LA-UR 93-0062

EVALUATION OF THE TOTAL MASS OF SPENT FUEL AND PLUTONIUM GENERATED BY U.S. AND GLOBAL NUCLEAR REACTORS

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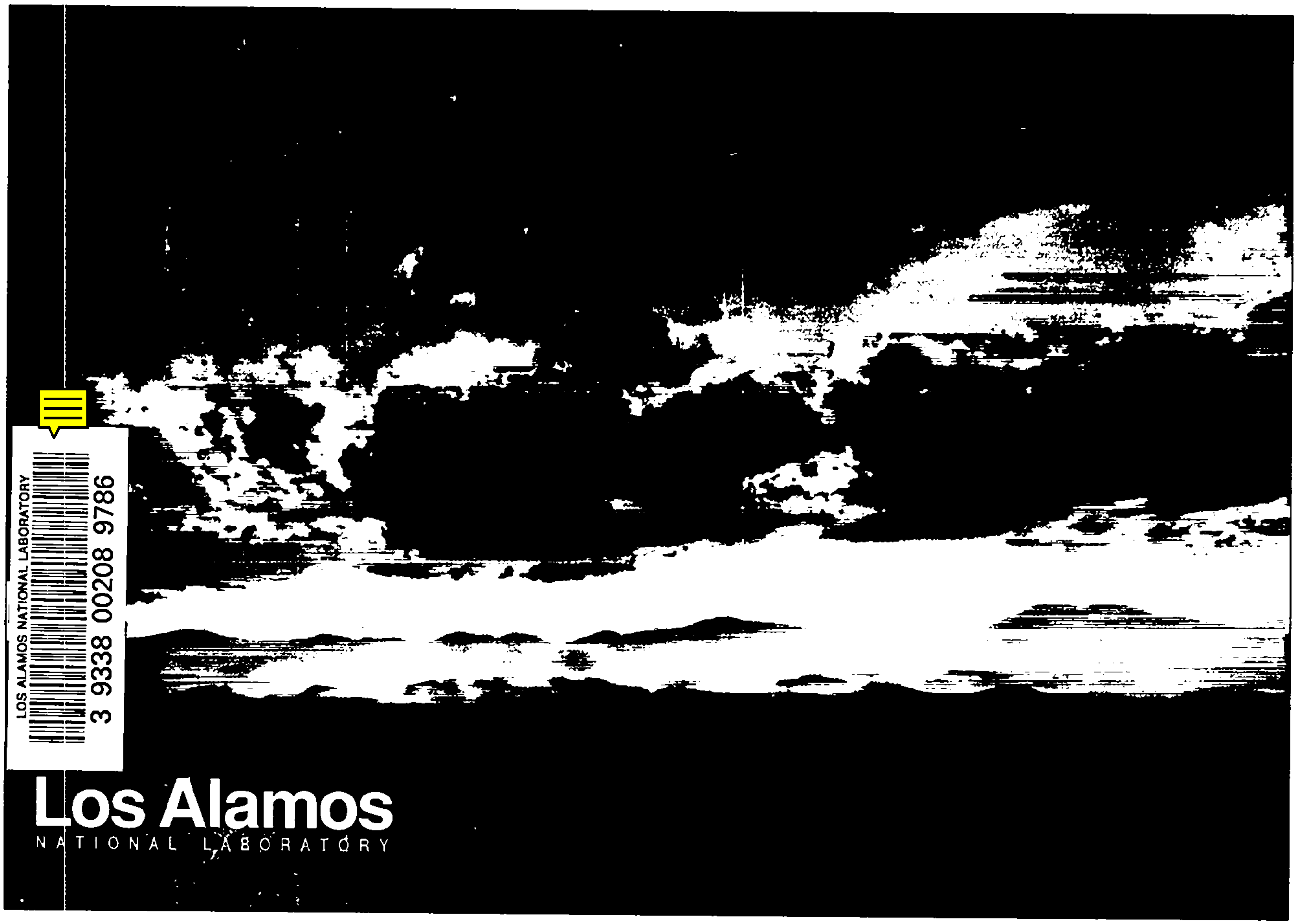

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DETERMINATION OF THE PLUTONIUM IN SPENT FUEL

The plutonium generated by U.S. and global nuclear reactors can be estimated from two factors: the amount of reactor spent fuel generated, and the fraction of the spent fuel that is plutonium. Energy production depends on the power of the reactor and the burnup of the fissile fuel in the reactor. The burnup of a reactor is a measure of the fission energy produced and is usually expressed in terms of megawatt(thermal)-days per metric ton of the initial heavy metal fuel load(MWt-d/MTIHM). For brevity, MTIHM will simply be abbreviated as T.

