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NUCLEAR MASS INVENTORY, PHOTON DOSE RATE AND THERMAL DECAY HEAT OF SPENT RESEARCH REACTOR FUEL ASSEMBLIES*

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SUMMARY

This document has been prepared to assist research reactor operators possessing spent fuel containing enriched uranium of United States origin to prepare part of the documentation necessary to ship this fuel to the United States. Data are included on the nuclear mass inventory, photon dose rate, and thermal decay heat of spent research reactor fuel assemblies.

Isotopic masses of U, Np, Pu and Am that are present in spent research reactor fuel are estimated for MTR, TRIGA and DIDO fuel assembly types. The isotopic masses of each fuel assembly type are given as functions of U-235 burnup in the spent fuel, and of initial U-235 enrichment and U-235 mass in the fuel assembly.

Photon dose rates of spent MTR, TRIGA and DIDO-type fuel assemblies are estimated for fuel assemblies with up to 80% U-235 burnup and specific power densities between 0.089 and 2.857 MW/kg^{235}U, and for fission product decay times of up to 20 years.

Thermal decay heat loads are estimated for spent fuel based upon the fuel assembly irradiation history (average assembly power vs. elapsed time) and the spent fuel cooling time.

INTRODUCTION

As part of the Department of Energy's spent nuclear fuel acceptance criteria, the mass of uranium and transuranic elements in spent research reactor fuel must be specified. These data are, however, not always known or readily determined. It is the purpose of this report to provide estimates of these data for some of the more common research reactor fuel assembly types. The specific types considered here are MTR, TRIGA and DIDO fuel assemblies.

The degree of physical protection given to spent fuel assemblies is largely dependent upon the photon dose rate of the spent fuel material. These data also, are not always known or readily determined. Because of a self-protecting dose rate level of radiation (dose rate greater than 100 rem/h at 1 m in air), it is important to know the dose rate of spent fuel assemblies at all time. Estimates of the photon dose rate for spent MTR, TRIGA and DIDO-type fuel assemblies are given in this report.

For safe spent fuel assembly containment, the thermal heat load generated by the decay of fission products in spent fuel material is an important consideration. This heat load can be estimated by a simple analytical expression that is given in this report.

NUCLEAR MASS INVENTORY

The mass inventory of the heavy metals in research reactor fuels has been calculated using the WIMS code[1] for unit-cell models of MTR, TRIGA and DIDO fuel assembly types. Models of each fuel assembly type were neutronically burned for a length of time corresponding to typical fuel-cycle lengths and U-235 burnup[2]. Table 1 summarizes the fuel assembly models for which mass inventory calculations were made.

Table 1. Fuel Assembly Models

Assembly Type	U-235 Burnup, %	U-235 Enrichment, %	U-235 Mass, g
MTR (19 fuel plates)	5, 10, 20, 30, 40, 50, 60, 70, 80	93 45 19.75	100 200 300 400 200 300 400 100 200 300 400 500
TRIGA (single rod)	5, 10, 15, 20, 25, 30, 35	70 (8.5wt% U) 20 (20wt% U) 20 (12wt% U) 20 (8.5wt% U)	133 98 54 38
TRIGA (25 rod cluster)	10, 20, 30, 40, 50, 60	93.1 (10wt% U) 19.7 (45wt% U)	41.4 53.6
DIDO (4 fuel tubes)	10, 20, 30, 40, 50, 60	93, 80, 60 20	150 200

Mass inventory calculations for MTR models were made for 19-fuel plate assemblies with up to 80% U-235 burnup, for 93, 45 and 19.75% U-235 enrichments, and for initial U-235 masses of 100 to 500 g. The mass inventory of MTR-type fuel assemblies is not a strong function of the number of fuel plates[3]. Similar calculations were made for two TRIGA assembly types – a single rod model and a 25-rod cluster model. The maximum U-235 burnup in these models were respectively, 35 and 60%. There were four fuel types for the single rod model and two fuel types for the cluster model. For DIDO fuel assembly types, mass inventory calculations were made for a 4-fuel tube model with up to 60% U-235 burnup, and for four fuel enrichments and assembly masses.

The results of the mass inventory calculations are shown in the following tables:

Table 2 — MTR Fuel 93% Enrichment
Table 3 — MTR Fuel 45% Enrichment
Table 4 — MTR Fuel 19.75% Enrichment
Table 5 — TRIGA Fuel Single-Rod Model
Table 6 — TRIGA Fuel 25-Rod Cluster Model
Table 7 — DIDO Fuel

The tables show the isotopic masses of U, Np, Pu and Am that are present in spent fuel as functions of the fuel assembly U-235 burnup and initial U-235 mass. As will be noted in the tables for most fuel assembly types, the uranium fuel compositions have excluded initial enrichments of U-234 and U-236. In order to account for initial enrichments of U-234 and/or U-236 in the tables, initial U-234 and U-236 masses can be simply added to the spent fuel mass

