}Nd contents. A unit cell consisted of H_2O moderator, cladding, and a fuel rod. The standard SRL multigroup (84) cross section set was used, with one exception. A 13% reduction was made in the neutron width and capture width of the ^{238}U resonance at 6.7 ev to achieve better agreement between calculated and measured Pu contents.

H. B. Robinson Fuel

Input parameters were derived from cell geometries and operating conditions of the H. B. Robinson reactor (Table 1). The cell pitch used was 5% larger than the "true" pitch to mock up H_2O in empty pin positions in the fuel bundle.

The results of the calculations are shown in Table 2 for two exposures. The most interesting parameters are the ^{235}U, ^{236}U, and ^{239}Pu isotopic fractions and the ratio of ^{239}Pu to ^{238}U. The agreement between calculated and measured[5] values for these parameters is good at both exposures. ^{235}U depletion calculated by GLASS is somewhat more than measured, but the ^{236}U values are in very good agreement. ^{239}Pu production calculated by GLASS is somewhat higher than measured, but the ratios of ^{239}Pu to total Pu are in good agreement.

Yankee Fuel

GLASS calculations were performed for Yankee fuel having an initial ^{235}U enrichment of 3.4%. Input parameters are given in Table 1. Reference 6 presents measured results of content versus exposure for an extensive core evaluation program in which more than 100 individual fuel pins were analyzed. Also, additional analyses were made at Pacific Northwest Laboratory (PNL), described in Reference 7. Comparisons of calculated and measured results are given in Figures 2-5. Reference 6 results are shown as a smooth curve drawn through the 100 data points.

TABLE 1

GLASS Input Parameters

Parameter	*Reactor* *H. B. ROBINSON*	*YANKEE-ROWE*	*STANDARD LWR FUEL*
Pin Array (square)	15x15	6x6	17x17
Number empty positions	21	0	25
True pitch, in.	.563	.422	.496
Effective pitch, in.	.591	.422	.519
Fuel pellet OD (hot), in.	.371	.298	.325
Clad OD (hot), in.	.420	.340	.370
Clad material	Zircaloy	Stainless	Zircaloy
Density of UO_2 (hot), g/cm^3	10.16	10.16	10.16
U_0 metal,[a] g/ft	190.3	122.8	145.8
^{235}U enrichment, %	2.56	3.40	3.20
Moderator (H_2O)			
Temperature, °C	300	268	309
Density, g/cm^3	.713	.769	.693
Natural boron, ppm	450	none	500
Specific Exposure			
MWD/MTM	31,000	25,000[b] 15,000[c]	33,000
MWD/ft	5.90	3.07 1.84	4.81
Irradiation Time, Days	1100	930 330	1100

a. U_0 metal is the initial uranium content.

b,c. Two irradiation intervals.

TABLE 2

Comparison of Calculated and Measured Actinide Contents - H. B. Robinson Fuel

Parameter	*Nuclide*	*Exp = 24,570 MWD/MTM*		*Exp = 30,920 MWD/MTM*	
		Calc	*Meas*	*Calc*	*Meas*
U Isotopic (atom %)	234	.02	.02	.02	.01
	235[a]	.80	.82	.56	.61
	236	.32	.33	.35	.35
	238	98.86	98.83	99.07	99.03
Pu Isotopic (atom %)	238	1.02	1.13	1.52	1.66
	239	58.91	59.09	53.61	53.79
	240	23.78	23.11	25.49	24.89
	241	11.90	12.53	12.97	13.75
	242	4.39	4.14	6.41	5.91
$^{239}Pu/^{238}U$		.00508	.00494	.00529	.00518

a. Initial ^{235}U = 2.56%

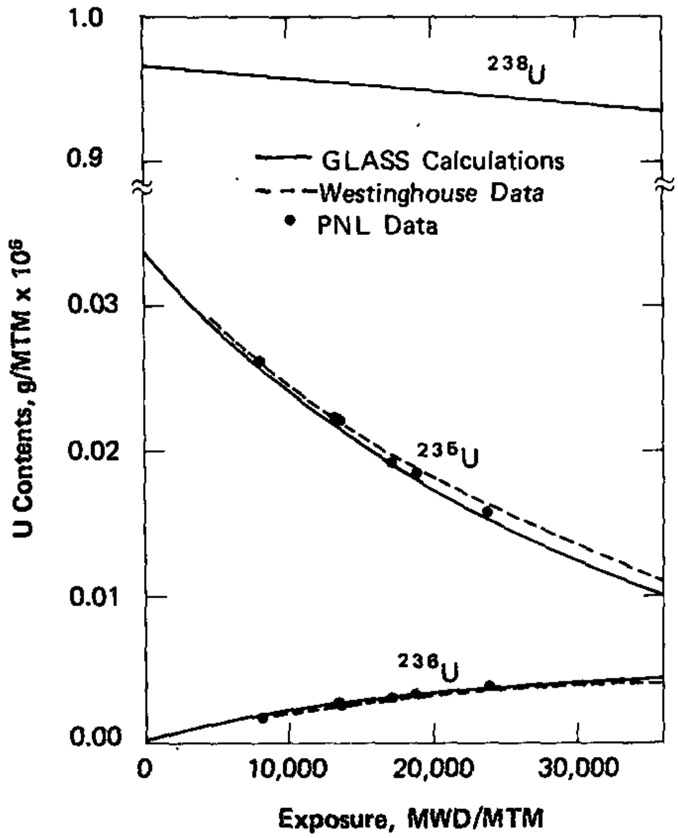


FIGURE 2. Yankee-Rowe Fuel, Uranium Contents vs Exposure

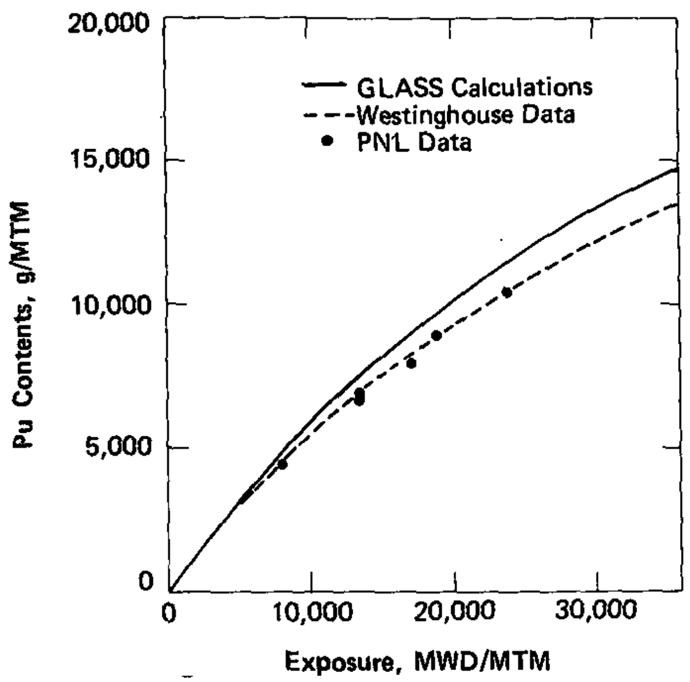


FIGURE 3. Yankee-Rowe Fuel, Total Plutonium Contents vs Exposure

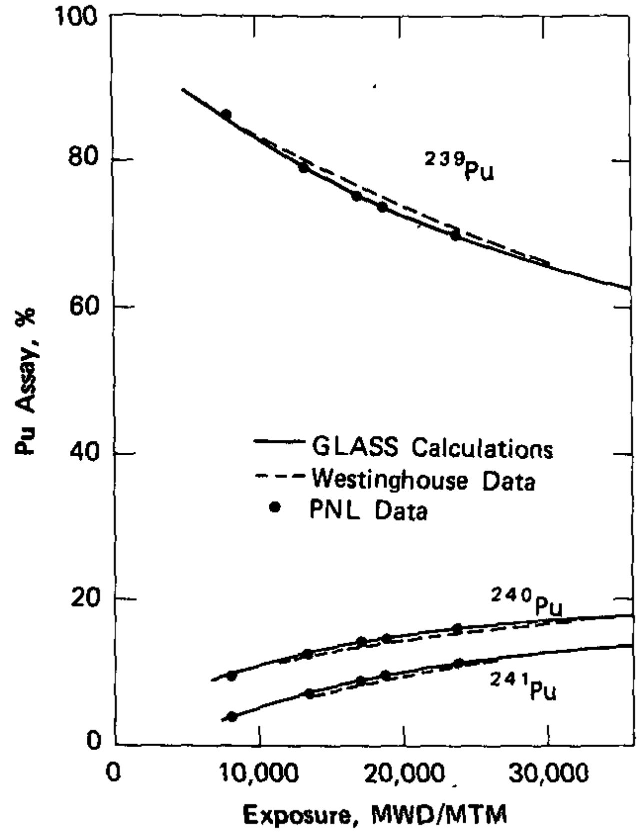


FIGURE 4. Yankee-Rowe Fuel, Plutonium Assay vs Exposure

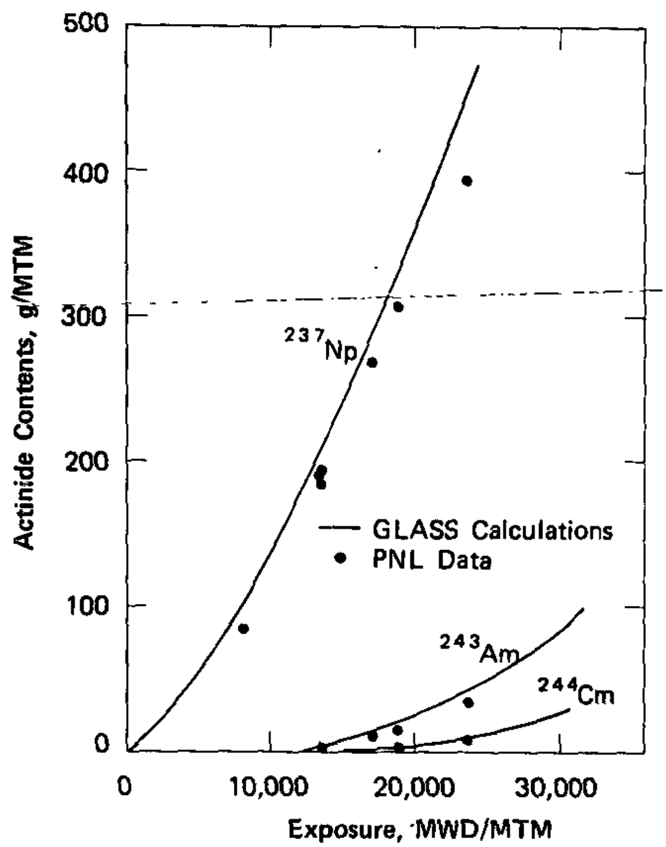


FIGURE 5. Yankee-Rowe Fuel, Other Actinide Contents vs Exposure

^{235}U depletion, calculated by GLASS, is somewhat more than measured, but the ^{236}U contents agree (Figure 2). The calculated total Pu content (Figure 3) is about 8% greater than measured. However, the calculated Pu isotopic ratios (Figure 4) agree well with measurements. Figure 5 shows results for ^{237}Np, ^{243}Am, and ^{244}Cm for a few measured data points. Calculated values are about 10% higher than measured.

The stainless steel cladding of the Yankee fuel had a very marked effect on the neutron spectrum and the transuranium production rates. In calculations in which Zircaloy was substituted for steel cladding, the transuranium contents were reduced 8 to 10% at any given exposure. All other fuel types in this study were clad with Zircaloy.

DESCRIPTION OF ACTINIDE RECYCLE ALTERNATIVES

The actinide recycle options were divided into four general groups with additional sub-division within the groups. The terms "waste actinides" and "all actinides" are used. "All actinides" includes the complete list of actinides through ^{252}Cf. "Waste actinides" does not include U or Pu. An outline of the various cases follows:

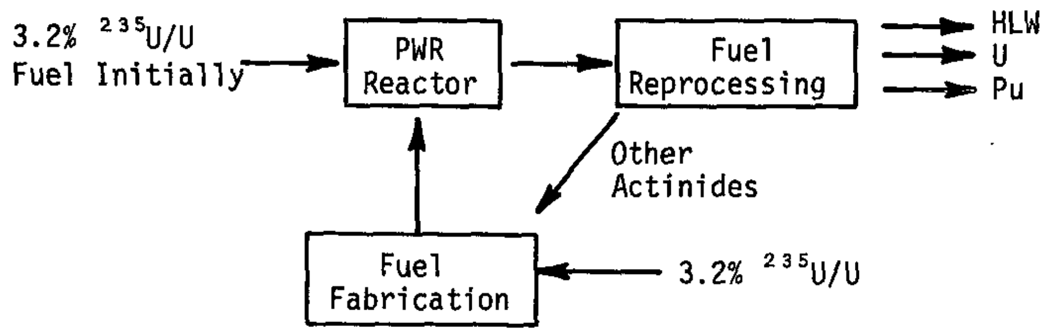
Group 1 - Uranium used as diluent (Figure 6)

- Case 1.1 - Waste actinides from each LWR U-assembly recycled into new assembly.
- Case 1.2 - All actinides from each LWR U-assembly recycled into assembly with variable ^{235}U.
- Case 1.3 - All actinides (except U) from five LWR U-assemblies recycled into one assembly of natural U.
- Case 1.4 - Waste actinides from twenty LWR fuel rods recycled into one target rod of depleted U.

Group 2 - Zirconium used as diluent; separate target rods charged to LWR fuel assembly (Figure 7)

- Case 2.1 - Waste actinides from 100 LWR U-fuel rods recycled into one target rod.
- Case 2.2 - Waste actinides from 50 LWR U-fuel rods recycled into one target rod.

1.1 Waste actinides from each LWR U-assembly recycled into new assembly



1.2 All actinides from each LWR U-assembly recycled into new assembly with variable ^{235}U

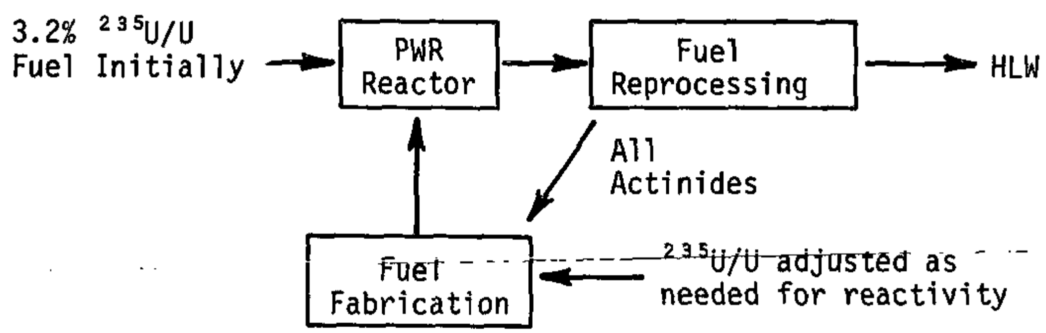
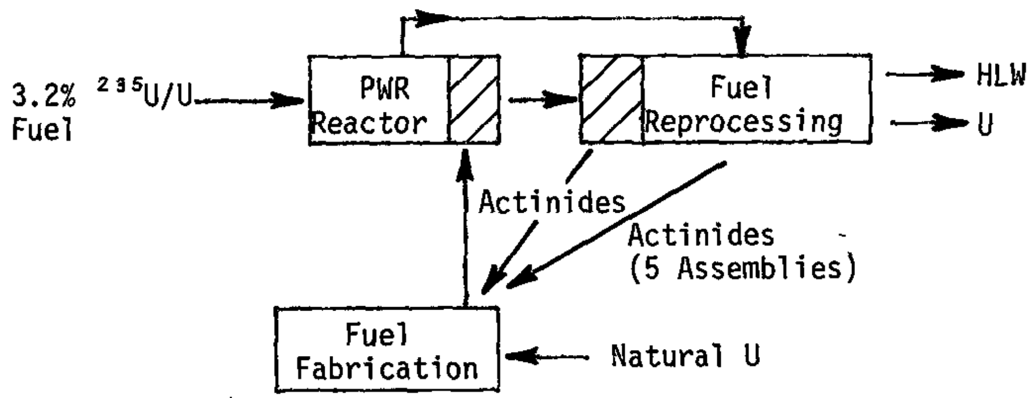