As an example, using 200MeV as the energy release from one fission event of ^{235}U, one kilogram of ^{235}U produces approximately 1000 Mwt-d . If the fuel were all fissile material, this is the largest burnup and specific energy output that could be achieved from a reactor. For light water reactors (LWR), natural uranium fuel is enriched in the fissile isotope to a level of 3%. If we now normalize the burnup to the total metal mass of fuel, we get for the above example, 33,000 MWt-d/T. By the late 1980's, typical BWR and PWR burnups were around 33,000MWt-d/T with an enrichment level of 3.2% ^{235}U. Advances in fuel assemblies and fuel management techniques, combined with higher enrichment levels of 5% now yield burnup levels of 50,000MWt-d/T.[1]

The typical thermal-to- electrical conversion efficiency for a reactor is 33%. Consequently, 33,000MWt-d corresponds to approximately 10,000MWe-d/T.

In actual reactor operation, the situation is somewhat more complicated. Most of the fuel is ^{238}U, which by itself will contribute less than 10% to the fissile energy release. However, some of the ^{238}U will be converted to ^{239}Pu through successive neutron capture reactions, which will contribute to the fission power of the reactor. The amount of uranium that is converted to plutonium in the reactor is expressed by the conversion ratio, C, and depends upon how the reactor is operated. For typical operation of a LWR, after 15 years, about half of the power generated by fission results from burning Pu. Consequently, it is necessary to distinguish the mass of Pu in spent fuel, waste, and reactor inventory. For most LWR reactors, the spent fuel mass is predominately ^{238}U. "Waste" generally denotes the mass of actnides and fission products generated. As an example, a one GWe reactor operating for one year produces approximately 33 T of spent fuel, 330 Kg of actinides (300 Kg of Pu), and 1000 Kg of fission products. All of these values depend strongly on the reactor fuel cycle, the fuel enrichment, and the specific operation of the reactor. In the following estimates, we assume "typical LWR operation" as currently exists in most current reactor cycles.

It is also necessary to take into account the fraction of on-time or "load factor" of the reactor to estimate the actual burnup and mass of spent fuel. A typical historical load factor for U.S. reactors has been 60%, compared to other nations that average 70-80%.[2] In these estimates we will assume 0.6 for U.S. reactors and 0.75 for non-U.S. nuclear reactors.

The total amount of spent fuel produced from a reactor can be estimated as follows. An energy output of 10,000 MWe-d= 27.4 MWe-yr. For a 1.0 GWe reactor operating for one year, the spent fuel produced is 1000 MW/27.4= 36 T. Multiplying by the average load factor of 0.6 for U.S. reactors, we obtain an average discharge of 36*0.6= 22 T. In recent years the burnup rate for U.S. reactors has increased to 40,000MWt-d/T which gives a current value quoted for the annual spent fuel discharge of approximately 33 T.

The amount of plutonium produced in the spent fuel is a complicated function of the burnup factor. For 33,000 MWt-d, the amount of total plutonium produced is 9 Kg/T or 9*33=297 Kg for a 3 GWt(1GWe) reactor. A summary of isotopic composition and plutonium mass for other values of reactor burnup is presented in Table 1. These results were computed from the ORIGEN2 code developed for detailed reactor burnup calculations for a standard PWR. The other actinides add an additional 35 Kg to the mass of plutonium.

ESTIMATES FOR U.S. PLUTONIUM GENERATED FROM LWR'S

Currently there are 110 operating reactors in the U.S. that produce 100 GWe of electrical power. For purposes of these estimates, we assume an average reactor power of 0.9 MWe. Using a load factor of 0.6, a burnup factor of 33,000MWt-d/T, and an average power of 0.9 GWe, 110 reactors will produce 110*36 T/GWe*0.6*0.9 GWe = 2100 T/yr. This value is equal to that given by the 1991 "Integrated data base for radioactive waste inventories and projections"[3]. According to this study, the total annual spent fuel grew linearly from 1970 to the present and will remain approximately constant at 2100 T/yr out to 2010. The values of the total spent fuel discharge and the total plutonium content(assuming 9 Kg/T) is summarized in Table 2.