Table 2A. 100 g U-235 MTR Fuel, 93% Enrichment

U-235: Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	5	10	20	30	40	50	60	70	80
U-234	0	0	0	0	0	0	0	0	0	0
U-235	100	95	90	80	70	60	50	40	30	20
U-236	0	1	2	3	5	6	8	9	11	12
U-238	8	8	8	8	7	7	7	7	7	7
U	108	103	99	91	82	74	65	56	48	39
Np-237	0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3
Np	0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-239	0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Pu-240	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu	0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2	0.2
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2B. 200 g U-235 MTR Fuel, 93% Enrichment

U-235: Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	10	20	40	60	80	100	120	140	160
U-234	0	0	0	0	0	0	0	0	0	0
U-235	200	190	180	160	140	120	100	80	60	40
U-236	0	2	3	6	10	13	16	19	21	24
U-238	15	15	15	15	15	15	15	15	14	14
U	215	207	198	181	164	147	130	113	96	78
Np-237	0	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.6	0.8
Np	0	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.6	0.8
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
Pu-239	0	0.0	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3
Pu-240	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
Pu-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu	0	0.0	0.1	0.2	0.2	0.3	0.3	0.4	0.5	0.6
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2C. 300 g U-235 MTR Fuel, 93% Enrichment

U-235: Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	15	30	60	90	120	150	180	210	240
U-234	0	0	0	0	0	0	0	0	0	0
U-235	300	285	270	240	210	180	150	120	90	60
U-236	0	3	5	10	15	19	24	28	33	37
U-238	23	23	22	22	22	22	22	21	21	21
U	323	310	297	272	247	221	196	170	144	118
Np-237	0	0.0	0.0	0.1	0.2	0.4	0.6	0.8	1.1	1.5
Np	0	0.0	0.0	0.1	0.2	0.4	0.6	0.8	1.1	1.5
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3
Pu-239	0	0.1	0.2	0.3	0.4	0.4	0.5	0.5	0.5	0.5
Pu-240	0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.2
Pu-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu	0	0.1	0.2	0.3	0.4	0.5	0.7	0.8	0.9	1.1
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 2D. 400 g U-235 MTR Fuel, 93% Enrichment

U-235: Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	20	40	80	120	160	200	240	280	320
U-234	0	0	0	0	0	0	0	0	0	0
U-235	400	380	360	320	280	240	200	160	120	80
U-236	0	3	7	14	20	26	33	39	44	50
U-238	30	30	30	30	29	29	29	28	28	27
U	430	413	397	363	329	295	261	227	192	157
Np-237	0	0.0	0.0	0.2	0.4	0.6	0.9	1.3	1.7	2.2
Np	0	0.0	0.0	0.2	0.4	0.6	0.9	1.3	1.7	2.2
Pu-238	0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.5
Pu-239	0	0.1	0.2	0.4	0.6	0.7	0.7	0.7	0.7	0.7
Pu-240	0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2	0.2
Pu-241	0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Pu	0	0.1	0.3	0.5	0.7	0.9	1.1	1.2	1.4	1.7
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 3A. 200 g U-235 MTR Fuel, 45% Enrichment

U-235:

Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	10	20	40	60	80	100	120	140	160
U-234	0	0	0	0	0	0	0	0	0	0
U-235	200	190	180	160	140	120	100	80	60	40
U-236	0	2	3	6	10	13	16	19	21	24
U-238	244	244	244	243	242	241	240	239	237	236
U	444	436	427	409	391	374	356	337	319	300
Np-237	0	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.6	0.8
Np	0	0.0	0.0	0.0	0.1	0.2	0.3	0.4	0.6	0.8
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2
Pu-239	0	0.4	0.7	1.3	1.7	2.0	2.3	2.4	2.3	2.2
Pu-240	0	0.0	0.0	0.1	0.2	0.3	0.5	0.6	0.8	0.9
Pu-241	0	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.3	0.4
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2
Pu	0	0.4	0.7	1.4	2.0	2.5	2.9	3.3	3.6	3.8
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 3B. 300 g U-235 MTR Fuel, 45% Enrichment

U-235:

Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	15	30	60	90	120	150	180	210	240
U-234	0	0	0	0	0	0	0	0	0	0
U-235	300	285	270	240	210	180	150	120	90	60
U-236	0	3	5	10	15	19	24	29	33	37
U-238	367	366	365	364	362	361	359	357	355	352
U	667	654	640	614	587	560	533	505	477	449
Np-237	0	0.0	0.0	0.1	0.2	0.4	0.6	0.9	1.2	1.5
Np	0	0.0	0.0	0.1	0.2	0.4	0.6	0.9	1.2	1.5
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3
Pu-239	0	0.6	1.2	2.2	2.9	3.4	3.8	3.9	3.8	3.6
Pu-240	0	0.0	0.0	0.2	0.3	0.6	0.8	1.0	1.2	1.4
Pu-241	0	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.6	0.7
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.3
Pu	0	0.6	1.3	2.4	3.4	4.2	5.0	5.6	6.0	6.3
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 3C. 400 g U-235 MTR Fuel, 45% Enrichment

