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Characteristics of Spent Fuel from Plutonium Disposition Reactors Vol. 4: Westinghouse Pressurized-Water-Reactor Fuel Cycle Without Integral Absorber

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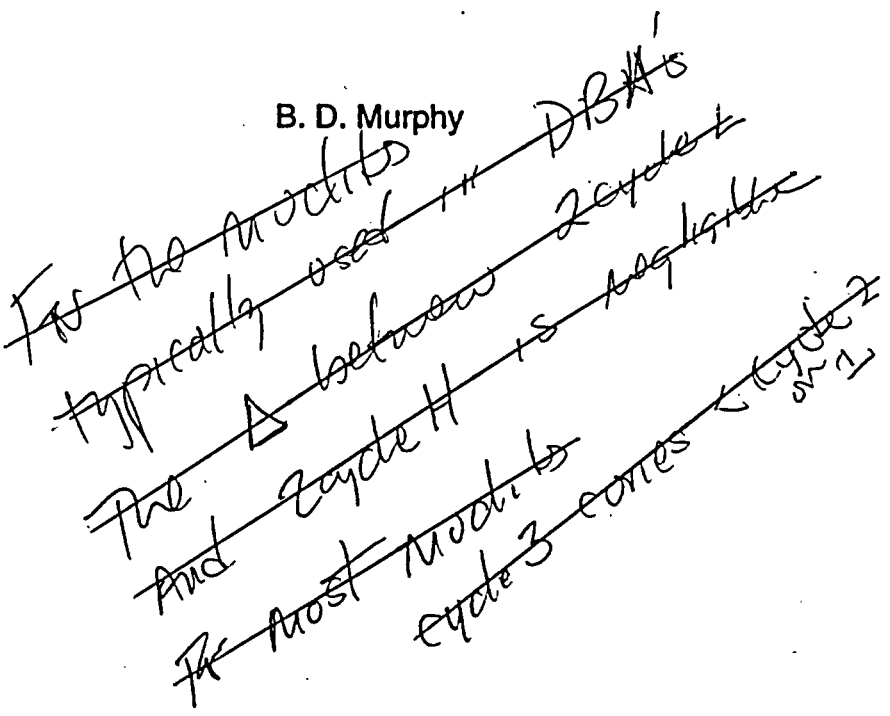

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CHARACTERISTICS OF SPENT FUEL FROM PLUTONIUM DISPOSITION REACTORS VOL. 4: WESTINGHOUSE PRESSURIZED-WATER-REACTOR FUEL CYCLE WITHOUT INTEGRAL ABSORBER

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ABSTRACT

This report is a continuation of a series of studies on the burning of mixed-oxide (MOX) fuel in light-water reactors. It considers a 17 × 17 Westinghouse pressurized-water reactor in what might be a typical transition period between a full UO_2 core loading and a steady-state MOX loading. Westinghouse has reported to the United States Department of Energy (USDOE) that these same assembly designs could be used in an equilibrium fuel cycle in which every assembly in the reactor core contained MOX fuel. Two distinct arrangements are simulated for study purposes: a high-reactivity assembly with 4.8% plutonium content that is burned to approximately 64,700 MWd/t and a low-reactivity assembly with 4.25% plutonium content that is burned to approximately 21,500 MWd/t. These two arrangements were chosen because they would produce spent fuel with the highest radiological source intensity and with the highest amount of fissile material, respectively. Isotopic composition, activities, decay heat, plus gamma and neutron dose rates, were examined.

1. INTRODUCTION

A previous report[1] described the characteristics of spent fuel from a Westinghouse pressurized-water reactor (PWR) burning mixed-oxide (MOX) fuel containing weapons-grade plutonium. The MOX fuel was composed of oxides of uranium and plutonium, with the plutonium comprising 4.56 wt % of the heavy metal, as well as supplying most of the fissile material (the uranium was tails uranium). This fuel design was a possible steady-state scenario for the disposal of weapons-grade plutonium in a commercial reactor. The time-dependent isotopic composition, together with the activities, dose rates, and various other safety-related characteristics of this spent MOX fuel, were reported.

If weapons-grade plutonium is to be burned in a commercial reactor, there will be a transition period in which the core loading arrangement will be different from both the UO_2 case and the steady-state MOX case. The work discussed in this report is a study of the properties of the spent fuel resulting from the cycles of such a transition period. This report will describe the types of transition assemblies being burned and the burnup simulations performed, and it will document the isotopic compositions and various other calculated characteristics of the spent fuel. Note that even though the terminology "transition cycle" is used in this report, the fuel-assembly designs could be used in an equilibrium core configuration. These studies represent an extension of work performed by Westinghouse for the USDOE during FY 1996.[2]

1.1 WESTINGHOUSE TRANSITION-CYCLE FUEL ASSEMBLIES

Before describing the details of the fuel assemblies, two important differences between the current (transition-cycle) study and the previous study[1] must be mentioned:

- The transition cycle involves a fuel rod that is about 4% smaller in diameter.
- The transition-cycle fuel pellets do not contain an integral fuel burnable absorber coating of ZrB_2, as was the case for the previous study.

As in the steady-state case, the calculations described here involve a 17 × 17 Westinghouse assembly. Of the 289 fuel-pin grid locations, 25 contain guide-tube thimbles, leaving 264 fuel rods. Two types of transition-cycle fuel assemblies were studied: a high-reactivity assembly with an average plutonium content of 4.803 wt % and an average fissile plutonium content of 4.515 wt %; and a low-reactivity assembly with an average plutonium content of 4.247 wt % and an average fissile plutonium content of 3.992 wt %. The fissile content of the plutonium is 94% by weight: 93.6% ^{239}Pu and 0.4% ^{241}Pu. The detailed isotopic compositions of the uranium and plutonium fuel are contained in Table 1. The major design parameters for the transition-cycle assemblies are shown in Table 2.[2] The outside dimension of the fuel clad was provided in ref. 2 for the transition-cycle case. No inside dimension was quoted; therefore, it was assumed to be equal to the outer dimension of the fuel pellet. Even though there is a gap, the neutronic impact of "smearing" the fuel and gap regions is insignificant. (The effective density of the MOX including the gap was calculated from the total heavy metal in a transition-cycle assembly, 0.422 tonnes, and the dimensions of the fuel rods.) For comparison purposes, the differences between the transition and ref. 1 cases are shown

in Table 3. Notice that the fuel pellet size is about 4.5% larger in diameter resulting in about 9% more fuel per assembly.

Table 1. Characteristics of Westinghouse transition-cycle MOX fuel

Plutonium fuel characteristics	%
^{239}Pu:	93.6
^{240}Pu:	5.9
^{241}Pu:	0.4
^{242}Pu:	0.1
Uranium fuel characteristics	
^{234}U:	0.002
^{235}U:	0.2
^{236}U:	0.001
^{238}U:	99.797

Table 2. Design parameters for transition-cycle MOX assemblies

Density of oxide (effective)	10.26 g/ml
Pellet diameter	0.7844 cm
Rod pitch	1.26 cm
Active fuel length	365.8 cm
Clad outside diameter (OD)	0.9144 cm
Clad material	Zircaloy-4
Average moderator boron (cycles 1, 2, 3)	710, 825, 880 ppm
Burnup per cycle	21,564 MWd/t
Fuel temperature (K)	901
Clad temperature (K)	607
Moderator temperature (K)	583

Table 3. Comparison between transition-cycle and ref. 1 MOX assemblies

	Transition cycle	Ref. 1
Fuel pellet OD (cm)	0.7844	0.8192
Fuel rod OD (cm)	0.9144	0.95
Tonnes of HM/assembly	0.422	0.462
Pu wt %	4.803 (high reactivity) 4.247 (low reactivity)	4.56
Pu fissile (% of HM)	4.515 (high reactivity) 3.992 (low reactivity)	4.29

2. BURNUP SIMULATION

2.1 FUEL CYCLES AND BURNUP SIMULATION

Various loading arrangements are associated with the transition cycles. It is anticipated that some low-reactivity assemblies will be burned for one cycle and some for two cycles; and that some high-reactivity assemblies will be burned for two cycles and some for three cycles. For safety assessments, it is necessary to study two types of spent fuel assemblies: assemblies that would contain the largest amount of fissile material, and assemblies that would deliver the greatest dose rates. A preliminary calculation indicated (as expected) that these would be the low-reactivity assembly following one reactor cycle and the high-reactivity assembly following three reactor cycles, respectively.

Simulations were performed where a low-reactivity assembly was burned for one reactor cycle and a high-reactivity assembly was burned for three reactor cycles. The composition of the discharged spent fuel for these two arrangements was determined using the SAS2H sequence of the ORNL SCALE system.[3] In simulating the reactor burnup, the cycle length was chosen as 18 months, with a 3.5-month downtime between cycles. The simulation process is the same as that described previously in ref. 1. The SAS2H sequence generates the composition of the spent fuel at discharge, the ORIGEN-S code determines spent fuel composition at any arbitrary time following discharge, and the SAS1 code uses the results from ORIGEN-S to calculate dose rates. Specifically, these simulations were carried out with SCALE-4.3 and made use of the 44-energy-group ENDF/B-V library.

The SAS2H modeling approach assumes that the assembly is composed of circular zones. Of the 289 locations in the Westinghouse PWR assembly, the central location was modeled as a guide-tube thimble (i.e., an instrument hole). There were 24 other guide-tube thimbles that could accommodate burnable absorbers. (The details of the assembly layout are shown in Fig. 1 of ref. 1.) All 25 guide-tube locations contained moderator material for purposes of simulation. The zoning arrangement used was as follows: the central hole was modeled as a moderator zone surrounded by a Zircaloy zone and, in turn, surrounded by a moderator zone (i.e., an instrument-tube hole containing a Zircaloy thimble). Outside of this central hole was a zone of 40 fuel pins (homogenized), then a zone of eight guide tubes, followed by a second fuel zone containing 84 pins (homogenized). This zone, in turn, was surrounded by a zone of 16 guide tubes followed by a third and final fuel zone containing 140 pins (homogenized). Thus, there were, in total, 264 fuel pins and 24 guide tubes surrounding the central hole. The guide tubes were similar to the central instrument-tube hole in that they were composed of moderator (water) and Zircaloy. The details of the SAS2H modeling approach have been outlined previously.[1] Suffice to say that the SAS2H calculations involve a two-step process: The first step treats a unit fuel-pin cell. The second step treats the assembly as a whole, and the assembly is divided into circular zones. Cell-weighted cross sections calculated in the first step are used in treating the zones containing fuel in the second step.

3. SPENT FUEL CHARACTERISTICS

3.1 NUCLIDE INVENTORIES IN SPENT FUEL

Figure 1 is a plot of the plutonium content of a low-reactivity assembly at various times following discharge. Cooling times to 250,000 years are shown. Figure 2 is a similar plot showing plutonium content for a high-reactivity assembly. The nonplutonium actinide concentrations for the low-reactivity case are shown in Fig. 3, and for the high-reactivity case they are shown in Fig. 4. In the low-burnup case, the ^{239}Pu content at discharge is about 66%, so it is considerably below weapons grade. In the high-burnup case, the ^{239}Pu content is about 39%. The ^{244}Cm content is considerably greater in the high-reactivity/high-burnup case since ^{244}Cm generation scales at a rate much greater than the burnup. Detailed numerical results showing isotopic inventories are contained in Appendix A (Tables A.1 and A.2).

3.2 ACTIVITIES AND DECAY HEAT

Activities from light elements, actinides, fission products, and the sum of these three are shown in Figs. 5 and 6 for the low- and high-burnup cases, respectively. Similarly, decay-heat values are shown in Figs. 7 and 8.

For the actinides, activities are largely the result of alpha decays. For the fission products and light elements, beta and gamma activities dominate. Consistent with this, the activities at shorter times following discharge are due primarily to the fission products, whereas at larger decay times, actinide activities dominate. Note that the actinide contribution to the decay heat increases in the 10-to-100-year time frame. This increase is caused by the ingrowth of ^{241}Am and its subsequent decay, which is somewhat more noticeable in the low-burnup case.