Year	Total Spent Fuel(T)	Total plutonium(T)
1990	21, 868	196
2000	41,300	371
2010	60,300	543

TABLE 2

GLOBAL PLUTONIUM GENERATED IN NUCLEAR REACTORS

Estimates for the global production of plutonium are slightly more complicated and more uncertain. Approximately 85% of all reactors in the world are PWR's and BWR's. The rest produce smaller amounts of plutonium. For these estimates we assume that the spent fuel discharge from PWR's and BWR's are approximately equal and that the 412 nuclear reactors in the world have a typical burnup of 33,000MWt-d/T. The current global power production is 325 GWe, resulting in an average reactor of 325/412 = 0.8 GWe. Assuming a 0.75 load factor and a waste production rate of 36 T/GWe as derived previously, the annual production of global nuclear spent fuel is 36*0.8*0.75= 21.6 T/reactor or 412* 21.6 = 8900 T/yr total. Using the results in Table 1, we obtain a Plutonium fraction of 9 Kg/T. The annual production of plutonium from global reactor spent fuel is then 8900 T/yr*9 Kg/T= 80 T/yr. A more current burnup value for many Euorpean reactors is 50,000 MWt-d/T, which results in a lower discharge of total spent fuel but a higher fraction of plutonium. Using the appropriate values from Table 1 we obtain 8900 T/yr*10.9 Kg/T= 97 T/yr. For purposes of this estimate we will assume an global annual plutonium production of 100 T/yr.

In order to obtain the current world reactor waste estimate we use the data from the IAEA[1] that by the end of 1991, a total of 6038 years-reactor operating experience had been accumulated in the course of generating a total of 20,145 TWe-h. This average energy generation corresponds to 839 x 10^6 MWe-d. Assuming a burnup factor of 33,000 MWt-d/T = 10,000 MWe-d/T, the spent fuel generated during this time is 839 x 10^6 MWe-d/10,000 MWe-d/T = 83,900 T. Using the plutonium conversion fraction of 9 Kg/T gives a value of 83,900 T*9 Kg/T = 755 T for the plutonium generated globally to date in spent fuel. We will round this off to 800 T of plutonium in spent fuel in 1990.

PLUTONIUM INVENTORY IN REACTORS

In addition to the plutonium in spent fuel, there is also a significant mass of plutonium in the reactor fuel inventory. This can be estimated as follows. We assume three refuelings for the reactor. On any refueling interval, the mean burnup is approximately 1/2 of the average discharge burnup rate for the reactor or 33,000 MW-d /2= 16,500 MW-d/T. Using Table 1, this corresponds to 5.9 Kg of Pu per ton of total uranium fuel inventory. For a typical one GWe reactor with a uranium fuel inventory of 100-33= 67 T, the Pu inventory is 393 Kg. For 110 U.S. reactors, the average Pu inventory is approximately 43 T. Using the same procedure for global reactors, the Pu inventory is 412* 393 Kg= 161 T.

SUMMARY

In 1990, the U.S. had 110 reactors operating at an average electrical power output of 0.9 GWe giving a total capacity of 100 GWe. From the period of 1970 through 1990, these reactors generated 20,868 T of total spent fuel of which approximately 200 T is plutonium. Assuming replacement of all current nuclear capacity, but no new growth, the total spent fuel will increase at a rate of 2100 T/yr and plutonium at a rate of 19 T/yr.

Currently there are 412 nuclear reactors in the world with a total electrical generation capacity of 325 GWe. The accumulated spent fuel generated up to 1990 is 83,900 T; of this the plutonium content is 800 T. Assuming replacement of all current nuclear capacity but no new growth, the total global spent fuel will increase at a rate of 8900 T/yr and the plutonium will increase at a rate of 100 T/yr.

As a comparison, the amount of plutonium expected to be recovered from dismantled nuclear weapons for both the U. S. and the CIS is approximately 100 T.

Plots of historical and projected electrical generation, total spent fuel production and plutonium production for the U.S. and the world are shown in Figures (1), (2), (3), and(4) respectively.

REFERENCES

(1) "Nuclear Power Reactor Characteristics", The Uranium Institute, IAEA, Bowater House, London, England, 1992.

(2) "Nuclear Power" National Research Council, National Academy Press, Washington, D.C. , 1992. p50.

(3) "Integrated Data Base For 1991: U.S. Spent Fuel and Radioactive Waste Inventories, Projections, and Characteristics", Oak Ridge National Laboratory Report DOE/RW-0006, 1991; p21.

