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Effect of Fuel Recycling on Radioactivity and Thermal Power of High-Level Wastes

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AND THERMAL POWER OF HIGH-LEVEL WASTES

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CONTENTS

	<u>Page</u>
ABSTRACT	1
1. INTRODUCTION	1
2. METHOD	3
3. RESULTS AND CONCLUSIONS	19
4. REFERENCES	41

LIST OF TABLES

	<u>Page</u>
Table 1. Annual amount of fuel reprocessed after 160 days cooling (MTHM charged to the reactor) for the cases of No Recycle, Uranium Recycle and Uranium and Plutonium Recycle	4
Table 2. Isotopic composition of exposure groups in fresh PWR fuel in kilograms per MTHM	5
Table 3. Isotopic concentration of actinide elements and their daughters in spent PWR fuel at discharge in kilograms per MTHM charged to the reactor	9
Table 4. Radioactivity and thermal power of spent fuel per MTHM of fresh fuel charged to the reactor vs years since discharge under the No Recycle Option . .	10
Table 5. Radioactivity and thermal power of high-level wastes per MTHM of fresh fuel charged to the reactor vs years since discharge under the Uranium Recycle Option	12
Table 6. Radioactivity and thermal power of plutonium recovered from uranium fuel per MTHM of fresh fuel charged to the reactor vs years since discharge under the Uranium Recycle Option	14
Table 7. Radioactivity and thermal power of high-level wastes recovered from mixed oxide fuel fabricated from fresh plutonium per MTHM of fresh fuel charged to the reactor vs years since discharge under the No Recycle Option	15
Table 8. Radioactivity and thermal power of high-level wastes recovered from mixed oxide fuel fabricated from once-recycled plutonium per MTHM of fresh fuel charged to the reactor vs years since discharge under the No Recycle Option	17
Table 9. Radioactivity and thermal power of high-level waste recovered from mixed oxide fuel fabricated from twice-recycled plutonium per MTHM of fresh fuel charged to the reactor vs years since discharge	18
Table 10. Radioactivity and thermal power of spent fuel transferred to pool storage annually during the years 1975-2005 under the No Recycle Option	20

	<u>Page</u>
Table 11. Accumulated inventory of radioactivity and thermal power of spent fuel in pool storage during the years 1975-2010 under the No Recycle Option	21
Table 12. Radioactivity and thermal power of spent fuel shipments to Federal Repositories annually during the years 1975-2010 under the No Recycle Option	22
Table 13. Accumulated inventory of radioactivity and thermal power of spent fuel at Federal Repositories during the years 1975-2010 under the No Recycle Option	23
Table 14. Radioactivity and thermal power of high-level waste generated annually during the years 1975-2005 under the Uranium Recycle Option	25
Table 15. Radioactivity and thermal power of waste plutonium generated annually during the years 1975-2005 under the Uranium Recycle Option	26
Table 16. Inventory of radioactivity and thermal power of high-level waste at reprocessing plants during the years 1975-2005 under the Uranium Recycle Option	27
Table 17. Inventory of radioactivity and thermal power of waste plutonium stored at reprocessing plants during the years 1975-2005 under the Uranium Recycle Option	28
Table 18. Radioactivity and thermal power of shipments of high-level waste to Federal Repositories during the years 1975-2005 under the Uranium Recycle Option	29
Table 19. Radioactivity and thermal power of annual shipments of waste plutonium to Federal Repositories during the years 1975-2005 under the Uranium Recycle Option	30
Table 20. Inventory of radioactivity and thermal power of high-level waste at Federal Repositories during the years 1975-2005 under the Uranium Recycle Option	31
Table 21. Inventory of radioactivity and thermal power of waste plutonium stored in Federal Repositories during the years 1975-2005 under the Uranium Recycle Option	32
Table 22. Annual rate of waste generation for various exposure groups for the Uranium and Plutonium Recycling Option, MTHM	34

	<u>Page</u>
Table 23. Radioactivity and thermal power of high-level waste produced at reprocessing plants during the years 1975-2005 under the Uranium and Plutonium Recycle Option	36
Table 24. Inventory of radioactivity and thermal power of high-level waste at reprocessing plants for the years 1975-2005 under the Uranium and Plutonium Recycle Option	37
Table 25. Radioactivity and thermal power of high-level waste shipments to Federal Repositories during the years 1975-2005 under the Uranium and Plutonium Recycle Option	38
Table 26. Inventory of radioactivity and thermal power of high-level waste at Federal Repositories for the years 1975-2005 under the Uranium and Plutonium Recycle Option	40

EFFECT OF FUEL RECYCLING ON RADIOACTIVITY AND THERMAL POWER OF HIGH-LEVEL WASTES

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ABSTRACT

The radioactivity and thermal power of high-level and plutonium-bearing wastes from the nuclear fuel cycle have been calculated for the years 1975-2005 using the rate of generation of such wastes projected for the Generic Environmental Statement on Mixed Oxide Fuel (NUREG-0002). Three modes of fuel recycle are considered: (1) no recycle, (2) uranium recycle, and (3) prompt uranium and plutonium recycle. These cases are compared with respect to radioactivity and thermal power of the generated waste, the waste shipments, and the accumulated inventories at reactor sites, reprocessing facilities, and ultimate disposal sites.

1. INTRODUCTION

The radioactivity and thermal characteristics of the radioactive wastes from the commercial fuel cycle depend upon the extent to which uranium and plutonium are recycled. When reprocessed uranium spent fuels are returned to the enrichment plants as feed material, they contain many uranium isotopes that have been formed in the reactor during the process of irradiation and are not characteristic of feed material obtained from uranium ore. Of these, ^{234}U and ^{236}U are of particular importance since they tend to accompany the ^{235}U during the enrichment process so that, as recycling continues, the isotopic composition of the enriched uranium changes. Similarly, continued

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recycling of plutonium results in plutonium dioxide fuel material in which the content of the heavier plutonium isotopes increases. These modes of fuel recycle interact; uranium recycle increases the ^{236}U isotopic content which, in turn, causes increased production of ^{238}Pu during irradiation in the reactor, thus altering the plutonium isotopic composition in succeeding recycle steps.

In order to study the environmental impact of reactor fuel recycling, it is necessary to compare the inventories of hazardous waste materials for each of the recycle options. This has been done for the cases of (1) no recycle, (2) uranium recycle, and (3) prompt uranium and plutonium recycle. Since the isotopic composition of the fuel changes with continued recycling for each of the recycle modes, account must be taken of the year-to-year inventories of both fresh and spent fuels. Tables are presented which show the projected inventories of total radioactivity, actinide activity, plutonium activity, and fission product thermal power for each of the years 1975-2005. This information supplements that given in the Generic Environmental Statement on Mixed Oxide Fuels.¹

2. METHOD

In preparing the Generic Environmental Statement on Mixed Oxide Fuels (GESMO),¹ the Nuclear Regulatory Commission (NRC) evaluated many different cases of Light Water Reactor (LWR) fuel recycle. These cases were analyzed by the Battelle Pacific Northwest Laboratories and are designated by the case numbers assigned by them. The base case for no recycle is designated Case 40 in the GESMO report. Case 39 is the base case for uranium recycle and assumes that fuel reprocessing begins in 1986. The uranium and plutonium recycle alternative, Case 36, assumes that reprocessing starts in 1978 and that plutonium recycle begins in 1981.

Table 1 shows the annual amount of spent fuel reprocessed for each of the three recycle options as projected for the GESMO report.² To simplify the analysis of the data of Table 1, it was assumed that the reactors are Pressurized Water Reactors (PWRs) and that the fuel elements charged to these reactors have the isotopic compositions shown in Table 2. These fuel compositions are those of the model PWRs described by Wachter³ for the several recycle options. The reactors were based on a three-year cycle with annual refueling. The average specific power density was assumed to be 37.5 MW/MTHM (megawatts/MTHM or megawatts/metric ton of heavy metal) at full power. The load factor was 80%, and the reactors were assumed to operate at a power density of 30 MW/MTHM continuously throughout the fuel exposure.