FIGURE 6. Flow Diagrams of Actinide Recycle - Four U Diluent Cases

1.3 All actinides (except U) from 5 LWR U-assemblies recycled into assembly of natural U



1.4 Waste actinides from 20 LWR U-fuel rods recycled into 1 target rod of depleted U

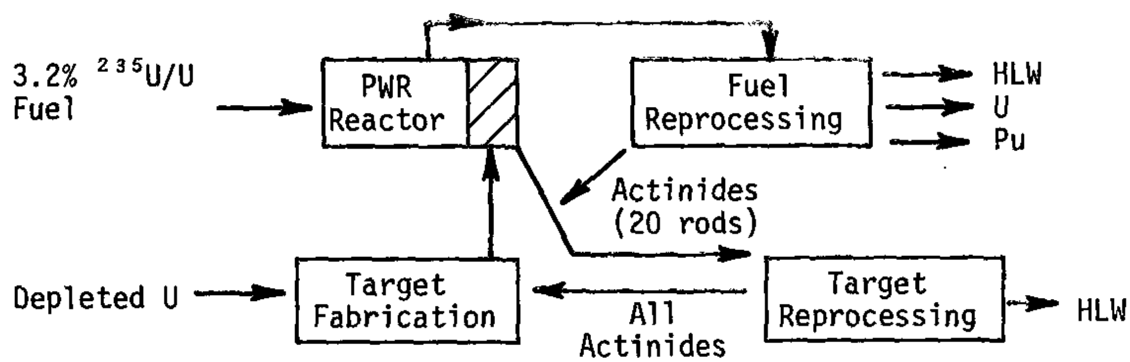
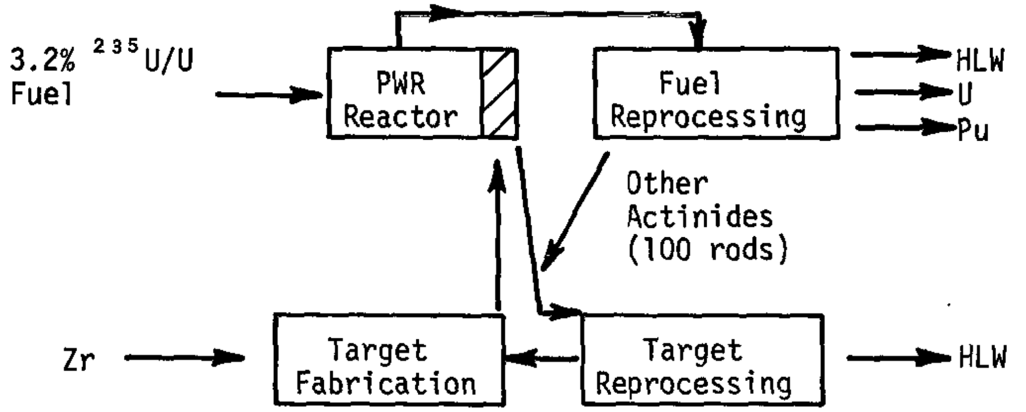
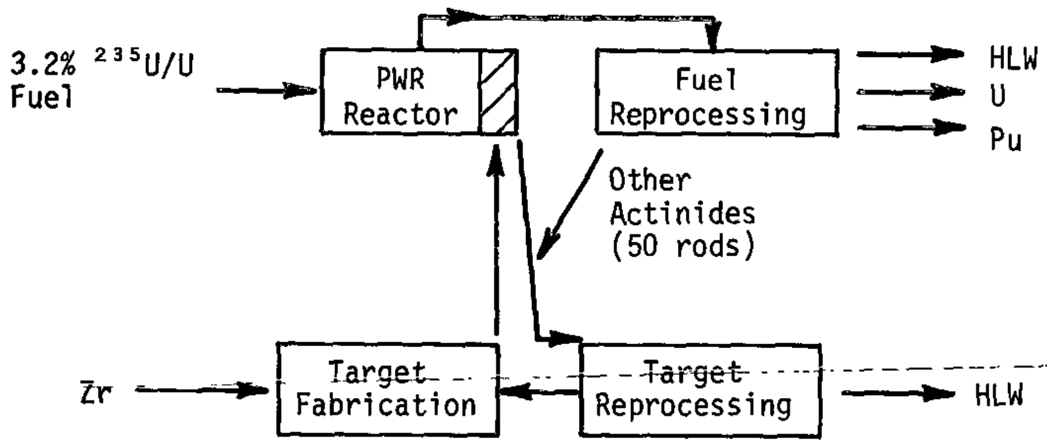


FIGURE 6. Continued

2.1 Waste actinides from 100 LWR U-fuel rods recycled into 1 target rod of zirconium



2.2 Waste actinides from 50 LWR U-fuel rods recycled into 1 target rod of zirconium



2.3 Waste actinides from 50 LWR U-fuel rods irradiated for 10 consecutive fuel cycles (no reprocessing between cycles)

FIGURE 7. Flow Diagrams of Actinide Recycle - Three Zr Diluent Cases

Case 2.3 - Waste actinides from 50 LWR U-fuel rods irradiated for ten consecutive fuel cycles (no reprocessing between cycles).

Group 3 - Waste actinides from advanced charge designs (Figure 8)

Case 3.1 - Waste actinides from five U and two and one-half Pu fuel assemblies recycled into one target assembly in a mixed U/Pu lattice.

Case 3.2 - Waste actinides from 20 U and 10 Pu fuel assemblies recycled into one target assembly in a mixed U/Pu lattice.

Case 3.3 - Waste actinides from a Th assembly enriched in ^{233}U and ^{235}U recycled into one new assembly.

Group 4 - D_2O Reactor systems (Figure 9)

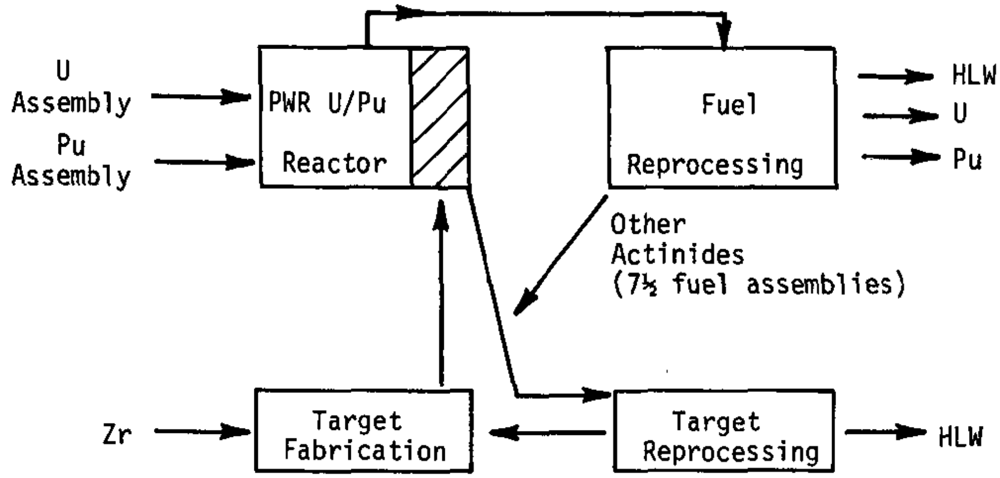
Case 4.1 - Waste actinides from 100 LWR fuel rods recycled into one target in Savannah River Plant (SRP) D_2O lattice.

Case 4.2 - Waste actinides from each CANDU-Pu assembly recycled into new assembly.

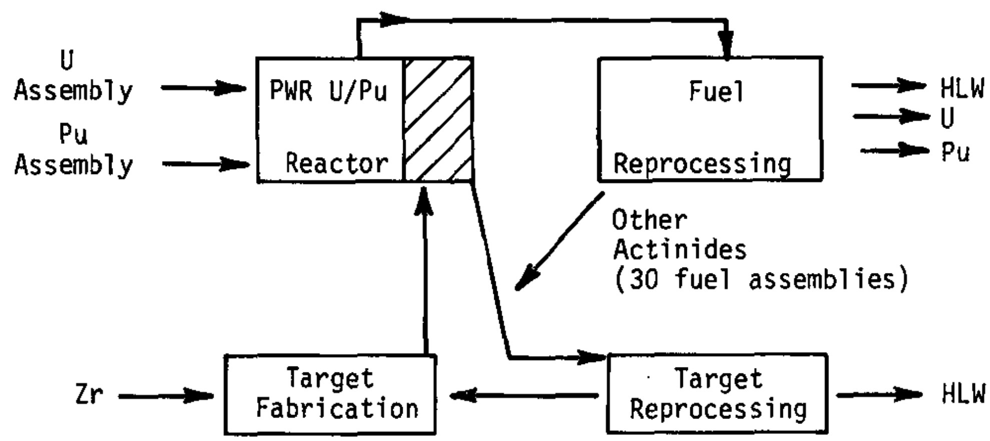
The choice of diluent is an important consideration in both the chemical partitioning and the reactor transmutation phases of the P-T concept. The waste actinides must be mixed with a diluent to achieve acceptable power generation in the fuel or target rods during reactor operation. If zirconium is used as the diluent, irradiation of the actinides is straightforward, but dissolution of the target rods during chemical recovery operations is difficult. Use of uranium as the diluent simplifies the dissolution operations, but will result in the formation of unwanted actinides during irradiation. The use of both types of diluent was included in the study.

Detailed results from the calculations for each of the twelve cases are presented in subsequent sections of this report. A one year cooling period follows the irradiation period, which is 3 years for most cases. Because reprocessing losses are expected to be small, it was assumed that 100% of the actinides were recovered from fission products and other waste. Contents are expressed in units of grams per metric tonne of original fuel material. Although light water reactors (LWR) could be either pressurized (PWR) or boiling water (BWR), only PWR's were considered in this study.

3.1 Waste actinides from 5 U and 2½ Pu fuel assemblies recycled into 1 target assembly in a mixed U/Pu lattice



3.2 Waste actinides from 20 U and 10 Pu fuel assemblies recycled into 1 target assembly in a mixed U/Pu lattice



3.3 Waste actinides from a Th assembly enriched in ^{233}U and ^{235}U recycled into 1 new assembly

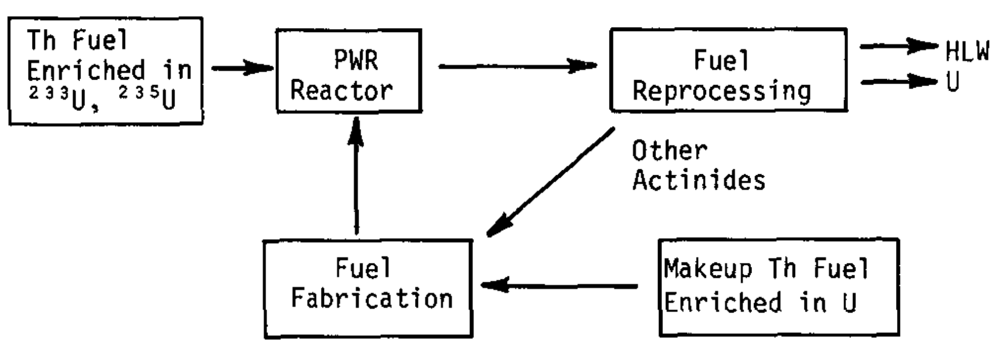
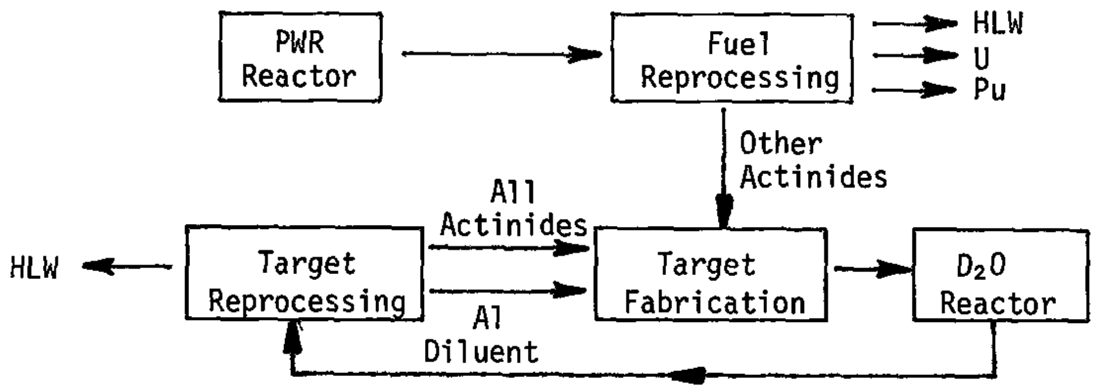


FIGURE 8. Flow Diagram of Actinide Recycle - Two Advanced Charge Designs

4.1 Waste actinides from 100 LWR fuel rods recycled into 1 target in SRP lattice



4.2 Waste actinides from each CANDU-Pu assembly recycled into new assembly

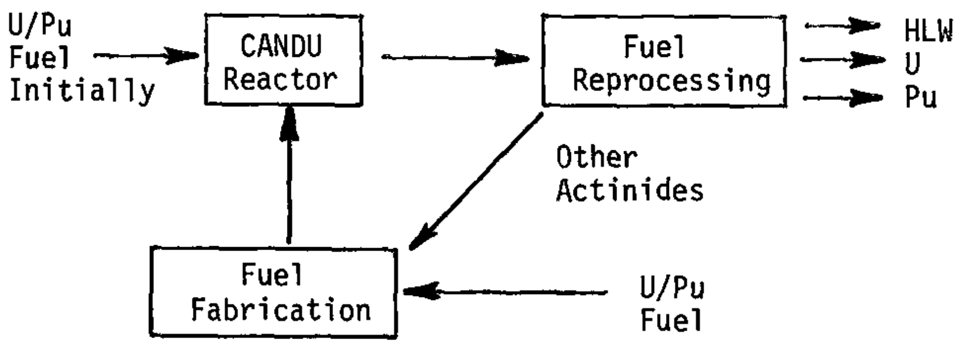


FIGURE 9. Flow Diagrams of Actinide Recycle - Two D_2O Reactor Cases

Actinides from LWR Fuel - U Diluent (Group 1)

All GLASS calculations for Group 1 cases were done with 84 neutron energy groups. The fuel parameters are shown in the last column of Table 1.[8] The fuel rod arrangement was a 17 x 17 square pattern with a rod pitch of 0.496 inch. The pitch used in the calculations was 5% larger, to mock up H_2O in empty rod positions in the fuel bundle. A unit cell consisted of H_2O moderator, cladding, and one fuel rod. The end-of-life exposure was 33,000 MWD/MTM (MTM is the mass of U-metal at zero exposure).

The calculated beginning and ending actinide contents of the base-case fuel are shown in Table A.1. The initial ^{235}U enrichment was 3.2%. The total Pu content was 0.101 x 10^5 g/MTM of which 56.9% was ^{239}Pu; actinides other than U and Pu totaled 782 g/MTM. Cooling time after shutdown was one year.

Case 1.1

The waste actinides (no U or Pu) from one LWR fuel rod were charged to a new fuel rod for 3 years of irradiation to 33,000 MWD/MTM. After a one year cooling and recovery period, all waste actinides were again recycled. Five such recycles were conducted. The initial ^{235}U content was 3.2% each time. Results are given in Table A.2 and Figure 10.

The ^{237}Np and ^{243}Am concentrations equilibrated after five recycles, but the higher isotopes of Cm and Cf were still increasing. The Pu assay was changed from the base value, with the ^{238}Pu component raised from 1.7% to 5.0%. The waste actinide inventory after five recycles was 1488 g/MTM compared to 4690 g/MTM that would have accumulated without recycle. This is a ratio of 0.32. However, the fraction of waste actinides fissioned after five recycles was only about 15%, because all the ^{237}Np transmuted to Pu was removed after each fuel cycle in this option.

A static reactivity calculation showed that the reactivity loss resulting from the presence of the waste actinides in recycle 5 could be compensated for by increasing the initial ^{235}U content from 3.2% to 3.4%. Also, the relatively dilute concentrations of the waste actinides assured that self-shielding of the resonance capture cross sections was not an important consideration in calculating transmutation rates.