At long decay times the actinide activities are due primarily to ^{239}Pu, ^{242}Pu, ^{237}Np (with ^{233}Pa in equilibrium), some other uranium isotopes, and species in various decay chains down to the region of ^{208}Pb. This is the region of the closed proton and neutron shells at the magic numbers 82 and 126, respectively. After many thousands of years of decay, the nuclides in chains that decay down to this region start to play a role as they do in the naturally occurring radioactive decay series. Thus, these nuclides are included in the "actinide" library in these calculations. Although these lower-mass nuclides are not actinides, they are the decay products of actinide species and are present in spent fuel as a direct result of the actinide component of the fuel.

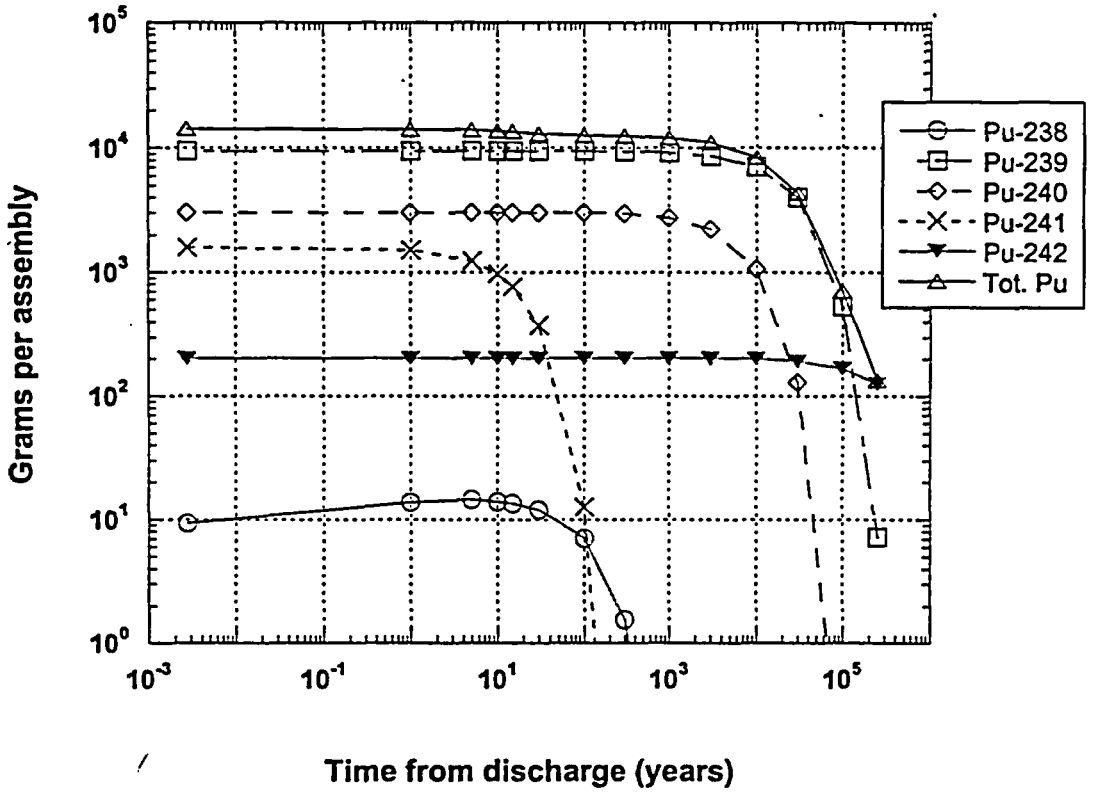

Fig. 1. The plutonium content of a low-reactivity, transition assembly following one reactor cycle.

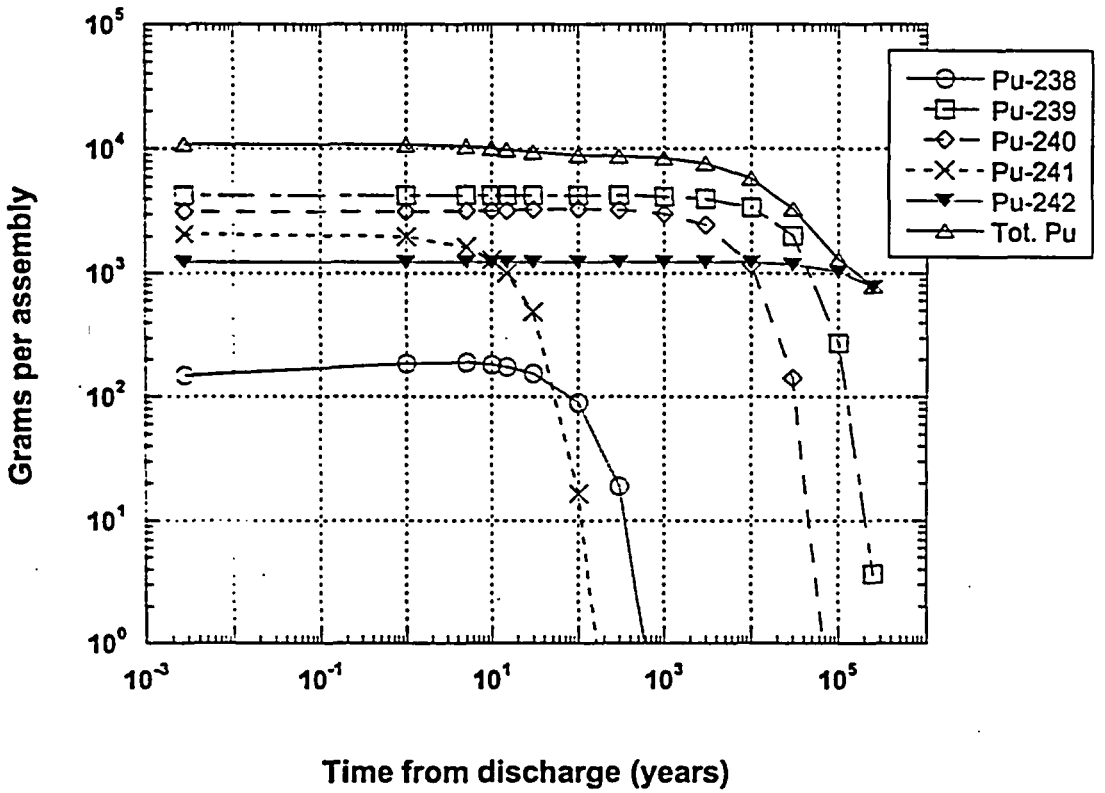

Fig. 2. The plutonium content of a high-reactivity, transition assembly following three reactor cycles.

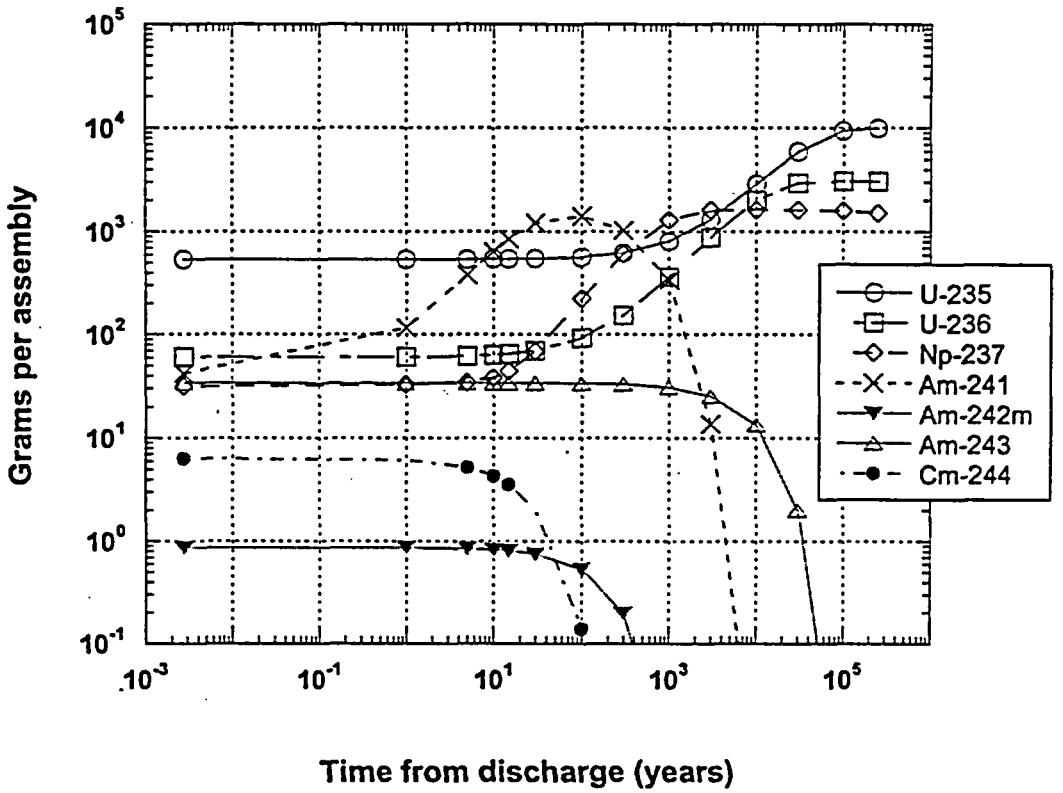

Fig. 3. The nonplutonium actinide content of a low-reactivity, transition-assembly following one reactor cycle.

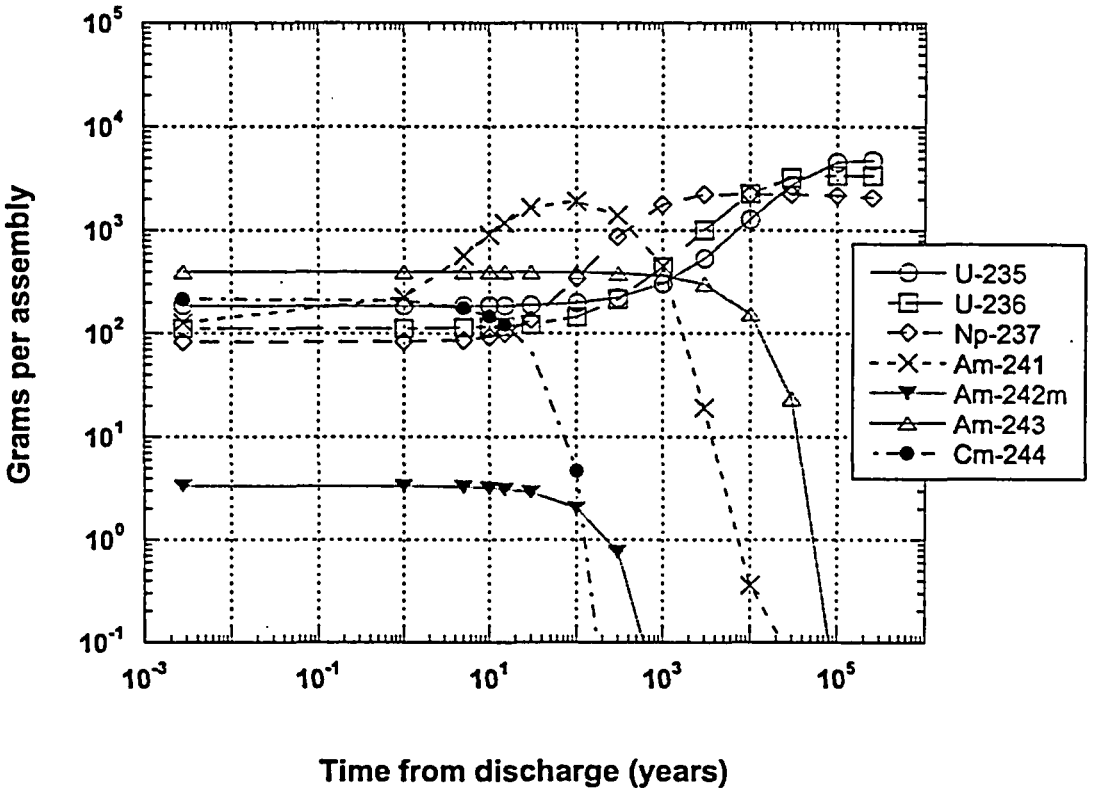

Fig. 4. The nonplutonium actinide content of a high-reactivity, transition-assembly following three reactor cycles.