U-235:

Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	20	40	80	120	160	200	240	280	320
U-234	0	0	0	0	0	0	0	0	0	0
U-235	400	380	360	320	280	240	200	160	120	80
U-236	0	3	7	14	20	27	33	39	45	50
U-238	489	488	487	485	482	480	477	474	471	467
U	889	871	854	818	782	746	710	673	636	597
Np-237	0	0.0	0.0	0.2	0.4	0.6	1.0	1.4	1.8	2.4
Np	0	0.0	0.0	0.2	0.4	0.6	1.0	1.4	1.8	2.4
Pu-238	0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.5
Pu-239	0	0.9	1.8	3.2	4.2	4.9	5.4	5.5	5.4	5.0
Pu-240	0	0.0	0.1	0.3	0.5	0.8	1.1	1.4	1.6	1.9
Pu-241	0	0.0	0.0	0.1	0.2	0.3	0.6	0.8	1.0	1.1
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.5
Pu	0	0.9	1.9	3.5	4.9	6.2	7.2	8.1	8.7	9.1
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4A. 100 g U-235 MTR Fuel, 19.75% Enrichment

U-235:

Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	5	10	20	30	40	50	60	70	80
U-234	0	0	0	0	0	0	0	0	0	0
U-235	100	95	90	80	70	60	50	40	30	20
U-236	0	1	2	3	5	6	8	9	11	12
U-238	406	406	406	405	404	403	402	401	399	398
U	506	502	497	488	479	469	460	450	440	429
Np-237	0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3
Np	0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Pu-239	0	0.3	0.7	1.2	1.7	2.0	2.3	2.5	2.5	2.5
Pu-240	0	0.0	0.0	0.1	0.2	0.3	0.4	0.6	0.8	1.0
Pu-241	0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.3
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Pu	0	0.3	0.7	1.3	1.9	2.4	2.9	3.3	3.7	4.0
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4B. 200 g U-235 MTR Fuel, 19.75% Enrichment

U-235:										
Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	10	20	40	60	80	100	120	140	160
U-234	0	0	0	0	0	0	0	0	0	0
U-235	200	190	180	160	140	120	100	80	60	40
U-236	0	2	3	6	10	13	16	19	22	24
U-238	813	812	811	809	807	805	802	800	796	792
U	1013	1003	994	975	957	937	918	898	878	856
Np-237	0	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.6	0.9
Np	0	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.6	0.9
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2
Pu-239	0	0.8	1.5	2.8	3.8	4.6	5.1	5.4	5.5	5.3
Pu-240	0	0.0	0.1	0.2	0.4	0.7	1.0	1.4	1.7	2.1
Pu-241	0	0.0	0.0	0.0	0.1	0.2	0.3	0.5	0.7	0.9
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.4
Pu	0	0.8	1.6	3.1	4.4	5.5	6.6	7.5	8.2	8.8
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 4C. 300 g U-235 MTR Fuel, 19.75% Enrichment

U-235:										
Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	15	30	60	90	120	150	180	210	240
U-234	0	0	0	0	0	0	0	0	0	0
U-235	300	285	270	240	210	180	150	120	90	60
U-236	0	3	5	10	15	20	24	29	33	37
U-238	1219	1218	1216	1213	1209	1205	1201	1197	1191	1184
U	1519	1505	1491	1463	1434	1405	1375	1345	1314	1281
Np-237	0	0.0	0.0	0.1	0.2	0.4	0.6	0.9	1.2	1.6
Np	0	0.0	0.0	0.1	0.2	0.4	0.6	0.9	1.2	1.6
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3
Pu-239	0	1.3	2.6	4.7	6.3	7.5	8.3	8.7	8.7	8.4
Pu-240	0	0.0	0.1	0.4	0.7	1.2	1.7	2.2	2.7	3.2
Pu-241	0	0.0	0.0	0.1	0.2	0.4	0.7	1.0	1.4	1.6
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.4	0.7
Pu	0	1.4	2.7	5.1	7.3	9.2	10.9	12.3	13.4	14.3
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1

Table 4D. 400 g U-235 MTR Fuel, 19.75% Enrichment

U-235:										
Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	20	40	80	120	160	200	240	280	320
U-234	0	0	0	0	0	0	0	0	0	0
U-235	400	380	360	320	280	240	200	160	120	80
U-236	0	4	7	14	20	27	33	39	45	50
U-238	1625	1623	1621	1616	1611	1605	1599	1592	1584	1574
U	2025	2007	1988	1950	1911	1872	1832	1791	1749	1704
Np-237	0	0.0	0.0	0.2	0.4	0.7	1.0	1.4	1.9	2.5
Np	0	0.0	0.0	0.2	0.4	0.7	1.0	1.4	1.9	2.5
Pu-238	0	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.6
Pu-239	0	2.0	3.8	6.8	9.1	10.8	11.8	12.4	12.3	11.7
Pu-240	0	0.0	0.2	0.6	1.1	1.7	2.4	3.1	3.7	4.3
Pu-241	0	0.0	0.0	0.1	0.4	0.7	1.2	1.7	2.2	2.6
Pu-242	0	0.0	0.0	0.0	0.0	0.1	0.2	0.4	0.7	1.2
Pu	0	2.0	3.9	7.5	10.6	13.4	15.8	17.7	19.3	20.4
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1