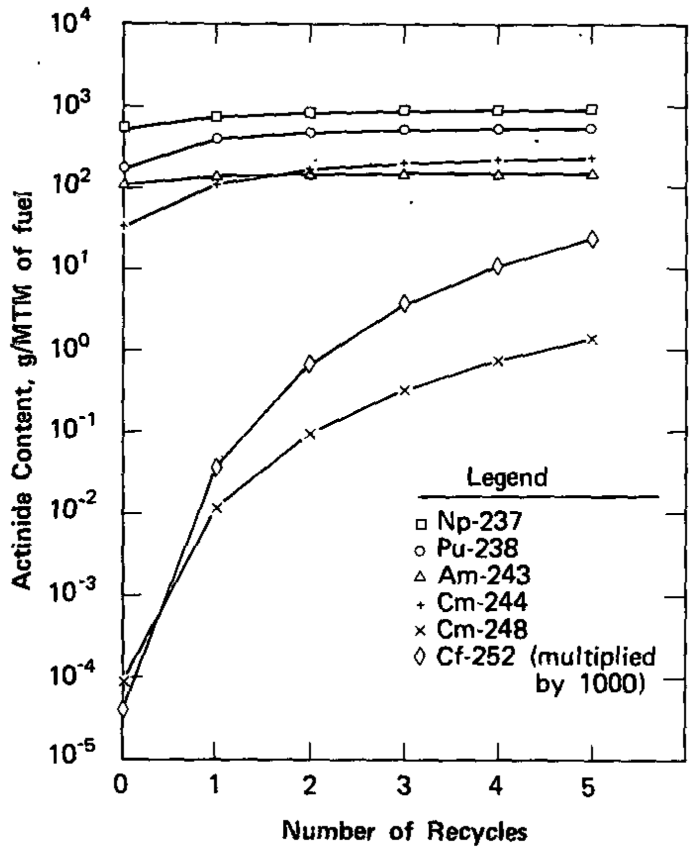


FIGURE 10. Waste Actinides from each LWR U-Assembly Recycled into New Assembly - Case 1.1

Case 1.2

All the actinides from one fuel rod were charged to a new U-fuel rod. The ^{235}U content was adjusted to give an initial k_∞ value of 1.10. Irradiation was carried to 33,000 MWD/MTM. After a one year cooling and recovery period, all actinides were again recycled; five such recycles were conducted. The starting ^{235}U required to yield a k_∞ value of 1.10 was as follows for each recycle: 2.0%, 2.6%, 2.8%, 3.2%, and 3.3%, respectively. The increase resulted from both the changing Pu isotopic fractions and the waste actinide recycle. Cycle-ending contents are given in Table A.3 and Figure 11.

None of the actinide concentrations equilibrated after five recycles, and the higher isotopes of Cm and Cf were still increasing rapidly. The ^{238}Pu fraction of the Pu assay increased from 2% at the start to 13% at the end of recycle 5. The actinide inventory (excluding U) after five recycles was 0.329×10^5 g/MTM compared to 0.653×10^5 g/MTM that would have accumulated without recycle. This ratio is 0.50. The remaining 50% of the actinides were fissioned.

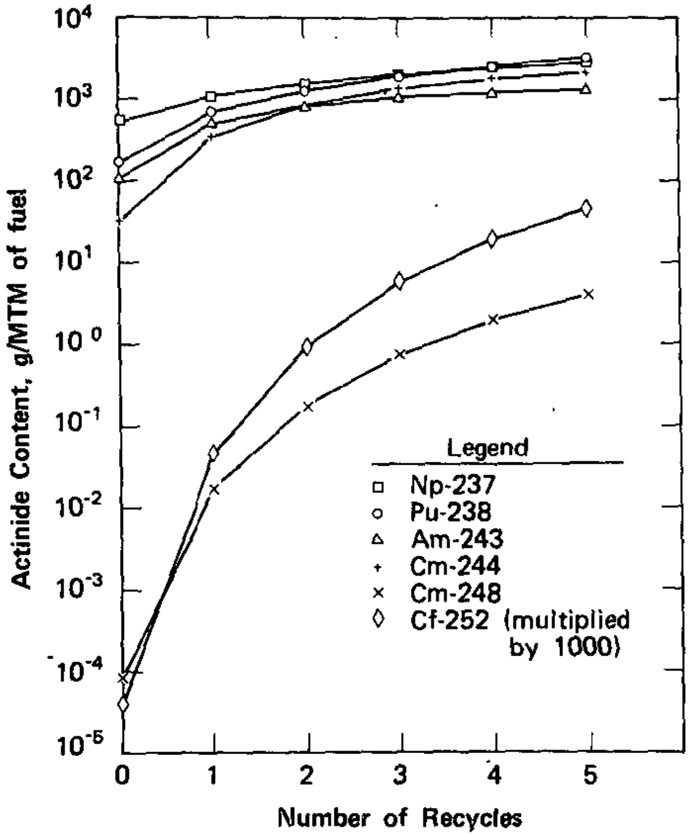


FIGURE 11. All Actinides from each LWR U-Assembly Recycled into New Assembly with Variable ^{235}U - Case 1.2

Case 1.3

All the actinides except U from five fuel rods were charged to one rod of natural U. After irradiation to 33,000 MWD/MTM and a one year cooling-recovery period, the actinides were added to those from five additional fuel rods for recycle. Initial reactivity values for five recycles were as follows: 1.11, 1.11, 1.12, 1.13, and 1.15, respectively. Cycle ending contents are given in Table A.4 in units of g/MTM of the fuel supplying the waste actinides.

The actinide inventory (excluding U) after five recycles was 0.408 x 10^5 g/MTM compared to 0.544 x 10^5 g/MTM that would have accumulated without recycle. This is a ratio of 0.75. This case is impractical for any extended operation because the new Pu added from the five regular fuel rods at the start of each recycle far exceeded the Pu burned, and the Pu content increased to unacceptable values. If the number of fuel rods supplying Pu was reduced below five, the reactivity values were too low.

Case 1.4

The waste actinides (no U or Pu) from 20 LWR fuel rods were charged to one rod of depleted U. The target rod was placed in an environment of standard, 3.2% ^{235}U fuel rods for 3 years of irradiation. The unit cell for GLASS calculations was a 3 x 3 array of clad rods in H_2O moderator. After a one year cooling-recovery period, all the remaining actinides in the target rod were added to the waste actinides from 20 additional fuel rods for recycle. After five recycles, the power of the target rod had equilibrated to a value 20% greater than the power of the regular fuel rods.

Cycle ending contents are given in Table A.5 and Figure 12 in units of g/MTM of the fuel supplying the waste actinides. The actinide inventory (excluding U) after five recycles was 3080 g/MTM compared to 3910 g/MTM that would have accumulated without recycle. This is a ratio of 0.79. The ratio is greater than 1.0 until after three recycles because of the "unwanted" Pu produced in the depleted U diluent.

Comparison of Cases in Group 1

There are several criteria that can be used to judge the merits of the four cases described. These considerations are listed below, with yes and no votes applied as appropriate. The statements are worded such that a yes vote is favorable.

Criterion	*Case* 1.1	1.2	1.3	1.4
• Uranium used as diluent	yes	yes	yes	yes
• Actinides fission rate acceptable	no	yes	no	no
• Disposal of Pu provided for	no	yes	yes	no
• Actinides present in "manageable" amounts	yes	yes	no	yes
• Most of fuel fabrication uncontaminated by actinides	no	no	yes	yes
• Only one type of rod in fuel bundle	yes	yes	yes	no

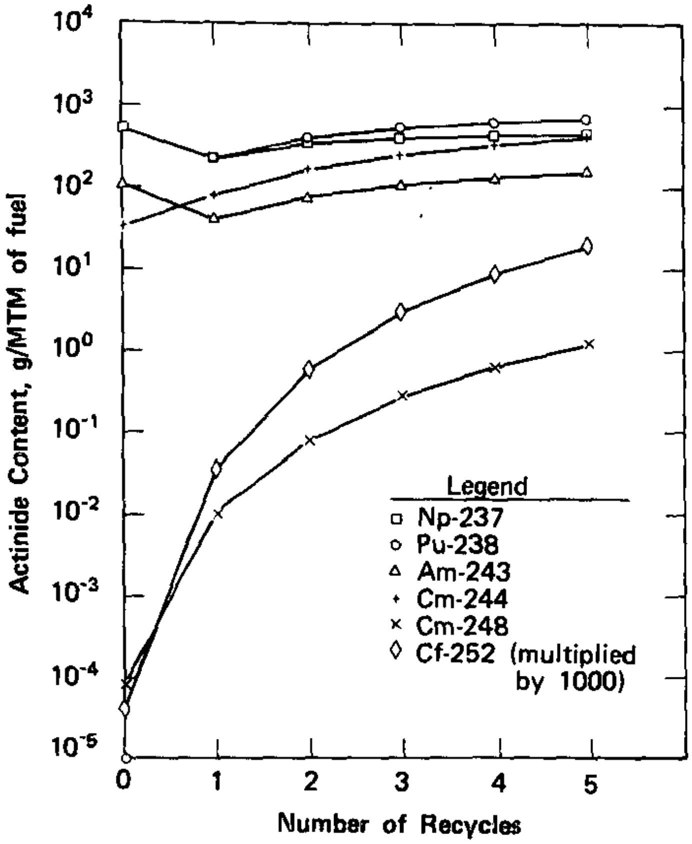


FIGURE 12. Waste Actinides from 20 LWR U-Fuel Rods Recycled into One Target Rod of Depleted U - Case 1.4

The third criterion is important if the Pu produced in an LWR fuel cycle has no future application, e.g., in a breeder reactor or a U/Pu fueled reactor. In Cases 1.1 and 1.4, the Pu was not recycled, so a stockpile would accumulate for disposal by some other means. In Cases 1.2 and 1.3, the Pu cycle was "closed" in that all Pu is returned for fission.

The fourth criterion implies that the recycled actinides were present in amounts that would not require major revision to fuel fabrication technology or reactor operation. Case 1.3 is unacceptable because of the relatively large amounts of Pu present.

Case 1.2 is the most attractive option of the four. The only negative consideration is the contamination of all the recycled fuel with radioactive actinides; this necessitates shielding in fuel fabrication facilities. One simplifying assumption made in evaluating Case 1.2 was that pure ^{235}U would be available. The ratio of ^{238}U to ^{235}U will in fact be about four. The volume occupied by the additional ^{238}U is about 7%

of the total volume and this necessitates some holdup of the actinide inventory in successive recycles. This case will be pursued further in later studies.

Actinides from LWR Fuel - Zirconium Diluent (Group 2)

The waste actinides to be disposed of were the same as those considered in the Group 1 calculations (Table A.1). However, zirconium was used as the diluent, and target rods containing actinides were included in the fuel assembly. The difficulties introduced into the chemical recovery operations by the zirconium were recognized; however, the burnup calculations were useful in evaluating actinide fission rates in separate target rods where the diluent is inert. The results are applicable for any other diluent material having a low neutron absorption cross section.

All GLASS calculations for Group 2 cases were done in 84 neutron energy groups. The unit cell was a 3 x 3 array of clad rods in H_2O moderator; eight regular LWR fuel rods surrounded the target rod.

Case 2.1

The waste actinides (no U or Pu) from 100 LWR fuel rods were charged to one target rod of zirconium. The target rod was placed in an environment of standard 3.2% ^{235}U fuel rods for 3 years of irradiation. After a one year cooling-recovery period, all remaining actinides in the target rod were added to the waste actinides from 100 additional fuel rods for recycle. Five such recycles were conducted. Cycle ending contents are given in Table A.6.

The total actinide inventory after 5 recycles was 63% of the inventory if there were no recycle, i.e., 37% of the actinides were fissioned. The ratio of the thermal neutron flux in the target to that in the adjacent fuel rods was 0.67. However, this case is not acceptable because the target rod power was excessive. After five recycles, the power of the target rod exceeded the fuel power by 50%, and had not equilibrated.

Case 2.2

This case differs from the preceding one in that the source of waste actinides was 50 fuel rods rather than 100. Cycle ending contents are given in Table A.7 and Figure 13. Forty-six percent of the waste actinides were fissioned after five recycles. The ratio of target to fuel rod thermal neutron flux was 0.90. The ratio of target to fuel rod power was 0.90 after five recycles and would equilibrate at about 1.1. Actinides in the target rod were primarily ^{237}Np, ^{238}Pu, ^{243}Am and ^{244}Cm.

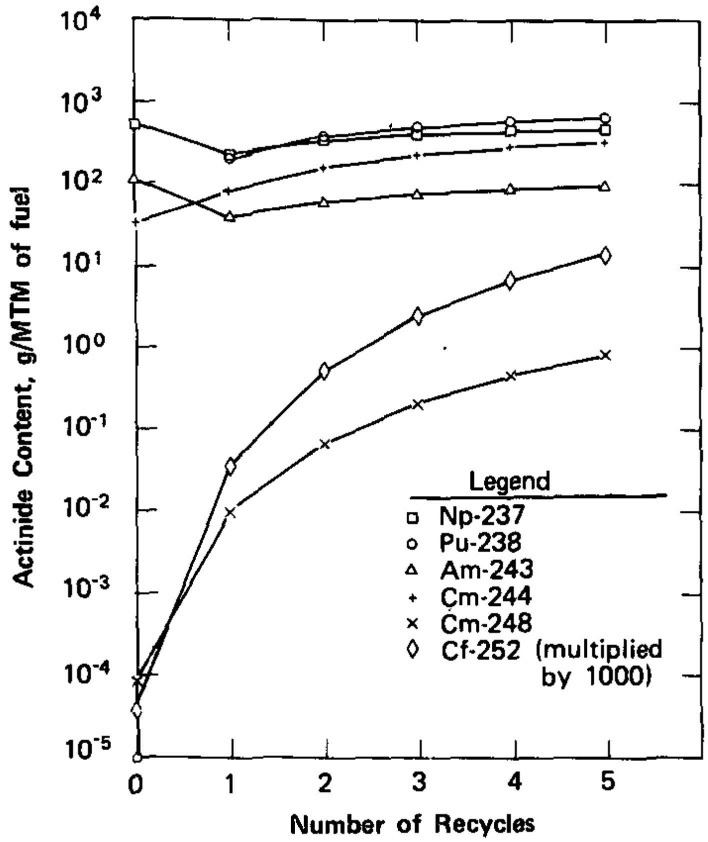


FIGURE 13. Waste Actinides from 50 LWR U-Fuel Rods Recycled into One Target Rod of Zirconium - Case 2.2

Case 2.3

The waste actinides (no U or Pu) from 50 LWR fuel rods were charged to one target rod of zirconium. The target rod was irradiated for ten consecutive fuel cycles without interruption in an environment of standard 3.2% ^{235}U fuel rods. Cycle-ending contents are shown in Table A.8 and Figure 14. Ninety-six percent of the actinides were fissioned during ten cycle (30 year) irradiation. By the tenth recycle transuranic nuclides through ^{247}Cm were decreasing with exposure.

Comparison of Cases in Group 2

Cases 2.2 and 2.3 each constitute a reasonable method for fissioning the waste actinides in separate target rods. About 10% of the actinides present were fissioned each fuel cycle. The irradiation of the same target rod for several consecutive fuel cycles may not be feasible because of irradiation damage to the zirconium clad. Special disassembly techniques would be required to separate target rods from regular fuel rods before shearing.

The reactivity of a lattice containing five target rods per fuel assembly (Case 2.2) would be reduced by about 2% Δk_∞ after five recycles. The five target rods could accommodate all the recycled waste actinides of one fuel assembly.