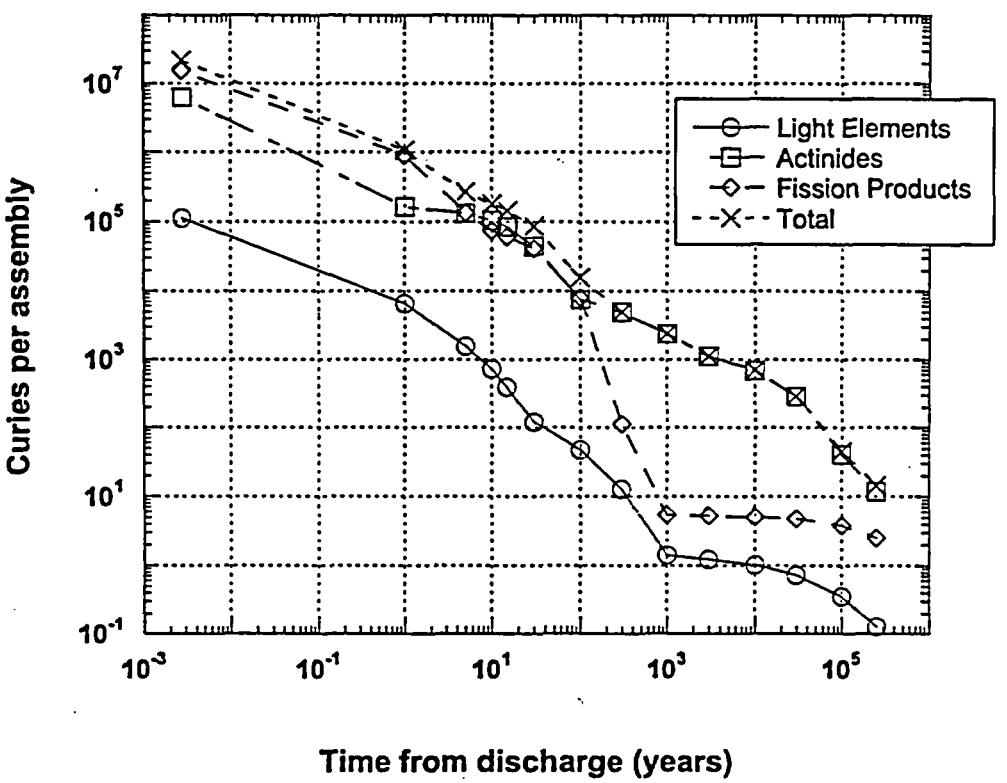

Fig. 5. Activities for a low-reactivity transition assembly following one reactor cycle.

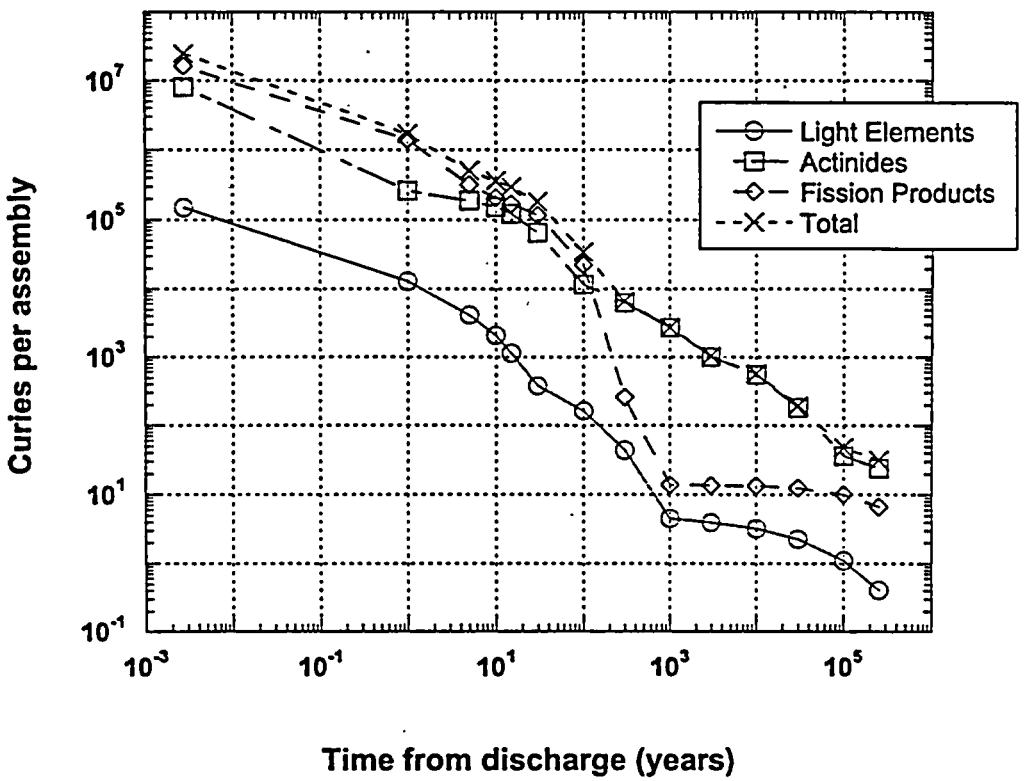

Fig. 6. Activities for a high-reactivity transition assembly following three reactor cycles.

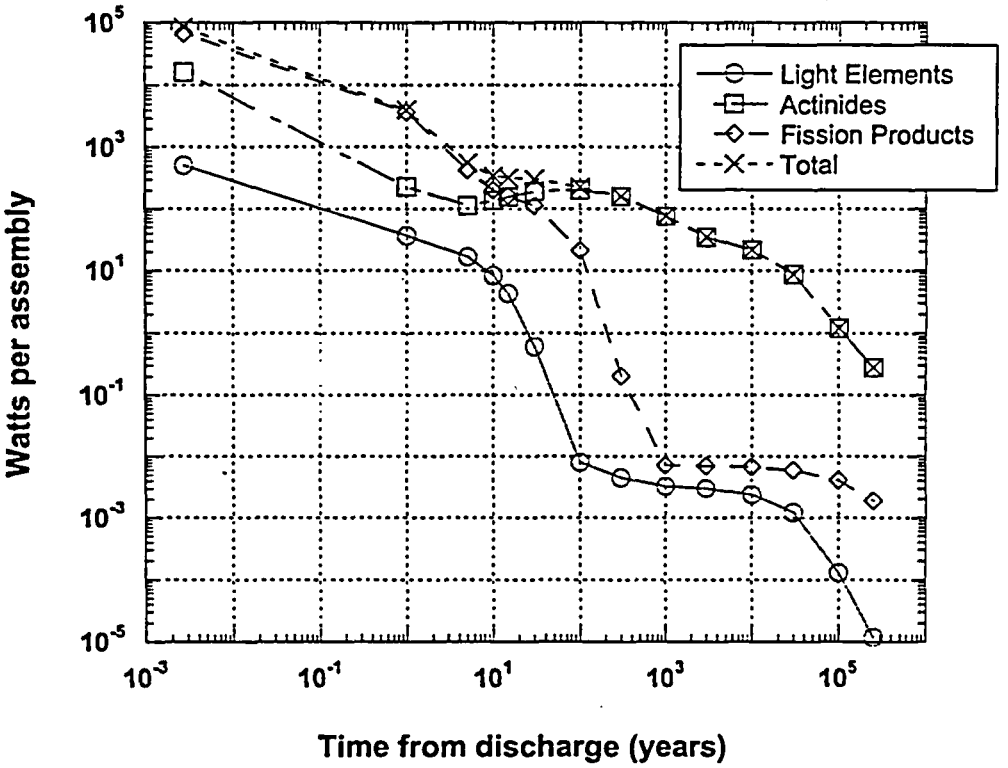

Fig. 7. Decay-heat results for a low-reactivity assembly (one reactor cycle).

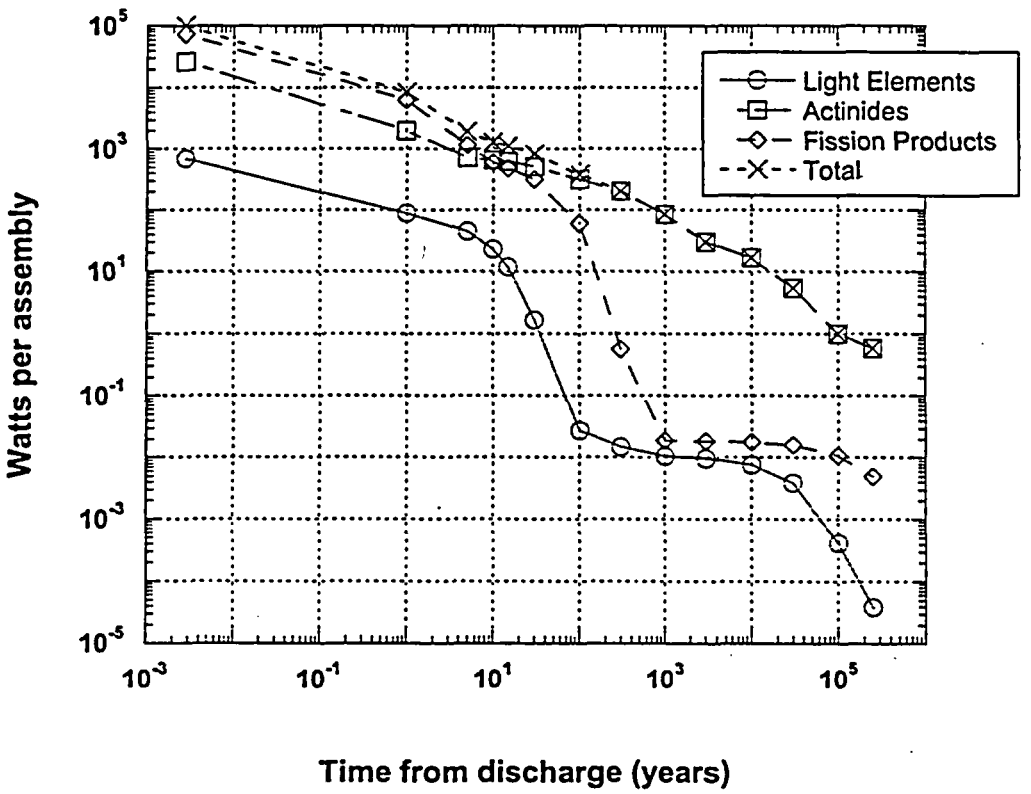

Fig. 8. Decay-heat results for a high-reactivity assembly (three reactor cycles).

At shorter decay times the actinide activities come from a different set of nuclides. At a 10-year decay time in the case of the low-reactivity assembly, for instance, the actinide activities are due primarily to ^{241}Pu, ^{241}Am, ^{240}Pu, ^{239}Pu, ^{244}Cm, and ^{238}Pu in that order of priority. Because of their prominence at earlier decay times, these nuclides will, of necessity, have died out after long decay times. It is a consequence of the definition of activity that those species that are important at earlier decay times are not the ones of importance after long decay times. Earlier on, the short-lived nuclides contribute to the activity. At very long decay times they are replaced by the long-lived plutonium species, actinides such as ^{235}U, ^{236}U, and ^{237}Np that "grow in", and the species in decay chains below uranium down to the region of ^{208}Pb.

For the higher-burnup case, the spent fuel actinide activities are higher, as might be expected, and, for most nuclides not present in the fresh fuel, the concentrations tend to be higher in proportion to the amount of burnup. An exception, however, is the case of ^{244}Cm. As noted, ^{244}Cm is generated at a rate that increases greatly with burnup. This increase is evident by comparing Figs. 3 and 4. The amount of ^{244}Cm generated in the high-burnup case is almost an order of magnitude greater than for the low-burnup case.

