Neutronics Studies of the Gas-Carried Li_2O Cooling/Breeding Fusion Reactor Blanket and Shield

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UNIVERSITY OF WISCONSIN

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Abstract

The neutronics and photonics of the gas-carried Li_2O blanket have been studied. The blankets studied consist of 20-30% Li_2O solid particles and 2% 316 SS structural material in volume. Li_2O blanket can achieve a high tritium breeding ratio without a neutron multiplier due to its high lithium atom density. The effects of the design variations on the tritium breeding ratio and total nuclear heating are summarized as follows:

(1) The tritium breeding ratio is relatively insensitive to the graphite reflector thickness and, as found in the UWMAK-I design, also insensitive to the ^6Li enrichment.

(2) The total nuclear heating is ~15 MeV per D-T neutron. The contribution from gamma-ray heating is ~20%.

The performance of the shield and the thermal behavior of the magnet in case of a loss of coolant accident (LOCA) are also investigated. The superconducting TF coil will go normal about 100 seconds after a LOCA occurs, which is about one order of magnitude longer than required to shut down the plasma.

The radioactivity and afterheat after shutdown of the reactor have been calculated and found comparable to the stainless steel structured UWMAK-I design.

I. Introduction

A stream of Li_2O particles suspended in low-pressure helium gas was proposed as the cooling and breeding material for a D-T fusion reactor.(1) Such a blanket provides advantages in tritium breeding, tritium handling and recovery, blanket design and safety. The mechanical and thermal-hydraulic design has been discussed by Sze et al.(2) The tritium considerations have been presented previously.(3) This paper discusses results for the neutronics studies of such a blanket. The most important results of the neutronic calculations for a D-T fusion reactor blanket are the tritium breeding ratio, which is the tritium production per D-T fusion reaction, and the total nuclear heating in the blanket, which is the total energy released per D-T fusion reaction. Hence, we will investigate mainly the influence of the design variations, such as ^6Li enrichment, graphite reflector thickness and so on, on these quantities.

In Section II, the blanket and neutronics calculational models are briefly described. The neutronic results are then presented in the following sections. The effects on the tritium breeding and the total nuclear heating due to design variations are discussed in Sections III and IV, respectively. In Section V, the neutronic effect of a loss-of-coolant accident on the superconducting magnet is studied. Finally, the radioactivity and afterheat after shutdown of the reactor are discussed in Section VI.

II. Blanket Model and Neutronics Calculations

The blanket investigated here is structurally made of Type 316 stainless steel. The first wall is 5 mm thick. The cooling/breeding zone consists of a homogenized mixture of 2% volume structure, 20 to 30% Li_2O solid concentration by volume, and the balance of helium. A 30% volumetric solid suspended in a gas appears attainable.(4) The breeding zone is divided into two regions by a graphite reflector. The total thickness of the blanket is limited to ~ 1 m. All the neutronics calculations are performed using the ANISN[5] program with the P_3S_8 approximation in cylindrical geometry.[6] All neutron and gamma group cross sections used are the same as that used elsewhere.[7] The energy group structure consists of 46 neutron groups and 43 gamma groups. The plasma and first wall radius are taken from the UWMAK-II (Ref. 8) design. An albedo of 0.3 for every energy group is used at the outer boundary of the blanket to simulate the effect of a shield. This procedure significantly reduces the computing time and the integral quantities from the calculation are reasonably accurate.

Several Li_2O blankets with design variations in ^6Li enrichment, breeding zone thickness, Li_2O concentration and graphite reflector arrangement are shown in Table I, and labeled as designs A, B, C and D accordingly. Design A is basically a natural lithium oxide blanket. The Li_2O solid concentration in the blanket is 31.3% by volume, which is about the maximum attainable concentration in this gas carried solid concept. The cooling/breeding zones are 540 and 60 mm thick respectively and the graphite reflector is 300 mm thick. Design B is a variation of design A with 30% enriched ^6Li. Design C is also a natural lithium blanket. However, the first breeding zone is increased to 640 mm and the graphite reflector is decreased to 200 mm in order to keep the blanket thickness constant. Design D is the same as design A, except the Li_2O solid concentration in this design is decreased to 20% by volume in the blanket. Note that an additional 200 mm graphite reflector is put at the back of the blanket as part of the shield and is included in the calculation for design C. The tritium breeding ratio, neutron balance, and nuclear heating for these designs are tabulated in Table II. Along with the neutronic calculations for the above mentioned blanket designs, which serve as standards, several neutronic calculations were performed with variations of the graphite reflector thickness in their designs. Using the results from these calculations as references, the method of variational interpolation[9] is used to interpolate the desired quantities in the range of design variations of interest. This includes the graphite reflector thickness, the ^{6}Li enrichment in total lithium and the solid concentration in the blanket.