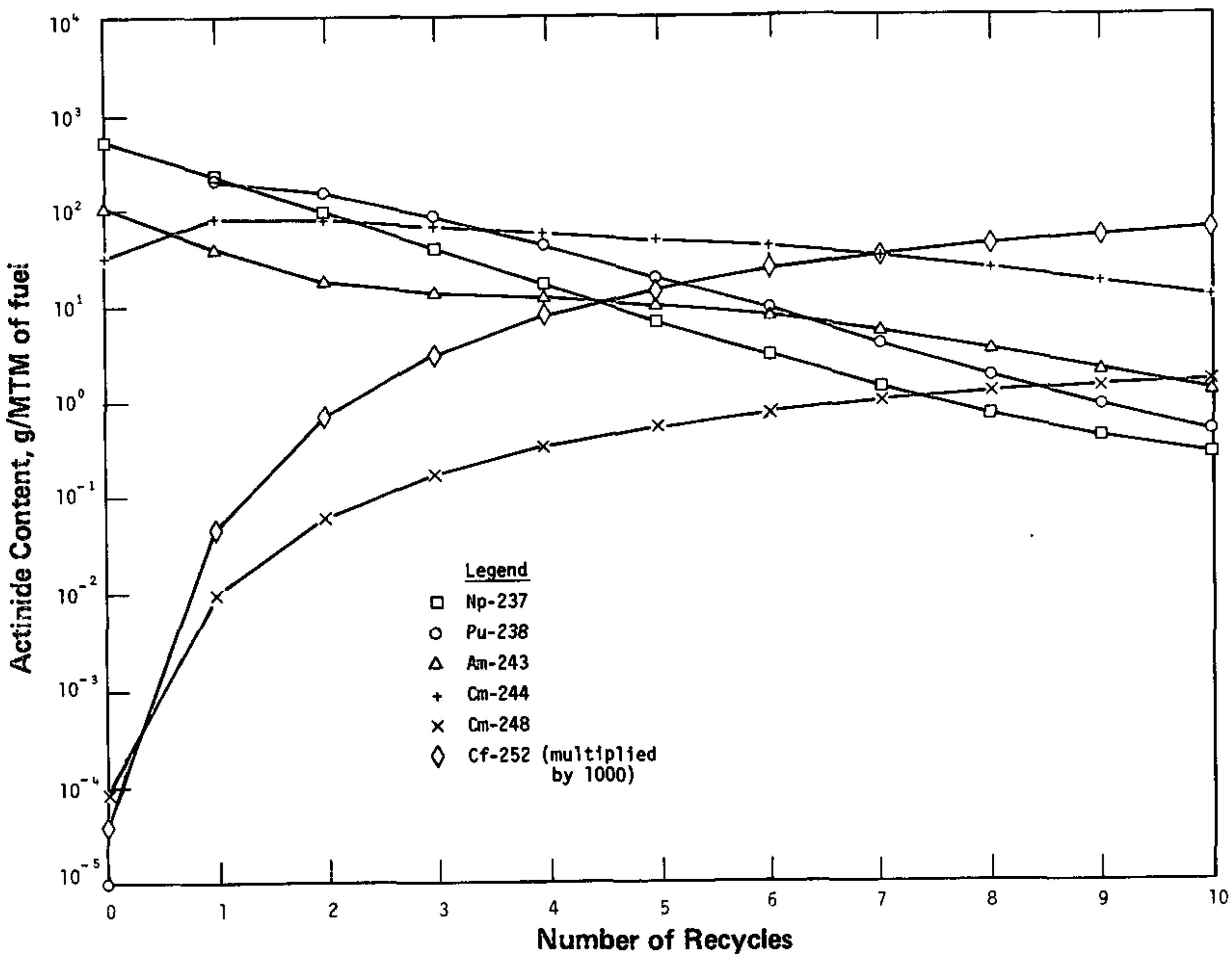


FIGURE 14 Waste Actinides from 50 LWR U-Fuel Rods Irradiated for Ten Consecutive Fuel Cycles - Case 2.3

Actinides from Advanced-Charge Design (Group 3)

Two advanced-charge design types were investigated. They were a mixed U/Pu lattice and a Th lattice enriched in ^{233}U and ^{235}U. In Cases 3.1 and 3.2 a separate target assembly with actinides was irradiated in a lattice of U and Pu fuel assemblies. In Case 3.3, the waste actinides from Th/U fuel were homogeneously mixed with the fuel for recycle. This mixing is similar to Case 1.1.

Case 3.1

Figure 8 shows the flow diagram for this case. It was assumed that the reactor charge was made of U and U/Pu assemblies with the initial contents given in Tables A.1 and A.9, respectively. The initial contents of each type were the same for all recycles. The waste actinides (no U or Pu) from the U and U/Pu assemblies were combined into one separate target assembly with zirconium diluent. After one fuel cycle, all remaining actinides in the target were recovered and combined with a new batch of waste actinides for the next recycle.

A cylindricized model of a complete LWR assembly was developed for use in the GLASS code. (In all cases considered in the Group 1 or 2 options, a cell consisted of either a single fuel rod or eight fuel rods surrounding a target rod.) Geometry restrictions require that a full assembly in an array of assemblies be approximated by concentric rings of clad, fuel and coolant. The chosen model consisted of eight fuel rings, each having a core width equal to the radius of one fuel rod to preserve the surface to volume (S/4V) ratio of the rod geometry. Spaces between the fuel rings were filled with H_2O coolant.

The beginning and ending reactivity calculated for the annular model of an LWR U-assembly differed from that for a single U-fuel rod cell by only 0.4% k_∞. Also, the actinide content per metric tonne of U at 33,000 MWD/MTM agreed well with that calculated for the single rod. Thus, actinide depletion rates could be accepted with confidence if the rates were calculated by using the annular model.

The supercell used for recycle calculations consisted of an actinide target assembly surrounded by four U assemblies and four U/Pu assemblies. Because of symmetry restrictions in the model, the two to one ratio of U to U/Pu assemblies in the lattice could have been achieved only at the expense of excessive computer time. All calculations were done using 37 neutron energy groups.

Initial static reactivity calculations showed that if the target assembly contained actinides in the innermost fuel positions, the thermal neutron flux was strongly depressed in the center. To achieve higher fluxes and higher transmutation rates in the target material, waste actinides were loaded only in the outer positions of the cell. The outer positions comprise about 65% of the total fuel volume available. The inner positions contained H_2O.

The waste actinide content of the two types of fuel assemblies at the end of one 3-year cycle are compared in Table A.10. Column 1 lists the contents calculated when using the single rod model for U (Case 1.1, Table A.1). Columns 2 and 3 give contents calculated in the U and U/Pu assemblies when using the nine assembly model. Waste actinides in the U/Pu assembly are about four times those in the U assembly. The ^{237}Np content is about one-third that of the U assembly, but the Am and Cm contents are 10 to 100 times that of the U assembly.

The waste actinides from five U and two and one-half U/Pu assemblies were combined in one target assembly for recycle. Calculated contents of the target assembly at the end of each recycle are given in Table A.11 and Figure 15. Fifty-four percent of the waste actinide inventory was fissioned. The Pu assay is made up primarily of the even numbered Pu isotopes; the fissile isotopes comprise only 14% of the total Pu after five recycles.

The specific power of the waste actinide assembly was only one-third that of the fuel assemblies after five recycles. Thus, the actinide loading could be increased to reduce the total number of target assemblies required in the lattice. The resulting penalty is depression of the thermal neutron flux in the target and increased resonance self-shielding; both effects reduce the rate of actinide fissions.

The fission power of the U/Pu assembly was about 10% greater than the fission power of the U assembly.

Case 3.2

In this case waste actinides were supplied by 20 U and 10 U/Pu fuel assemblies (Case 3.1 had five U and two and one-half U/Pu.) The specific power of the target assembly was equal to that of the fuel assemblies after five recycles and was approaching equilibrium.

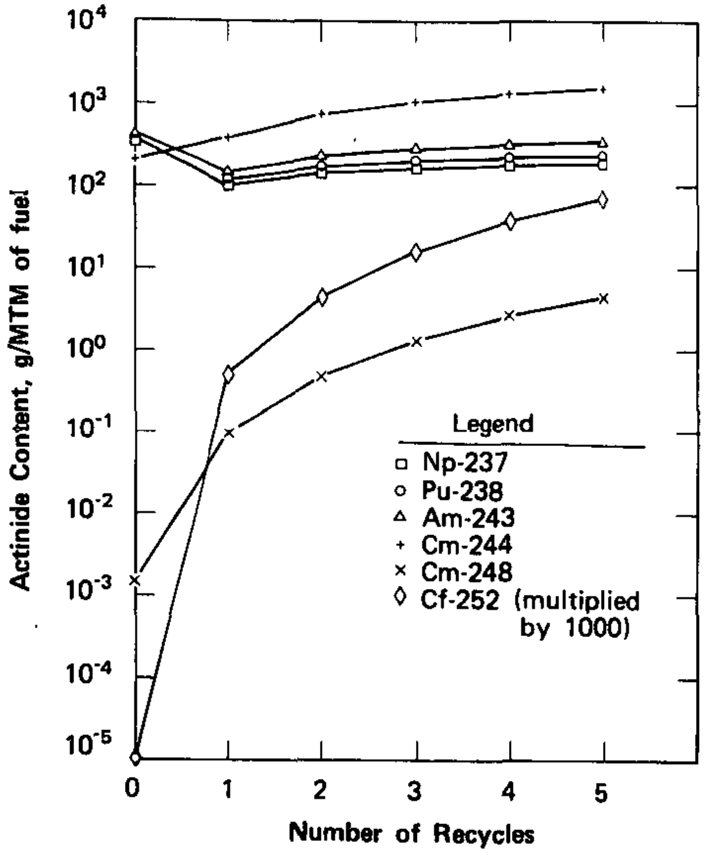


FIGURE 15. Waste Actinide Content of Light Target Assembly in U/Pu Lattice - Case 3.1

Calculated contents of the target assembly are given in Table A.12 and Figure 16. Only 25% of the actinides were fissioned. Because equilibrium content values were not reached after five recycles, it is improper to conclude that the long term fission rate for Case 3.2 is only half that for Case 3.1. However, the results do show that the transmutation rate is very sensitive to the waste actinide loading of a separate target assembly.

Case 3.3

This case approximates the irradiation conditions expected in a thorium lattice enriched in ^{233}U and ^{235}U. A single fuel rod was used to represent the assembly, which was a composite of the U loadings predicted for a lattice containing both ^{233}U-enriched and ^{235}U-enriched Th assemblies.[9]

Initial U Content of Composite Rod

Isotope	*Wt %*
^{233}U	1.8
^{234}U	0.9
^{235}U	2.1
^{236}U	1.3
^{238}U	0.2

After irradiation to 33,000 MWD/MTM and recovery, all actinides except U were recycled into a new rod. The initial U content was the same for all five recycles. Ending contents are given in Table A.13.

The ^{238}Pu content after five recycles is relatively high (2570 g/MTM). The high initial ^{236}U content (1.3%) promotes the production of ^{237}Np and ^{238}Pu. The ^{248}Cm content is lower than for any other case studied, because of the reduced quantities of total Pu and Am. Forty-eight percent of the actinides (excluding U) were fissioned in five recycles.

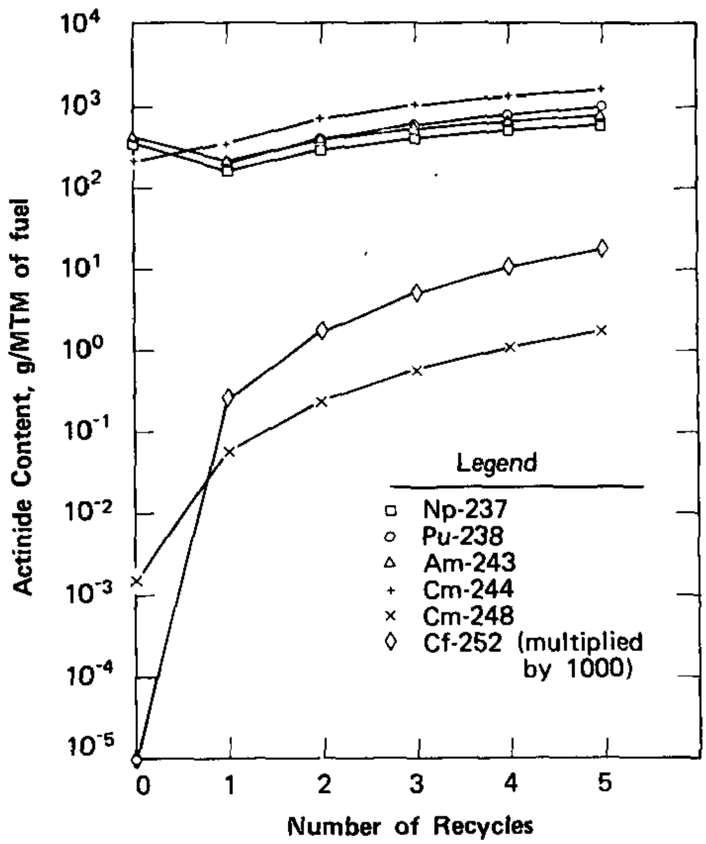


FIGURE 16. Waste Actinide Content of Heavy Target Assembly in U/Pu Lattice - Case 3.2

A static reactivity calculation showed that the reactivity loss resulting from the waste actinides in recycle 5 could be compensated for by increasing the initial ^{233}U content from 1.8% to 2.2%.

Actinides Irradiated in D_2O Reactors (Group 4)

Case 4.1

If waste actinides (excluding U and Pu) from LWR fuel were irradiated in a Savannah River production reactor, significantly higher fission rates could be achieved than in any standard LWR reactor.

The waste actinides from 100 LWR fuel rods were charged to one aluminum target rod, which was placed in a 13 foot tubular fuel assembly containing 3300 g ^{235}U. The fuel assembly was operated at a power of 6.5 MW for 10 months, or about 70% burnup. After a one year cooling period, the waste actinides were recovered and added to waste actinides from an additional 100 LWR fuel rods for recycle. Five recycles were conducted. Ending contents are given in Table A.14 and Figure 17.

Recycle 5 contents for this case are very similar to those for Case 2.1, in which actinides from 100 fuel rods were irradiated in a separate target in a LWR lattice. However, the total elapsed time for Case 4.1 is only nine years and for Case 2.1 it is twenty years. In Case 4.1 thirty-five percent of the actinides were fissioned; and the ratio of target power to fuel power was 0.08 at the end of recycle 5. A more efficient mode of operation is to extend the irradiation of a target to several fuel cycles, and thus reduce time out of the reactor.

The use of any high power density reactor for fissioning the waste actinides introduces additional considerations into the transmutation concept. Even if existing reactors were used, new designs for fuel and target as well as means for shipping components would be required. Unless a new reactor design provides for the generation of steam or electricity, the cost of operating the reactor would probably be charged to the actinide program. In an SRP reactor, the energy from both the ^{235}U fissions and the waste actinide fissions would be discharged as waste heat. Perhaps the production of special isotopes such as ^{238}Pu, ^{244}Cm, or ^{60}Co could help defray the cost.

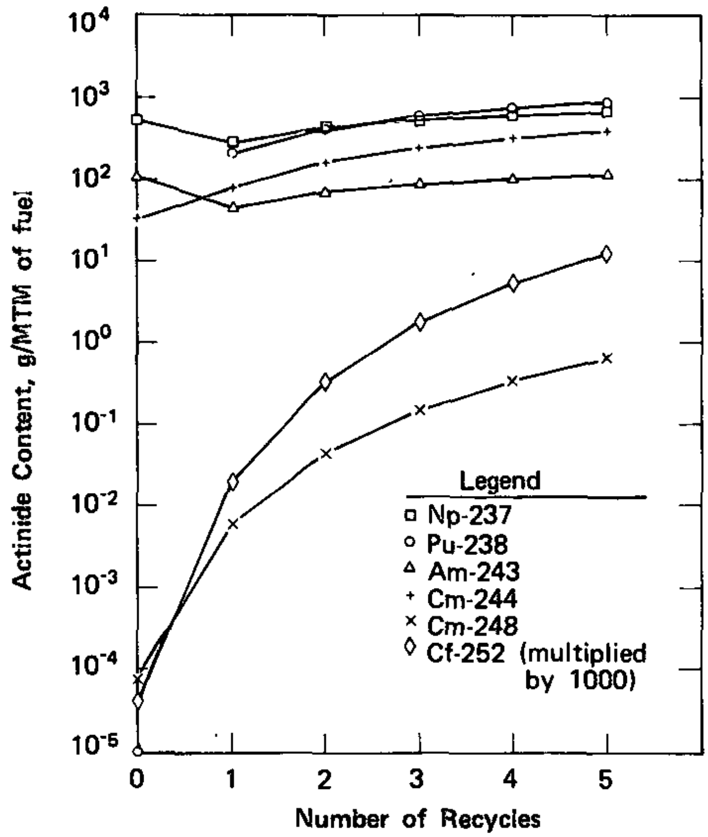


FIGURE 17. Waste Actinides from 100 LWR U-Fuel Rods Recycled into Target in SRP Lattice - Case 4.1

Case 4.2

Actinide production and transmutation calculations were made for the CANDU-Pickering lattice. Figure 18 shows the fuel rod configuration in the assembly. A cylindricized model was developed to represent the 28 fuel rods as three concentric rings for GLASS calculations. Columns 1 and 2 in Table A.15 show the beginning and ending contents of natural uranium fuel irradiated to 8000 MWD/MTM for about 1.2 years. Ending contents have been cooled one year.