Table 4E. 500 g U-235 MTR Fuel, 19.75% Enrichment

U-235:										
Burnup, %	0	5	10	20	30	40	50	60	70	80
Burned, g	0	25	50	100	150	200	250	300	350	400
U-234	0	0	0	0	0	0	0	0	0	0
U-235	500	475	450	400	350	300	250	200	150	100
U-236	0	4	9	18	26	34	42	50	57	64
U-238	2032	2029	2026	2019	2012	2004	1996	1987	1976	1962
U	2532	2508	2484	2437	2388	2338	2288	2236	2183	2126
Np-237	0	0.0	0.1	0.3	0.6	1.0	1.5	2.1	2.8	3.6
Np	0	0.0	0.1	0.3	0.6	1.0	1.5	2.1	2.8	3.6
Pu-238	0	0.0	0.0	0.0	0.0	0.1	0.2	0.4	0.6	0.9
Pu-239	0	2.6	5.0	9.0	12.1	14.3	15.6	16.2	16.1	15.3
Pu-240	0	0.1	0.2	0.8	1.5	2.3	3.2	4.0	4.7	5.4
Pu-241	0	0.0	0.0	0.2	0.6	1.1	1.8	2.5	3.2	3.6
Pu-242	0	0.0	0.0	0.0	0.0	0.1	0.3	0.6	1.0	1.7
Pu	0	2.7	5.3	10.0	14.2	17.9	21.1	23.7	25.7	27.0
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1

Table 5A.	133 g U-235 TRIGA Fuel, 8.5wt% U, 70% Enrichment							
U-235:								
Burnup, %	0	5	10	15	20	25	30	35
Burned, g	0	7	13	20	27	33	40	47
U-234	0	0	0	0	0	0	0	0
U-235	133	126	120	113	106	100	93	87
U-236	0	1	3	4	5	6	7	8
U-238	57	57	56	56	56	56	55	55
U	190	184	179	173	167	162	156	150
Np-237	0	0.0	0.0	0.1	0.1	0.1	0.2	0.3
Np	0	0.0	0.0	0.1	0.1	0.1	0.2	0.3
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-239	0	0.3	0.5	0.7	0.8	0.9	1.0	1.1
Pu-240	0	0.0	0.0	0.0	0.1	0.1	0.1	0.2
Pu-241	0	0.0	0.0	0.0	0.0	0.0	0.1	0.1
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu	0	0.3	0.5	0.7	0.9	1.1	1.2	1.4
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 5B.	98 g U-235 TRIGA Fuel, 20wt% U, 20% Enrichment							
U-235:								
Burnup, %	0	5	10	15	20	25	30	35
Burned, g	0	5	10	15	20	25	29	34
U-234	0	0	0	0	0	0	0	0
U-235	98	93	88	83	78	74	69	64
U-236	0	1	2	3	4	4	5	6
U-238	392	391	391	390	389	388	388	387
U	490	485	481	476	471	466	461	457
Np-237	0	0.0	0.0	0.0	0.1	0.1	0.1	0.2
Np	0	0.0	0.0	0.0	0.1	0.1	0.1	0.2
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-239	0	0.6	1.1	1.6	2.0	2.4	2.7	2.9
Pu-240	0	0.0	0.1	0.1	0.2	0.3	0.3	0.4
Pu-241	0	0.0	0.0	0.0	0.0	0.1	0.1	0.2
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu	0	0.6	1.2	1.7	2.3	2.7	3.2	3.6
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 5C.	54 g U-235 TRIGA Fuel, 12wt% U, 20% Enrichment							
U-235:								
Burnup, %	0	5	10	15	20	25	30	35
Burned, g	0	3	5	8	11	14	16	19
U-234	0	0	0	0	0	0	0	0
U-235	54	51	49	46	43	41	38	35
U-236	0	0	1	1	2	2	3	3
U-238	216	216	215	215	215	215	214	214
U	270	268	265	262	260	257	255	252
Np-237	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Np	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-239	0	0.3	0.5	0.7	0.9	1.1	1.2	1.3
Pu-240	0	0.0	0.0	0.0	0.1	0.1	0.1	0.2
Pu-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu	0	0.3	0.5	0.8	1.0	1.2	1.4	1.6
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 5D.	38 g U-235 TRIGA Fuel, 8.5wt% U, 20% Enrichment							
U-235:								
Burnup, %	0	5	10	15	20	25	30	35
Burned, g	0	2	4	6	8	10	11	13
U-234	0	0	0	0	0	0	0	0
U-235	38	36	34	32	30	29	27	25
U-236	0	0	1	1	1	2	2	2
U-238	152	152	152	151	151	151	151	151
U	190	188	186	185	183	181	179	177
Np-237	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Np	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-239	0	0.2	0.3	0.5	0.6	0.7	0.8	0.9
Pu-240	0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
Pu-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pu	0	0.2	0.3	0.5	0.6	0.8	0.9	1.0
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6A. 41.4 g U-235 TRIGA Fuel