Table 1. Annual amount of fuel reprocessed after 160 days cooling (MTHM charged to the reactor) for the cases of No Recycle, Uranium Recycle, and Uranium and Plutonium Recycle

Year	No recycle	Uranium recycle	U and Pu recycle
1978	0	0	500
1979	0	0	999
1980	0	0	1499
1981	0	0	1499
1982	0	0	1748
1983	0	0	1998
1984	0	0	2249
1985	0	0	2249
1986	3500	1348	2848
1987	3500	3397	3549
1988	3500	5843	4249
1989	3500	7445	4249
1990	3500	7849	4846
1991	3571	8249	5545
1992	4101	8241	6248
1993	4608	8248	6848
1994	4927	8248	7548
1995	5472	8248	8248
1996	6131	8248	8248
1997	6669	9248	9248
1998	7150	10248	10248
1999	7799	10248	10248
2000	8401	10248	10248

Table 2. Isotopic composition of exposure groups in fresh PWR fuel in kilograms per MTHM

Isotope	No Recycle	U Recycle	Pu Recycle		
	U	U	Pu-1	Pu-1-2	Pu-1-2-3
²³⁴ U	0.0	0.40	0.054	0.053	0.052
²³⁵ U	33	33	6.83	6.63	6.51
²³⁶ U	0.0	3.5	0.0	0.0	0.0
²³⁸ U	967	964	954	925	909
Total U	1,000	1,000	960.6	931.7	915.7
²³⁸ Pu	0	0	0.640	1.98	3.57
²³⁹ Pu	0	0	22.6	26.6	27.2
²⁴⁰ Pu	0	0	9.38	18.7	27.2
²⁴¹ Pu	0	0	4.77	11.7	17.1
²⁴² Pu	0	0	1.96	8.36	15.3
Total Pu	0	0	39.4	68.3	84.3

The model reactors corresponding to the No Recycle and Uranium Recycle cases utilize fuel enriched to 3.3 wt % in the ^{235}U isotope. No account is taken of the minor uranium isotopes (those other than ^{235}U and ^{238}U) in the No Recycle case. The Uranium Recycle case assumes buildup of these isotopes to 0.04 wt % ^{234}U and 0.35 wt % ^{236}U . These concentrations correspond to projections⁴ of enrichment plant product compositions for PWR reload fuel in about the year 1990, assuming that uranium recycle was started in 1975 and extended to 1990. In order to bound the variations in uranium composition, the ^{234}U and ^{236}U isotopic compositions of Table 2 for the 1990 Uranium Recycle Case have been conservatively used in this study for all the years for which inventories are presented.

Most current all-uranium reactors can be modified to make use of plutonium-enriched fuel. The first plutonium recycle reactors (PRRs) are therefore assumed to utilize plutonium having the isotopic composition corresponding to that recovered from all-uranium reactors which have reached equilibrium and which have used uranium characteristic of the Uranium Recycle mode.

In Table 2, the designation "Pu-1" refers to plutonium-enriched fuel rods fabricated from plutonium formed in an all-uranium reactor, i. e., "first-pass" plutonium. The recovered plutonium is assumed to be converted to the oxide form and to be mixed with uranium oxide made from uranium of natural isotopic composition (0.711 wt % ^{235}U). The isotopic composition of the fresh fuel shown in Table 2 is that of Deonigi,⁵ in which the proportion of plutonium in the mixed oxide fuel has been

defined so that the fuel rods can be intermixed with all-uranium fuel rods in the reactor. The overall fissile content from both the uranium and the plutonium fissile isotopes is therefore sufficiently greater than that of the original all-uranium fuel rods to compensate for the poisoning (neutron-absorbing) characteristics of the nonfissile plutonium isotopes.

The amount of mixed oxide fuel available to make up an annual reload for each reactor does not exceed 40% of the total charge. The remaining fresh fuel is made up of enriched uranium rods of the same isotopic composition as specified for the uranium recycle reactors.

When fuel rods of type Pu-1 are reprocessed after exposure in the reactor, the isotopic composition of the recovered plutonium differs from that of the fresh Pu-1 fuel because of the additional neutron irradiation of the several plutonium isotopes. This mixed oxide fuel is designated "Pu-1-2" in Table 2. The plutonium isotopic compositions have been calculated by Deonigi for the recycle plutonium. Compared to the Pu-1 fresh fuel, the proportion of the heavier plutonium isotopes is increased as a consequence of the additional exposure in the reactor. The ^{242}Pu isotope is increased nearly 4 times over that found in the Pu-1 feed material, while ^{239}Pu is increased very little. The lightest plutonium isotope, ^{238}Pu , is also increased; however, this is largely because of the irradiation of the ^{236}U in the recycled enriched-uranium feed.

The Pu-1-2-3 contains plutonium obtained from the reprocessed Pu-1-2 spent fuel rods. The isotopic compositions of Table 2 have been obtained from the ORIGEN calculations described in ref. 3.

The ORIGEN computer⁶ code was used to calculate the radionuclide inventory in the spent fuel. In order to calculate the radioactivity of the spent fuel and its cladding, it is necessary to include hundreds of nuclides in the irradiation and decay chains. Many of these do not contribute significantly to the radioactivity, but they enter into the transmutation and decay chains and cannot be omitted from the calculation. The ORIGEN code includes 674 nuclides (all naturally occurring nuclides of atomic number 84 or below) as well as 100 actinide elements and 461 fission products. Table 3 shows the concentrations in spent fuel of major actinide isotopes calculated from the fresh fuel compositions of Table 2 based on a burnup of 33,000 MWD/MTM charged to the reactor.

The ORIGEN code has also been used to determine the changes in the inventory of radioactive nuclides in each of the spent fuel types during the 25 years following discharge of the fuel from the reactor. Table 4 shows the radioactivity and thermal power of the fuel withdrawn from a uranium reactor based on a No-Recycle uranium supply. The first row of the table (year 0) defines the activity and power at 160 days following discharge of the spent fuel for each MTM of fuel originally charged to the reactor three years earlier. The column headed "Total" shows that the total activity decreases from 4353.8 kCi/MTM to 246.6 kCi/MTM 25 years later. Contributing to this total activity is the fission product activity, which drops from 4190.5 kCi/MTM at discharge to 207 kCi/MTM

Table 3. Isotopic concentration of actinide elements and their daughters in spent PWR fuel at discharge in kilograms per MTHM charged to the reactor

Isotope	No recycle	U recycle	Pu recycle		
	U	U	Pu-1	Pu-1-2	Pu-1-2-3
^{234}U	1.79	184	36.5	63.1	90.9
^{235}U	7,880	8,040	2,720	3,410	3,650
^{236}U	4,540	7,380	848	691	624
^{237}U	10.6	16.1	2.77	1.76	1.45
^{238}U	940,000	940,000	931,000	909,000	895,000
^{237}Np	472	868	136	94.5	80.9
^{239}Np	79.9	79.1	77.3	55.2	57.7
^{238}Pu	162	328	564	1,620	2,830
^{239}Pu	5,170	5,200	11,400	13,600	14,700
^{240}Pu	2,166	2,160	7,440	12,200	14,100
^{241}Pu	1,030	1,030	4,480	8,770	10,900
^{242}Pu	355	353	2,700	7,110	11,600
^{241}Am	25	25	223	578	834
^{242m}Am	0.941	0.941	14.9	37.9	53.8
^{243}Am	95	93.5	1,550	4,040	6,400
^{242}Cm	10.1	10.0	98.6	185	234
^{244}Cm	30.5	29.0	1,000	2,100	2,990
^{246}Cm	0.225	0.218	14	179	20.2

Table 4. Radioactivity and thermal power of spent fuel per MTHM of fresh fuel charged to the reactor vs years since discharge under the No Recycle Option

Years	Total Activity (kCi/MTHM)	Fission Products (kCi/MTHM)	Total Cladding (kCi/MTHM)	Total Actinide (kCi/MTHM)	Actinide Alpha (kCi/MTHM)	Total Pu (kCi/MTHM)	Pu Alpha (kCi/MTHM)	Thermal Power (kW/MTHM)
0	4353.8	4190.5	37.296	125.992	23.364	106.560	3.632	19.728
1	1768.7	1648.8	11.222	108.669	9.988	102.307	3.681	7.992
2	1103.2	995.1	8.069	100.033	7.195	97.012	3.675	4.680
3	785.9	683.7	6.542	95.677	6.637	92.771	3.653	3.103
4	632.2	535.0	5.510	91.718	6.535	88.728	3.631	2.296
5	549.5	457.0	4.743	87.702	6.551	84.818	3.611	1.838
6	494.5	406.4	4.117	83.954	6.582	81.064	3.592	1.565
7	455.3	371.3	3.602	80.357	6.606	77.424	3.571	1.387
8	425.9	345.7	3.175	76.966	6.626	73.974	3.551	1.265
9	403.0	326.4	2.815	73.779	6.637	70.720	3.532	1.178
10	383.9	310.7	2.513	70.694	6.639	67.562	3.511	1.111
11	367.6	297.6	2.257	67.725	6.638	64.525	3.491	1.057
12	353.4	286.5	2.038	64.891	6.633	61.627	3.470	1.013
13	341.0	276.9	1.850	62.202	6.626	58.878	3.450	0.976
14	329.9	268.6	1.686	59.656	6.618	56.282	3.430	0.946
15	320.0	261.2	1.543	57.246	6.606	53.828	3.410	0.920
20	277.5	229.9	1.058	46.569	6.611	43.039	3.309	0.796
25	246.6	207.0	0.803	38.800	6.680	35.300	3.220	0.695

after 25 years. The cladding and other materials of construction of the fuel rods are collected in the category "cladding" and contributed 37.3 kCi/MTHM initially, decreasing to 0.803 kCi/MTHM at the end of the decay period.