Initial CANDU fuel contents for a Pu recycle mode were obtained from Reference 10. The beginning and ending contents, at an exposure of 8000 MWD/MTM, are given in Table A.15. Boron at 20 ppm was added to the D_2O moderator to reduce the reactivity to equal that calculated for the natural uranium lattice. The waste actinides (no U or Pu) from one assembly were charged to a new assembly for irradiation. After a one year period for cooling and recovery, all waste actinides were again recycled. Five such recycles were conducted. The initial U and Pu contents were the same each time. Results are given in Table A.16 and Figure 19.

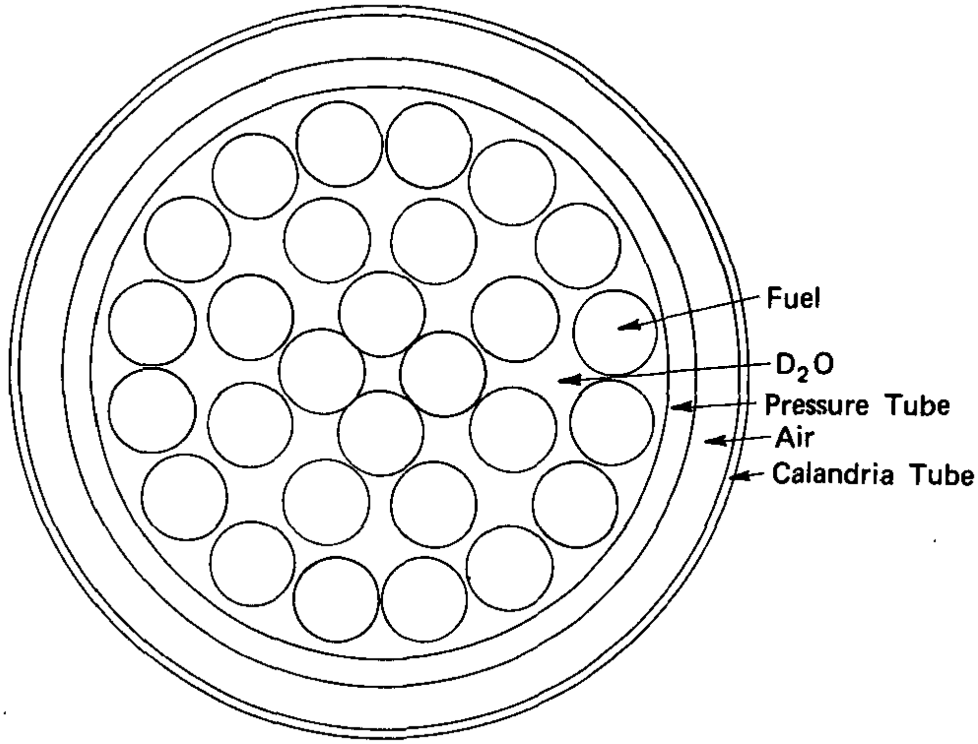


FIGURE 18. CANDU-Pickering Assembly

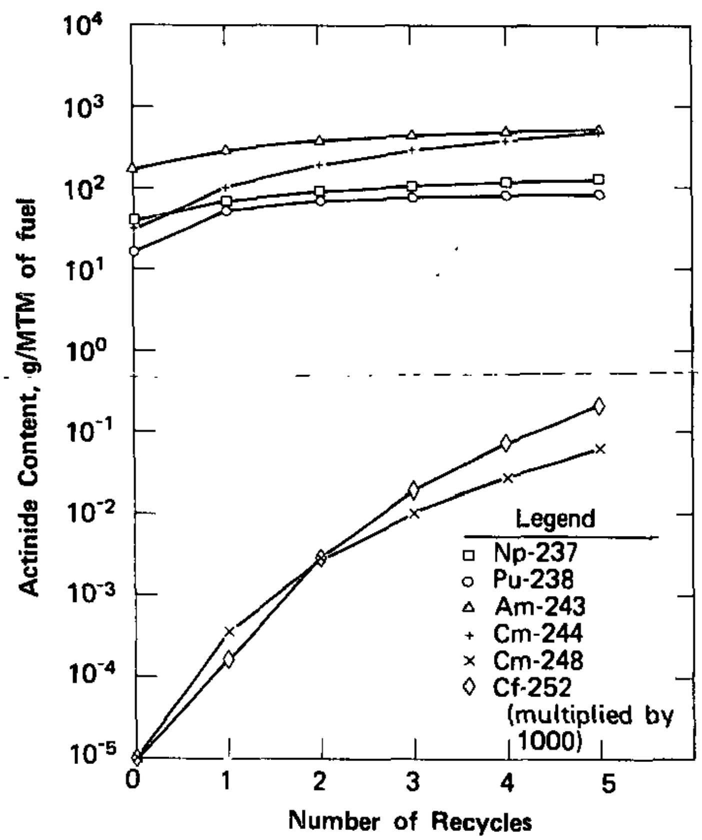


FIGURE 19. Waste Actinides from Each CANDU U/Pu Assembly Recycled into New Assembly - Case 4.2

As in the Pu-enriched Cases 3.1 and 3.2 the ^{237}Np fraction of waste actinides is very low (∿10%). As a result, the ^{238}Pu fraction of the Pu is also low (<1%). About 34% of the waste actinides were fissioned in five recycles. The reactivity loss resulting from the addition of the waste actinides was 1.6% in k_∞ after five recycles, but removal of 13% of the boron in the D_2O moderator restored the k_∞ to its base-case value.

FUTURE STUDY

Of the four cases in which actinides were recycled in some type of U-assembly (Group 1, Figure 6). Case 1.2 was the most attractive. All actinides including Pu were recycled, i.e., the system was "closed". In addition to being an effective waste management alternative, this case is also desirable for safeguards or non-profileration considerations. The Pu isotopes are always diluted by U, and therefore would be more difficult to recover for weapons production. Case 1.2 will be examined more in future studies.

Irradiation of actinides in target rods in a U-fuel assembly (Group 2, Figure 7), would be difficult because special handling is required during assembly and disassembly of the fuel rod bundle. All irradiated fuel assemblies containing several target rods would require partial disassembly before shearing. No further work is planned for Group 2 cases.

If Pu material will not be fissioned with the waste actinides, the use of separate target assemblies is attractive (Group 3, Figure 8). Fuel and target materials must be kept separated, but an entire target assembly could be processed without special disassembly measures. The use of zirconium as a diluent is the major disadvantage. Recycle of waste actinides in a separate target in mixed U/Pu lattices will be examined more in future studies.

TABLE A.1

Beginning and Ending Actinide Content of Base-Case LWR Fuel, g/MTM

	BEGIN	END	(ONE YEAR DECAY)
U232	0.0	0.5239D-03	
U233	0.0	0.1803D-04	
U234	0.2894D 03	0.1536D 03	
U235	0.3200D 05	0.8136D 04	
U236	0.0	0.4008D 04	
U238	0.9677D 06	0.9428D 06	
NP237	0.0	0.5225D 03	
PU236	0.0	0.1090D-02	
PU238	0.0	0.1728D 03	
PU239	0.0	0.5744D 04	
PU240	0.0	0.2362D 04	
PU241	0.0	0.1269D 04	
PU242	0.0	0.5507D 03	
PU244	0.0	0.2311D-01	
AM241	0.0	0.1111D 03	
AM242M	0.0	0.7269D 00	
AM243	0.0	0.1090D 03	
CM242	0.0	0.3367D 01	
CM243	0.0	0.3456D 00	
CM244	0.0	0.3319D 02	
CM245	0.0	0.1810D 01	
CM246	0.0	0.1941D 00	
CM247	0.0	0.1934D-02	
CM248	0.0	0.8435D-04	
BK249	0.0	0.4725D-06	
CF249	0.0	0.7200D-06	
CF250	0.0	0.2894D-06	
CF251	0.0	0.1070D-06	
CF252	0.0	0.3916D-07	
SUM U	0.1000D 07	0.9551D 06	
SUM PU	0.0	0.1010D 05	
SUM ACT	0.0	0.7823D 03	
SUM ALL	0.1000D 07	0.9660D 06	

TABLE A.2

Waste Actinides From Each LWR U-Assembly Recycled Into New Assembly - Case 1.1

	ENDING CONTENTS, G/MTM					
	BASE CASE	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
U232	0.5239D-03	0.1329D-02	0.1685D-02	0.1835D-02	0.1897D-02	0.1931D-02
U233	0.1803D-04	0.7674D-04	0.1021D-03	0.1130D-03	0.1178D-03	0.1198D-03
U234	0.1536D 03	0.1583D 03	0.1596D 03	0.1603D 03	0.1609D 03	0.1609D 03
U235	0.8136D 04	0.8235D 04	0.8275D 04	0.8300D 04	0.8313D 04	0.8320D 04
U236	0.4008D 04	0.3998D 04	0.3993D 04	0.3993D 04	0.3985D 04	0.3985D 04
U238	0.9428D 06	0.9420D 06	0.9417D 06	0.9415D 06	0.9414D 06	0.9414D 06
NP237	0.5225D 03	0.7469D 03	0.8425D 03	0.8834D 03	0.9039D 03	0.9107D 03
PU236	0.1090D-02	0.2241D-02	0.2740D-02	0.2958D-02	0.3047D-02	0.3095D-02
PU238	0.1728D 03	0.3988D 03	0.4788D 03	0.5129D 03	0.5266D 03	0.5341D 03
PU239	0.5744D 04	0.5859D 04	0.5898D 04	0.5917D 04	0.5923D 04	0.5923D 04
PU240	0.2362D 04	0.2385D 04	0.2397D 04	0.2404D 04	0.2404D 04	0.2403D 04
PU241	0.1269D 04	0.1281D 04	0.1288D 04	0.1294D 04	0.1294D 04	0.1294D 04
PU242	0.5506D 03	0.5564D 03	0.5555D 03	0.5547D 03	0.5547D 03	0.5546D 03
PU244	0.2311D-01	0.2405D-01	0.2397D-01	0.2397D-01	0.2397D-01	0.2390D-01
AM241	0.1111D 03	0.1165D 03	0.1178D 03	0.1178D 03	0.1178D 03	0.1185D 03
AM242M	0.7269D 00	0.8360D 00	0.8494D 00	0.8560D 00	0.8560D 00	0.8559D 00
AM243	0.1090D 03	0.1405D 03	0.1480D 03	0.1500D 03	0.1500D 03	0.1500D 03
CM242	0.3367D 01	0.4536D 01	0.4596D 01	0.4616D 01	0.4615D 01	0.4615D 01
CM243	0.3456D 00	0.6825D 00	0.7055D 00	0.7122D 00	0.7122D 00	0.7121D 00
CM244	0.3319D 02	0.1096D 03	0.1658D 03	0.1993D 03	0.2184D 03	0.2287D 03
CM245	0.1810D 01	0.1014D 02	0.1706D 02	0.2130D 02	0.2369D 02	0.2499D 02
CM246	0.1941D 00	0.3830D 01	0.1171D 02	0.2205D 02	0.3328D 02	0.4458D 02
CM247	0.1934D-02	0.9799D-01	0.4500D 00	0.1061D 01	0.1856D 01	0.2732D 01
CM248	0.8434D-04	0.1151D-01	0.9453D-01	0.3274D 00	0.7601D 00	0.1397D 01
BK249	0.4725D-06	0.9867D-04	0.9453D-03	0.3500D-02	0.8423D-02	0.1589D-01
CF249	0.7200D-06	0.1672D-03	0.1678D-02	0.6376D-02	0.1554D-01	0.2951D-01
CF250	0.2894D-06	0.8976D-04	0.9932D-03	0.3917D-02	0.9724D-02	0.1869D-01
CF251	0.1070D-06	0.4358D-04	0.5247D-03	0.2144D-02	0.5417D-02	0.1055D-01
CF252	0.3916D-07	0.3584D-04	0.6850D-03	0.3616D-02	0.1082D-01	0.2356D-01
SUM U	0.9551D 06	0.9544D 06	0.9541D 06	0.9539D 06	0.9539D 06	0.9538D 06
SUM PU	0.1010D 05	0.1048D 05	0.1062D 05	0.1068D 05	0.1070D 05	0.1071D 05
SUM ACT	0.7823D 03	0.1134D 04	0.1310D 04	0.1401D 04	0.1456D 04	0.1488D 04
SUM ALL	0.9660D 06	0.9660D 06	0.9660D 06	0.9660D 06	0.9660D 06	0.9660D 06

TABLE A.3

All Actinides From Each LWR U-Assembly Recycled Into New Assembly With Variable U-235 - Case 1.2

		ENDING CONTENTS, G/MTM				
	START RECY1	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
U232	0.5239D-03	0.2290D-02	0.4409D-02	0.6528D-02	0.8640D-02	0.1070D-01
U233	0.1803D-04	0.1495D-03	0.3230D-03	0.4958D-03	0.6610D-03	0.8229D-03
U234	0.1536D 03	0.9052D 02	0.7749D 02	0.8777D 02	0.1125D 03	0.1467D 03
U235	0.1978D 05	0.5314D 04	0.9168D 04	0.1104D 05	0.1404D 05	0.1646D 05
U236	0.4008D 04	0.5726D 04	0.7749D 04	0.9614D 04	0.1156D 05	0.1350D 05
U238	0.9652D 06	0.9386D 06	0.9279D 06	0.9199D 06	0.9111D 06	0.9030D 06
NP237	0.5225D 03	0.1097D 04	0.1591D 04	0.2043D 04	0.2469D 04	0.2880D 04
PU236	0.1090D-02	0.3696D-02	0.6322D-02	0.8915D-02	0.1145D-01	0.1399D-01
PU238	0.1728D 03	0.6995D 03	0.1303D 04	0.1941D 04	0.2599D 04	0.3278D 04
PU239	0.5744D 04	0.6549D 04	0.7769D 04	0.8688D 04	0.9676D 04	0.1055D 05
PU240	0.2362D 04	0.3442D 04	0.3874D 04	0.4272D 04	0.4615D 04	0.4944D 04
PU241	0.1269D 04	0.1941D 04	0.2366D 04	0.2688D 04	0.2990D 04	0.3264D 04
PU242	0.5506D 03	0.1618D 04	0.2297D 04	0.2784D 04	0.3120D 04	0.[illegible]374D 04
PU244	0.2311D-01	0.1467D 00	0.2976D 00	0.4546D 00	0.6007D 00	0.7337D 00
AM241	0.1111D 03	0.1982D 03	0.2750D 03	0.3360D 03	0.4012D 03	0.4649D 03
AM242M	0.7269D 00	0.1749D 01	0.3127D 01	0.4348D 01	0.5870D 01	0.7475D 01
AM243	0.1090D 03	0.5081D 03	0.8503D 03	0.1090D 04	0.1255D 04	0.1371D 04
CM242	0.3367D 01	0.9943D 01	0.1330D 02	0.1570D 02	0.1762D 02	0.1954D 02
CM243	0.3456D 00	0.1543D 01	0.2167D 01	0.2633D 01	0.2983D 01	0.3312D 01
CM244	0.3319D 02	0.3504D 03	0.8572D 03	0.1378D 04	0.1831D 04	0.2201D 04
CM245	0.1810D 01	0.3031D 02	0.9600D 02	0.1742D 03	0.2558D 03	0.3319D 03
CM246	0.1941D 00	0.7817D 01	0.3484D 02	0.8366D 02	0.1467D 03	0.2194D 03
CM247	0.1934D-02	0.1735D 00	0.1207D 01	0.3861D 01	0.8297D 01	0.1447D 02
CM248	0.8435D-04	0.1687D-01	0.1797D 00	0.7680D 00	0.2057D 01	0.4210D 01
BK249	0.4725D-06	0.1454D-03	0.1899D-02	0.9120D-02	0.2613D-01	0.5630D-01
CF249	0.7200D-06	0.2428D-03	0.3484D-02	0.1755D-01	0.5294D-01	0.1186D 00
CF250	0.2894D-06	0.1275D-03	0.1879D-02	0.9600D-02	0.2873D-01	0.6391D-01
CF251	0.1070D-06	0.6117D-04	0.1049D-02	0.5870D-02	0.1893D-01	0.4450D-01
CF252	0.3916D-07	0.4553D-04	0.9532D-03	0.5993D-02	0.1995D-01	0.4752D-01
SUM U	0.9891D 06	0.9497D 06	0.9449D 06	0.9407D 06	0.9368D 06	0.9331D 06
SUM PU	0.1010D 05	0.1425D 05	0.1761D 05	0.2037D 05	0.2300D 05	0.2541D 05
SUM ACT	0.7823D 03	0.2205D 04	0.3724D 04	0.5133D 04	0.6395D 04	0.7518D 04
SUM ALL	0.1000D 07	0.9662D 06	0.9662D 06	0.9662D 06	0.9662D 06	0.9660D 06