Most of the actinide species that are the major sources of activity are also responsible for the decay heat. It is important to keep in mind, however, that the correlation between sources of activity and sources of decay heat is loose and qualitative. Furthermore, activity is only a qualitative indicator of radiological hazard. Activities are reported here because spent fuel activity is a frequently quoted quantity. One should realize, however, that activity is only a measure of disintegration rate. With spent MOX fuel, the relative concentration of the various actinide species will be different than in the case of spent low-enriched uranium (LEU) fuel. Also, in comparing the low-reactivity assembly with the high-reactivity assembly, since the fissile contents are different, the importance of various species is not just dependent on burnup.

The fission-product activities at shorter decay times are result from the presence of ^{85}Kr, ^{90}Sr, ^{106}Ru, ^{125}Sb, ^{134}Cs, ^{137}Cs, ^{147}Pm, ^{154}Eu, and ^{155}Eu — fission products with decay half-lives measured in years. When compared with most other fission products, these ones would be considered long lived. At very long decay times, the fission-product activity is dominated by ^{99}Tc, a species that has a particularly long half-life for a fission product. Fission-product activities tend to scale with burnup. Exceptions to this would be those species with high capture cross sections or those that can result from capture by a neighboring species where that capture process has a high cross section.

The sources of fission-product decay heat are, of course, many of the same species that are responsible for the majority of the activity. After a 10-year decay, for instance, the major contributors are ^{90}Y (from ^{90}Sr), ^{137}Cs, ^{137m}Ba (from ^{137}Cs), and ^{154}Eu. At very long decay times the main contributors are ^{99}Tc and ^{126m}Sb (a decay product of the long-lived fission product ^{126}Sn).

The light-element activities are low relative to the actinides and fission products. Light-element activity is also subject to much uncertainty because it depends on the detailed composition of the structural materials. In the assemblies studied here, and in most cases, the predominant contributor to light-element activity and decay heat is ^{60}Co. The amount of ^{60}Co in a spent fuel assembly depends on the amount of cobalt in the ferrous metal of the assembly structural materials. The cobalt content of the assemblies for this study are representative of assemblies commonly in use. The numerical results of the activity and decay-heat calculations are shown in Tables A.3 through A.6. For an extensive discussion on the importance of various spent fuel nuclides in a number of contexts, one is referred to a report by Broadhead et al.[4]

3.3 GAMMA AND NEUTRON DOSE RATES

Gamma and neutron dose rates are of interest both for a bare assembly and for the exterior of a transportation cask containing spent fuel assemblies. Figures 9 and 10 show the gamma and neutron dose rates, respectively (at the surface and at 1 m from the surface), for a high-reactivity unshielded assembly following three reactor cycles.

The gamma and neutron dose rates at 1 m from the surface of a Transnuclear cask[5] containing 24 spent fuel assemblies are shown in Fig. 11. Again, these rates were for high-reactivity assemblies that had been in the reactor for three cycles. For the unshielded assemblies, dose rates are shown for decay times up to 100 years. For the case of a cask, the attenuation is such that values are shown only for decay times up to 10 years.

Numerical results from the dose-rate calculations are given in Tables A.7 through A.9. In the case of the bare assembly, both the one-cycle and three-cycle dose rates are listed. In the case of the transportation cask, only the higher dose rates from the three-cycle case are listed.

3.4 SEVERE ACCIDENT ANALYSES

Design-basis accidents usually involve destruction of the fuel by some mechanism with consequent release to the environment of various fission products and actinides. One question of concern to the plutonium disposition program is whether the consequences of a severe accident with MOX fuel exceeds the consequences of a similar accident with LEU fuel. Even though the analysis of such an accident is beyond the scope of these studies, input to severe accident studies can be obtained from ORIGEN analyses.

Selected nuclides commonly input to accident analyses are shown in Tables 4 and 5. Table 4 gives nuclide activities at discharge, and Table 5 contains activities at 10 years following discharge. Most of this report has concentrated on the one-cycle, low-activity case and the three-cycle, high-activity case. However, Tables 4 and 5 show more extensive sets of results. Results are shown for a low-reactivity assembly following both one and two reactor cycles and for a high-reactivity assembly following both two and three reactor cycles.

The nuclides in Tables 4 and 5 will, in general, tend to have short half-lives, and one notes that many of them have insignificant activities after 10 years (i.e., where there is no value in Table 5). However, since many of these nuclides result from the decay of other species, the half-life is not necessarily a good indication of activity at a future date, and one can see that some species with quite short half-lives are still in evidence after 10 years. For practical reasons it is not possible to list values for an extensive number of decay times, but Table 5 should give an indication of the species that may be important at later decay times.

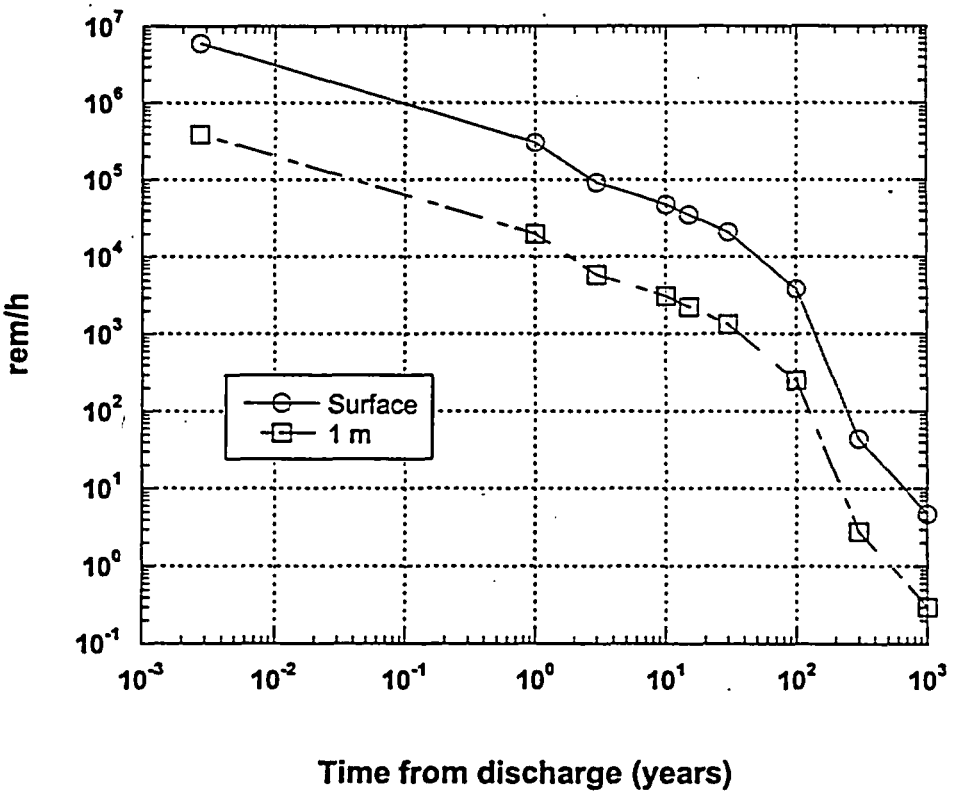

Fig. 9. Gamma-dose rates at the surface and at 1 m from the side of a high-reactivity assembly following three reactor cycles.

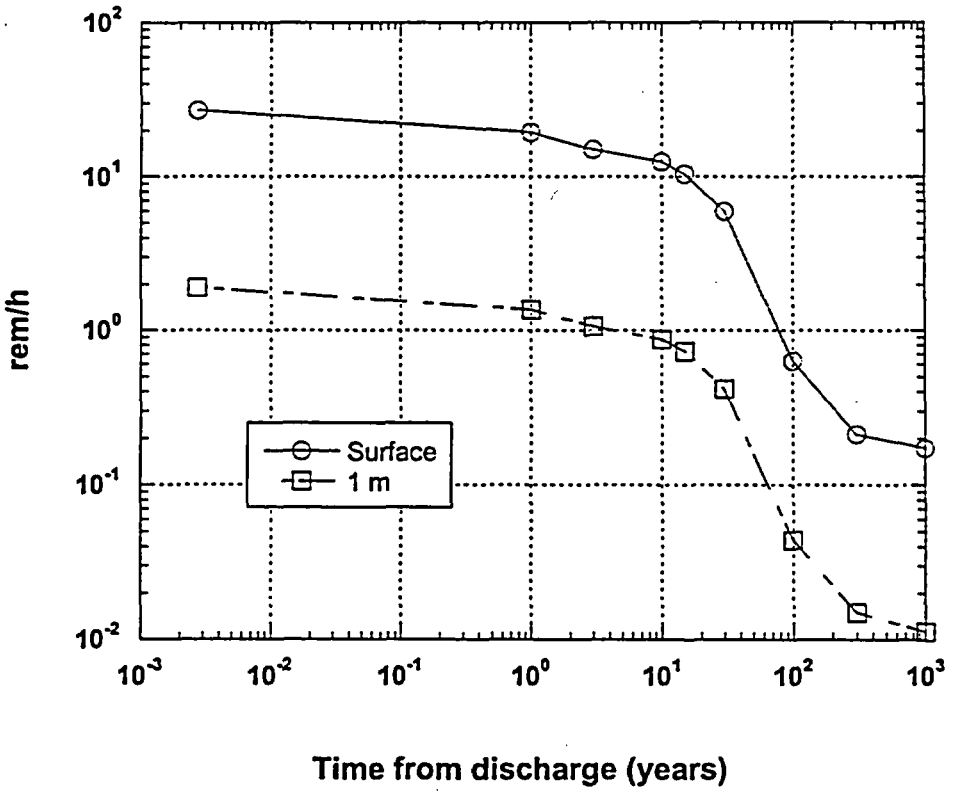

Fig. 10. Neutron-dose rates at the surface and at 1 m from the side of a high-reactivity assembly following three reactor cycles.

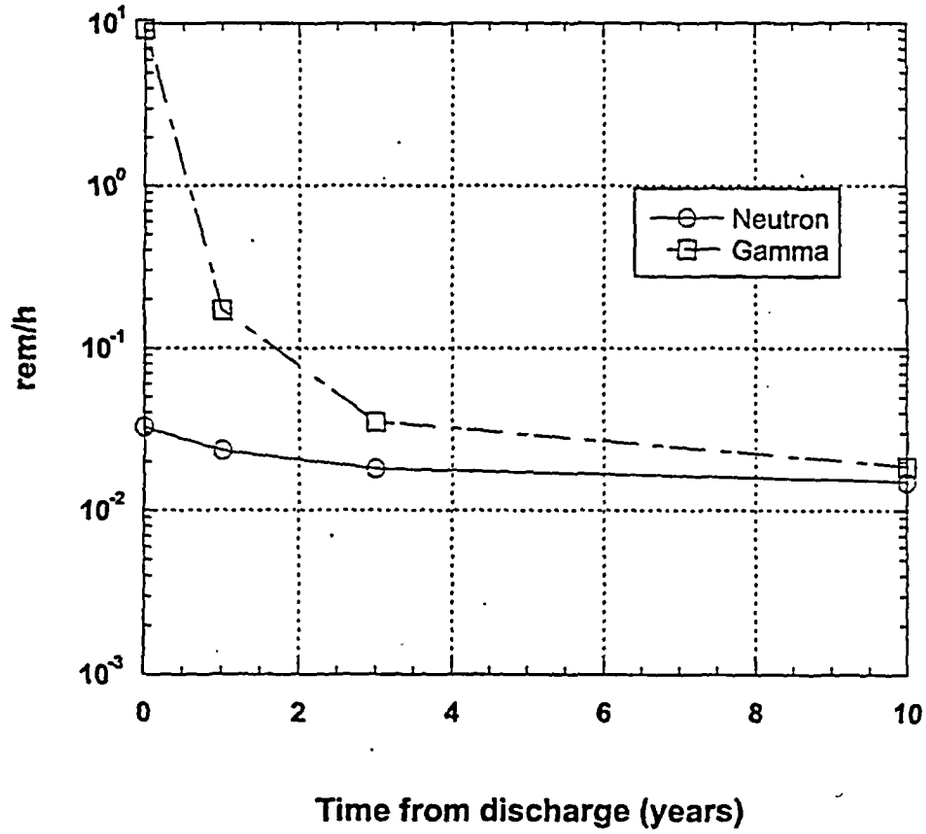

Fig. 11. Neutron and gamma-dose rates at 1 m from the side of a transportation cask containing 24 spent fuel assemblies. These were high-reactivity assemblies exposed to three reactor cycles.