The specific radioactivity of the actinide elements is shown in greater detail because of its long-term importance. The total actinide activity decreases from 126 kCi/MTHM to 38.8 kCi/MTHM over the 25-year period. This activity is further subdivided to show the amount that is due to alpha-particle emission. The alpha-particle specific radioactivity decreases from 23.36 kCi/MTHM after the 160-day cooling period following discharge from the reactor to a minimum of 6.6 kCi/MTHM 15 years following discharge. The alpha activity increases slightly thereafter owing to the production, through decay processes, of nuclides which are alpha-particle emitters. Much of the alpha-particle activity is due to the plutonium isotopes as shown in the next two columns of Table 4. The specific plutonium alpha activity, listed in the next column, increases initially due to alpha-emitters growing in and then decreases slowly thereafter.

The amount of thermal heat produced by this radioactivity is shown in the last column of Table 4. The total thermal heat decreases from 19.7 kW/MTHM at discharge to 0.695 kW/MTHM after 25 years.

In the Uranium Recycle Option, the spent fuel is assumed to be processed 160 days after discharge. It is further assumed that 0.5% of the uranium and plutonium and 0.1% of the bromine and iodine are carried through to the waste. Table 5 shows the radioactivity of the waste

Table 5. Radioactivity and thermal power of high-level wastes per MTHM of fresh fuel charged to the reactor vs years since discharge under the Uranium Recycle Option

Years	Total Activity (kCi/MTHM)	Fission Products (kCi/MTHM)	Total Cladding (kCi/MTHM)	Total Actinide (kCi/MTHM)	Actinide Alpha (kCi/MTHM)	Total Pu (kCi/MTHM)	Pu Alpha (kCi/MTHM)	Thermal Power (kW/MTHM)
0	4227.2	4170.0	37.100	20.100	19.500	0.545	0.032	20.063
1	1659.0	1641.2	11.150	6.683	6.098	0.587	0.099	8.077
2	991.8	980.0	8.032	3.763	3.263	0.579	0.113	4.667
3	686.9	677.3	6.506	3.059	2.583	0.560	0.116	3.094
4	529.4	521.1	5.481	2.840	2.380	0.539	0.115	2.277
5	445.5	438.0	4.707	2.717	2.268	0.519	0.115	1.828
6	395.0	388.3	4.089	2.628	2.192	0.500	0.115	1.555
7	362.0	355.8	3.578	2.537	2.119	0.481	0.114	1.380
8	339.1	333.5	3.154	2.449	2.050	0.464	0.113	1.259
9	322.7	317.5	2.799	2.365	1.985	0.447	0.113	1.172
10	310.2	305.4	2.499	2.280	1.920	0.431	0.112	1.107
11	299.6	295.2	2.246	2.198	1.857	0.416	0.111	1.054
12	290.5	286.4	2.029	2.118	1.795	0.401	0.111	1.010
13	282.5	278.7	1.843	2.042	1.735	0.387	0.110	0.973
14	275.5	271.9	1.681	1.970	1.678	0.374	0.109	0.941
15	269.3	265.9	1.540	1.900	1.623	0.361	0.108	0.914
20	237.0	234.3	1.056	1.612	1.389	0.305	0.105	0.792
25	204.2	202.0	0.782	1.400	1.210	0.259	0.103	0.683

material after reprocessing and for succeeding years thereafter. The radioactivity and thermal power of the wastes from fuel reprocessing differ from that of the spent fuel of the No Recycle case because (1) most of the uranium and plutonium have been removed, (2) the activity has been decreased by the removal of the cladding and low-level reprocessing wastes, and (3) slight activity differences in the radioactive nuclide inventory result from the buildup of the ^{234}U and ^{236}U in the Uranium Recycle case.

In the Uranium Recycle Option, the recovered plutonium is a waste material. Table 6 shows the corresponding radioactivity and thermal power of this plutonium. The total actinide activity from the recovered plutonium added to that in the high-level wastes is about 2% greater than that of the No Recycle case, reflecting the changes in isotopic composition of the spent fuel resulting from the buildup of the minor uranium isotopes.

In the Uranium and Plutonium Recycle Option, the recovered plutonium, which is a waste material in the Uranium Recycle Option, is purified, converted to PuO_2 , and mixed with UO_2 made from uranium of normal isotopic composition in order to be fabricated into fuel rods. When this mixed oxide fuel, designated Pu-1 in Tables 2 and 3, is reprocessed in its turn, the high-level waste has the radioactivity and thermal power characteristics shown in Table 7. For calculational purposes, it is assumed that the fuel rods containing the Pu-1 mixed oxide fuel are processed together as a single batch and are not diluted with any other material. Table 7 shows that the fission product activity is slightly increased because of the different operating

Table 6. Radioactivity and thermal power of plutonium recovered from uranium fuel per MTHM of fresh fuel charged to the reactor vs years since discharge under the Uranium Recycle Option

Years	Total Activity (kCi/MTHM)	Fission Products (kCi/MTHM)	Total Cladding (kCi/MTHM)	Total Actinide (kCi/MTHM)	Actinide Alpha (kCi/MTHM)	Total Pu (kCi/MTHM)	Pu Alpha (kCi/MTHM)	Thermal Power (kW/MTHM)
0	109.0	0.0	0.0	109.000	6.420	109.000	6.420	0.215
1	104.2	0.0	0.0	104.213	6.528	104.114	6.363	0.219
2	99.5	0.0	0.0	99.526	6.640	99.182	6.330	0.222
3	95.2	0.0	0.0	95.175	6.742	95.076	6.285	0.225
4	91.3	0.0	0.0	91.299	6.840	90.709	6.240	0.228
5	87.4	0.0	0.0	87.408	6.930	86.678	6.199	0.231
6	83.7	0.0	0.0	83.748	7.013	82.940	6.159	0.234
7	80.2	0.0	0.0	80.239	7.089	79.309	6.117	0.236
8	76.9	0.0	0.0	76.918	7.158	75.862	6.075	0.239
9	73.8	0.0	0.0	73.806	7.222	72.628	6.033	0.241
10	70.8	0.0	0.0	70.833	7.281	69.534	5.990	0.243
11	68.0	0.0	0.0	67.954	7.334	66.538	5.948	0.245
12	65.2	0.0	0.0	65.198	7.383	63.668	5.906	0.246
13	62.6	0.0	0.0	62.573	7.428	60.938	5.865	0.248
14	60.1	0.0	0.0	60.084	7.470	58.353	5.824	0.249
15	57.7	0.0	0.0	57.728	7.509	55.910	5.784	0.250
20	47.3	0.0	0.0	47.268	7.660	45.124	5.594	0.255
25	38.9	0.0	0.0	38.900	7.760	36.600	5.420	0.257

Table 7. Radioactivity and thermal power of high-level wastes recovered from mixed oxide fuel fabricated from fresh plutonium per MTHM of fresh fuel charged to the reactor vs years since discharge under the No Recycle Option

Years	Total Activity (kCi/MTHM)	Fission Products (kCi/MTHM)	Total Cladding (kCi/MTHM)	Total Actinide (kCi/MTHM)	Actinide Alpha (kCi/MTHM)	Total Pu (kCi/MTHM)	Pu Alpha (kCi/MTHM)	Thermal Power (kW/MTHM)
0	4643.3	4360.0	32.309	251.000	248.000	2.440	0.063	29.583
1	1892.7	1767.4	8.863	116.430	113.448	2.984	0.725	12.636
2	1121.9	1029.2	6.092	86.635	83.938	3.030	0.867	7.862
3	763.8	681.3	4.829	77.748	75.183	2.964	0.898	5.741
4	581.9	503.9	4.021	73.902	71.400	2.880	0.905	4.668
5	483.0	408.6	3.427	70.975	68.487	2.790	0.908	4.055
6	423.6	352.2	2.961	68.463	66.017	2.704	0.909	3.666
7	385.7	317.2	2.576	65.973	63.621	2.621	0.910	3.395
8	359.8	293.9	2.259	63.565	61.326	2.543	0.910	3.189
9	341.3	278.0	1.993	61.269	59.152	2.470	0.910	3.024
10	327.3	266.5	1.770	59.017	57.021	2.401	0.910	2.885
11	315.4	257.1	1.580	56.815	54.929	2.334	0.910	2.761
12	305.3	249.2	1.419	54.689	52.902	2.270	0.910	2.649
13	296.4	242.5	1.280	52.651	50.953	2.209	0.909	2.548
14	288.6	236.8	1.159	50.706	49.090	2.151	0.909	2.455
15	281.8	231.9	1.054	48.855	47.313	2.096	0.909	2.371
20	245.8	204.3	0.695	40.755	39.413	1.847	0.903	2.002
25	208.9	174.0	0.493	34.400	33.100	1.640	0.895	1.701

characteristics of a plutonium recycle reactor. The actinide activity is increased by more than a factor of 10 because of the larger amount of plutonium in the spent fuel. Table 7 is not based on a real or logical processing mode, and this activity increase is not factual with respect to the total spent fuel mix. The actual increase in the activity of the mix depends upon the fraction of Pu-1 fuel present, and Table 7 provides the information necessary to calculate the activity contributed by Pu-1 fuel to any blend of uranium and mixed oxide fuels.