TABLE A.4

All Actinides (Except U) From 5 LWR U-Assemblies Recycled Into 1 Assembly of Natural U - Case 1.3

		ENDING CONTENTS, G/MTM				
	START RECY1	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
U232	0.0	0.1522D-02	0.3146D-02	0.4581D-02	0.5829D-02	0.6940D-02
U233	0.0	0.1149D-03	0.2391D-03	0.3442D-03	0.4334D-03	0.5074D-03
U234	0.0	0.8914D 01	0.2226D 02	0.3758D 02	0.5445D 02	0.7173D 02
U235	0.1323D 04	0.6940D 03	0.8189D 03	0.8503D 03	0.8517D 03	0.8380D 03
U236	0.0	0.1326D 03	0.1072D 03	0.9244D 02	0.8174D 02	0.7337D 02
U238	0.1878D 06	0.1833D 06	0.1746D 06	0.1666D 06	0.1589D 06	0.1515D 06
NP237	0.5225D 03	0.3223D 03	0.5578D 03	0.7488D 03	0.9148D 03	0.1063D 04
PU236	0.1090D-02	0.1961D-02	0.3833D-02	0.5417D-02	0.6802D-02	0.8009D-02
PU238	0.1728D 03	0.4279D 03	0.9604D 03	0.1542D 04	0.2148D 04	0.2759D 04
PU239	0.5744D 04	0.3425D 04	0.6624D 04	0.9658D 04	0.1256D 05	0.1533D 05
PU240	0.2362D 04	0.2252D 04	0.4262D 04	0.6206D 04	0.8160D 04	0.1013D 05
PU241	0.1269D 04	0.1302D 04	0.2326D 04	0.3106D 04	0.3722D 04	0.4213D 04
PU242	0.5506D 03	0.8160D 03	0.1551D 04	0.2238D 04	0.2894D 04	0..'521D 04
PU244	0.2311D-01	0.6185D-01	0.1061D 00	0.1687D 00	0.2277D 00	0.2811D 00
AM241	0.1111D 03	0.1934D 03	0.4671D 03	0.7845D 03	0.1137D 04	0.1513D 04
AM242M	0.7269D 00	0.3442D 01	0.1237D 02	0.2510D 02	0.4032D 02	0.5719D 02
AM243	0.1090D 03	0.2400D 03	0.4383D 03	0.5952D 03	0.7296D 03	0.8503D 03
CM242	0.3367D 01	0.7077D 01	0.1186D 02	0.1646D 02	0.1989D 02	0.2263D 02
CM243	0.3456D 00	0.1118D 01	0.1978D 01	0.2647D 01	0.3154D 01	0.3538D 01
CM244	0.3319D 02	0.1797D 03	0.4163D 03	0.6418D 03	0.8434D 03	0.1018D 04
CM245	0.1810D 01	0.2455D 02	0.7845D 02	0.1454D 03	0.2153D 03	0.2825D 03
CM246	0.1941D 00	0.3099D 01	0.1002D 02	0.2016D 02	0.3264D 02	0.4636D 02
CM247	0.1934D-02	0.7584D-01	0.4108D 00	0.1125D 01	0.2263D 01	0.3826D 01
CM248	0.8434D-04	0.5129D-02	0.3394D-01	0.1034D 00	0.2222D 00	0.3936D 00
BK249	0.4725D-06	0.5198D-04	0.4383D-03	0.1481D-02	0.3360D-02	0.6076D-02
CF249	0.7200D-06	0.9545D-04	0.9274D-03	0.3429D-02	0.8242D-02	0.1550D-01
CF250	0.2894D-06	0.4087D-04	0.4232D-03	0.1728D-02	0.4553D-02	0.9408D-02
CF251	0.1070D-06	0.2249D-04	0.2789D-03	0.1219D-02	0.3333D-02	0.7022D-02
CF252	0.3916D-07	0.7954D-05	0.7927D-04	0.3031D-03	0.7324D-03	0.1360D-02
SUM U	0.1891D 06	0.1841D 06	0.1755D 06	0.1675D 06	0.1599D 06	0.1525D 06
SUM PU	0.1010D 05	0.8222D 04	0.1572D 05	0.2275D 05	0.2949D 05	0.3595D 05
SUM ACT	0.7823D 03	0.9747D 03	0.1995D 04	0.2981D 04	0.3939D 04	0.4860D 04
SUM ALL	0.2000D 06	0.1933D 06	0.1932D 06	0.1933D 06	0.1933D 06	0.1933D 06

TABLE A-5

Waste Actinides From 20 LWR U-Fuel Rods Recycled Into 1 Target Rod of Depleted U - Case 1.4

		ENDING CONTENTS, G/MTM				
	START RECY1	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
U234	0.0	0.4457D 01	0.1166D 02	0.1920D 02	0.2571D 02	0.3086D 02
U235	0.9943D 02	0.2331D 02	0.8572D 01	0.7200D 01	0.9257D 01	0.1200D 02
U236	0.0	0.1234D 02	0.1269D 02	0.1131D 02	0.1063D 02	0.1029D 02
U238	0.4912D 05	0.4786D 05	0.4676D 05	0.4607D 05	0.4556D 05	0.4517D 05
NP237	0.5225D 03	0.2307D 03	0.3429D 03	0.3977D 03	0.4286D 03	0.4423D 03
PU236	0.0	0.1097D-02	0.1886D-02	0.2366D-02	0.2640D-02	0.2811D-02
PU238	0.0	0.2215D 03	0.4039D 03	0.5325D 03	0.6172D 03	0.6737D 03
PU239	0.0	0.3274D 03	0.3922D 03	0.4330D 03	0.4601D 03	0.4780D 03
PU240	0.0	0.1450D 03	0.2359D 03	0.2955D 03	0.3398D 03	0.3737D 03
PU241	0.0	0.6960D 02	0.1121D 03	0.1358D 03	0.1522D 03	0.1642D 03
PU242	0.0	0.3977D 02	0.1097D 03	0.1776D 03	0.2397D 03	0.2959D 03
PU244	0.0	0.2263D-02	0.9600D-02	0.2057D-01	0.3360D-01	0.4800D-01
AM241	0.1111D 03	0.9943D 01	0.1680D 02	0.2057D 02	0.2297D 02	0.2503D 02
AM242M	0.7269D 00	0.1234D 00	0.2160D 00	0.2709D 00	0.3120D 00	0.3429D 00
AM243	0.1090D 03	0.4114D 02	0.7680D 02	0.1066D 03	0.1313D 03	0.1509D 03
CM242	0.3367D 01	0.1337D 01	0.1851D 01	0.2126D 01	0.2263D 01	0.2400D 01
CM243	0.3456D 00	0.3429D 00	0.4457D 00	0.5006D 00	0.5314D 00	0.5486D 00
CM244	0.3319D 02	0.8057D 02	0.1642D 03	0.2475D 03	0.3274D 03	0.4005D 03
CM245	0.1810D 01	0.6514D 01	0.1303D 02	0.1851D 02	0.2331D 02	0.2743D 02
CM246	0.1941D 00	0.3120D 01	0.9257D 01	0.1817D 02	0.2846D 02	0.3977D 02
CM247	0.1934D-02	0.8572D-01	0.3772D 00	0.8914D 00	0.1646D 01	0.2537D 01
CM248	0.8434D-04	0.1063D-01	0.7886D-01	0.2674D 00	0.6172D 00	0.1166D 01
BK249	0.4725D-06	0.9257D-04	0.8229D-03	0.2949D-02	0.7200D-02	0.1406D-01
CF249	0.7200D-06	0.1543D-03	0.1474D-02	0.5486D-02	0.1337D-01	0.2640D-01
CF250	0.2894D-06	0.8572D-04	0.8572D-03	0.3292D-02	0.8229D-02	0.1646D-01
CF251	0.1070D-06	0.4114D-04	0.4457D-03	0.1851D-02	0.4800D-02	0.9600D-02
CF252	0.3916D-07	0.3566D-04	0.5829D-03	0.2949D-02	0.8572D-02	0.1886D-01
SUM U	0.4922D 05	0.4790D 05	0.4679D 05	0.4611D 05	0.4561D 05	0.4523D 05
SUM PU	0.0	0.8033D 03	0.1254D 04	0.1574D 04	0.1809D 04	0.1986D 04
SUM ACT	0.7823D 03	0.3739D 03	0.6260D 03	0.8132D 03	0.9675D 03	0.1093D 04
SUM ALL	0.5000D 05	0.4908D 05	0.4867D 05	0.4850D 05	0.4838D 05	0.4830D 05

TABLE A.6

Waste Actinides From 100 LWR U-Fuel Rods Recycled Into 1 Target Rod of Zirconium - Case 2.1

		ENDING CONTENTS, G/MTM				
	START RECY1	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
U232	0.0	0.8229D-03	0.2016D-02	0.3182D-02	0.4183D-02	0.5006D-02
U233	0.0	0.5808D-04	0.2167D-03	0.4087D-03	0.5911D-03	0.7474D-03
U234	0.0	0.4183D 01	0.1145D 02	0.2009D 02	0.2942D 02	0.3895D 02
U235	0.0	0.4855D 00	0.2537D 01	0.5808D 01	0.9737D 01	0.1406D 02
U236	0.0	0.3799D-01	0.3504D 00	0.1104D 01	0.2304D 01	0.3881D 01
U238	0.0	0.2825D-04	0.4732D-03	0.2112D-02	0.5678D-02	0.1159D-01
NP237	0.5225D 03	0.2490D 03	0.3977D 03	0.4965D 03	0.5664D 03	0.6178D 03
PU236	0.0	0.1186D-02	0.2311D-02	0.3237D-02	0.3977D-02	0.4574D-02
PU238	0.0	0.2141D 03	0.4048D 03	0.5678D 03	0.7077D 03	0.8284D 03
PU239	0.0	0.3840D 02	0.7399D 02	0.1038D 03	0.1291D 03	0.1509D 03
PU240	0.0	0.1714D 02	0.4430D 02	0.7564D 02	0.1072D 03	0.1371D 03
PU241	0.0	0.8160D 01	0.2009D 02	0.3209D 02	0.4341D 02	0.5383D 02
PU242	0.0	0.1241D 02	0.2853D 02	0.4704D 02	0.6713D 02	0.[illegible]846D 02
PU244	0.0	0.9943D-03	0.2894D-02	0.5465D-02	0.8503D-02	0.1186D-01
AM241	0.1111D 03	0.5973D 01	0.1042D 02	0.1467D 02	0.1872D 02	0.2249D 02
AM242M	0.7269D 00	0.1200D 00	0.2194D 00	0.3230D 00	0.4258D 00	0.5266D 00
AM243	0.1090D 03	0.4505D 02	0.7104D 02	0.8853D 02	0.1014D 03	0.1118D 03
CM242	0.3367D 01	0.1371D 01	0.1659D 01	0.1872D 01	0.2050D 01	0.2208D 01
CM243	0.3456D 00	0.3676D 00	0.4204D 00	0.4519D 00	0.4759D 00	0.4972D 00
CM244	0.3319D 02	0.7783D 02	0.1552D 03	0.2244D 03	0.2840D 03	0.3346D 03
CM245	0.1810D 01	0.4334D 01	0.8572D 01	0.1269D 02	0.1646D 02	0.1989D 02
CM246	0.1941D 00	0.2119D 01	0.5733D 01	0.1022D 02	0.1529D 02	0.2064D 02
CM247	0.1934D-02	0.6336D-01	0.2592D 00	0.5856D 00	0.1015D 01	0.1529D 01
CM248	0.8434D-04	0.8503D-02	0.5520D-01	0.1687D 00	0.3648D 00	0.6453D 00
BK249	0.4725D-06	0.7543D-04	0.6172D-03	0.2126D-02	0.4951D-02	0.9257D-02
CF249	0.7200D-06	0.1296D-03	0.1131D-02	0.4039D-02	0.9669D-02	0.1831D-01
CF250	0.2894D-06	0.7200D-04	0.6473D-03	0.2345D-02	0.5644D-02	0.1077D-01
CF251	0.1070D-06	0.3511D-04	0.3724D-03	0.1481D-02	0.3806D-02	0.7612D-02
CF252	0.3916D-07	0.3045D-04	0.4176D-03	0.1858D-02	0.5033D-02	0.1029D-01
SUM U	0.0	0.4707D 01	0.1434D 02	0.2701D 02	0.4147D 02	0.5691D 02
SUM PU	0.0	0.2902D 03	0.5717D 03	0.8264D 03	0.1054D 04	0.1259D 04
SUM ACT	0.7823D 03	0.3862D 03	0.6513D 03	0.8504D 03	0.1007D 04	0.1133D 04
SUM ALL	0.7823D 03	0.6811D 03	0.1237D 04	0.1704D 04	0.2103D 04	0.2448D 04

TABLE A.7

Waste Actinides From 50 LWR U-Fuel Rods Recycled Into 1 Target Rod of Zirconium - Case 2.2

		ENDING CONTENTS, G/MTM				
	START RECYI	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
U232	0.0	0.7269D-03	0.1646D-02	0.2469D-02	0.3017D-02	0.3429D-02
U233	0.0	0.5212D-04	0.1783D-03	0.3154D-03	0.4389D-03	0.5212D-03
U234	0.0	0.4238D 01	0.1104D 02	0.1824D 02	0.2496D 02	0.3086D 02
U235	0.0	0.5047D 00	0.2455D 01	0.5280D 01	0.8338D 01	0.1126D 02
U236	0.0	0.4375D-01	0.3936D 00	0.1206D 01	0.2455D 01	0.4005D 01
U238	0.0	0.3497D-04	0.5856D-03	0.2619D-02	0.6967D-02	0.1399D-01
NP237	0.5225D 03	0.2304D 03	0.3497D 03	0.4169D 03	0.4571D 03	0.4823D 03
PU236	0.0	0.1029D-02	0.1838D-02	0.2400D-02	0.2784D-02	0.3017D-02
PU238	0.0	0.2115D 03	0.3811D 03	0.5074D 03	0.6004D 03	0.6691D 03
PU239	0.0	0.4101D 02	0.7639D 02	0.1026D 03	0.1216D 03	0.1356D 03
PU240	0.0	0.1797D 02	0.4320D 02	0.7008D 02	0.9491D 02	0.1166D 03
PU241	0.0	0.9902D 01	0.2318D 02	0.3484D 02	0.4485D 02	0.5321D 02
PU242	0.0	0.1303D 02	0.3168D 02	0.5308D 02	0.7570D 02	0.[illegible]847D 02
PU244	0.0	0.1153D-02	0.3621D-02	0.7214D-02	0.1163D-01	0.1659D-01
AM241	0.1111D 03	0.4485D 01	0.7200D 01	0.9573D 01	0.1159D 02	0.1328D 02
AM242M	0.7269D 00	0.8064D-01	0.1271D 00	0.1701D 00	0.2071D 00	0.2386D 00
AM243	0.1090D 03	0.4018D 02	0.6213D 02	0.7749D 02	0.8956D 02	0.9957D 02
CM242	0.3367D 01	0.1214D 01	0.1426D 01	0.1591D 01	0.1728D 01	0.1824D 01
CM243	0.3456D 00	0.3456D 00	0.3909D 00	0.4197D 00	0.4416D 00	0.4594D 00
CM244	0.3319D 02	0.7954D 02	0.1566D 03	0.2251D 03	0.2844D 03	0.3357D 03
CM245	0.1810D 01	0.4800D 01	0.8969D 01	0.1251D 02	0.1550D 02	0.1810D 02
CM246	0.1941D 00	0.2606D 01	0.7310D 01	0.1326D 02	0.1989D 02	0.2688D 02
CM247	0.1934D-02	0.7282D-01	0.3058D 00	0.6940D 00	0.1204D 01	0.1797D 01
CM248	0.8434D-04	0.9888D-02	0.6871D-01	0.2181D 00	0.4800D 00	0.8626D 00
BK249	0.4725D-06	0.8174D-04	0.6926D-03	0.2414D-02	0.5664D-02	0.1056D-01
CF249	0.7200D-06	0.1385D-03	0.1236D-02	0.4444D-02	0.1064D-01	0.2016D-01
CF250	0.2894D-06	0.7913D-04	0.7447D-03	0.2715D-02	0.6556D-02	0.1243D-01
CF251	0.1070D-06	0.3662D-04	0.3909D-03	0.1536D-02	0.3854D-02	0.7529D-02
CF252	0.3916D-07	0.3552D-04	0.5349D-03	0.2496D-02	0.6953D-02	0.1454D-01
SUM U	0.0	0.4787D 01	0.1389D 02	0.2473D 02	0.3576D 02	0.4614D 02
SUM PU	0.0	0.2934D 03	0.5556D 03	0.7680D 03	0.9375D 03	0.1073D 04
SUM ACT	0.7823D 03	0.3637D 03	0.5943D 03	0.7579D 03	0.8822D 03	0.9812D 03
SUM ALL	0.7823D 03	0.6619D 03	0.1164D 04	0.1551D 04	0.1855D 04	0.2100D 04