Table 4. Comparison of principal activity sources at discharge (curies per assembly)

		Low reactivity		High reactivity	
Nuclide	Half-life	One cycle	Two cycles	Two cycles	Three cycles
^{241}Am	432.7 a	1.43×10^{2}	3.47×10^{2}	3.95×10^{2}	4.34×10^{2}
^{140}Ba	12.75 d	7.41×10^{5}	7.45×10^{5}	7.44×10^{5}	7.42×10^{5}
^{14}C	5715 a	2.58×10^{-1}	5.88×10^{-1}	5.32×10^{-1}	9.05×10^{-1}
^{141}Ce	32.5 d	6.90×10^{5}	6.77×10^{5}	6.78×10^{5}	6.68×10^{5}
^{143}Ce	1.377 d	5.84×10^{5}	5.83×10^{5}	5.82×10^{5}	5.79×10^{5}
^{144}Ce	284.6 d	3.84×10^{5}	4.65×10^{5}	4.64×10^{5}	4.81×10^{5}
^{242}Cm	162.8 d	1.90×10^{4}	9.53×10^{4}	9.38×10^{4}	1.60×10^{5}
^{244}Cm	18.1 a	5.14×10^{2}	5.42×10^{3}	4.65×10^{3}	1.75×10^{4}
^{58}Co	70.88 d	6.02×10^{3}	6.24×10^{3}	6.25×10^{3}	6.32×10^{3}
^{60}Co	5.271 a	1.99×10^{3}	3.94×10^{3}	3.68×10^{3}	5.44×10^{3}
^{134}Cs	2.065 a	2.77×10^{4}	9.02×10^{4}	8.66×10^{4}	1.60×10^{5}
^{134m}Cs	2.90 h	1.07×10^{4}	2.20×10^{4}	2.09×10^{4}	3.18×10^{4}
^{136}Cs	13.16 d	2.40×10^{4}	4.02×10^{4}	4.17×10^{4}	6.02×10^{4}
^{137}Cs	30.07 a	3.08×10^{4}	6.00×10^{4}	6.00×10^{4}	8.77×10^{4}
^{3}H	12.32 a	1.55×10^{2}	2.93×10^{2}	2.94×10^{2}	4.17×10^{2}
^{131}I	8.02 d	4.69×10^{5}	4.48×10^{5}	4.51×10^{5}	4.39×10^{5}
^{132}I	2.28 h	6.70×10^{5}	6.45×10^{5}	6.48×10^{5}	6.34×10^{5}
^{133}I	20.8 h	8.88×10^{5}	8.76×10^{5}	8.78×10^{5}	8.68×10^{5}
^{135}I	6.57 h	8.48×10^{5}	8.50×10^{5}	8.49×10^{5}	8.46×10^{5}
^{85}Kr	10.76 a	1.56×10^{3}	2.83×10^{3}	2.84×10^{3}	3.91×10^{3}
^{85m}Kr	4.48 h	7.03×10^{4}	6.62×10^{4}	6.66×10^{4}	6.43×10^{4}
^{88}Kr	2.84 h	1.80×10^{5}	1.73×10^{5}	1.73×10^{5}	1.68×10^{5}
^{140}La	1.678 d	7.50×10^{5}	7.64×10^{5}	7.61×10^{5}	7.73×10^{5}
^{140}La	3.90 h	6.78×10^{5}	6.66×10^{5}	6.67×10^{5}	6.58×10^{5}
^{99}Mo	2.75 d	7.98×10^{5}	7.95×10^{5}	7.95×10^{5}	7.93×10^{5}
^{95}Nb	34.97 d	6.47×10^{5}	6.32×10^{5}	6.26×10^{5}	6.08×10^{5}
^{95m}Nb	3.61 d	7.24×10^{3}	6.98×10^{3}	7.01×10^{3}	6.83×10^{3}
^{147}Nd	10.98 d	2.75×10^{5}	2.79×10^{5}	2.78×10^{5}	2.80×10^{5}
^{238}Np	2.117 d	1.95×10^{4}	4.51×10^{4}	4.08×10^{4}	6.53×10^{4}
^{143}Pr	13.57 d	5.82×10^{5}	5.80×10^{5}	5.80×10^{5}	5.76×10^{5}
^{238}Pu	87.7 a	1.58×10^{2}	1.05×10^{3}	1.01×10^{3}	2.54×10^{3}
^{239}Pu	2.41×10^{4} a	5.85×10^{2}	3.34×10^{2}	4.07×10^{2}	2.63×10^{2}

Table 4 (continued)

Nuclide	Half-life	Low reactivity		High reactivity	
		One cycle	Two cycles	Two cycles	Three cycles
^{240}Pu	6.56×10^3 a	6.93×10^2	7.35×10^2	8.30×10^2	7.14×10^2
^{241}Pu	14.4 a	1.63×10^5	2.17×10^5	2.38×10^5	2.14×10^5
^{86}Rb	18.65 d	2.31×10^2	5.30×10^2	5.09×10^2	8.45×10^2
^{105}Rh	35.4 h	6.53×10^5	6.55×10^5	6.59×10^5	6.54×10^5
^{105m}Rh	40 s	1.95×10^5	1.98×10^5	1.97×10^5	1.99×10^5
^{103}Ru	39.27 d	8.85×10^5	8.65×10^5	8.68×10^5	8.57×10^5
^{105}Ru	4.44 h	6.85×10^5	6.95×10^5	6.95×10^5	7.00×10^5
^{106}Ru	1.02 a	3.63×10^5	4.88×10^5	4.86×10^5	5.33×10^5
^{127}Sb	3.84 d	5.32×10^4	4.82×10^4	4.90×10^4	4.64×10^4
^{129}Sb	4.4 h	1.68×10^5	1.55×10^5	1.57×10^5	1.50×10^5
^{89}Sr	50.52 d	2.40×10^5	2.28×10^5	2.29×10^5	2.21×10^5
^{90}Sr	28.78 a	1.09×10^4	2.08×10^4	2.08×10^4	2.99×10^4
^{91}Sr	9.5 h	3.38×10^5	3.26×10^5	3.26×10^5	3.19×10^5
^{92}Sr	2.71 h	3.99×10^5	3.85×10^5	3.86×10^5	3.78×10^5
^{99m}Tc	6.01 h	7.05×10^5	7.05×10^5	7.06×10^5	7.06×10^5
^{127}Te	9.4 h	5.32×10^4	4.82×10^4	4.90×10^4	4.63×10^4
^{127m}Te	109 d	9.49×10^3	8.65×10^3	8.79×10^3	8.19×10^3
^{129}Te	1.16 h	1.61×10^5	1.48×10^5	1.50×10^5	1.44×10^5
^{129m}Te	33.6 d	3.38×10^4	3.08×10^4	3.12×10^4	2.96×10^4
^{132}Te	3.2 d	6.52×10^5	6.30×10^5	6.32×10^5	6.20×10^5
^{131m}Xe	11.9 d	5.92×10^3	6.43×10^3	6.44×10^3	6.91×10^3
^{133}Xe	5.243 d	8.91×10^5	8.79×10^5	8.81×10^5	8.72×10^5
^{133m}Xe	2.19 d	2.95×10^4	2.86×10^4	2.87×10^4	2.83×10^4
^{135}Xe	9.10 h	4.24×10^5	3.33×10^5	3.77×10^5	2.96×10^5
^{135m}Xe	15.3 m	2.08×10^5	1.99×10^5	2.00×10^5	1.95×10^5
^{90}Y	2.67 d	1.12×10^4	2.15×10^4	2.14×10^4	3.10×10^4
^{91}Y	58.5 d	3.48×10^5	3.34×10^5	3.34×10^5	3.25×10^5
^{91m}Y	49.7 m	1.96×10^5	1.89×10^5	1.89×10^5	1.85×10^5
^{92}Y	3.54 h	4.01×10^5	3.87×10^5	3.88×10^5	3.79×10^5
^{93}Y	10.2 h	3.37×10^5	3.24×10^5	3.25×10^5	3.18×10^5
^{95}Zr	64.02 d	6.43×10^5	6.20×10^5	6.22×10^5	6.06×10^5
^{97}Zr	16.8 h	6.62×10^5	6.48×10^5	6.49×10^5	6.41×10^5

Table 5. Comparison of principal activity sources at 10 years following discharge (curies per assembly)

		Low reactivity		High reactivity	
Nuclide	Half-life	One cycle	Two cycles	Two cycles	Three cycles
^{241}Am	432.7 a	2.20×10^{3}	3.07×10^{3}	3.39×10^{3}	3.12×10^{3}
^{140}Ba	12.75 d	------- [a]	-------	------	-------
^{14}C	5715 a	2.57×10^{-1}	5.88×10^{-1}	5.31×10^{-1}	9.04×10^{-1}
^{141}Ce	32.5 d	-------	------	-------	-------
^{143}Ce	1.377 d	-------	-------	-------	-------
^{144}Ce	284.6 d	5.32×10^{1}	6.44×10^{1}	6.43×10^{1}	6.66×10^{1}
^{242}Cm	162.8 d	7.12×10^{0}	2.13×10^{1}	2.49×10^{1}	2.73×10^{1}
^{244}Cm	18.1 a	3.52×10^{2}	3.71×10^{3}	3.18×10^{3}	1.20×10^{4}
^{58}Co	70.88 d	-------	-------	-------	-------
^{60}Co	5.271 a	5.34×10^{2}	1.06×10^{3}	9.87×10^{2}	1.46×10^{3}
^{134}Cs	2.065 a	9.61×10^{2}	3.13×10^{3}	3.00×10^{3}	5.55×10^{3}
^{134m}Cs	2.90 h	-------	-------	-------	-------
^{136}Cs	13.16 d	-------	-------	------	-------
^{137}Cs	30.07 a	2.44×10^{4}	4.76×10^{4}	4.76×10^{4}	6.96×10^{4}
^{3}H	12.32 a	8.84×10^{1}	1.67×10^{2}	1.67×10^{2}	2.38×10^{2}
^{131}I	8.02 d	-------	-------	-------	-------
^{132}I	2.28 h	-------	-------	------	-------
^{133}I	20.8 h	-------	-------	-------	-------
^{135}I	6.57 h	-------	-------	-------	-------
^{85}Kr	10.76 a	8.16×10^{2}	1.48×10^{3}	1.49×10^{3}	2.05×10^{3}
^{85m}Kr	4.48 h	-------	-------	-------	-------
^{88}Kr	2.84 h	-------	-------	-------	-------
^{140}La	1.678 d	-------	-------	-------	-------
^{141}La	3.90 h	-------	-------	-------	-------
^{99}Mo	2.75 d	-------	-------	-------	-------
^{95}Nb	34.97 d	-------	-------	-------	-------
^{95m}Nb	3.61 d	-------	-------	-------	-------
^{147}Nd	10.98 d	-------	-------	-------	-------
^{238}Np	2.117 d	3.89×10^{-2}	1.17×10^{-1}	1.36×10^{-1}	1.49×10^{-1}
^{143}Pr	13.57 d	-------	-------	-------	-------
^{238}Pu	87.7 a	2.39×10^{2}	1.42×10^{3}	1.38×10^{3}	3.11×10^{3}
^{239}Pu	2.41×10^{4} a	5.87×10^{2}	3.36×10^{2}	4.09×10^{2}	2.66×10^{2}

Table 5 (continued)