Pu Content In PWR/U Fuel at Discharge
(g/MTHM)

Burnup (GW-d)	1.0	2.5	5.0	10.0	15.0	16.5	20.0	25.0	27.5	30.0	33.0
pu238	0	0	1	6	17	22	36	64	81	101	128
pu239	472	1175	2102	3318	4027	4185	4472	4722	4809	4879	4939
pu240	11	63	209	588	998	1129	1409	1775	1965	2132	2306
pu241	0	6	41	221	458	522	694	932	1015	1108	1223
pu242	0	0	1	17	60	79	133	237	299	366	454
pu total	483	1244	2355	4151	5560	5936	6743	7730	8169	8586	9050

Pu Content In PWR/U Fuel at Discharge
(g/MTHM)

Burnup (GW-d)	35.0	37.5	40.0	42.5	45.0	47.5	50.0	52.5	55.0	57.5	60.0
pu238	148	174	203	234	266	299	333	367	402	437	471
pu239	4965	4987	5000	5006	5009	5008	5006	5002	4997	4992	4986
pu240	2409	2519	2609	2683	2742	2789	2828	2854	2878	2892	2905
pu241	1296	1385	1468	1542	1608	1664	1711	1750	1781	1806	1826
pu242	516	599	685	773	864	955	1045	1134	1221	1305	1385
pu total	9334	9663	9964	10240	10490	10720	10920	11110	11280	11430	11570