U-235: *10wt% U, 93.1% Enrichment*

Burnup, %	0	10	20	30	40	50	60
Burned, g	0.0	4.1	8.3	12.4	16.6	20.7	24.8
U-234	0.4	0.4	0.4	0.4	0.4	0.3	0.3
U-235	41.4	37.2	33.1	29.0	24.8	20.7	16.6
U-236	0.2	1.0	1.7	2.4	3.1	3.8	4.4
U-238	2.4	2.4	2.4	2.3	2.3	2.2	2.2
U	44.5	41.0	37.6	34.1	30.6	27.1	23.5
Np-237	0	0.0	0.0	0.1	0.1	0.2	0.2
Np	0	0.0	0.0	0.1	0.1	0.2	0.2
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-239	0	0.0	0.1	0.1	0.1	0.1	0.1
Pu-240	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-241	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu	0	0.0	0.1	0.1	0.1	0.1	0.2
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0

Table 6B. 53.6 g U-235 TRIGA Fuel

U-235: *45wt% U, 19.7% Enrichment*

Burnup, %	0	10	20	30	40	50	60
Burned, g	0.0	5.4	10.7	16.1	21.4	26.8	32.2
U-234	0.4	0.4	0.4	0.3	0.3	0.3	0.3
U-235	53.6	48.3	42.9	37.5	32.2	26.8	21.4
U-236	0.7	1.7	2.7	3.7	4.6	5.5	6.4
U-238	217.4	216.5	215.6	214.6	213.5	212.3	210.9
U	272.1	266.9	261.6	256.1	250.6	244.9	239.0
Np-237	0	0.0	0.1	0.1	0.2	0.3	0.4
Np	0	0.0	0.1	0.1	0.2	0.3	0.4
Pu-238	0	0.0	0.0	0.0	0.0	0.1	0.1
Pu-239	0	0.7	1.3	1.7	1.9	2.1	2.1
Pu-240	0	0.0	0.1	0.2	0.3	0.4	0.5
Pu-241	0	0.0	0.0	0.1	0.2	0.3	0.4
Pu-242	0	0.0	0.0	0.0	0.0	0.1	0.1
Pu	0	0.8	1.4	2.0	2.5	2.9	3.2
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7A. 150 g U-235 DIDO Fuel, 93% Enr.

U-235:

Burnup, %	0	10	20	30	40	50	60
Burned, g	0	15	30	45	60	75	90
U-234	0	0	0	0	0	0	0
U-235	150	135	120	105	90	75	60
U-236	0	2	5	7	9	12	14
U-238	11	11	11	11	11	11	11
U	161	149	136	123	110	98	85
Np-237	0	0.0	0.0	0.1	0.1	0.2	0.3
Np	0	0.0	0.0	0.1	0.1	0.2	0.3
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-239	0	0.0	0.1	0.1	0.1	0.1	0.2
Pu-240	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-241	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu	0	0.0	0.1	0.1	0.2	0.2	0.2
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7B. 150 g U-235 DIDO Fuel, 80% Enr.

U-235:

Burnup, %	0	10	20	30	40	50	60
Burned, g	0	15	30	45	60	75	90
U-234	0	0	0	0	0	0	0
U-235	150	135	120	105	90	75	60
U-236	0	2	5	7	9	12	14
U-238	38	37	37	37	37	37	37
U	188	175	162	149	136	123	110
Np-237	0	0.0	0.0	0.1	0.1	0.2	0.3
Np	0	0.0	0.0	0.1	0.1	0.2	0.3
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-239	0	0.1	0.2	0.3	0.3	0.4	0.4
Pu-240	0	0.0	0.0	0.0	0.1	0.1	0.1
Pu-241	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu	0	0.1	0.2	0.3	0.4	0.5	0.6
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7C. 150 g U-235 DIDO Fuel, 60% Enr.

U-235:

Burnup, %	0	10	20	30	40	50	60
Burned, g	0	15	30	45	60	75	90
U-234	0	0	0	0	0	0	0
U-235	150	135	120	105	90	75	60
U-236	0	2	5	7	9	12	14
U-238	100	100	100	99	99	99	98
U	250	237	224	211	198	185	172
Np-237	0	0.0	0.0	0.1	0.1	0.2	0.3
Np	0	0.0	0.0	0.1	0.1	0.2	0.3
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu-239	0	0.2	0.4	0.6	0.7	0.7	0.8
Pu-240	0	0.0	0.0	0.1	0.1	0.2	0.2
Pu-241	0	0.0	0.0	0.0	0.0	0.1	0.1
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.0
Pu	0	0.2	0.5	0.7	0.8	1.0	1.1
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0

Table 7D. 200 g U-235 DIDO Fuel, 20% Enr.