Nuclide	Half-life	Low reactivity		High reactivity	
		One cycle	Two cycles	Two cycles	Three cycles
^{240}Pu	6.56×10^3 a	6.93×10^2	7.39×10^2	8.33×10^2	7.29×10^2
^{241}Pu	14.4 a	1.01×10^5	1.34×10^5	1.47×10^5	1.32×10^5
^{86}Rb	18.65 d	-------	-------	-------	-------
^{105}Rh	35.4 h	-------	-------	-------	-------
^{105m}Rh	40 s	-------	-------	-------	-------
^{103}Ru	39.27 d	-------	-------	-------	-------
^{105}Ru	4.44 h	-------	-------	-------	-------
^{106}Ru	1.02 a	3.99×10^2	5.37×10^2	5.35×10^2	5.86×10^2
^{127}Sb	3.84 d	-------	-------	-------	-------
^{129}Sb	4.4 h	-------	-------	-------	-------
^{89}Sr	50.52 d	-------	-------	-------	-------
^{90}Sr	28.78 a	8.54×10^3	1.63×10^4	1.63×10^4	2.34×10^4
^{91}Sr	9.5 h	-------	-------	-------	-------
^{92}Sr	2.71 h	-------	-------	-------	-------
^{99m}Tc	6.01 h	-------	-------	-------	-------
^{127}Te	9.4 h	7.88×10^{-7}	7.18×10^{-7}	7.30×10^{-7}	6.81×10^{-7}
^{127m}Te	109 d	8.05×10^{-7}	7.33×10^{-7}	7.46×10^{-7}	6.95×10^{-7}
^{129}Te	1.16 h	-------	-------	-------	-------
^{129m}Te	33.6 d	-------	-------	-------	-------
^{132}Te	3.2 d	-------	-------	-------	-------
^{131m}Xe	11.9 d	-------	-------	-------	-------
^{133}Xe	5.243 d	-------	-------	-------	-------
^{133m}Xe	2.19 d	-------	-------	-------	-------
^{135}Xe	9.10 h	-------	-------	-------	-------
^{135m}Xe	15.3 m	-------	-------	-------	-------
^{90}Y	2.67 d	8.54×10^3	1.63×10^4	1.63×10^4	2.34×10^4
^{91}Y	58.5 d	-------	-------	-------	-------
^{91m}Y	49.7 m	-------	-------	-------	-------
^{92}Y	3.54 h	-------	-------	-------	-------
^{93}Y	10.2 h	-------	-------	-------	-------
^{95}Zr	64.02 d	-------	-------	-------	-------
^{97}Zr	16.8 h	-------	-------	-------	-------

[a] Nuclides marked in this manner have a negligible contribution.

3.5 CRITICALITY SAFETY FOR GEOLOGIC REPOSITORY

Assessment of repository safety involves analyses covering time periods thousands of years into the future. Even though actinide concentrations have been presented above, criticality analyses for a repository include selected nuclides that have significant absorption cross sections (i.e., they are good neutron poisons). Estimates of the quantities of these nuclides can be obtained from ORIGEN calculations, and they are listed in Tables 6 and 7 at the time of discharge and at 10 years following discharge, respectively. Results are shown for a low-reactivity assembly following one and two reactor cycles, and similarly for a high-reactivity assembly following two and three reactor cycles.

Table 6. Nuclides of interest for criticality safety
(g/assembly at discharge)

	Low reactivity		High reactivity	
Nuclide	One cycle	Two cycles	Two cycles	Three cycles
^{16}O	6.20×10^{4}	6.20×10^{4}	6.20×10^{4}	6.20×10^{4}
^{95}Mo	1.33×10^{2}	2.95×10^{2}	2.97×10^{2}	4.42×10^{2}
^{101}Ru	2.29×10^{2}	4.44×10^{2}	4.45×10^{2}	6.47×10^{2}
^{99}Tc	2.22×10^{2}	4.12×10^{2}	4.14×10^{2}	5.74×10^{2}
^{103}Rh	2.04×10^{2}	3.43×10^{2}	3.55×10^{2}	4.29×10^{2}
^{109}Ag	6.08×10^{1}	9.98×10^{1}	1.01×10^{2}	1.27×10^{2}
^{143}Nd	2.22×10^{2}	3.99×10^{2}	4.10×10^{2}	5.31×10^{2}
^{145}Nd	1.66×10^{2}	3.12×10^{2}	3.14×10^{2}	4.40×10^{2}
^{147}Sm	1.43×10^{1}	3.83×10^{1}	3.94×10^{1}	5.70×10^{1}
^{149}Sm	2.62×10^{0}	2.15×10^{0}	2.53×10^{0}	1.95×10^{0}
^{150}Sm	8.43×10^{1}	1.76×10^{2}	1.75×10^{2}	2.56×10^{2}
^{151}Sm	1.29×10^{1}	1.37×10^{1}	1.55×10^{1}	1.53×10^{1}
^{152}Sm	4.92×10^{1}	8.28×10^{1}	8.38×10^{1}	1.06×10^{2}
^{151}Eu	2.32×10^{-2}	1.96×10^{-2}	2.49×10^{-2}	------ [a]
^{153}Eu	3.70×10^{1}	8.73×10^{1}	8.62×10^{1}	1.29×10^{2}
^{155}Gd	2.81×10^{-2}	6.49×10^{-2}	7.46×10^{-2}	1.14×10^{-1}
^{234}U	6.15×10^{0}	4.79×10^{0}	4.90×10^{0}	4.60×10^{0}
^{235}U	5.39×10^{2}	3.13×10^{2}	3.47×10^{2}	1.86×10^{2}
^{236}U	6.06×10^{1}	9.79×10^{1}	9.37×10^{1}	1.12×10^{2}
^{238}U	3.98×10^{5}	3.91×10^{5}	3.89×10^{5}	3.82×10^{5}
^{237}Np	3.18×10^{1}	6.13×10^{1}	6.04×10^{1}	8.21×10^{1}
^{238}Pu	9.23×10^{0}	6.10×10^{1}	5.88×10^{1}	1.48×10^{2}
^{239}Pu	9.42×10^{3}	5.38×10^{3}	6.56×10^{3}	4.24×10^{3}
^{240}Pu	3.05×10^{3}	3.24×10^{3}	3.66×10^{3}	3.15×10^{3}
^{241}Pu	1.58×10^{3}	2.09×10^{3}	2.30×10^{3}	2.07×10^{3}
^{242}Pu	2.02×10^{2}	7.13×10^{2}	6.59×10^{2}	1.24×10^{3}
^{241}Am	4.17×10^{1}	1.01×10^{2}	1.15×10^{2}	1.26×10^{2}
^{242m}Am	8.66×10^{-1}	2.60×10^{0}	3.03×10^{0}	3.32×10^{0}
^{243}Am	3.39×10^{1}	1.88×10^{2}	1.70×10^{2}	3.97×10^{2}
^{245}Cm	------	4.00×10^{0}	3.48×10^{0}	1.62×10^{1}

[a] Indicates that the concentration is negligible.

Table 7. Nuclides of interest for criticality safety
(g/assembly at 10 years)

	Low reactivity		High reactivity	
Nuclide	One cycle	Two cycles	Two cycles	Three cycles
^{16}O	6.20×10^{4}	6.20×10^{4}	6.20×10^{4}	6.20×10^{4}
^{95}Mo	1.79×10^{2}	3.40×10^{2}	3.42×10^{2}	4.86×10^{2}
^{101}Ru	2.29×10^{2}	4.44×10^{2}	4.45×10^{2}	6.47×10^{2}
^{99}Tc	2.23×10^{2}	4.13×10^{2}	4.16×10^{2}	5.75×10^{2}
^{103}Rh	2.32×10^{2}	3.70×10^{2}	3.82×10^{2}	4.56×10^{2}
^{109}Ag	6.09×10^{1}	1.00×10^{2}	1.02×10^{2}	1.27×10^{2}
^{143}Nd	2.32×10^{2}	4.08×10^{2}	4.19×10^{2}	5.40×10^{2}
^{145}Nd	1.66×10^{2}	3.12×10^{2}	3.14×10^{2}	4.40×10^{2}
^{147}Sm	7.91×10^{1}	1.17×10^{2}	1.21×10^{2}	1.38×10^{2}
^{149}Sm	3.25×10^{0}	2.88×10^{0}	3.25×10^{0}	2.72×10^{0}
^{150}Sm	8.43×10^{1}	1.76×10^{2}	1.75×10^{2}	2.56×10^{2}
^{151}Sm	1.20×10^{1}	1.28×10^{1}	1.45×10^{1}	1.43×10^{1}
^{152}Sm	4.93×10^{1}	8.28×10^{1}	8.38×10^{1}	1.06×10^{2}
^{151}Eu	9.87×10^{-1}	1.04×10^{0}	1.18×10^{0}	------ [a]
^{153}Eu	3.74×10^{0}	8.79×10^{1}	8.68×10^{1}	1.30×10^{2}
^{155}Gd	1.37×10^{0}	3.46×10^{0}	3.40×10^{0}	5.67×10^{0}
^{234}U	7.25×10^{0}	1.14×10^{1}	1.13×10^{1}	1.90×10^{1}
^{235}U	5.42×10^{2}	3.15×10^{2}	3.49×10^{2}	1.88×10^{2}
^{236}U	6.37×10^{1}	1.01×10^{2}	9.75×10^{1}	1.15×10^{2}
^{238}U	3.98×10^{5}	3.91×10^{5}	3.89×10^{5}	3.82×10^{5}
^{237}Np	3.84×10^{1}	7.07×10^{1}	7.07×10^{1}	9.20×10^{1}
^{238}Pu	1.39×10^{1}	8.30×10^{1}	8.06×10^{1}	1.81×10^{2}
^{239}Pu	9.45×10^{3}	5.42×10^{3}	6.59×10^{3}	4.28×10^{3}
^{240}Pu	3.05×10^{3}	3.26×10^{3}	3.67×10^{3}	3.21×10^{3}
^{241}Pu	9.73×10^{2}	1.29×10^{3}	1.42×10^{3}	1.28×10^{3}
^{242}Pu	2.02×10^{2}	7.13×10^{2}	6.59×10^{2}	1.24×10^{3}
^{241}Am	6.40×10^{2}	8.95×10^{2}	9.87×10^{2}	9.10×10^{2}
^{242m}Am	8.25×10^{-1}	2.47×10^{0}	2.88×10^{0}	3.16×10^{0}
^{243}Am	3.40×10^{1}	1.88×10^{2}	1.70×10^{2}	3.97×10^{2}
^{245}Cm	------	4.00×10^{0}	3.48×10^{0}	1.62×10^{1}

[a] Indicates that the concentration is negligible.

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APPENDIX A

DETAILED CALCULATED RESULTS

This appendix contains the calculated numerical values corresponding to the graphical results presented in the main body of the report. The tables that follow show calculated values for actinide concentrations, activities and decay heat, and gamma and neutron dose rates for an unshielded assembly, as well as values for the exterior of a transportation cask containing spent fuel assemblies. The tables cover a variety of cooling times, and they refer to both low- and high-reactivity assemblies (burned for one and three reactor cycles, respectively). The conditions that are pertinent to the particular results reported in Tables A.1–A.9 are explained in the table captions. Some of these tables report values out to 250,000 years. Dose rates are reported out to 1000 years only. For some nuclides, the concentrations are negligible after long decay times; in such cases, values are not shown in the tables.