Repeated recycle of the plutonium causes further buildup of the actinides. This can be seen in Tables 8 and 9, which show the change, with time, of the radioactivity and thermal power of the high-level wastes from reprocessing mixed oxide fuels of types Pu-1-2 and Pu-1-2-3.

These tables, which also give the variation with time of the radioactivity and thermal power of a MTHM of spent fuel having specified irradiation history, have been used in conjunction with the estimates of fuel reprocessing loads to project the inventory of radioactivity in reprocessing wastes for the period 1975-2005. This has been done for each of the possible modes of recycle, and the results are described in the next section.

Table 8. Radioactivity and thermal power of high-level wastes recovered from mixed oxide fuel fabricated from once-recycled plutonium per MTHM of fresh fuel charged to the reactor vs years since discharge under the No Recycle Option

Years	Total Activity (kCi/MTHM)	Fission Products (kCi/MTHM)	Total Cladding (kCi/MTHM)	Total Actinide (kCi/MTHM)	Actinide Alpha (kCi/MTHM)	Total Pu (kCi/MTHM)	Pu Alpha (kCi/MTHM)	Thermal Power (kW/MTHM)
0	4823.7	4310.0	23.700	490.000	484.000	4.520	0.162	37.558
1	1990.6	1746.1	6.438	237.993	232.784	5.568	1.406	16.434
2	1203.3	1018.3	4.431	180.090	175.040	5.650	1.670	10.766
3	839.8	673.7	3.514	162.581	157.980	5.529	1.731	8.416
4	652.9	495.0	2.921	154.998	150.006	5.370	1.750	7.255
5	551.9	400.5	2.488	148.966	143.955	5.210	1.760	6.564
6	491.1	345.2	2.150	143.707	138.827	5.055	1.765	6.105
7	451.5	311.1	1.872	138.517	133.828	4.905	1.768	5.762
8	423.8	288.6	1.643	133.500	129.035	4.763	1.769	5.484
9	403.6	273.4	1.451	128.719	124.493	4.629	1.770	5.250
10	387.8	262.5	1.290	124.035	120.045	4.501	1.770	5.041
11	374.2	253.6	1.153	119.458	115.674	4.378	1.770	4.846
12	362.2	246.1	1.036	115.038	111.437	4.261	1.770	4.664
13	351.6	239.8	0.935	110.802	107.363	4.149	1.770	4.495
14	342.0	234.4	0.847	106.759	103.466	4.043	1.769	4.336
15	333.5	229.8	0.771	102.909	99.750	3.942	1.769	4.188
20	289.3	202.7	0.507	86.016	83.185	3.492	1.765	3.521
25	245.1	172.0	0.358	72.701	69.901	3.120	1.760	2.967

Table 9. Radioactivity and thermal power of high-level waste recovered from mixed oxide fuel fabricated from twice-recycled plutonium per MTHM of fresh fuel charged to the reactor vs years since discharge

Years	Total Activity (kCi/MTHM)	Fission Products (kCi/MTHM)	Total Cladding (kCi/MTHM)	Total Actinide (kCi/MTHM)	Actinide Alpha (kCi/MTHM)	Total Pu (kCi/MTHM)	Pu Alpha (kCi/MTHM)	Thermal Power (kW/MTHM)
0	4966.8	4300.0	20.800	646.000	638.000	5.680	0.268	42.939
1	2077.9	1744.6	5.635	327.682	319.956	6.999	1.853	19.391
2	1266.2	1009.2	3.881	253.106	246.076	7.120	2.189	13.160
3	898.0	664.3	3.080	230.680	223.459	6.971	2.271	10.627
4	713.5	490.9	2.560	219.990	213.011	6.771	2.290	9.381
5	611.7	398.5	2.179	211.016	204.903	6.578	2.300	8.629
6	549.1	344.0	1.881	203.263	197.745	6.393	2.305	8.110
7	507.5	310.0	1.638	195.918	190.508	6.211	2.310	7.702
8	477.7	287.3	1.437	188.964	183.445	6.036	2.313	7.358
9	455.5	271.8	1.271	182.433	176.675	5.870	2.317	7.058
10	437.7	260.5	1.130	176.080	170.036	5.711	2.320	6.785
11	422.0	251.2	1.011	169.831	163.575	5.558	2.323	6.526
12	408.1	243.4	0.908	163.766	157.356	5.413	2.326	6.282
13	395.6	236.8	0.820	157.928	151.411	5.274	2.328	6.052
14	384.3	231.2	0.744	152.339	145.750	5.142	2.331	5.837
15	374.0	226.3	0.677	147.004	140.371	5.017	2.333	5.634
20	322.6	199.3	0.446	122.820	117.107	4.462	2.336	4.726
25	273.3	170.0	0.314	103.001	99.101	4.010	2.330	3.982

3. RESULTS AND CONCLUSIONS

3.1 Case I. No Recycling

Table 1 shows the annual generation of spent fuel under the No Recycle Option for the years 1978-2000. The radioactivity and thermal power of these fuel assemblies are shown in Table 10, based on the specific activities of Table 4. In this case, the spent fuel rods are stored in water pools at the reactor site or elsewhere for 10 years before shipment to permanent storage. Table 11 shows the accumulations in these water pools. The storage requirements continue to increase because of the increase in number of reactors until the end of the study period at 2000. Thereafter, the accumulations decrease as the fuel is shipped out.

The quantities of radioactivity shipped annually from the water storage pools to the Federal Waste Repositories for each of the years 1975-2010 are shown in Table 12. The accumulated inventory at these Federal Repositories is shown for these years in Table 13. For the purpose of this study, it is assumed that no fuel is transferred to waste management facilities beyond the year 2000; thus the radioactivity inventory decreases thereafter.

Table 10. Radioactivity and thermal power of spent fuel transferred to pool storage annually during the years 1975-2005 under the No Recycle Option

Year	Reproc- essing Load (MTHM)	Total Activity (MCi)	Fission Products (MCi)	Total Cladding (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-85	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1986	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1987	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1988	3500.0	15238.4	14666.9	130.536	440.972	81.774	372.960	12.711	69.047
1989	3500.0	15238.4	14666.9	130.536	440.972	81.774	372.960	12.711	69.047
1990	3500.0	15238.4	14666.9	130.536	440.972	81.774	372.960	12.711	69.047
1991	3571.0	15547.5	14964.4	133.184	449.917	83.432	380.526	12.969	70.447
1992	4101.0	17855.1	17185.4	152.950	516.693	95.815	437.002	14.894	80.903
1993	4608.0	20062.4	19310.0	171.859	580.571	107.661	491.028	16.735	90.905
1994	4927.0	21451.3	20645.8	183.757	620.762	115.114	525.021	17.893	97.198
1995	5471.0	23819.8	22926.4	204.046	689.302	127.824	582.990	19.869	107.930
1996	6131.0	26693.3	25692.2	228.661	772.457	143.244	653.319	22.266	120.950
1997	6669.0	29035.7	27946.7	248.726	840.240	155.814	710.648	24.220	131.563
1998	7150.0	31129.9	29962.4	266.666	900.842	167.052	761.904	25.967	141.052
1999	7799.0	33955.5	32682.0	290.871	982.611	182.215	831.061	28.323	153.856
2000	8401.0	36576.5	35204.7	313.323	1058.458	196.280	895.210	30.510	165.732
2001-05	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 11. Accumulated inventory of radioactivity and thermal power of spent fuel in pool storage during the years 1975-2010 under the No Recycle Option