III. Tritium Breeding

Tritium breeding is necessary for a D-T fusion reactor since tritium is not naturally available. The main source of tritium production is the nuclear reaction of neutrons with the element lithium. Natural lithium consists of 92.58% ^{7}Li and 7.42% ^{6}Li. The basic nuclear reactions which convert lithium into tritium are:

$$^{6}\mathrm{Li}(n,\alpha)T + 4.78\ \mathrm{MeV}$$

and

$$^{7}\mathrm{Li}(n,n',\alpha)T - 2.47\ \mathrm{MeV}.$$

The sum over the above two reactions per incoming D-T neutron is the tritium breeding ratio. For a blanket employing a lithium compound for breeding,the existence of non-breeding elements, such as oxygen in Li_2O, will result in competition with the tritium production reactions and thus reduce the production rate of tritium. In the following, we will discuss the influence on tritium breeding due to ^{6}Li enrichment, Li_2O solid concentration in the breeder-cooling zones and the graphite reflector thickness.

III. A. ^6Li Enrichment

The increase of the ^6Li concentration does not contribute much to the tritium production from the $^6Li(n,\alpha)T$ reactions for a blanket within the range of solid Li_2O concentration investigated here. The reason is that the structure is only a few volume percent of the zone and the absorption of neutrons in the ^6Li isotope is about saturated for this blanket with natural lithium. However, the ^7Li concentration is decreased due to the enrichment of ^6Li and the tritium production from the $^7Li(n,n'\alpha)T$ reactions goes down. This finally results in a slight decrease of the tritium breeding in the blanket as can be seen from Fig. 1. In this figure, all the blankets studied were the type with fixed breeding zone thickness (600 mm) and 31.3% solid Li_2O concentration in the breeding zones. The graphite reflector thickness is varied to 150, 300 and 450 mm for comparison.

The neutron nuclear heating for an enriched lithium blanket is slightly enhanced as can be seen from Table II. The total nuclear heating is about 2% higher for design B (30% enriched lithium in ^6Li) than design A (natural lithium). Thus, we conclude that enrichment of ^6Li will not significantly affect the tritium breeding ratio nor the total nuclear heating for this type of blanket.

III. B. Graphite Zone Thickness and Li_2O Density in the Breeding Zone

Since the solid Li_2O concentration in the stream flowing through the breeding zone is designed to vary from 20 to 30%, it is of interest to know the effect of this variation on the tritium breeding ratio. Here we consider two designs of varying graphite thickness. In one design the total blanket thickness is fixed at 900 mm; while in the other design, the overall thickness of cooling/breeding zones is 600 mm. In both designs the second breeding zone, which is behind the graphite zone is kept at 60 mm. Hence, in the design of fixed total blanket thickness, the increase of the graphite zone thickness causes only a decrease of the first breeding zone thickness. The tritium breeding ratios for 20 and 31.3% solid Li_2O concentration blankets as a function of graphite reflector thickness are shown in Fig. 2. From this figure, it is seen that for a total blanket thickness of 900 mm, the tritium breeding ratio is not very sensitive to the change of the graphite zone thickness as the graphite zone thickness varies from 150 to 350 mm. The optimal tritium breeding ratio changes from 1.00 to 1.20 when the Li_2O solid concentration varies from 20 to 31.3%. The neutron leakage to the shield for these various designs is depicted in Fig. 3. For this optimal range of graphite zone thickness, the neutron leakage to the shield can vary from ~ 5 to 30% when the solid Li_2O concentration changes from 31.3 to 20%. In order to utilize this large fraction of leaked neutrons to enhance the tritium breeding, a second graphite reflector may be added as the first zone of the shield as in design C. A 200 mm-thick second reflector increases the tritium breeding ratio by 5 to 10% when the solid Li_2O solid concentration varies in the desired range from dense to dilute. A breeding ratio of 1.10 to 1.24 can be obtained for such a design as is shown in Fig. 4.