TABLE A.8

Waste Actinides From 50 LWR U-Fuel Rods Irradiated for 10 Consecutive Fuel Cycles - Case 2.3

		ENDING CONTENTS, G/MTM				
	START RECY1	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
U232	0.0	0.4512D-03	0.5884D-03	0.4252D-03	0.2427D-03	0.1229D-03
U233	0.0	0.5212D-04	0.1033D-03	0.8887D-04	0.5554D-04	0.2962D-04
U234	0.0	0.2565D 01	0.4471D 01	0.4293D 01	0.3237D 01	0.2139D 01
U235	0.0	0.5047D 00	0.1481D 01	0.1810D 01	0.1550D 01	0.1112D 01
U236	0.0	0.4389D-01	0.2990D 00	0.6761D 00	0.9806D 00	0.1125D 01
U238	0.0	0.3497D-04	0.5157D-03	0.1947D-02	0.4197D-02	0.6734D-02
NP237	0.5225D 03	0.2304D 03	0.9792D 02	0.4060D 02	0.1673D 02	0.6926D 01
PU236	0.0	0.1307D-02	0.7913D-03	0.3634D-03	0.1509D-03	0.6117D-04
PU238	0.0	0.2081D 03	0.1552D 03	0.8709D 02	0.4279D 02	0.1961D 02
PU239	0.0	0.4101D 02	0.3648D 02	0.2181D 02	0.1104D 02	0.5129D 01
PU240	0.0	0.1481D 02	0.1989D 02	0.1259D 02	0.6226D 01	0.3072D 01
PU241	0.0	0.1044D 02	0.1632D 02	0.1248D 02	0.7200D 01	0.3840D 01
PU242	0.0	0.1304D 02	0.1989D 02	0.2359D 02	0.2085D 02	0..522D 02
PU244	0.0	0.1152D-02	0.2825D-02	0.4841D-02	0.6706D-02	0.8023D-02
AM241	0.1111D 03	0.3950D 01	0.7625D 00	0.5692D 00	0.3429D 00	0.1824D 00
AM242M	0.7269D 00	0.8037D-01	0.1369D-01	0.1004D-01	0.5993D-02	0.3168D-02
AM243	0.1090D 03	0.4018D 02	0.1824D 02	0.1362D 02	0.1221D 02	0.1018D 02
CM242	0.3367D 01	0.5719D 01	0.5856D 00	0.3813D 00	0.2496D 00	0.1385D 00
CM243	0.3456D 00	0.3538D 00	0.3456D-01	0.1440D-01	0.9655D-02	0.5527D-02
CM244	0.3319D 02	0.8284D 02	0.8092D 02	0.6844D 02	0.5746D 02	0.4828D 02
CM245	0.1810D 01	0.4786D 01	0.4951D 01	0.4210D 01	0.3511D 01	0.2976D 01
CM246	0.1941D 00	0.2606D 01	0.5788D 01	0.8530D 01	0.1064D 02	0.1221D 02
CM247	0.1934D-02	0.7282D-01	0.2482D 00	0.4526D 00	0.6309D 00	0.7708D 00
CM248	0.8434D-04	0.9875D-02	0.6295D-01	0.1769D 00	0.3442D 00	0.5458D 00
BK249	0.4725D-06	0.1824D-03	0.1334D-02	0.3881D-02	0.7598D-02	0.1206D-01
CF249	0.7200D-06	0.3607D-04	0.3099D-03	0.9491D-03	0.1893D-02	0.3017D-02
CF250	0.2894D-06	0.8311D-04	0.6994D-03	0.2181D-02	0.4402D-02	0.7132D-02
CF251	0.1070D-06	0.3648D-04	0.3292D-03	0.1029D-02	0.2071D-02	0.3333D-02
CF252	0.3916D-07	0.4704D-04	0.7159D-03	0.3127D-02	0.7913D-02	0.1481D-01
SUM U	0.0	0.3114D 01	0.6252D 01	0.6782D 01	0.5771D 01	0.4383D 01
SUM PU	0.0	0.2874D 03	0.2478D 03	0.1576D 03	0.8811D 02	0.4688D 02
SUM ACT	0.7823D 03	0.3710D 03	0.2095D 03	0.1370D 03	0.1022D 03	0.8225D 02
SUM ALL	0.7823D 03	0.6615D 03	0.4636D 03	0.3013D 03	0.1960D 03	0.1335D 03

	RECYCLE 6	RECYCLE 7	RECYCLE 8	RECYCLE 9	RECYCLE 10
U232	0.5829D-04	0.2661D-04	0.1208D-04	0.5582D-05	0.2715D-05
U233	0.1440D-04	0.6706D-05	0.3045D-05	0.1399D-05	0.6610D-06
U234	0.1304D 01	0.7543D 00	0.4197D 00	0.2290D 00	0.1243D 00
U235	0.7159D 00	0.4320D 00	0.2496D 00	0.1385D 00	0.7584D-01
U236	0.1123D 01	0.1030D 01	0.8942D 00	0.7461D 00	0.6076D 00
U238	0.9038D-02	0.1079D-01	0.1188D-01	0.1237D-01	0.1234D-01
NP237	0.2962D 01	0.1356D 01	0.6926D 00	0.4060D 00	0.2688D 00
PU236	0.2496D-04	0.1066D-04	0.4924D-05	0.2565D-05	0.1536D-05
PU238	0.8681D 01	0.3826D 01	0.1742D 01	0.8517D 00	0.4608D 00
PU239	0.2290D 01	0.1012D 01	0.4567D 00	0.2194D 00	0.1160D 00
PU240	0.1646D 01	0.9628D 00	0.6034D 00	0.3895D 00	0.2565D 00
PU241	0.2139D 01	0.1267D 01	0.7954D 00	0.5170D 00	0.3401D 00
PU242	0.9792D 01	0.5925D 01	0.3511D 01	0.2098D 01	0.1289D 01
PU244	0.8709D-02	0.8887D-02	0.8709D-02	0.8338D-02	0.7858D-02
AM241	0.9943D-01	0.5774D-01	0.3580D-01	0.2304D-01	0.1509D-01
AM242M	0.1714D-02	0.9888D-03	0.6089D-03	0.3922D-03	0.2565D-03
AM243	0.7598D 01	0.5143D 01	0.3278D 01	0.2016D 01	0.1240D 01
CM242	0.7570D-01	0.4375D-01	0.2688D-01	0.1728D-01	0.1133D-01
CM243	0.3031D-02	0.1742D-02	0.1070D-02	0.6857D-03	0.4498D-03
CM244	0.3950D 02	0.3099D 02	0.2318D 02	0.1659D 02	0.1141D 02
CM245	0.2510D 01	0.2043D 01	0.1605D 01	0.1193D 01	0.8530D 00
CM246	0.1330D 02	0.1399D 02	0.1426D 02	0.1413D 02	0.1371D 02
CM247	0.8736D 00	0.9463D 00	0.9902D 00	0.1008D 01	0.9998D 00
CM248	0.7625D 00	0.9792D 00	0.1186D 01	0.1371D 01	0.1536D 01
BK249	0.1687D-01	0.2167D-01	0.2633D-01	0.3058D-01	0.3415D-01
CF249	0.4238D-02	0.5472D-02	0.6652D-02	0.7749D-02	0.8695D-02
CF250	0.1012D-01	0.1312D-01	0.1605D-01	0.1865D-01	0.2098D-01
CF251	0.4718D-02	0.6117D-02	0.7461D-02	0.8709D-02	0.9765D-02
CF252	0.2331D-01	0.3250D-01	0.4183D-01	0.5102D-01	0.5925D-01
SUM U	0.3152D 01	0.2227D 01	0.1575D 01	0.1126D 01	0.8200D 00
SUM PU	0.2456D 02	0.1300D 02	0.7117D 01	0.4084D 01	0.2470D 01
SUM ACT	0.6775D 02	0.5564D 02	0.4536D 02	0.3687D 02	0.3018D 02
SUM ALL	0.9546D 02	0.7086D 02	0.5405D 02	0.4208D 02	0.3347D 02

TABLE A.9

Beginning and Ending Actinide Content of Mixed U/Pu Fuel, g/MTM

	BEGIN	END	(ONE YEAR DECAY)
U234	0.2650D 03	0.1783D 03	
U235	0.6580D 04	0.3045D 04	
U236	0.0	0.7065D 03	
U238	0.9477D 06	0.9270D 06	
NP237	0.0	0.1838D 03	
PU238	0.1010D 04	0.9945D 03	
PU239	0.2240D 05	0.1051D 05	
PU240	0.1160D 05	0.1038D 05	
PU241	0.6650D 04	0.5165D 04	
PU242	0.3790D 04	0.5487D 04	
AM241	0.0	0.6516D 03	
AM242M	0.0	0.8231D 01	
AM243	0.0	0.1118D 04	
CM242	0.0	0.2860D 02	
CM243	0.0	0.3635D 01	
CM244	0.0	0.5926D 03	
CM245	0.0	0.5316D 02	
CM246	0.0	0.6173D 01	
CM247	0.0	0.9054D-01	
CM248	0.0	0.4417D-02	
SUM U	0.9546D 06	0.9309D 06	
SUM PU	0.4545D 05	0.3254D 05	
SUM ACT	0.0	0.2646D 04	
SUM ALL	0.1000D 07	0.9661D 06	

TABLE A.10

Comparison of Waste Actinides Generated in 3 Fuel Types

ENDING CONTENTS, G/MTM

	SEPARATE ROD	U ASS'Y	U/PU ASS'Y	(ONE YEAR DECAY)
NP237	0.5225D 03	0.4617D 03	0.1848D 03	
AM241	0.1111D 03	0.9039D 02	0.6556D 03	
AM242M	0.7269D 00	0.5429D 00	0.8209D 01	
AM243	0.1090D 03	0.8982D 02	0.1122D 04	
CM242	0.3367D 01	0.2906D 01	0.2870D 02	
CM243	0.3456D 00	0.2786D 00	0.3662D 01	
CM244	0.3319D 02	0.2546D 02	0.5959D 03	
CM245	0.1810D 01	0.1207D 01	0.5339D 02	
CM246	0.1941D 00	0.1413D 00	0.6188D 01	
CM247	0.1934D-02	0.1304D-02	0.9059D-01	
CM248	0.8434D-04	0.5881D-04	0.4432D-02	
SUM U	0.0	0.0	0.0	
SUM PU	0.0	0.0	0.0	
SUM ACT	0.7823D 03	0.6724D 03	0.2658D 04	
SUM ALL	0.7823D 03	0.6724D 03	0.2658D 04	

TABLE A.11

Waste Actinide Content of Target Assembly in U/Pu Lattice - Case 3.1

		ENDING CONTENTS, G/MTM				
	START RECY1	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
NP237	0.3696D 03	0.1031D 03	0.1462D 03	0.1680D 03	0.1810D 03	0.1886D 03
PU238	0.0	0.1199D 03	0.1745D 03	0.2043D 03	0.2245D 03	0.2386D 03
PU239	0.0	0.3150D 02	0.4544D 02	0.5307D 02	0.5804D 02	0.6109D 02
PU240	0.0	0.5002D 02	0.8935D 02	0.1214D 03	0.1481D 03	0.1714D 03
PU241	0.0	0.1520D 02	0.2528D 02	0.3295D 02	0.3933D 02	0.4467D 02
PU242	0.0	0.4506D 02	0.9775D 02	0.1481D 03	0.1955D 03	0.2394D 03
AM241	0.2784D 03	0.1615D 01	0.2829D 01	0.3761D 01	0.4544D 01	0.5269D 01
AM242M	0.3089D 01	0.1008D-01	0.1917D-01	0.2635D-01	0.3314D-01	0.3895D-01
AM243	0.4315D 03	0.1489D 03	0.2302D 03	0.2818D 03	0.3188D 03	0.3486D 03
CM242	0.1149D 02	0.1478D 01	0.1817D 01	0.1997D 01	0.2176D 01	0.2299D 01
CM243	0.1405D 01	0.4047D 00	0.4964D 00	0.5346D 00	0.5766D 00	0.6033D 00
CM244	0.2150D 03	0.3856D 03	0.7522D 03	0.1069D 04	0.1329D 04	0.1558D 04
CM245	0.1859D 02	0.7484D 01	0.1352D 02	0.1844D 02	0.2245D 02	0.2574D 02
CM246	0.2150D 01	0.1565D 02	0.3971D 02	0.6911D 02	0.1016D 03	0.1359D 03
CM247	0.3100D-01	0.3543D 00	0.1176D 01	0.2367D 01	0.3849D 01	0.5498D 01
CM248	0.1512D-02	0.9775D-01	0.4887D 00	0.1313D 01	0.2658D 01	0.4544D 01
BK249	0.0	0.4124D-03	0.2371D-02	0.6873D-02	0.1470D-01	0.2600D-01
CF249	0.0	0.6262D-03	0.3708D-02	0.1096D-01	0.2360D-01	0.4200D-01
CF250	0.0	0.5346D-03	0.3200D-02	0.9469D-02	0.2043D-01	0.3643D-01
CF251	0.0	0.1795D-03	0.1130D-02	0.3440D-02	0.7560D-02	0.1367D-01
CF252	0.0	0.5269D-03	0.4506D-02	0.1588D-01	0.3807D-01	0.7255D-01
SUM U	0.0	0.0	0.0	0.0	0.0	0.0
SUM PU	0.0	0.2617D 03	0.4323D 03	0.5599D 03	0.6655D 03	0.7553D 03
SUM ACT	0.1331D 04	0.6647D 03	0.1109D 04	0.1616D 04	0.1967D 04	0.2275D 04
SUM ALL	0.1331D 04	0.9264D 03	0.1621D 04	0.2176D 04	0.2632D 04	0.3030D 04