Year	Reproc- essing Load (MTHM)	Total Activity (MCi)	Fission Products (MCi)	Total Cladding (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-85	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1986	3500.0	15238.4	14666.9	130.536	440.972	81.774	372.960	12.711	69.047
1987	3500.0	21428.8	20437.7	169.812	821.313	116.731	731.034	25.593	97.017
1988	3500.0	25289.8	23920.4	198.052	1171.428	141.912	1070.577	38.455	113.397
1989	3500.0	28040.6	26313.4	220.948	1506.297	165.140	1395.277	51.240	124.257
1990	3500.0	30253.4	28185.9	240.233	1827.308	188.014	1705.824	63.948	132.293
1991	3571.0	32485.7	30083.0	259.481	2143.212	212.602	2010.254	76.846	140.127
1992	4101.0	36649.5	33843.5	294.455	2511.541	248.732	2357.719	91.603	156.626
1993	4608.0	41466.0	38212.2	332.492	2921.364	289.505	2743.839	108.155	176.050
1994	4927.0	45882.6	42170.9	365.931	3345.842	329.496	3146.613	125.817	193.523
1995	5471.0	51246.5	47023.8	407.602	3815.212	376.250	3589.390	145.384	215.106
1996	6131.0	56206.7	51666.5	447.469	4092.738	406.693	3846.405	154.988	236.887
1997	6669.0	61214.1	56311.0	487.017	4416.125	439.138	4149.320	166.546	258.560
1998	7150.0	66190.1	60886.5	526.477	4777.184	473.473	4489.879	179.832	279.717
1999	7799.0	72020.1	66250.0	573.471	5196.676	514.645	4884.379	195.440	304.384
2000	8401.0	78101.5	71815.3	621.845	5664.434	559.532	5325.539	213.198	329.838
2001	0.0	45230.2	39855.1	336.246	5038.992	397.531	4847.004	200.149	178.455
2002	0.0	33059.7	28295.5	263.394	4500.762	342.348	4349.516	184.737	121.030
2003	0.0	25866.5	21670.6	212.623	3983.303	306.917	3946.261	167.506	88.776
2004	0.0	20984.2	17346.4	171.607	3466.200	274.052	3343.291	149.261	68.260
2005	0.0	17038.6	13970.7	136.142	2931.718	238.487	2825.272	129.222	53.216
2006	0.0	13437.3	10958.8	104.156	2374.335	198.457	2285.391	106.970	40.860
2007	0.0	10027.4	8149.4	75.149	1802.855	154.629	1733.007	82.951	29.938
2008	0.0	6720.7	5450.1	48.625	1221.997	107.424	1172.999	57.178	19.811
2009	0.0	3385.5	2742.1	23.650	619.820	55.756	594.118	29.669	9.895
2010	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 12. Radioactivity and thermal power of spent fuel shipments to Federal Repositories annually during the years 1975-2010 under the No Recycle Option

Year	Reproc- essing Load (MTM)	Total Activity (MCi)	Fission Products (MCi)	Total Cladding (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-85	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1986	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1987	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1988	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1989	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1990	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1991	3571.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1992	4101.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1993	4608.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1994	4927.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1995	5471.0	1410.5	1142.4	9.853	258.227	23.229	247.520	12.361	4.122
1996	6131.0	1410.5	1142.4	9.853	258.227	23.229	247.520	12.361	4.122
1997	6669.0	1410.5	1142.4	9.853	258.227	23.229	247.520	12.361	4.122
1998	7150.0	1410.5	1142.4	9.853	258.227	23.229	247.520	12.361	4.122
1999	7799.0	1410.5	1142.4	9.853	258.227	23.229	247.520	12.361	4.122
2000	8401.0	1439.1	1165.6	10.053	263.466	23.700	252.541	12.611	4.206
2001	0.0	1652.7	1338.6	11.545	302.569	27.218	290.022	14.483	4.830
2002	0.0	1857.0	1504.0	12.972	339.975	30.583	325.877	16.274	5.427
2003	0.0	1985.5	1608.2	13.870	363.510	32.700	348.437	17.400	5.803
2004	0.0	2204.8	1785.7	15.402	403.646	36.310	386.909	19.321	6.444
2005	0.0	2470.7	2001.2	17.260	452.341	40.691	433.584	21.652	7.221
2006	0.0	2687.6	2176.8	18.774	492.034	44.261	471.631	23.552	7.855
2007	0.0	2881.4	2333.8	20.128	527.522	47.453	505.647	25.251	8.421
2008	0.0	3142.9	2545.6	21.955	575.405	51.761	551.545	27.543	9.186
2009	0.0	3385.5	2742.1	23.650	619.820	55.756	594.118	29.669	9.895
2010	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 13. Accumulated inventory of radioactivity and thermal power of spent fuel at Federal Repositories during the years 1975-2010 under the No Recycle Option

Year	Reproc- essing Load (MTHM)	Total Activity (MCi)	Fission Products (MCi)	Total Cladding (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-85	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1986	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1987	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1988	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1989	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1990	3500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1991	3571.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1992	4101.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1993	4608.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1994	4927.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1995	5471.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1996	6131.0	1343.8	1087.6	8.794	247.427	23.238	236.472	12.290	3.888
1997	6669.0	2630.4	2129.3	16.693	484.463	46.470	462.308	24.508	7.588
1998	7150.0	3867.5	3132.0	23.826	711.582	69.687	678.001	36.655	11.134
1999	7799.0	5060.9	4101.3	30.300	929.287	92.879	884.075	48.730	14.551
2000	8401.0	6215.6	5041.3	36.202	1138.083	116.040	1081.062	60.735	17.860
2001	0.0	7362.9	5977.7	41.781	1343.464	139.633	1274.258	72.919	21.158
2002	0.0	8679.9	7053.7	48.239	1577.983	166.716	1494.800	86.893	24.953
2003	0.0	10150.7	8256.5	55.441	1838.764	197.154	1739.873	102.563	29.192
2004	0.0	11697.7	9523.4	62.854	2111.419	229.713	1995.669	119.261	33.645
2005	0.0	13405.5	10923.1	71.036	2411.393	265.895	2276.939	137.768	38.556
2006	0.0	15313.4	12487.4	80.215	2745.302	306.478	2590.429	158.483	44.035
2007	0.0	17368.2	14173.5	89.997	3104.655	350.656	2926.520	180.964	49.928
2008	0.0	19544.1	15960.9	100.196	3482.975	398.055	3280.410	205.000	56.159
2009	0.0	21902.8	17899.6	111.210	3891.900	449.796	3662.717	231.174	62.907
2010	0.0	24420.8	19971.1	122.857	4326.906	505.574	4069.062	259.306	70.104

3.2 Case II. Uranium Recycling

The radioactivity and thermal power of wastes from the reprocessing of 160-day-cooled reactor fuel for the years 1975-2000 are presented in Table 14. No wastes are present until 1986 since GESMO Case 39 assumes no reprocessing until 1986 due to uncertainty in licensing action and to provide a chance to observe yellow cake pricing. It is assumed that these wastes are retained at the reprocessing plants for 5 years before shipment to the ultimate waste disposal sites.

The uranium recovered in the reprocessing is shipped to enrichment plants for recycle, and the recovered plutonium is assumed to be retained at the reprocessing plant as a waste material. The annual radioactivity of the plutonium is shown in Table 15.

The inventory of high-level wastes at the reprocessing plants for each of the years of the study is summarized in Table 16. After the initial 5-year accumulation, the inventory levels off as material is shipped out. The inventory fluctuates thereafter with the changing processing load. The buildup of plutonium at the plants parallels that of the high-level waste as is seen in Table 17, which shows the accumulations of recovered plutonium in the reprocessing plant storage vaults. Shipments of the high-level wastes and the recovered plutonium from the reprocessing plants to Federal Repositories are shown in Tables 18 and 19. The initial shipments reach the disposal sites in 1990, 5 years after the start of reprocessing. The inventories will continue to build up as is seen in Tables 20 and 21, which summarize the accumulations of high-level waste and plutonium at the Federal Repositories for each of the years included in the study.

Table 14. Radioactivity and thermal power of high-level waste generated annually during the years 1975-2005 under the Uranium Recycle Option

Year	Reprocessing Load (MTU/yr)	Total Activity (MCi)	Fission Products (MCi)	Total Cladding (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-85	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1986	1348	5698.3	5621.1	50.011	27.095	26.286	0.735	0.043	27.045
1987	3397	14359.8	14165.5	126.029	68.280	66.242	1.851	0.109	68.154
1988	5843	24599.5	24365.2	216.776	117.444	113.939	3.184	0.188	117.228
1989	7245	30626.0	30211.6	268.790	145.624	141.278	3.949	0.233	145.356
1990	7849	33179.2	32730.2	291.138	157.765	153.056	4.278	0.253	157.474
1991	8249	34870.1	34398.2	306.039	165.805	160.856	4.496	0.266	165.500
1992	8241	34836.3	34364.9	305.742	165.644	160.700	4.491	0.265	165.339
1993	8248	34865.9	34394.1	306.001	165.785	160.837	4.495	0.266	165.480
1994	8248	34865.9	34394.1	306.001	165.785	160.837	4.495	0.266	165.480
1995	8248	34865.9	34394.1	306.001	165.785	160.837	4.495	0.266	165.480
1996	8248	34865.9	34394.1	306.001	165.785	160.837	4.495	0.266	165.480
1997	9248	39093.0	38564.1	343.102	185.885	180.337	5.040	0.298	185.543
1998	10248	43320.2	42734.1	380.202	205.985	199.837	5.585	0.330	205.606
1999	10248	43320.2	42734.1	380.202	205.985	199.837	5.585	0.330	205.606
2000	10248	43320.2	42734.1	380.202	205.985	199.837	5.585	0.330	205.606
2001-05	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 15. Radioactivity and thermal power of waste plutonium generated annually during the years 1975-2005 under the Uranium Recycle Option