IV. Nuclear Heating

The total nuclear heating in such gas-carried Li_2O blankets is ~ 15.0 MeV per 14.1 MeV D-T fusion neutron, ~ 20% of which is contributed from gamma-ray heating as stated in Table II. A more detailed analysis of nuclear heat deposition in the blanket can be made as follows. A two-graphite zone blanket (design C of Table I) is used for this purpose. In this blanket, the neutron and gamma-ray heating are 12.0 and 3.2 MeV per fusion neutron respectively. The spatial nuclear energy deposition is shown in Fig. 5. The nuclear energy deposition for each zone is tabulated in Table III. We see from this table that ~ 90% of the total energy is deposited in the breeding zones (zone 4 and zone 6) and most of that is carried by the solid particles. As a whole, this blanket intercepts the fusion neutrons and receives more than 99% of the total nuclear heating in the reactor.

V. Loss-of-Coolant Accident (LOCA)

Some effects of a loss-of-coolant accident (LOCA) were studied. When a LOCA occurs, the shielding effect of the lithium oxide disappears. The most severe problem is probably the heating of the magnet. With a shield of 400 mm 90% B_4C + 10% 316 SS and 400 mm 90% Pb + 10% 316 SS, the energy attenuation of the shield is on the order of 10^{-5}. The total nuclear heating of the magnet for a neutron wall loading of 1 MW/m^2 is ~ 45 KW (about 2% of which is contributed by the gamma-ray heating). The temperature of the magnet is 4.2°K and it can be heated up to 5.5°K without serious effect. The time required for the magnet to reach 5.5°K is ~ 100 sec. This is 10 times longer than the time required to shut down the plasma.

VI. Radioactivity and Afterheat

The radioactivity and afterheat following shutdown for the case of a 2-yr operating period have been calculated. For the designs mentioned in Table I (designs A, B, C and D), the differences of radioactivity and afterheat after shutdown are very small. This can be seen in Figs. 6 and 7. The reason is that the stainless steel first wall and structure dominate the radioactivity and afterheat after shutdown.

The first wall and breeding zone contribute more than 99% of the total activity and afterheat at shutdown. Reaction products from lithium oxide, such as ^{16}N, ^{6}He and ^{8}Li in the breeding zone, are short half-life isotopes and their rapid decay results in the prompt drop of afterheat within 1 minute after shutdown. By the same token, the radioactivity contributed from the first wall, which is ~ 40% of the total at shutdown, increases to ~ 60% within 1 minute. The trend of the radioactivity and afterheat thereafter is similar to that of the stainless steel blanket of the UWMAK-I design.[(10)]

At shutdown, the radioactivity and afterheat for the design A blanket are ~ 58.1 GBq per watt of operating power (1.57 curie per watt) and 2.5% of the operating power respectively; they reduce to ~ 12.2 GBq per watt of operation power (0.33 curie per watt) and 0.05% respectively one year after shutdown.

The biological hazard potential (BHP)[(11)] for this design is ~ 0.31 km^3 of air/watt at shutdown and drops to ~ 0.08 km^3 of air/watt one year after shutdown.

VII. Conclusions

The neutronics and photonics of the gas-carried Li_2O cooling-breeding fusion reactor blanket have been studied. Li_2O can achieve a high tritium breeding ratio without a neutron multiplier due to its high lithium atom density. The tritium breeding ratio is relatively insensitive to the graphite reflector thickness and, as found in UWMAK-I, also insensitive to the ^{6}Li enrichment. The most important variables are the Li_2O density and blanket thickness, i.e., total lithium atoms in the blanket. The total nuclear heating in the system is ~ 15 MeV per D-T neutron, which is lower than in the UWMAK-I or II designs. This is due to the presence of small amounts of first wall and structural material in the blanket. The contribution of gamma-ray heating is only 20%.

There is a possibility of a loss of coolant accident in the gas-carried system due to mechanical system failure. The performance of the shield should provide thermal protection to the superconducting magnets. When a loss of coolant accident occurs, the time needed to heat up the superconducting magnet with a serious effect is found to be about 10 times longer than the time required to shut down the plasma.

The radioactivity and afterheat a few minutes after shutdown are found comparable to the stainless steel structured blankets such as the UWMAK-I and II designs.

Acknowledgement

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References

1. D. K. SZE, E. M. LARSEN, E. T. CHENG and R. G. CLEMMER, "A Gas-Carried Li_2O Cooling/Breeding Fusion Reactor Blanket Concept," Trans. Am. Nucl. Soc., 22, 21 (1975).

2. D. K. SZE, D. C. SCHLUDERBERG and I. N. SVIATOSLAVSKY, "Gravity Circulated Solid Blanket Design for a Tokamak Fusion Reactor," Proceedings of the Second ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Richland, Washington, September 21-23, 1976.

3. E. M. LARSEN, R. G. CLEMMER and D. K. SZE, "Tritium Recovery and Handling in a Gas-Carried Li_2O CTR Blanket," Trans. Am. Nucl. Soc. 23, 56 (1976).