Table A.1. Actinide concentrations from one-cycle, low-reactivity, spent fuel assembly

	(Plutonium; per assembly in grams)					
	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	Total Pu
Charge	0.00×10^{0}	1.68×10^{4}	1.06×10^{3}	7.17×10^{1}	1.79×10^{1}	1.79×10^{4}
Discharge	9.23×10^{0}	9.42×10^{3}	3.05×10^{3}	1.58×10^{3}	2.02×10^{2}	1.43×10^{4}
1 day	9.28×10^{0}	9.43×10^{3}	3.05×10^{3}	1.58×10^{3}	2.02×10^{2}	1.43×10^{4}
1 year	1.37×10^{1}	9.45×10^{3}	3.05×10^{3}	1.50×10^{3}	2.02×10^{2}	1.42×10^{4}
5 years	1.45×10^{1}	9.45×10^{3}	3.05×10^{3}	1.24×10^{3}	2.02×10^{2}	1.40×10^{4}
10 years	1.39×10^{1}	9.45×10^{3}	3.05×10^{3}	9.73×10^{2}	2.02×10^{2}	1.37×10^{4}
15 years	1.34×10^{1}	9.45×10^{3}	3.05×10^{3}	7.64×10^{2}	2.02×10^{2}	1.35×10^{4}
30 years	1.19×10^{1}	9.45×10^{3}	3.05×10^{3}	3.70×10^{2}	2.02×10^{2}	1.31×10^{4}
100 years	7.01×10^{0}	9.43×10^{3}	3.03×10^{3}	1.26×10^{1}	2.02×10^{2}	1.27×10^{4}
300 years	1.56×10^{0}	9.37×10^{3}	2.96×10^{3}	1.18×10^{-3}	2.02×10^{2}	1.25×10^{4}
1000 years	1.36×10^{-2}	9.19×10^{3}	2.75×10^{3}	3.63×10^{-4}	2.02×10^{2}	1.21×10^{4}
3000 years	4.59×10^{-7}	8.68×10^{3}	2.23×10^{3}	3.08×10^{-4}	2.02×10^{2}	1.11×10^{4}
10,000 years	---------[a]	7.11×10^{3}	1.06×10^{3}	1.74×10^{-4}	1.99×10^{2}	8.37×10^{3}
30,000 years	---------	4.01×10^{3}	1.29×10^{2}	3.41×10^{-5}	1.92×10^{2}	4.33×10^{3}
100,000 years	---------	5.36×10^{2}	7.91×10^{-2}	1.13×10^{-7}	1.68×10^{2}	7.04×10^{2}
250,000 years	---------	7.18×10^{0}	2.50×10^{-7}	---------	1.27×10^{2}	1.34×10^{2}

	(Other actinides; per assembly in grams)							
	^{235}U	^{236}U	^{238}U	^{237}Np	^{241}Am	^{242m}Am	^{243}Am	^{244}Cm
Charge	8.08×10^{2}	4.04×10^{0}	4.03×10^{5}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}
Discharge	5.39×10^{2}	6.06×10^{1}	3.98×10^{5}	3.18×10^{1}	4.17×10^{1}	8.66×10^{-1}	3.39×10^{1}	6.34×10^{0}
1 day	5.39×10^{2}	6.06×10^{1}	3.98×10^{5}	3.19×10^{1}	4.19×10^{1}	8.66×10^{-1}	3.40×10^{1}	6.37×10^{0}
1 year	5.39×10^{2}	6.09×10^{1}	3.98×10^{5}	3.28×10^{1}	1.16×10^{2}	8.62×10^{-1}	3.40×10^{1}	6.13×10^{0}
5 years	5.40×10^{2}	6.21×10^{1}	3.98×10^{5}	3.44×10^{1}	3.79×10^{2}	8.45×10^{-1}	3.40×10^{1}	5.26×10^{0}
10 years	5.42×10^{2}	6.37×10^{1}	3.98×10^{5}	3.84×10^{1}	6.40×10^{2}	8.25×10^{-1}	3.40×10^{1}	4.34×10^{0}
15 years	5.43×10^{2}	6.53×10^{1}	3.98×10^{5}	4.43×10^{1}	8.43×10^{2}	8.05×10^{-1}	3.40×10^{1}	3.59×10^{0}
30 years	5.47×10^{2}	7.01×10^{1}	3.98×10^{5}	6.92×10^{1}	1.21×10^{3}	7.47×10^{-1}	3.39×10^{1}	2.02×10^{0}
100 years	5.66×10^{2}	9.21×10^{1}	3.98×10^{5}	2.24×10^{2}	1.41×10^{3}	5.30×10^{-1}	3.37×10^{1}	1.38×10^{1}
300 years	6.19×10^{2}	1.54×10^{2}	3.98×10^{5}	6.08×10^{2}	1.03×10^{3}	1.98×10^{-1}	3.31×10^{1}	6.52×10^{-5}
1000 years	8.03×10^{2}	3.62×10^{2}	3.98×10^{5}	1.29×10^{3}	3.37×10^{2}	6.35×10^{-3}	3.09×10^{1}	---------
3000 years	1.31×10^{3}	8.77×10^{2}	3.98×10^{5}	1.61×10^{3}	1.37×10^{1}	3.41×10^{-7}	2.56×10^{1}	---------
10,000 years	2.87×10^{3}	2.02×10^{3}	3.98×10^{5}	1.62×10^{3}	5.43×10^{-3}	---------	1.33×10^{1}	---------
30,000 years	5.93×10^{3}	2.94×10^{3}	3.98×10^{5}	1.61×10^{3}	1.03×10^{-3}	---------	2.02×10^{0}	---------
100,000 years	9.34×10^{3}	3.06×10^{3}	3.98×10^{5}	1.57×10^{3}	3.40×10^{-6}	---------	2.80×10^{-3}	---------
250,000 years	9.86×10^{3}	3.05×10^{3}	3.98×10^{5}	1.50×10^{3}	---------	---------	2.48×10^{-8}	---------

[a] Indicates that the value is negligible.

Table A.2. Actinide concentrations from three-cycle, high-reactivity, spent fuel assembly

(Plutonium; per assembly in grams)

	^{238}Pu	^{239}Pu	^{240}Pu	^{241}Pu	^{242}Pu	Total Pu
Charge	0.00×10^{0}	1.90×10^{4}	1.20×10^{3}	8.11×10^{1}	2.03×10^{1}	2.03×10^{4}
Discharge	1.48×10^{2}	4.24×10^{3}	3.15×10^{3}	2.07×10^{3}	1.24×10^{3}	1.08×10^{4}
1 day	1.48×10^{2}	4.25×10^{3}	3.15×10^{3}	2.07×10^{3}	1.24×10^{3}	1.09×10^{4}
1 year	1.85×10^{2}	4.28×10^{3}	3.15×10^{3}	1.97×10^{3}	1.24×10^{3}	1.08×10^{4}
5 years	1.89×10^{2}	4.28×10^{3}	3.18×10^{3}	1.63×10^{3}	1.24×10^{3}	1.05×10^{4}
10 years	1.81×10^{2}	4.28×10^{3}	3.21×10^{3}	1.28×10^{3}	1.24×10^{3}	1.02×10^{4}
15 years	1.74×10^{2}	4.28×10^{3}	3.23×10^{3}	1.00×10^{3}	1.24×10^{3}	9.92×10^{3}
30 years	1.55×10^{2}	4.28×10^{3}	3.28×10^{3}	4.86×10^{2}	1.24×10^{3}	9.44×10^{3}
100 years	8.97×10^{1}	4.28×10^{3}	3.32×10^{3}	1.65×10^{1}	1.24×10^{3}	8.95×10^{3}
300 years	1.89×10^{1}	4.26×10^{3}	3.26×10^{3}	2.73×10^{-2}	1.24×10^{3}	8.78×10^{3}
1000 years	1.04×10^{-1}	4.20×10^{3}	3.02×10^{3}	1.19×10^{-2}	1.24×10^{3}	8.46×10^{3}
3000 years	1.77×10^{-6}	4.02×10^{3}	2.45×10^{3}	2.11×10^{-2}	1.23×10^{3}	7.70×10^{3}
10,000 years	---------[a]	3.42×10^{3}	1.17×10^{3}	1.19×10^{-2}	1.22×10^{3}	5.81×10^{3}
30,000 years	---------	2.01×10^{3}	1.41×10^{2}	2.33×10^{-3}	1.17×10^{3}	3.32×10^{3}
100,000 years	---------	2.73×10^{2}	8.69×10^{-2}	7.72×10^{-6}	1.03×10^{3}	1.30×10^{3}
250,000 years	---------	3.66×10^{0}	4.56×10^{-6}	---------	7.81×10^{2}	7.85×10^{2}

(Other actinides; per assembly in grams)

	^{235}U	^{236}U	^{238}U	^{237}Np	^{241}Am	^{242m}Am	^{243}Am	^{244}Cm
Charge	8.03×10^{2}	4.02×10^{0}	4.01×10^{5}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}
Discharge	1.86×10^{2}	1.12×10^{2}	3.82×10^{5}	8.21×10^{1}	1.26×10^{2}	3.32×10^{0}	3.97×10^{2}	2.16×10^{2}
1 day	1.86×10^{2}	1.12×10^{2}	3.82×10^{5}	8.22×10^{1}	1.27×10^{2}	3.32×10^{0}	3.97×10^{2}	2.17×10^{2}
1 year	1.87×10^{2}	1.12×10^{2}	3.82×10^{5}	8.36×10^{1}	2.24×10^{2}	3.31×10^{0}	3.97×10^{2}	2.09×10^{2}
5 years	1.87×10^{2}	1.14×10^{2}	3.82×10^{5}	8.61×10^{1}	5.68×10^{2}	3.24×10^{0}	3.97×10^{2}	1.79×10^{2}
10 years	1.88×10^{2}	1.15×10^{2}	3.82×10^{5}	9.20×10^{1}	9.10×10^{2}	3.16×10^{0}	3.97×10^{2}	1.48×10^{2}
15 years	1.88×10^{2}	1.17×10^{2}	3.82×10^{5}	1.00×10^{2}	1.18×10^{3}	3.09×10^{0}	3.97×10^{2}	1.22×10^{2}
30 years	1.90×10^{2}	1.22×10^{2}	3.82×10^{5}	1.35×10^{2}	1.66×10^{3}	2.87×10^{0}	3.96×10^{2}	6.87×10^{1}
100 years	1.99×10^{2}	1.46×10^{2}	3.82×10^{5}	3.44×10^{2}	1.91×10^{3}	2.03×10^{0}	3.94×10^{2}	4.71×10^{0}
300 years	2.23×10^{2}	2.15×10^{2}	3.82×10^{5}	8.65×10^{2}	1.40×10^{3}	7.60×10^{-1}	3.86×10^{2}	2.22×10^{-3}
1000 years	3.06×10^{2}	4.43×10^{2}	3.82×10^{5}	1.79×10^{3}	4.57×10^{2}	2.43×10^{-2}	3.62×10^{2}	---------
3000 years	5.39×10^{2}	1.01×10^{3}	3.82×10^{5}	2.23×10^{3}	1.92×10^{1}	1.31×10^{-6}	3.00×10^{2}	---------
10,000 years	1.27×10^{3}	2.27×10^{3}	3.82×10^{5}	2.24×10^{3}	3.59×10^{-1}	---------	1.55×10^{2}	---------
30,000 years	2.78×10^{3}	3.27×10^{3}	3.82×10^{5}	2.24×10^{3}	7.03×10^{-2}	---------	2.36×10^{1}	---------
100,000 years	4.51×10^{3}	3.41×10^{3}	3.82×10^{5}	2.19×10^{3}	2.33×10^{-4}	---------	3.27×10^{-2}	---------
250,000 years	4.78×10^{3}	3.39×10^{3}	3.82×10^{5}	2.08×10^{3}	---------	---------	1.85×10^{-5}	---------

[a] Indicates that the value is negligible.