Year	Reproc- essing Load (MTM)	Total Activity (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-85	0	0.0	0.0	0.0	0.0	0.0	0.0
1986	1348	146.9	146.934	8.654	146.934	8.654	0.290
1987	3397	370.3	370.273	21.809	370.273	21.809	0.730
1988	5843	636.9	636.887	37.512	636.887	37.512	1.256
1989	7245	789.7	789.705	46.513	789.705	46.513	1.558
1990	7849	855.5	855.541	50.391	855.541	50.391	1.688
1991	8249	899.1	899.141	52.959	899.141	52.959	1.774
1992	8241	898.3	898.269	52.907	898.269	52.907	1.772
1993	8248	899.0	899.031	52.952	899.031	52.952	1.773
1994	8248	899.0	899.031	52.952	899.031	52.952	1.773
1995	8248	899.0	899.031	52.952	899.031	52.952	1.773
1996	8248	899.0	899.031	52.952	899.031	52.952	1.773
1997	9248	1008.0	1008.031	59.372	1008.031	59.372	1.988
1998	10248	1117.0	1117.031	65.792	1117.031	65.792	2.203
1999	10248	1117.0	1117.031	65.792	1117.031	65.792	2.203
2000	10248	1117.0	1117.031	65.792	1117.031	65.792	2.203
2001-05	0	0.0	0.0	0.0	0.0	0.0	0.0

Table 16. Inventory of radioactivity and thermal power of high-level waste at reprocessing plants during the years 1975-2005 under the Uranium Recycle Option

Year	Reprocessing Load (MTHM)	Total Activity (MCi)	Fission Products (MCi)	Total Cladding (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-85	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1986	1348	5698.3	5621.1	50.011	27.095	26.286	0.735	0.043	27.045
1987	3397	16595.9	16377.6	141.048	77.280	74.469	2.643	0.242	79.026
1988	5843	31672.1	31261.5	265.449	145.201	139.075	5.959	0.676	150.920
1989	7245	44614.4	44042.9	369.943	201.553	191.518	10.100	1.349	212.511
1990	7849	54040.5	53349.8	448.336	242.360	228.344	14.542	2.175	256.764
1991	8249	60888.3	60107.1	508.310	273.013	255.604	18.400	2.924	288.437
1992	8241	64375.0	63546.2	539.848	289.031	269.304	21.083	3.475	304.230
1993	8248	65945.3	65094.1	554.844	296.452	275.594	22.408	3.751	311.235
1994	8248	66543.3	65683.3	560.771	299.408	278.081	22.957	3.866	313.866
1995	8248	66756.6	65893.2	562.968	300.545	279.034	23.172	3.912	314.786
1996	8248	66757.2	65893.8	562.969	300.544	279.033	23.171	3.912	314.789
1997	9248	70988.1	70067.4	600.108	320.664	298.550	23.720	3.945	334.868
1998	10248	76874.1	75878.4	648.349	347.441	324.154	24.852	4.076	362.996
1999	10248	79525.3	78499.9	667.522	357.882	333.523	26.018	4.288	375.731
2000	10248	81203.8	80157.1	682.060	364.708	339.373	27.157	4.516	383.492
2001	0.0	39099.5	38621.1	313.845	164.622	144.499	22.671	4.417	183.256
2002	0.0	22629.2	22325.1	205.147	99.034	84.329	17.194	3.520	102.880
2003	0.0	12460.9	12277.7	122.847	60.453	50.864	11.260	2.363	55.030
2004	0.0	5427.6	5342.3	56.161	29.090	24.375	5.524	1.179	23.347
2005	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 17. Inventory of radioactivity and thermal power of waste plutonium stored at reprocessing plants during the years 1975–2005 under the Uranium Recycle Option

Year	Reprocessing Load (MTHM)	Total Activity (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975–85	0	0.0	0.0	0.0	0.0	0.0	0.0
1986	1348	146.9	146.932	8.654	146.932	8.654	0.290
1987	3397	510.7	510.718	30.609	510.581	30.388	1.025
1988	5843	1125.0	1124.978	68.640	1124.120	67.664	2.299
1989	7245	1864.9	1864.889	116.303	1862.854	113.673	3.894
1990	7849	2638.3	2638.346	168.610	2634.230	163.246	5.643
1991	8249	3304.3	3304.301	214.936	3298.133	206.691	7.190
1992	8241	3762.0	3761.970	247.689	3753.960	237.083	8.284
1993	8248	3987.2	3987.194	264.000	3978.154	252.154	8.828
1994	8248	4080.3	4080.342	270.820	4070.910	258.431	9.055
1995	8248	4116.8	4116.793	273.549	4107.125	260.921	9.146
1996	8248	4116.7	4116.727	273.541	4107.066	260.915	9.146
1997	9248	4226.4	4226.367	280.009	4216.703	267.379	9.363
1998	10248	4439.6	4439.555	292.957	4429.789	280.163	9.797
1999	10248	4643.3	4643.270	306.126	4633.023	292.857	10.237
2000	10248	4838.0	4837.988	319.508	4827.250	305.472	10.685
2001	0	3907.4	3907.439	267.297	3896.009	252.205	8.934
2002	0	2931.0	2931.011	207.236	2920.047	193.225	6.920
2003	0	1911.0	1911.037	139.184	1903.963	128.356	4.645
2004	0	935.5	935.543	70.097	929.610	63.950	2.337
2005	0	0.0	0.0	0.0	0.0	0.0	0.0

Table 18. Radioactivity and thermal power of shipments of high-level waste to Federal Repositories during the years 1975-2005 under the Uranium Recycle Option

Year	Reproc- essing Load (MIHM)	Total Activity (MCi)	Fission Products (MCi)	Total Cladding (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-85	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1986	1348	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1987	3397	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1988	5843	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1989	7245	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1990	7849	713.9	702.7	7.387	3.826	3.206	0.727	0.155	3.071
1991	8249	1799.1	1770.9	18.616	9.643	8.080	1.831	0.391	7.739
1992	8241	3094.6	3046.0	32.021	16.586	13.898	3.149	0.672	13.312
1993	8248	3837.1	3776.8	39.704	20.566	17.232	3.905	0.834	16.506
1994	8248	4157.0	4091.7	43.014	22.280	18.669	4.231	0.903	17.882
1995	8248	4368.8	4300.2	45.206	23.416	19.620	4.446	0.949	18.793
1996	8248	4364.6	4296.1	45.162	23.393	19.601	4.442	0.948	18.775
1997	9248	4368.3	4299.7	45.201	23.413	19.618	4.446	0.949	18.791
1998	10248	4368.3	4299.7	45.201	23.413	19.618	4.446	0.949	18.791
1999	10248	4368.3	4299.7	45.201	23.413	19.618	4.446	0.949	18.791
2000	10248	4368.3	4299.7	45.201	23.413	19.618	4.446	0.949	18.791
2001	0	4897.9	4821.0	50.681	26.252	21.996	4.985	1.064	21.069
2002	0	5427.6	5342.3	56.161	29.090	24.375	5.524	1.179	23.347
2003	0	5427.6	5342.3	56.161	29.090	24.375	5.524	1.179	23.347
2004	0	5427.6	5342.3	56.161	29.090	24.375	5.524	1.179	23.347
2005	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 19. Radioactivity and thermal power of annual shipments of waste plutonium to Federal Repositories during the years 1975-2005 under the Uranium Recycle Option

Year	Reproc- essing Load (MTHM)	Total Activity (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-85	0	0.0	0.0	0.0	0.0	0.0	0.0
1986	1348	0.0	0.0	0.0	0.0	0.0	0.0
1987	3397	0.0	0.0	0.0	0.0	0.0	0.0
1988	5843	0.0	0.0	0.0	0.0	0.0	0.0
1989	7245	0.0	0.0	0.0	0.0	0.0	0.0
1990	7849	123.059	123.059	9.220	122.279	8.412	0.307
1991	8249	427.941	427.941	32.577	425.011	29.555	1.086
1992	8241	943.203	943.203	72.962	936.300	65.825	2.432
1993	8248	1564.725	1564.725	123.427	1552.350	110.605	4.115
1994	8248	2215.353	2215.353	178.602	2196.319	158.855	5.955
1995	8248	2875.469	2875.469	237.097	2848.617	209.274	7.906
1996	8248	3507.639	3507.639	296.107	3471.970	259.295	9.875
1997	9248	4114.582	4114.582	355.689	4069.096	309.011	11.863
1998	10248	4696.867	4696.867	415.752	4640.574	358.380	13.868
1999	10248	5255.621	5255.621	476.256	5187.566	407.402	15.887
2000	10248	5791.910	5791.910	537.166	5711.199	456.081	17.920
2001	0	6398.031	6398.031	605.289	6303.234	510.661	20.193
2002	0	7071.055	7071.055	680.686	6960.668	571.107	22.709
2003	"	7716.914	7716.914	756.572	7589.992	631.142	25.239
2004	0	8336.871	8336.871	832.908	8192.531	690.770	27.785
2005	0	7996.574	7996.574	839.562	7839.918	686.045	28.006
2001-05	0	0.0	0.0	0.0	0.0	0.0	0.0