U-235:

Burnup, %	0	10	20	30	40	50	60
Burned, g	0	20	40	60	80	100	120
U-234	0	0	0	0	0	0	0
U-235	200	180	160	140	120	100	80
U-236	0	3	7	10	13	16	19
U-238	800	799	797	796	794	793	791
U	1000	982	964	946	927	908	890
Np-237	0	0.0	0.1	0.1	0.2	0.3	0.4
Np	0	0.0	0.1	0.1	0.2	0.3	0.4
Pu-238	0	0.0	0.0	0.0	0.0	0.0	0.1
Pu-239	0	1.1	2.0	2.7	3.2	3.5	3.7
Pu-240	0	0.0	0.2	0.3	0.6	0.8	1.0
Pu-241	0	0.0	0.0	0.1	0.2	0.3	0.4
Pu-242	0	0.0	0.0	0.0	0.0	0.0	0.1
Pu	0	1.2	2.2	3.1	4.0	4.7	5.3
Am-241	0	0.0	0.0	0.0	0.0	0.0	0.0
Am	0	0.0	0.0	0.0	0.0	0.0	0.0

inventory[3]. Within the uncertainty of the calculations, the results in Tables 2–7 can be used to estimate the spent fuel mass inventory in most MTR, TRIGA and DIDO fuel assembly types.

The mass inventories given in Tables 2–7 are at the time of reactor discharge and therefore do not account for decay of Pu-241 to Am-241 for times after discharge. When necessary to estimate mass inventories after discharge, the Pu-241 mass is decreased and the Am-241 mass is increased by an amount $\Delta M = M_0 \cdot (1 - e^{-\lambda t})$ where M_0 is the Pu-241 mass at discharge, $\lambda = 1.32 \cdot 10^{-4}$ d^{-1} (Pu-241 half-life, 14.4 y), and t is the time in days after discharge. No mass inventories are given for U-239 (half-life, 23.5 m) and Np-239 (half-life, 2.355 d) as they are assumed to decay instantaneously to Pu-239.

PHOTON DOSE RATE

Calculated dose rates for MTR-type fuel assemblies are shown in Table 8. These dose rates are from Ref. 4 and are for fuel assemblies with up to 80% U-235 burnup, specific power densities between 0.089 and 2.857 MW/kg^{235}U, and fission product decay times of up to 20 years.

The data in Table 8 are photon dose rates in air that are averaged over a 60-cm long cylindrical surface, located at a radius of 1 m from the fuel assembly axial center line. For MTR-type fuel assemblies, these average dose rates are independent of the assembly rotational orientation and the number of fuel plates in the assembly. These data also can be interpolated for specific decay time, burnup and assembly power density. In all cases, the dose rates must be multiplied by the mass of U-235 burned in the fuel assembly to estimate the fuel assembly dose rate. The mass of U-235 burned per fuel assembly that is necessary for an unshielded, 100 rem/h self-protecting dose rate at 1 m, is shown in Fig. 1.

Additional analyses have shown that the photon dose rates of MTR, TRIGA and DIDO-type fuel assemblies are similar, given the same fuel assembly characteristics of U-235 burnup, fission product decay time, and specific fuel assembly power density. The average dose rates at 1 m in air for TRIGA (25-rod) and DIDO (4-tube) fuel assemblies are respectively, 1.04 and 1.05 times the dose rates given in Table 8 for MTR fuel assemblies. The dose rates of all three fuel assembly types are for fuel assembly models (nominally 8cm by 8cm by 60cm) containing spent fuel in the form of either rods (TRIGA fuel), annuli (DIDO fuel) or plates (MTR fuel). The small difference in the dose rates are due to the different shielding effects of the fuel elements in the fuel assemblies.