TABLE A.12

Waste Actinide Content of Target Assembly in U/Pu Lattice - Case 3.2

		ENDING CONTENTS, G/MTM				
	START RECY1	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
NP237	0.3696D 03	0.1613D 03	0.2931D 03	0.4047D 03	0.5059D 03	0.5966D 03
PU238	0.0	0.2024D 03	0.3885D 03	0.5766D 03	0.7703D 03	0.9737D 03
PU239	0.0	0.4353D 02	0.7637D 02	0.1060D 03	0.1365D 03	0.1651D 03
PU240	0.0	0.4859D 02	0.1088D 03	0.1852D 03	0.2749D 03	0.3780D 03
PU241	0.0	0.1355D 02	0.3331D 02	0.5851D 02	0.8734D 02	0.1193D 03
PU242	0.0	0.3608D 02	0.7512D 02	0.1136D 03	0.1508D 03	0.1861D 03
AM241	0.2784D 03	0.8047D 01	0.2701D 02	0.5317D 02	0.8467D 02	0.1212D 03
AM242M	0.3089D 01	0.1165D 00	0.4716D 00	0.1069D 01	0.1919D 01	0.3055D 01
AM243	0.4315D 03	0.2167D 03	0.3856D 03	0.5269D 03	0.6491D 03	0.7579D 03
CM242	0.1149D 02	0.3351D 01	0.4983D 01	0.6042D 01	0.6806D 01	0.7388D 01
CM243	0.1405D 01	0.8267D 00	0.1079D 01	0.1222D 01	0.1289D 01	0..336D 01
CM244	0.2150D 03	0.3503D 03	0.6987D 03	0.1021D 04	0.1289D 04	0.1537D 04
CM245	0.1859D 02	0.7990D 01	0.2005D 02	0.3608D 02	0.5565D 02	0.7751D 02
CM246	0.2150D 01	0.1040D 02	0.2405D 02	0.3914D 02	0.5479D 02	0.7026D 02
CM247	0.3100D-01	0.2931D 00	0.9851D 00	0.2043D 01	0.3408D 01	0.5031D 01
CM248	0.1512D-02	0.5851D-01	0.2425D 00	0.5832D 00	0.1088D 01	0.1718D 01
BK249	0.0	0.3599D-03	0.2081D-02	0.6081D-02	0.1289D-01	0.2262D-01
CF249	0.0	0.5909D-03	0.3799D-02	0.1212D-01	0.2701D-01	0.4964D-01
CF250	0.0	0.4028D-03	0.2358D-02	0.7045D-02	0.1537D-01	0.2797D-01
CF251	0.0	0.1604D-03	0.1136D-02	0.3914D-02	0.9546D-02	0.1880D-01
CF252	0.0	0.2539D-03	0.1699D-02	0.5021D-02	0.1031D-01	0.1728D-01
SUM U	0.0	0.0	0.0	0.0	0.0	0.0
SUM PU	0.0	0.3441D 03	0.6821D 03	0.1040D 04	0.1420D 04	0.1822D 04
SUM ACT	0.1331D 04	0.7594D 03	0.1456D 04	0.2092D 04	0.2653D 04	0.3179D 04
SUM ALL	0.1331D 04	0.1104D 04	0.2138D 04	0.3132D 04	0.4073D 04	0.5001D 04

TABLE A.13

Waste Actinides From Th Assembly Enriched in U-233 and U-235 Recycled Into 1 New Assembly - Case 3.3

ENDING CONTENTS, G/MTM

	BASE CASE	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
TH232	0.9112D 06	0.9092D 06	0.9078D 06	0.9068D 06	0.9061D 06	0.9056D 06
PA231	0.2542D-04	0.3272D-04	0.3533D-04	0.3667D-04	0.3742D-04	0.3794D-04
U232	0.1744D 03	0.1759D 03	0.1767D 03	0.1774D 03	0.1781D 03	0.1781D 03
U233	0.1729D 05	0.1737D 05	0.1744D 05	0.1750D 05	0.1754D 05	0.1756D 05
U234	0.8460D 04	0.8482D 04	0.8497D 04	0.8520D 04	0.8527D 04	0.8535D 04
U235	0.7722D 04	0.7908D 04	0.8087D 04	0.8222D 04	0.8311D 04	0.8378D 04
U236	0.1371D 05	0.1369D 05	0.1366D 05	0.1364D 05	0.1363D 05	0.1362D 05
U238	0.1386D 04	0.1386D 04	0.1386D 04	0.1386D 04	0.1386D 04	0.1386D 04
NP237	0.1506D 04	0.2199D 04	0.2534D 04	0.2698D 04	0.2780D 04	0.2825D 04
PU238	0.4919D 03	0.1215D 04	0.1789D 04	0.2177D 04	0.2422D 04	0.2572D 04
PU239	0.1275D 03	0.2676D 03	0.3854D 03	0.4688D 03	0.5218D 03	0.5553D 03
PU240	0.3213D 02	0.7417D 02	0.1133D 03	0.1439D 03	0.1655D 03	0.1804D 03
PU241	0.2907D 02	0.7454D 02	0.1208D 03	0.1565D 03	0.1819D 03	0.1983D 03
PU242	0.1118D 02	0.4756D 02	0.9764D 02	0.1483D 03	0.1908D 03	0.2244D 03
AM241	0.2430D 01	0.6939D 01	0.1193D 02	0.1595D 02	0.1901D 02	0.2102D 02
AM242M	0.1521D-01	0.5546D-01	0.1058D 00	0.1513D 00	0.1863D 00	0.2109D 00
AM243	0.2177D 01	0.1558D 02	0.4174D 02	0.7327D 02	0.1036D 03	0.1282D 03
CM242	0.6857D-01	0.3011D 00	0.5948D 00	0.8572D 00	0.1058D 01	0.1200D 01
CM243	0.7976D-02	0.5829D-01	0.1327D 00	0.2080D 00	0.2676D 00	0.3116D 00
CM244	0.5568D 00	0.8274D 01	0.3213D 02	0.7320D 02	0.1245D 03	0.1774D 03
CM245	0.2780D-01	0.6336D 00	0.2900D 01	0.7372D 01	0.1342D 02	0.1998D 02
CM246	0.2743D-02	0.1416D 00	0.1021D 01	0.3630D 01	0.8795D 01	0.1685D 02
CM247	0.2490D-04	0.2639D-02	0.2795D-01	0.1267D 00	0.3690D 00	0.8125D 00
CM248	0.1081D-05	0.2504D-03	0.4211D-02	0.2631D-01	0.9839D-01	0.2654D 00
SUM TH	0.9112D 06	0.9092D 06	0.9078D 06	0.9068D 06	0.9061D 06	0.9056D 06
SUM U	0.4874D 05	0.4901D 05	0.4924D 05	0.4945D 05	0.4957D 05	0.4966D 05
SUM PU	0.6918D 03	0.1679D 04	0.2506D 04	0.3094D 04	0.3482D 04	0.3730D 04
SUM ACT	0.1511D 04	0.2231D 04	0.2625D 04	0.2873D 04	0.3052D 04	0.3191D 04
SUM ALL	0.9621D 06	0.9621D 06	0.9621D 06	0.9622D 06	0.9622D 06	0.9621D 06

TABLE A.14

Waste Actinides From 100 LWR U-Fuel Rods Recycled Into Target in SRP Lattice - Case 4.1

		ENDING CONTENTS, G/MTM				
	START RECY1	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
NP237	0.5225D 03	0.2798D 03	0.4457D 03	0.5527D 03	0.6254D 03	0.6768D 03
PU236	0.0	0.3977D-03	0.8092D-03	0.1166D-02	0.1454D-02	0.1680D-02
PU238	0.0	0.2123D 03	0.4236D 03	0.6041D 03	0.7543D 03	0.8791D 03
PU239	0.0	0.3593D 02	0.8256D 02	0.1234D 03	0.1570D 03	0.1845D 03
PU240	0.0	0.1145D 02	0.2997D 02	0.5013D 02	0.7063D 02	0.9052D 02
PU241	0.0	0.4718D 01	0.1625D 02	0.2928D 02	0.4142D 02	0.5246D 02
PU242	0.0	0.1104D 02	0.2448D 02	0.4066D 02	0.5842D 02	0.7680D 02
PU244	0.0	0.1858D-02	0.5746D-02	0.1152D-01	0.1899D-01	0.2777D-01
AM241	0.1111D 03	0.9806D 01	0.1323D 02	0.1618D 02	0.1899D 02	0.2133D 02
AM242M	0.7269D 00	0.1714D 00	0.2304D 00	0.2832D 00	0.3333D 00	0.3778D 00
AM243	0.1090D 03	0.4546D 02	0.7042D 02	0.8777D 02	0.1015D 03	0.1138D 03
CM242	0.3367D 01	0.7269D 01	0.8229D 01	0.8572D 01	0.8777D 01	0.8983D 01
CM243	0.3456D 00	0.1358D 01	0.1666D 01	0.1742D 01	0.1790D 01	0.1824D 01
CM244	0.3319D 02	0.8023D 02	0.1646D 03	0.2455D 03	0.3209D 03	0.3909D 03
CM245	0.1810D 01	0.4732D 01	0.9395D 01	0.1371D 02	0.1769D 02	0.2133D 02
CM246	0.1941D 00	0.2386D 01	0.6857D 01	0.1275D 02	0.1961D 02	0.2715D 02
CM247	0.1934D-02	0.4786D-01	0.2160D 00	0.5170D 00	0.9326D 00	0.1447D 01
CM248	0.8434D-04	0.5973D-02	0.4430D-01	0.1474D 00	0.3388D 00	0.6322D 00
BK249	0.4725D-06	0.4437D-04	0.4183D-03	0.1598D-02	0.4005D-02	0.7954D-02
CF249	0.7200D-06	0.6130D-04	0.5980D-03	0.2338D-02	0.5973D-02	0.1200D-01
CF250	0.2894D-06	0.4210D-04	0.4423D-03	0.1769D-02	0.4546D-02	0.9120D-02
CF251	0.1070D-06	0.1790D-04	0.2112D-03	0.9052D-03	0.2441D-02	0.5095D-02
CF252	0.3916D-07	0.1934D-04	0.3250D-03	0.1735D-02	0.5404D-02	0.1241D-01
SUM U	0.0	0.0	0.0	0.0	0.0	0.0
SUM PU	0.0	0.2754D 03	0.5768D 03	0.8476D 03	0.1082D 04	0.1283D 04
SUM ACT	0.7823D 03	0.4312D 03	0.7206D 03	0.9399D 03	0.1116D 04	0.1265D 04
SUM ALL	0.7823D 03	0.7067D 03	0.1297D 04	0.1788D 04	0.2198D 04	0.2548D 04

TABLE A.15

Beginning and Ending Contents of Two CANDU Fuel Types, g/MTM

	NATURAL U		PU ENRICHED		
	BEGIN	END	BEGIN	END	(ONE YEAR DECAY)
U232	0.0	0.6553D-05	0.0	0.6691D-05	
U233	0.0	0.7424D-07	0.0	0.6219D-07	
U234	0.0	0.1172D 00	0.0	0.2043D 00	
U235	0.7110D 04	0.1930D 04	0.7056D 04	0.3258D 04	
U236	0.0	0.7892D 03	0.0	0.6066D 03	
U238	0.9929D 06	0.9850D 06	0.9840D 06	0.9782D 06	
NP237	0.0	0.4415D 02	0.0	0.4005D 02	
PU236	0.0	0.1799D-04	0.0	0.1815D-04	
PU238	0.0	0.7009D 01	0.0	0.1669D 02	
PU239	0.0	0.2583D 04	0.2964D 04	0.3174D 04	
PU240	0.0	0.1105D 04	0.3149D 04	0.3122D 04	
PU241	0.0	0.2182D 03	0.8172D 03	0.8245D 03	
PU242	0.0	0.7920D 02	0.2019D 04	0.2290D 04	
PU244	0.0	0.9850D-03	0.0	0.2759D-01	
AM241	0.0	0.1539D 02	0.0	0.7635D 02	
AM242M	0.0	0.2906D-01	0.0	0.3166D 00	
AM243	0.0	0.4681D 01	0.0	0.1738D 03	
CM242	0.0	0.1954D 00	0.0	0.1921D 01	
CM243	0.0	0.8954D-02	0.0	0.1156D 00	
CM244	0.0	0.4209D 00	0.0	0.3142D 02	
CM245	0.0	0.5136D-02	0.0	0.6886D 00	
CM246	0.0	0.5828D-03	0.0	0.8709D-01	
CM247	0.0	0.1465D-05	0.0	0.3492D-03	
CM248	0.0	0.3346D-07	0.0	0.9116D-05	
BK249	0.0	0.2092D-08	0.0	0.2076D-07	
CF249	0.0	0.1302D-08	0.0	0.2800D-07	
CF250	0.0	0.1311D-08	0.0	0.1107D-07	
CF251	0.0	0.1441D-09	0.0	0.2181D-08	
CF252	0.0	0.3240D-09	0.0	0.8465D-09	
SUM U	0.1000D 07	0.9877D 06	0.9911D 06	0.9821D 06	
SUM PU	0.0	0.3993D 04	0.8949D 04	0.9427D 04	
SUM ACT	0.0	0.6488D 02	0.0	0.3247D 03	
SUM ALL	0.1000D 07	0.9918D 06	0.1000D 07	0.9918D 06	

TABLE A.16

Waste Actinides From Each CANDU U/Pu Assembly Recycled Into New Assembly - Case 4.2

	ENDING CONTENTS, G/MTM					
	BASE CASE	RECYCLE 1	RECYCLE 2	RECYCLE 3	RECYCLE 4	RECYCLE 5
U232	0.6691D-05	0.2091D-04	0.3148D-04	0.3936D-04	0.4521D-04	0.4968D-04
U233	0.6219D-07	0.3409D-06	0.5491D-06	0.7019D-06	0.8132D-06	0.9024D-06
U234	0.2043D 00	0.5704D 00	0.7541D 00	0.8458D 00	0.8945D 00	0.9350D 00
U235	0.3258D 04	0.3262D 04	0.3269D 04	0.3274D 04	0.3277D 04	0.3279D 04
U236	0.6066D 03	0.6046D 03	0.6052D 03	0.6043D 03	0.6035D 03	0.6024D 03
U238	0.9782D 06	0.9779D 06	0.9776D 06	0.9774D 06	0.9772D 06	0.9771D 06
NP237	0.4005D 02	0.6973D 02	0.9192D 02	0.1082D 03	0.1202D 03	0.1293D 03
PU236	0.1815D-04	0.4988D-04	0.7370D-04	0.9109D-04	0.1041D-03	0.1138D-03
PU238	0.1669D 02	0.5346D 02	0.7053D 02	0.7848D 02	0.8310D 02	0.8569D 02
PU239	0.3174D 04	0.3186D 04	0.3195D 04	0.3198D 04	0.3201D 04	0.3202D 04
PU240	0.3122D 04	0.3125D 04	0.3133D 04	0.3139D 04	0.3147D 04	0.3154D 04
PU241	0.8245D 03	0.8259D 03	0.8265D 03	0.8263D 03	0.8278D 03	0.8285D 03
PU242	0.2290D 04	0.2295D 04	0.2296D 04	0.2295D 04	0.2294D 04	0.2293D 04
PU244	0.2759D-01	0.2775D-01	0.2774D-01	0.2773D-01	0.2773D-01	0.2756D-01
AM241	0.7635D 02	0.1018D 03	0.1105D 03	0.1139D 03	0.1148D 03	0.1152D 03
AM242M	0.3166D 00	0.6160D 00	0.7175D 00	0.7523D 00	0.7684D 00	0.7724D 00
AM243	0.1738D 03	0.2967D 03	0.3848D 03	0.4481D 03	0.4944D 03	0.5285D 03
CM242	0.1921D 01	0.5110D 01	0.6239D 01	0.6612D 01	0.6765D 01	0.6805D 01
CM243	0.1156D 00	0.4646D 00	0.6638D 00	0.7474D 00	0.7823D 00	0.7943D 00
CM244	0.3142D 02	0.1035D 03	0.1943D 03	0.2920D 03	0.3893D 03	0.4824D 03
CM245	0.6886D 00	0.3084D 01	0.6239D 01	0.9516D 01	0.1260D 02	0.1537D 02
CM246	0.8709D-01	0.8218D 00	0.2693D 01	0.5815D 01	0.1016D 02	0.1561D 02
CM247	0.3492D-03	0.6624D-02	0.3246D-01	0.9272D-01	0.1968D 00	0.3512D 00
CM248	0.9116D-05	0.3556D-03	0.2709D-02	0.1065D-01	0.2935D-01	0.6447D-01
BK249	0.2076D-07	0.1155D-05	0.1074D-04	0.4709D-04	0.1390D-03	0.3211D-03
CF249	0.2800D-07	0.1798D-05	0.1749D-04	0.7954D-04	0.2407D-03	0.5887D-03
CF250	0.1107D-07	0.9520D-06	0.1066D-04	0.5230D-04	0.1659D-03	0.4008D-03
CF251	0.2181D-08	0.2571D-06	0.3197D-05	0.1659D-04	0.5391D-04	0.1333D-03
CF252	0.8465D-09	0.1644D-06	0.2961D-05	0.1976D-04	0.7766D-04	0.2220D-03
SUM U	0.9821D 06	0.9817D 06	0.9815D 06	0.9813D 06	0.9811D 06	0.9810D 06
SUM PU	0.9427D 04	0.9485D 04	0.9520D 04	0.9537D 04	0.9553D 04	0.9563D 04
SUM ACT	0.3247D 03	0.5818D 03	0.7981D 03	0.9857D 03	0.1150D 04	0.1295D 04
SUM ALL	0.9918D 06	0.9918D 06	0.9918D 06	0.9918D 06	0.9918D 06	0.9918D 06

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