Table 20. Inventory of radioactivity and thermal power of high-level waste at Federal Repositories during the years 1975-2005 under the Uranium Recycle Option

Year	Reproc- essing Load (MIHM)	Total Activity (MCi)	Fission Products (MCi)	Total Cladding (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-85	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1986	1348	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1987	3397	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1988	5843	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1989	7245	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1990	7849	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1991	8249	600.4	590.4	6.347	3.666	3.060	0.700	0.155	2.462
1992	8241	2045.5	2011.2	21.507	12.777	10.662	2.437	0.545	8.301
1993	8248	4432.3	4357.9	46.225	28.228	23.557	5.379	1.215	17.815
1994	8248	7222.0	7100.6	74.410	46.965	39.202	8.941	2.043	28.706
1995	8248	10060.3	9891.7	101.974	66.703	55.705	12.686	2.937	39.527
1996	8248	12893.2	12678.2	128.163	86.846	72.579	16.502	3.872	50.105
1997	9248	15569.6	15312.0	151.341	106.260	88.884	20.175	4.800	59.865
1998	10248	18135.0	17838.0	172.053	125.002	104.670	23.721	5.723	69.048
1999	10248	20609.7	20275.9	190.643	143.071	119.937	27.141	6.640	77.772
2000	10248	23008.6	22640.7	207.423	160.491	134.698	30.441	7.551	86.125
2001	0	25341.4	24941.4	222.649	177.289	148.973	33.625	8.456	94.167
2002	0	28059.6	27622.1	241.242	196.212	165.049	37.219	9.470	103.765
2003	0	31116.5	30636.5	262.757	217.197	182.868	41.207	10.593	114.678
2004	0	34035.8	33516.2	282.124	237.466	200.109	45.057	11.710	124.923
2005	0	36846.1	36289.3	299.663	257.057	216.805	48.774	12.820	134.665

Table 21. Inventory of radioactivity and thermal power of waste plutonium stored in Federal Repositories during the years 1975-2005 under the Uranium Recycle Option

Year	Reproc- essing Load (MTBM)	Total Activity (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-85	0	0.0	0.0	0.0	0.0	0.0	0.0
1986	1348	0.0	0.0	0.0	0.0	0.0	0.0
1987	3397	0.0	0.0	0.0	0.0	0.0	0.0
1988	5843	0.0	0.0	0.0	0.0	0.0	0.0
1989	7245	0.0	0.0	0.0	0.0	0.0	0.0
1990	7849	0.0	0.0	0.0	0.0	0.0	0.0
1991	8249	117.8	117.828	9.342	116.865	8.357	0.311
1992	8241	409.8	409.793	32.995	406.274	29.364	1.100
1993	8248	903.3	903.326	73.871	895.146	65.395	2.463
1994	8248	1498.8	1498.815	124.915	1484.326	109.876	4.165
1995	8248	2122.4	2122.415	180.673	2100.339	157.798	6.025
1996	8248	2755.3	2755.316	239.739	2724.417	207.869	7.996
1997	9248	3361.6	3361.621	299.273	3320.909	257.542	9.982
1998	10248	3943.9	3943.905	359.335	3892.387	306.911	11.987
1999	10248	4502.7	4502.660	419.839	4439.383	355.933	14.007
2000	10248	5038.9	5038.949	480.749	4963.016	404.612	16.040
2001	0	5553.8	5553.781	542.032	5464.336	452.952	18.085
2002	0	6135.5	6135.512	610.589	6031.059	507.157	20.372
2003	0	6781.4	6781.371	686.476	6660.383	567.192	22.903
2004	0	7401.3	7401.328	762.812	7262.922	626.821	25.448
2005	0	0.0	7996.574	839.562	7839.918	686.045	28.006

3.3 Case III. Uranium and Plutonium Recycle

In the Uranium and Plutonium Recycle Case the recovered plutonium is purified, mixed with uranium dioxide of natural isotopic composition, and used as fuel for a plutonium recycle reactor. The effect of this procedure on the composition of the wastes occurs when the spent mixed oxide fuel rods are sent to the reprocessing facility for recovery of the fissile content.

Reactor fuel assemblies could be segregated at the reprocessing plants according to whether they had been exposed in an all-uranium reactor or a plutonium recycle reactor. It is here assumed, however, that all fuel rods received at the reprocessing facility in a given year are processed together and that the resulting product, a blend of old and new plutonium, is fabricated into mixed oxide fuel rods characteristic of that year. In any year, this blend is determined by the overall processing load history.

The projected time sequence of the utilization of mixed oxide rods from first-, second-, and third-recycle plutonium depends on assumptions regarding the number and type of reactors, the start-up dates for reprocessing facilities, and the manner and degree of plutonium usage which reactor operators may elect. The assumptions made for the GESMO study are shown in Table 22, in which the annual reprocessing load for the Uranium and Plutonium Recycle Option of Table 1 has been expanded to show the amounts of mixed oxide in each of the categories.

Table 22. Annual rate of waste generation for various exposure groups for the Uranium and Plutonium Recycling Option, MTHM

Year	U	Pu-1	Pu-1-2	Pu-1-2-3	Total
1978	500	0	0	0	500
1979	999	0	0	0	999
1980	1499	0	0	0	1499
1981	1498	0	0	0	1498
1982	1748	0	0	0	1748
1983	1998	0	0	0	1998
1984	2249	0	0	0	2249
1985	2212	36	0	0	2248
1986	2690	158	0	0	2848
1987	3225	324	0	0	3549
1988	3858	391	0	0	4249
1989	3875	374	0	0	4249
1990	4453	393	0	0	4846
1991	5043	485	17	0	5545
1992	5623	550	75	0	6248
1993	6167	528	153	0	6848
1994	6776	586	186	0	7548
1995	7346	724	178	0	8248
1996	7170	891	187	0	8248
1997	7972	1029	239	8	9248
1998	8821	1093	298	36	10248
1999	8636	1214	325	73	10248
2000	8414	1376	369	89	10248

Initially, 100% of the recovered plutonium is obtained by reprocessing spent uranium fuel rods. Table 22 shows that, beginning in 1985, spent mixed oxide fuel rods appear in the reprocessing facility feed, so that the spent fuel composition shown in column "U" of Table 3 becomes mixed with a certain amount of spent fuel having the composition designated "Pu-1." The fraction of each is shown by the relative amounts of spent fuel given in Table 22. As the amount of Pu-1 fuel increases from 36 to 393 MTM, the fraction of Pu-1 spent fuel increases from 1.6% to 8.1%. From 1991 to 1996, the recovered plutonium contains a fraction of plutonium recovered from spent Pu-1-2 fuel. In the period from 1997 through 2000, small amounts of Pu-1-2-3 fuel are processed.

The radioactivity and thermal power of the high-level wastes generated annually for the period 1978-2000 are shown in Table 23. Initially, since only uranium rods are processed, the radioactivity and thermal power of the wastes differ from that of the first 7 years of uranium recycle only because of the different annual reprocessing loads.

The effect of the reprocessing of mixed oxide rods begins in 1985, while the impact of second-pass plutonium does not occur until 1991. The third recycle of plutonium begins in 1997, and the amount is not significant compared with that of Pu-1 and Pu-1-2, even in the year 2000.