Table 8. Photon Dose Rates At 1 M In Air, rem/h per g^{235}U burned

Decay Time, y	Burnup, %^{235}U	Assembly Power Density, MW/kg^{235}U					
		2.857	1.429	0.714	0.357	0.179	0.089
2	1%	1.84+0	1.84+0	1.83+0	1.80+0	1.77+0	1.70+0
3		1.13+0	1.13+0	1.13+0	1.13+0	1.11+0	1.11+0
4		9.01-1	9.01-1	9.01-1	9.01-1	9.01-1	8.92-1
2	10%	1.89+0	1.87+0	1.80+0	1.64+0	1.50+0	1.28+0
3		1.19+0	1.20+0	1.20+0	1.16+0	1.09+0	9.95-1
4		9.52-1	9.61-1	9.61-1	9.44-1	9.10-1	8.59-1
2	20%	2.01+0	1.98+0	1.86+0	1.66+0	1.42+0	1.19+0
3		1.31+0	1.32+0	1.28+0	1.21+0	1.11+0	9.78-1
4		1.04+0	1.05+0	1.04+0	9.99-1	9.44-1	8.63-1
5		8.97-1	9.10-1	9.05-1	8.80-1	8.46-1	7.95-1
10		6.67-1	6.67-1	6.67-1	6.59-1	6.50-1	6.25-1
15		5.78-1	5.78-1	5.74-1	5.70-1	5.61-1	5.44-1
20		5.10-1	5.10-1	5.10-1	5.06-1	4.97-1	4.85-1
2	40%	2.40+0	2.30+0	2.09+0	1.82+0	1.52+0	1.21+0
3		1.62+0	1.60+0	1.53+0	1.39+0	1.22+0	1.02+0
4		1.27+0	1.27+0	1.22+0	1.14+0	1.03+0	8.99-1
5		1.07+0	1.07+0	1.04+0	9.90-1	9.20-1	8.12-1
10		7.03-1	7.03-1	6.95-1	6.80-1	6.55-1	6.10-1
15		5.87-1	5.84-1	5.80-1	5.70-1	5.53-1	5.23-1
20		5.14-1	5.12-1	5.08-1	5.02-1	4.87-1	4.59-1
2	60%	2.95+0	2.79+0	2.52+0	2.15+0	1.74+0	1.34+0
3		2.05+0	2.00+0	1.87+0	1.66+0	1.40+0	1.12+0
4		1.59+0	1.56+0	1.49+0	1.35+0	1.17+0	9.63-1
5		1.30+0	1.29+0	1.24+0	1.15+0	1.02+0	8.54-1
10		7.55-1	7.51-1	7.37-1	7.07-1	6.70-1	6.02-1
15		5.96-1	5.96-1	5.88-1	5.72-1	5.50-1	5.04-1
20		5.17-1	5.17-1	5.13-1	4.99-1	4.76-1	4.39-1
2	80%	3.85+0	3.62+0	3.26+0	2.76+0	2.21+0	1.64+0
3		2.73+0	2.64+0	2.43+0	2.11+0	1.74+0	1.33+0
4		2.08+0	2.03+0	1.90+0	1.69+0	1.41+0	1.12+0
5		1.66+0	1.63+0	1.54+0	1.39+0	1.19+0	9.57-1
10		8.28-1	8.21-1	8.00-1	7.59-1	6.97-1	6.04-1
15		6.18-1	6.15-1	6.05-1	5.82-1	5.44-1	4.87-1
20		5.27-1	5.20-1	5.13-1	4.97-1	4.66-1	4.20-1