Table 1

HISTORICAL GROWTH OF U.S. NUCLEAR POWER

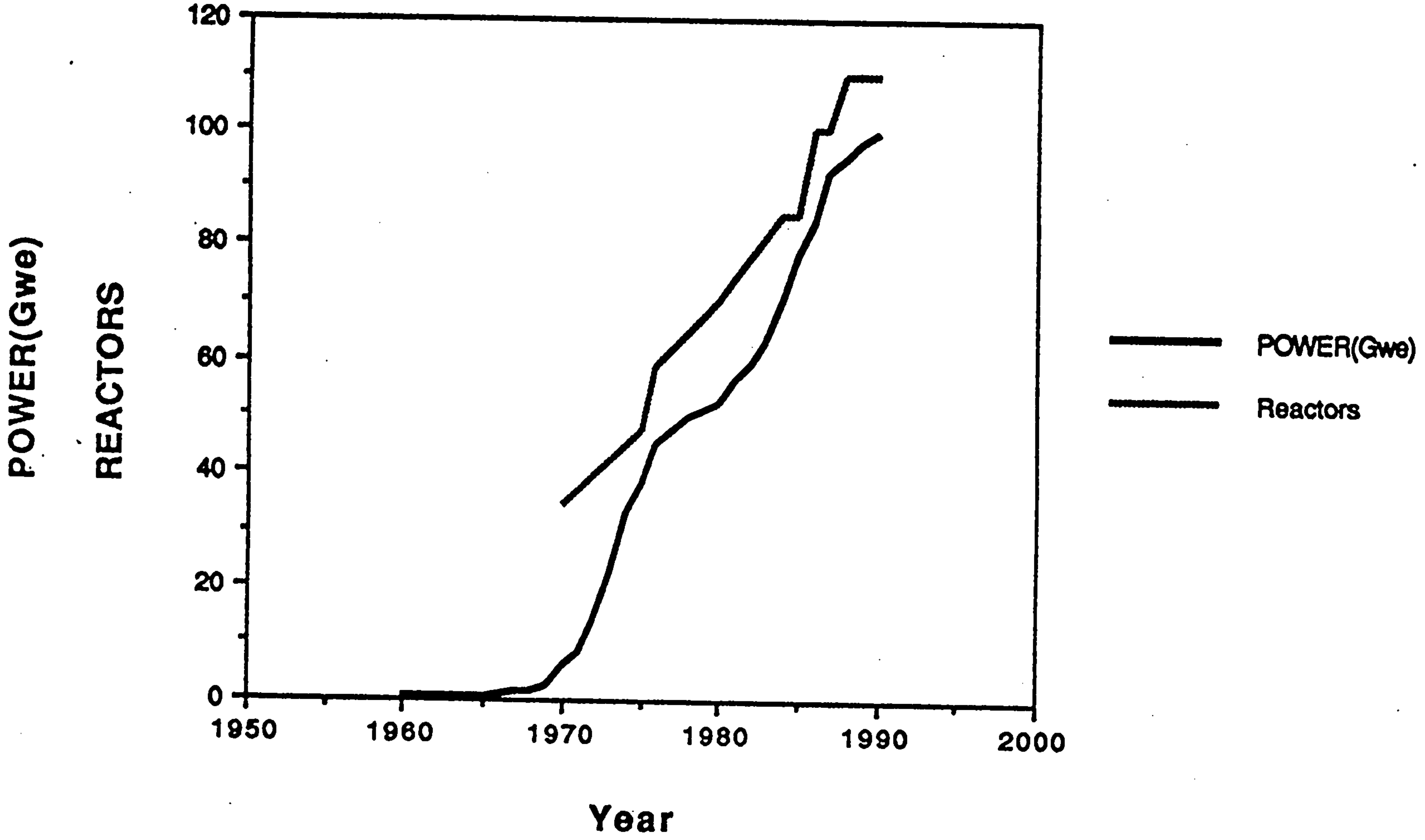