The inventory of radioactive wastes at the reprocessing plants is presented in Table 24. This presumes that the wastes are retained at the reprocessing plants for 5 years. The consequent radioactivity of shipments to the Federal Repositories is shown in Table 25, and the

Table 23. Radioactivity and thermal power of high-level waste produced at reprocessing plants during the years 1975-2005 under the Uranium and Plutonium Recycle Option

Year	Reproc- essing Load (MTHM)	Total Activity (MCi)	Fission Products (MCi)	Total Cladding (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-77	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1978	500.0	2113.6	2085.0	18.550	10.050	9.750	0.273	0.016	10.031
1979	999.0	4223.0	4165.8	37.063	20.080	19.481	0.544	0.032	20.043
1980	1499.0	6336.6	6250.8	55.613	30.130	29.231	0.817	0.048	30.074
1981	1498.0	6332.3	6246.6	55.576	30.110	29.211	0.816	0.048	30.054
1982	1748.0	7389.1	7289.1	64.851	35.135	34.086	0.953	0.056	35.070
1983	1998.0	8445.9	8331.6	74.126	40.160	38.961	1.089	0.064	40.086
1984	2249.0	9506.9	9378.3	83.438	45.205	43.856	1.226	0.072	45.122
1985	2248.0	9517.7	9381.0	83.228	53.497	52.062	1.293	0.073	45.444
1986	2848.0	12104.8	11906.1	104.903	93.727	91.639	1.852	0.097	58.644
1987	3549.0	15137.1	14860.8	130.113	146.146	143.240	2.548	0.124	74.288
1988	4249.0	18124.0	17792.6	155.762	175.687	172.199	3.057	0.149	88.970
1989	4249.0	18116.9	17789.3	155.843	171.761	168.315	3.024	0.148	88.808
1990	4846.0	20648.5	20282.4	177.901	188.148	184.298	3.386	0.168	100.967
1991	5545.0	23651.7	23217.1	203.164	231.429	226.847	4.009	0.196	116.164
1992	6248.0	26685.1	26169.1	228.156	287.822	282.349	4.746	0.228	131.902
1993	6848.0	29258.8	28677.8	249.477	331.455	325.253	5.341	0.257	145.095
1994	7548.0	32261.6	31612.5	274.726	374.423	367.484	5.963	0.285	160.268
1995	8248.0	35273.3	34556.5	300.141	416.598	408.951	6.575	0.311	175.486
1996	8248.0	35348.1	34589.5	299.219	459.388	451.291	6.927	0.317	177.234
1997	9248.0	39669.7	38794.1	334.829	540.794	531.426	7.981	0.362	199.703
1998	10248.0	43979.4	42988.1	370.375	620.920	610.274	9.026	0.411	222.048
1999	10248.0	44073.2	43019.7	368.829	684.705	673.348	9.552	0.427	224.519
2000	10248.0	44178.7	43058.7	367.201	752.801	740.699	10.116	0.441	227.197
2001-05	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 24. Inventory of radioactivity and thermal power of high-level waste at reprocessing plants for 1975-2005 under the Uranium and Plutonium Recycle Option

Year	Reproc- essing Load (MTHM)	Total Activity (MCi)	Fission Products (MCi)	Total Cladding (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-77	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1978	500.0	2113.6	2085.0	18.550	10.050	9.750	0.273	0.016	10.031
1979	999.0	5052.4	4986.3	42.634	23.413	22.532	0.838	0.082	24.076
1980	1499.0	8489.9	8380.4	70.759	38.683	36.961	1.693	0.203	40.466
1981	1498.0	10153.3	10024.4	83.554	45.410	42.915	2.555	0.367	48.355
1982	1748.0	12311.9	12153.8	102.820	55.257	51.896	3.529	0.546	58.379
1983	1998.0	14389.8	14204.1	120.861	64.894	60.773	4.360	0.694	68.089
1984	2249.0	16377.7	16166.1	137.699	73.966	69.196	5.057	0.813	77.444
1985	2248.0	17224.0	16994.4	143.915	85.638	80.395	5.556	0.895	81.729
1986	2848.0	20370.9	20068.1	170.509	132.234	125.893	6.620	1.027	97.600
1987	3549.0	24735.5	24324.0	205.051	206.514	198.403	8.325	1.275	120.099
1988	4249.0	29670.5	29151.8	244.022	274.733	264.481	10.511	1.690	145.050
1989	4249.0	31980.1	31406.7	260.699	312.741	300.639	12.576	2.198	156.907
1990	4846.0	36029.0	35373.0	295.680	360.367	346.200	14.866	2.713	176.735
1991	5545.0	40890.4	40125.6	335.626	429.243	412.859	17.163	3.143	201.115
1992	6248.0	46078.3	45188.1	376.641	513.636	494.897	19.501	3.526	227.613
1993	6848.0	50972.2	49959.8	414.625	597.805	576.591	22.011	3.986	252.777
1994	7548.0	56516.0	55363.5	459.140	693.432	669.160	25.245	4.645	281.087
1995	8248.0	62195.9	60895.6	504.591	795.840	768.261	28.772	5.399	310.251
1996	8248.0	64975.7	63554.0	523.898	897.945	867.311	32.023	6.129	326.122
1997	9248.0	70866.4	69258.4	571.948	1036.180	1002.040	35.569	6.820	357.288
1998	10248.0	77779.4	75963.4	625.689	1190.459	1152.250	39.654	7.632	393.831
1999	10248.0	80993.0	79006.2	645.598	1341.425	1299.262	43.736	8.550	413.342
2000	10248.0	82888.6	80727.9	656.767	1504.097	1458.006	47.816	9.523	426.929
2001	0.0	40052.0	38898.1	299.665	854.328	816.930	41.435	10.126	208.600
2002	0.0	23170.4	22385.0	195.056	590.310	562.118	32.245	8.379	120.128
2003	0.0	12759.4	12249.1	116.312	393.946	374.931	21.839	5.877	66.347
2004	0.0	5561.7	5306.5	52.948	202.297	192.524	11.082	3.063	29.104
2005	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 25. Radioactivity and thermal power of high-level waste shipments to Federal Repositories during the years 1975-2005 under the Uranium and Plutonium Recycle Option

[illegible]

cumulative inventories at these sites are given in Table 26.

The impact of plutonium recycle on the composition of reprocessing wastes arises primarily from the continued exposure of the plutonium isotopes of high mass to neutron bombardment in the reactor. At each pass through the reactor, the transplutonium actinides are stripped out, but the proportion of the plutonium represented by the heavier isotopes increases, providing source material for production of still more heavy actinide elements.

This effect is seen in comparing the actinide activities for the Uranium Recycle and the Uranium and Plutonium Recycle cases with respect to the accumulated waste at the Federal Repositories. The radioactivity of the actinides is nearly four times greater in the Plutonium Recycle case than in the Uranium-only Recycle case. By comparison, the thermal power and the radioactivity in the year 2005 are somewhat lower than for the Uranium Recycle case, reflecting the lower reprocessing loads in the interval 1988-1994.

Table 26. Inventory of radioactivity and thermal power of high-level waste at Federal Repositories for the years 1975-2005 under the Uranium and Plutonium Recycle Option

Year	Reprocessing Load (MTM)	Total Activity (MCi)	Fission Products (MCi)	Total Cladding (MCi)	Total Actinide (MCi)	Actinide Alpha (MCi)	Total Pu (MCi)	Pu Alpha (MCi)	Thermal Power (MW)
1975-77	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1978	500.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1979	999.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1980	1499.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1981	1498.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1982	1748.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1983	1998.0	222.7	219.0	2.354	1.360	1.135	0.260	0.057	0.913
1984	2249.0	642.5	631.7	6.748	4.029	3.362	0.768	0.172	2.602
1985	2248.0	1410.4	1379.3	14.095	17.004	15.577	1.606	0.344	4.982
1986	2848.0	2524.2	2449.4	23.437	51.427	49.009	2.625	0.515	7.076
1987	3549.0	3917.6	3785.4	34.735	97.444	93.818	3.855	0.714	9.436
1988	4249.0	4924.0	4761.5	43.318	119.140	114.523	4.943	0.940	12.047
1989	4249.0	5611.4	5441.5	49.634	120.262	114.830	5.923	1.194	14.903
1990	4846.0	6424.4	6235.4	56.289	132.686	126.298	7.036	1.474	17.615
1991	5545.0	7816.4	7575.9	67.325	173.120	165.081	8.877	1.919	21.528
1992	6248.0	9345.1	9046.1	79.676	219.397	209.188	11.338	2.575	26.788
1993	6848.0	10706.2	10365.7	91.261	249.243	236.749	14.024	3.362	33.046
1994	7548.0	12346.2	11945.4	104.048	296.744	281.859	16.775	4.134	38.760
1995	8248.0	14557.8	14070.8	121.026	366.064	348.347	19.987	4.987	45.245
1996	8248.0	17129.6	16539.4	140.669	449.548	428.532	23.738	6.019	52.848
1997	9248.0	19767.4	19073.7	160.806	532.884	508.278	27.876	7.275	61.618
1998	10248.0	22214.8	21431.2	179.452	604.139	575.835	32.223	8.708	71.197
1999	10248.0	25155.2	24249.1	201.389	704.697	671.887	37.445	10.319	81.709
2000	10248.0	28501.3	27446.3	225.943	829.114	791.098	43.456	12.103	93.089
2001	0.0	24573.0	23799.8	198.484	574.712	536.014	45.870	14.029	104.160
2002	0.0	27365.5	26470.0	218.047	677.374	633.283	52.359	16.279	117.091
2003	0.0	30477.3	29440.7	239.976	796.575	746.363	59.711	18.848	131.696
2004	0.0	33363.5	32169.3	258.989	935.182	878.482	67.493	21.582	145.727
2005	0.0	36034.3	34672.7	275.341	1086.277	1022.935	75.491	24.497	159.398

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