Table A.3. Activities from low-reactivity, one-cycle, spent fuel assembly (curies per assembly)

	Light elements	Actinides	Fission products	Total
Discharge	2.03×10^{5}	1.65×10^{7}	7.32×10^{7}	8.99×10^{7}
1 day	1.13×10^{5}	6.27×10^{6}	1.54×10^{7}	2.18×10^{7}
1 year	6.58×10^{3}	1.62×10^{5}	8.95×10^{5}	1.06×10^{6}
5 years	1.55×10^{3}	1.31×10^{5}	1.33×10^{5}	2.66×10^{5}
10 years	7.30×10^{2}	1.05×10^{5}	7.38×10^{4}	1.80×10^{5}
15 years	3.96×10^{2}	8.38×10^{4}	6.06×10^{4}	1.45×10^{5}
30 years	1.19×10^{2}	4.42×10^{4}	4.11×10^{4}	8.54×10^{4}
100 years	4.70×10^{1}	7.58×10^{3}	7.96×10^{3}	1.56×10^{4}
300 years	1.27×10^{1}	4.85×10^{3}	1.11×10^{2}	4.97×10^{3}
1000 years	1.41×10^{0}	2.37×10^{3}	5.40×10^{0}	2.38×10^{3}
3000 years	1.23×10^{0}	1.11×10^{3}	5.21×10^{0}	1.12×10^{3}
10,000 years	1.02×10^{0}	6.92×10^{2}	5.09×10^{0}	6.98×10^{2}
30,000 years	7.21×10^{-1}	2.84×10^{2}	4.77×10^{0}	2.89×10^{2}
100,000 years	3.51×10^{-1}	4.12×10^{1}	3.84×10^{0}	4.54×10^{1}
250,000 years	1.26×10^{-1}	1.18×10^{1}	2.51×10^{0}	1.44×10^{1}

Table A.4. Activities from high-reactivity, spent fuel assembly (curies per assembly)

	Light elements	Actinides	Fission products	Total
Discharge	2.60×10^{5}	2.18×10^{7}	7.63×10^{7}	9.84×10^{7}
1 day	1.49×10^{5}	8.12×10^{6}	1.64×10^{7}	2.47×10^{7}
1 year	1.29×10^{4}	2.60×10^{5}	1.41×10^{6}	1.68×10^{6}
5 years	4.17×10^{3}	1.89×10^{5}	3.18×10^{5}	5.11×10^{5}
10 years	2.05×10^{3}	1.52×10^{5}	2.04×10^{5}	3.58×10^{5}
15 years	1.14×10^{3}	1.22×10^{5}	1.70×10^{5}	2.93×10^{5}
30 years	3.83×10^{2}	6.55×10^{4}	1.16×10^{5}	1.82×10^{5}
100 years	1.64×10^{2}	1.15×10^{4}	2.22×10^{4}	3.39×10^{4}
300 years	4.40×10^{1}	6.33×10^{3}	2.58×10^{2}	6.63×10^{3}
1000 years	4.54×10^{0}	2.68×10^{3}	1.39×10^{1}	2.70×10^{3}
3000 years	3.93×10^{0}	1.01×10^{3}	1.36×10^{1}	1.03×10^{3}
10,000 years	3.22×10^{0}	5.54×10^{2}	1.33×10^{1}	5.71×10^{2}
30,000 years	2.26×10^{0}	1.81×10^{2}	1.25×10^{1}	1.96×10^{2}
100,000 years	1.10×10^{0}	3.69×10^{1}	1.01×10^{1}	4.81×10^{1}
250,000 years	4.04×10^{-1}	2.44×10^{1}	6.64×10^{0}	3.14×10^{1}

Table A.5. Decay-heat values, low-reactivitty assembly, 1 cycle
(watts per assembly)

	Light elements	Actinides	Fission products	Total
Discharge	1.08×10^{3}	4.35×10^{4}	8.76×10^{5}	9.21×10^{5}
1 day	5.10×10^{2}	1.62×10^{4}	6.72×10^{4}	8.39×10^{4}
1 year	3.70×10^{1}	2.32×10^{2}	3.73×10^{3}	4.00×10^{3}
5 years	1.63×10^{1}	1.11×10^{2}	4.26×10^{2}	5.53×10^{2}
10 years	8.33×10^{0}	1.37×10^{2}	2.01×10^{2}	3.46×10^{2}
15 years	4.30×10^{0}	1.57×10^{2}	1.65×10^{2}	3.26×10^{2}
30 years	6.05×10^{-1}	1.93×10^{2}	1.11×10^{2}	3.05×10^{2}
100 years	8.15×10^{-3}	2.06×10^{2}	2.10×10^{1}	2.27×10^{2}
300 years	4.54×10^{-3}	1.59×10^{2}	2.01×10^{-1}	1.59×10^{2}
1000 years	3.31×10^{-3}	7.61×10^{1}	7.17×10^{-3}	7.61×10^{1}
3000 years	3.08×10^{-3}	3.43×10^{1}	7.06×10^{-3}	3.43×10^{1}
10,000 years	2.41×10^{-3}	2.14×10^{1}	6.78×10^{-3}	2.14×10^{1}
30,000 years	1.22×10^{-3}	8.76×10^{0}	6.05×10^{-3}	8.77×10^{0}
100,000 years	1.29×10^{-4}	1.21×10^{0}	4.09×10^{-3}	1.21×10^{0}
250,000 years	1.17×10^{-5}	2.78×10^{-1}	1.89×10^{-3}	2.80×10^{-1}

Table A.6. Decay-heat values, high-reactivity assembly, 3 cycles
(watts per assembly)

	Light elements	Actinides	Fission products	Total
Discharge	1.41×10^{3}	6.33×10^{4}	9.13×10^{5}	9.78×10^{5}
1 day	6.87×10^{2}	2.64×10^{4}	7.33×10^{4}	1.00×10^{5}
1 year	8.78×10^{1}	2.00×10^{3}	6.35×10^{3}	8.44×10^{3}
5 years	4.44×10^{1}	7.25×10^{2}	1.16×10^{3}	1.93×10^{3}
10 years	2.28×10^{1}	6.68×10^{2}	6.05×10^{2}	1.30×10^{3}
15 years	1.18×10^{1}	6.21×10^{2}	4.80×10^{2}	1.11×10^{3}
30 years	1.66×10^{0}	5.11×10^{2}	3.17×10^{2}	8.30×10^{2}
100 years	2.73×10^{-2}	3.19×10^{2}	5.91×10^{1}	3.78×10^{2}
300 years	1.48×10^{-2}	2.06×10^{2}	5.60×10^{-1}	2.07×10^{2}
1000 years	1.05×10^{-2}	8.47×10^{1}	1.88×10^{-2}	8.47×10^{1}
3000 years	9.76×10^{-3}	2.97×10^{1}	1.86×10^{-2}	2.97×10^{1}
10,000 years	7.64×10^{-3}	1.63×10^{1}	1.78×10^{-2}	1.63×10^{1}
30,000 years	3.87×10^{-3}	5.39×10^{0}	1.59×10^{-2}	5.41×10^{0}
100,000 years	4.11×10^{-4}	9.99×10^{-1}	1.07×10^{-2}	1.01×10^{0}
250,000 years	3.82×10^{-5}	5.81×10^{-1}	4.95×10^{-3}	5.86×10^{-1}

Table A.7. Gamma dose rates from a Westinghouse transition-cycle bare assembly

Low-reactivity, one cycle		
	Surface	1 m
Time	(rem/h)	(rem/h)
1 day	5.47×10^{6}	3.54×10^{5}
1 year	1.20×10^{5}	7.74×10^{3}
5 years	2.60×10^{4}	1.67×10^{3}
10 years	1.47×10^{4}	9.48×10^{2}
15 years	1.14×10^{4}	7.32×10^{2}
30 years	7.15×10^{3}	4.59×10^{2}
100 years	1.36×10^{3}	8.70×10^{1}
300 years	1.57×10^{1}	1.00×10^{0}
1000 years	1.49×10^{0}	9.50×10^{-2}
High-reactivity, three cycles		
	Surface	1 m
Time	(rem/h)	(rem/h)
1 day	6.07×10^{6}	3.93×10^{5}
1 year	3.02×10^{5}	1.95×10^{4}
5 years	9.13×10^{4}	5.88×10^{3}
10 years	4.75×10^{4}	3.06×10^{3}
15 years	3.46×10^{4}	2.23×10^{3}
30 years	2.09×10^{4}	1.34×10^{3}
100 years	3.87×10^{3}	2.48×10^{2}
300 years	4.39×10^{1}	2.81×10^{0}
1000 years	4.71×10^{0}	2.98×10^{-1}

Table A.8. Neutron dose rates from a Westinghouse transition-cycle bare assembly

Low-reactivity, one cycle		
	Surface	1 m
Time	(rem/h)	(rem/h)
1 day	1.61×10^{0}	1.12×10^{-1}
1 year	7.70×10^{-1}	5.37×10^{-2}
5 years	4.82×10^{-1}	3.36×10^{-2}
10 years	4.11×10^{-1}	2.87×10^{-2}
15 years	3.53×10^{-1}	2.46×10^{-2}
30 years	2.31×10^{-1}	1.61×10^{-2}
100 years	7.90×10^{-2}	5.50×10^{-3}
300 years	5.71×10^{-2}	3.98×10^{-3}
1000 years	3.86×10^{-2}	2.69×10^{-3}
High-reactivity, three cycles		
	Surface	1 m
Time	(rem/h)	(rem/h)
1 day	2.71×10^{1}	1.89×10^{0}
1 year	1.95×10^{1}	1.36×10^{0}
5 years	1.51×10^{1}	1.06×10^{0}
10 years	1.25×10^{1}	8.74×10^{-1}
15 years	1.04×10^{1}	7.25×10^{-1}
30 years	5.96×10^{0}	4.16×10^{-1}
100 years	6.32×10^{-1}	4.41×10^{-2}
300 years	2.13×10^{-1}	1.49×10^{-2}
1000 years	1.73×10^{-1}	1.12×10^{-2}

Table A.9. Westinghouse transition, transportation cask dose rates (24 assemblies, high reactivity, 3 cycles)

Time	Surface		1 m	
	Neutron (rem/h)	Gamma (rem/h)	Neutron (rem/h)	Gamma (rem/h)
1 day	8.48×10^{-2}	2.01×10^{1}	3.25×10^{-2}	9.22×10^{0}
1 year	6.08×10^{-2}	3.74×10^{-1}	2.33×10^{-2}	1.69×10^{-1}
5 years	4.71×10^{-2}	8.05×10^{-2}	1.80×10^{-2}	3.49×10^{-2}
10 years	3.90×10^{-2}	4.35×10^{-2}	1.49×10^{-2}	1.85×10^{-2}
15 years	3.23×10^{-2}	3.05×10^{-2}	1.24×10^{-2}	1.28×10^{-2}
30 years	1.85×10^{-2}	1.42×10^{-2}	7.09×10^{-3}	5.90×10^{-3}
100 years	1.98×10^{-3}	1.42×10^{-3}	7.57×10^{-4}	5.85×10^{-4}
300 years	6.72×10^{-4}	4.05×10^{-4}	2.57×10^{-4}	1.65×10^{-4}
1000 years	5.43×10^{-4}	3.28×10^{-4}	2.08×10^{-4}	1.33×10^{-4}

APPENDIX B

IMPORTANT SCALE SYSTEM DATA FILES

Some important files that are pertinent to this work are contained on the diskette attached to this report.

The SAS2H code sequence was used to simulate the burnup of the fuel assemblies studied. Via ORIGEN-S the output from SAS2H was then used to calculate the isotopic composition and associated characteristics of an assembly following discharge. ORIGEN-S also provided source terms that were used by the SAS1 code sequence to determine neutron and gamma dose rates for spent fuel assemblies at various times following discharge.

In naming the files on the attached diskette, the designation L1 implies a low-reactivity assembly burned for one reactor cycle, and H3 implies a high-reactivity assembly burned for three reactor cycles. The following files are on the attached diskette:

L1SAS2.IN:	SAS2H input for the low-reactivity, one-cycle (L1) case.
H3SAS2.IN:	SAS2H input for the high-reactivity, three-cycle (H3) case.
L1ORG1.OUT:	ORIGEN-S output for earlier decay times in L1 case.
L1ORG2.OUT:	ORIGEN-S output for later decay times in L1 case.
H3ORG1.OUT:	ORIGEN-S output for earlier decay times in H3 case.
H3ORG2.OUT:	ORIGEN-S output for later decay times in H3 case.
L1SAS1.IN:	SAS1 input for one L1 spent fuel assembly.
H3SAS1.IN:	SAS1 input for one H3 spent fuel assembly.
CH3SAS1.IN:	SAS1 input for a cask containing 24 type-H3 spent fuel assemblies.

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