Figure 1

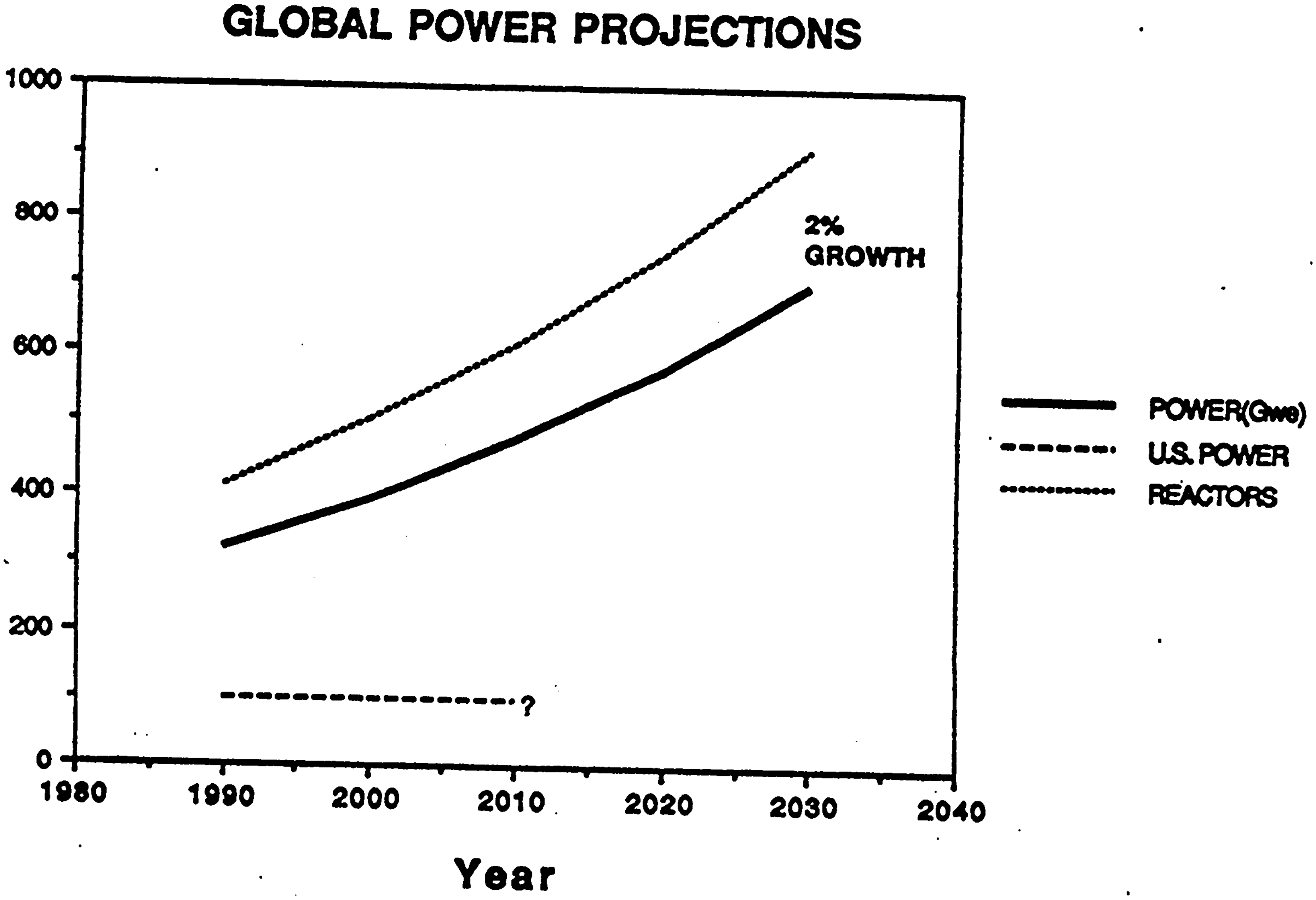
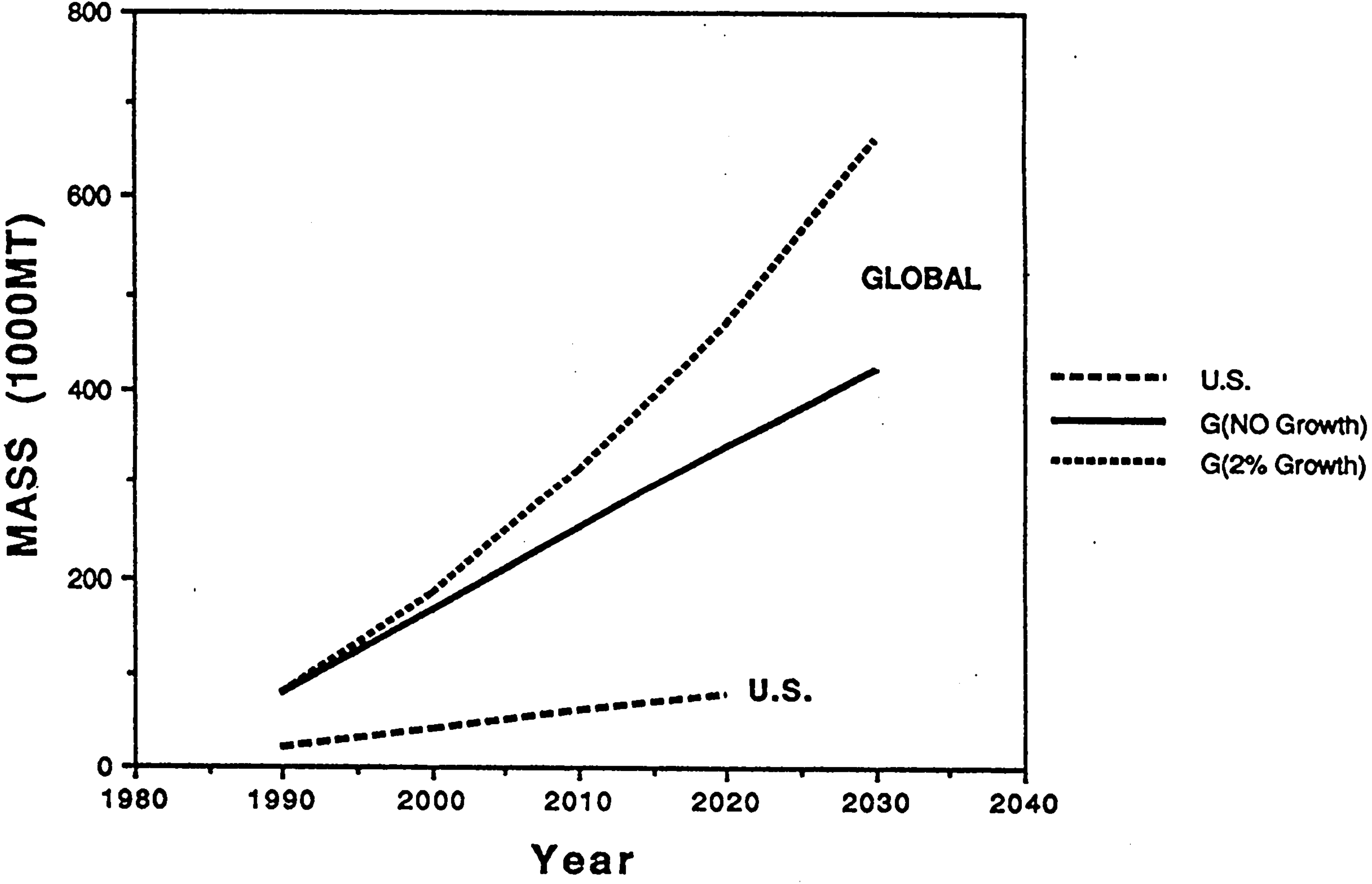