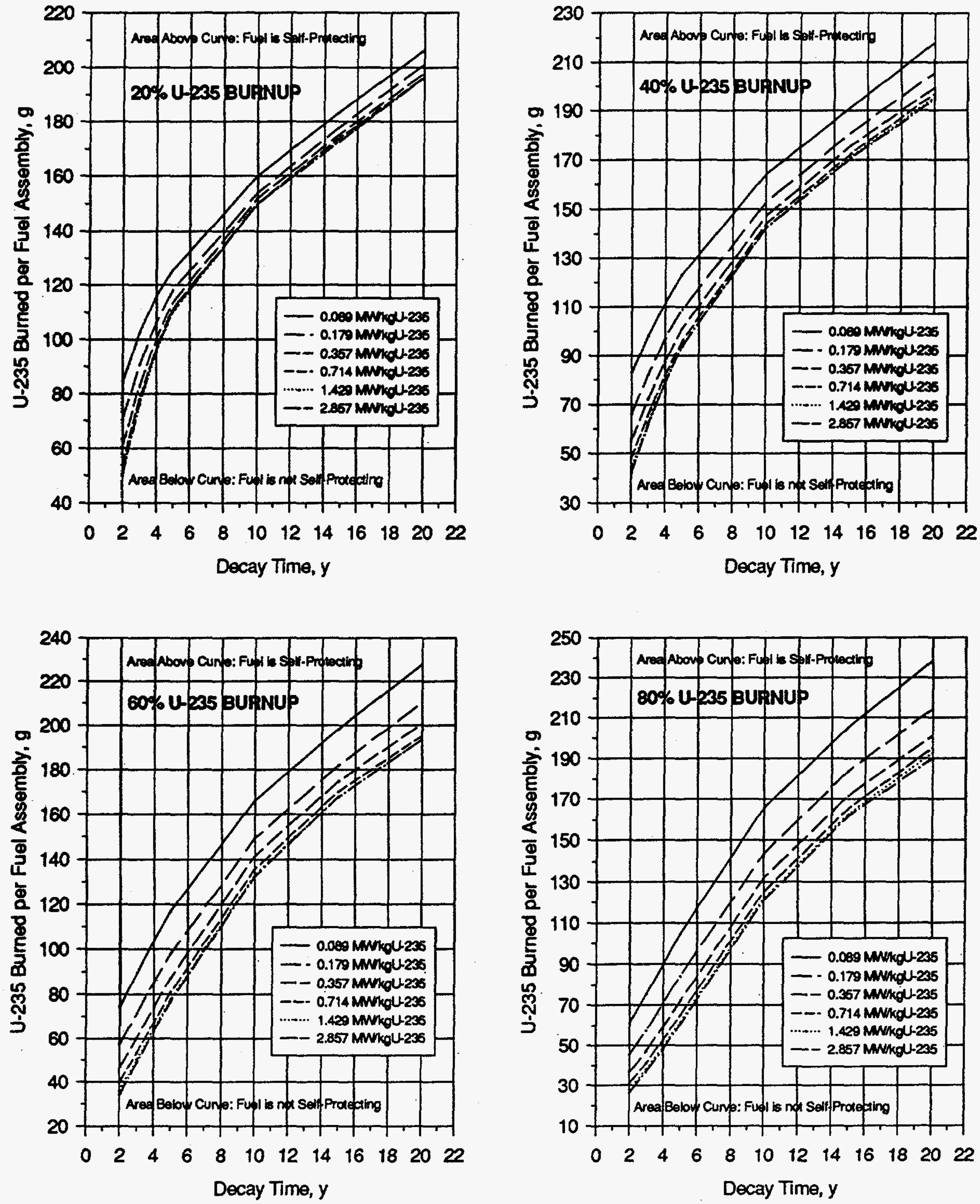

Figure 1. Mass of Burned ^{235}U per Fuel Assembly Necessary for an Unshielded 100 rem/h Dose Rate at 1 m for Fuel Assemblies with 20, 40, 60 and 80% ^{235}U Burnup and Power Densities from 0.089 to 2.857 MW/kg ^{235}U

THERMAL DECAY HEAT

The heat load from decaying fission products in a fuel assembly is proportional to empirical emission rates of beta and gamma radiation. The rates[5] per U-235 fission, and as a function of decay time t_d in days, are

$$\beta(t_d) = 1.50 \cdot 10^{-6} \cdot t_d^{-1.2}\,\text{MeV/s-f}$$
$$\gamma(t_d) = 1.67 \cdot 10^{-6} \cdot t_d^{-1.2}\,\text{MeV/s-f}$$

These energy rates are roughly equal for 0.4 MeV mean energy beta particles and 0.7 MeV mean energy gamma-rays.

For a fuel assembly irradiated continuously for t_i days at a constant fuel assembly power (P), the heat (H) load power per assembly, t_d days after irradiation is

$$H = 6.85 \cdot 10^{-3} \cdot P \cdot (t_d^{-0.2} - (t_i + t_d)^{-0.2})\,\text{Watts}$$

This expression[6] for the heat load is the integral of the above energy rates over the irradiation time, assuming 200 MeV per U-235 fission, and for the fuel assembly power in watts. For a low duty-factor fuel assembly irradiation, the power and irradiation time are replaced by an average power and an elapsed time. With $\overline{P} \cdot t_e = \sum (P \cdot t_i)$ over all irradiation segments, the heat (H) load power per assembly is

$$H \cong 6.85 \cdot 10^{-3} \cdot \overline{P} \cdot (t_d^{-0.2} - (t_e + t_d)^{-0.2})\,\text{Watts}$$

where $\overline{P}$ is the average fuel assembly power in watts and t_e is the elapsed time in days from the initial through the final irradiation segment.

A convenient estimate for the average power ($\overline{P}$) is

$$\overline{P} = (G / t_e) / 1.25 \cdot 10^{-6}\,\text{Watts}$$

where G is the mass of U-235 burned in the fuel assembly in grams, and the constant is g ^{235}U burned per Wd.

Fuel assembly decay heat loads calculated with these expressions are expected to be conservative, and within a factor of two or less of measured heat loads. This same conservative heat load estimate also has been found to be true for heat load calculations made with the ORIGEN code[7]. The thermal heat load of a fuel assembly is independent of the fuel assembly type.

CONCLUSIONS

Procedures have been developed to estimate the nuclear mass inventory, the photon dose rate and the thermal decay heat of spent research reactor fuel assemblies. The procedures should provide reasonable estimates based upon known fuel assembly parameters.

Isotopic mass inventories of U, Np, Pu and Am are tabulated in Tables 2–7 for MTR, TRIGA and DIDO fuel assembly types; photon dose rates at 1 m in air are shown in Table 8 for MTR-type fuel assemblies; and an analytical expression is given for the thermal decay heat load of spent uranium fuel. Estimates of TRIGA and DIDO fuel assembly dose rates are respectively, factors of 1.04 and 1.05 times the dose rate for MTR-type fuel assemblies with similar spent fuel material characteristics.

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