GLOBAL POWER PROJECTIONS
1000
800
600
400
200
0
1980
1990
2000
2010
2020
2030
2040
Year
2%
GROWTH
?
POWER(Gwe)
U.S. POWER
REACTORS

Figure 2



SPENT FUEL FROM NUCLEAR REACTORS

Figure 3

PLUTONIUM GENERATED BY NUCLEAR REACTORS

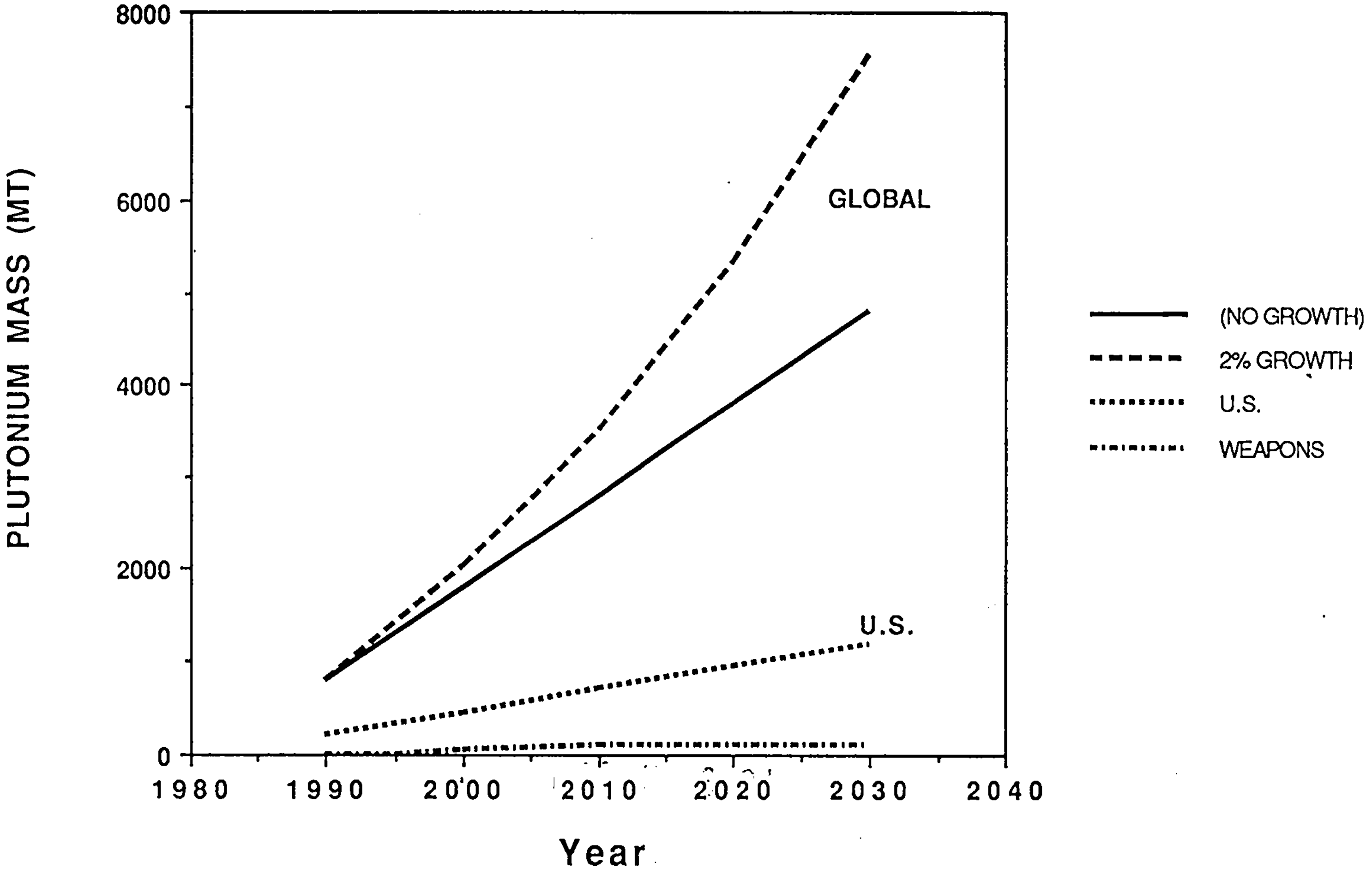


Figure 4