4. C. Y. WEN and H. P. SIMONS, J. Am. Inst. Chem. Eng., 5, 263 (1959).

5. W.W. ENGLE, JR., "A User's Manual for ANISN," K-1693, Union Carbide Corp. (1967).

6. C. W. MAYNARD and M. A. ABDOU, "Neutron and Gamma Physics Problems in Fusion Reactors," New Development in Reactor Physics and Shielding, USAEC Conf. - 270901, September 1972.

7. M. A. ABDOU and R. W. CONN, Nucl. Sci. Eng. 55, 256 (1974).

8. R. CONN, et al., "Major Design Features of the Conceptual D-T Tokamak Power Reactor, UWMAK-II," UWFDM-114, University of Wisconsin (Oct. 1974).

9. E. T. CHENG and R. W. CONN, "The Influence of Design Variations on Controlled Thermonuclear Reactor Blanket Neutronic Performance Using Variational Techniques," to be published in Nuclear Science and Engineering.

10. B. BADGER, et al., "UWMAK-I, A Wisconsin Toroidal Fusion Reactor Design," Vol. 1, UWFDM-68, The University of Wisconsin, Fusion Feasibility Group (Nov. 1973).

11. D. STEINER and A. P. FRASS, Nuclear Safety, 13, 353 (1972).

Figure Captions

1. Tritium breeding ratio as a function of ^6Li enrichment in total lithium for various graphite reflector thickness.

2. Tritium breeding ratio as a function of graphite reflector thickness.

3. Fraction of neutron leakage to the shield as a function of graphite reflector thickness.

4. Tritium production from $^6Li(n,\alpha)T$ (T_6), $^7Li(n,n'\alpha)T$ (T_7), and total tritium breeding for the two-reflector blanket as a function of Li_2O solid concentration.

5. Spatial distribution of nuclear heating rate in design C blanket. 1 MW/m^2 wall loading.

6. Radioactivity vs. shutdown time for Li_2O blankets (2-year operation).

7. Afterheat vs. shutdown time for Li_2O blankets (2-year operation).

Table I

Description of Several Li_2O Blanket Designs

Zone	Design A Composition (Thickness, mm)	Design B Composition (Thickness, mm)	Design C[c] Composition (Thickness, mm)	Design D Composition (Thickness, mm)
1	Plasma (5000)	Plasma (5000)	Plasma (5000)	Plasma (5000)
2	Vacuum (500)	Vacuum (500)	Vacuum (500)	Vacuum (500)
3	SS First Wall (5)	SS First Wall (5)	SS First Wall (5)	SS First Wall (5)
4	2% SS + 31.3% Li_2O [a] + 66.7% He (540)	2% SS + 31.3% Li_2O [b] + 66.7% He (540)	2% SS + 31.3% Li_2O [a] + 66.7% He (640)	2% SS + 20% Li_2O [a] + 78% He (540)
5	Graphite (300)	Graphite (300)	Graphite (300)	Graphite (300)
6	2% SS + 31.3% Li_2O [a] + 66.7% He (60)	2% SS + 31.3% Li_2O [b] + 66.7% He (60)	2% SS + 31.3% Li_2O [a] + 66.7% He (60)	2% SS + 20% Li_2O [a] + 78% He (60)

a) Natural lithium in the Li_2O

b) 30% ^6Li in total lithium

c) An additional 200 mm graphite reflector is attached at the back of the blanket which serves as part of the shield

Table II

Tritium Breeding Ratio, Neutron Balance and Nuclear Heating for Several Li_2O Blanket Designs

(Results in Reactions, Particles or MeV per D-T Neutron)

	Design A	Design B	Design C	Design D
$^6Li(n,\alpha)T$	0.7974	0.8534	0.8423	0.7035
$^7Li(n,n'\alpha)T$	0.3924	0.2903	0.4031	0.3166
Total Tritium Production	1.1898	1.1437	1.2454	1.0201
Total (n,2n)	0.0832	0.0868	0.0842	0.0639
Total Non-Tritium Producing Absorptions	0.2103	0.1798	0.1917	0.2403
Neutron Heating	11.71	12.11	11.99	10.87
Gamma Heating	3.10	3.06	3.21	3.32
Total Heating	14.81	15.17	15.20	14.19
Neutron Energy Leakage to the Shield	0.126	0.124	0.051	0.271
Neutron Particle Leakage to the Shield	0.0725	0.0507	0.0047	0.1355

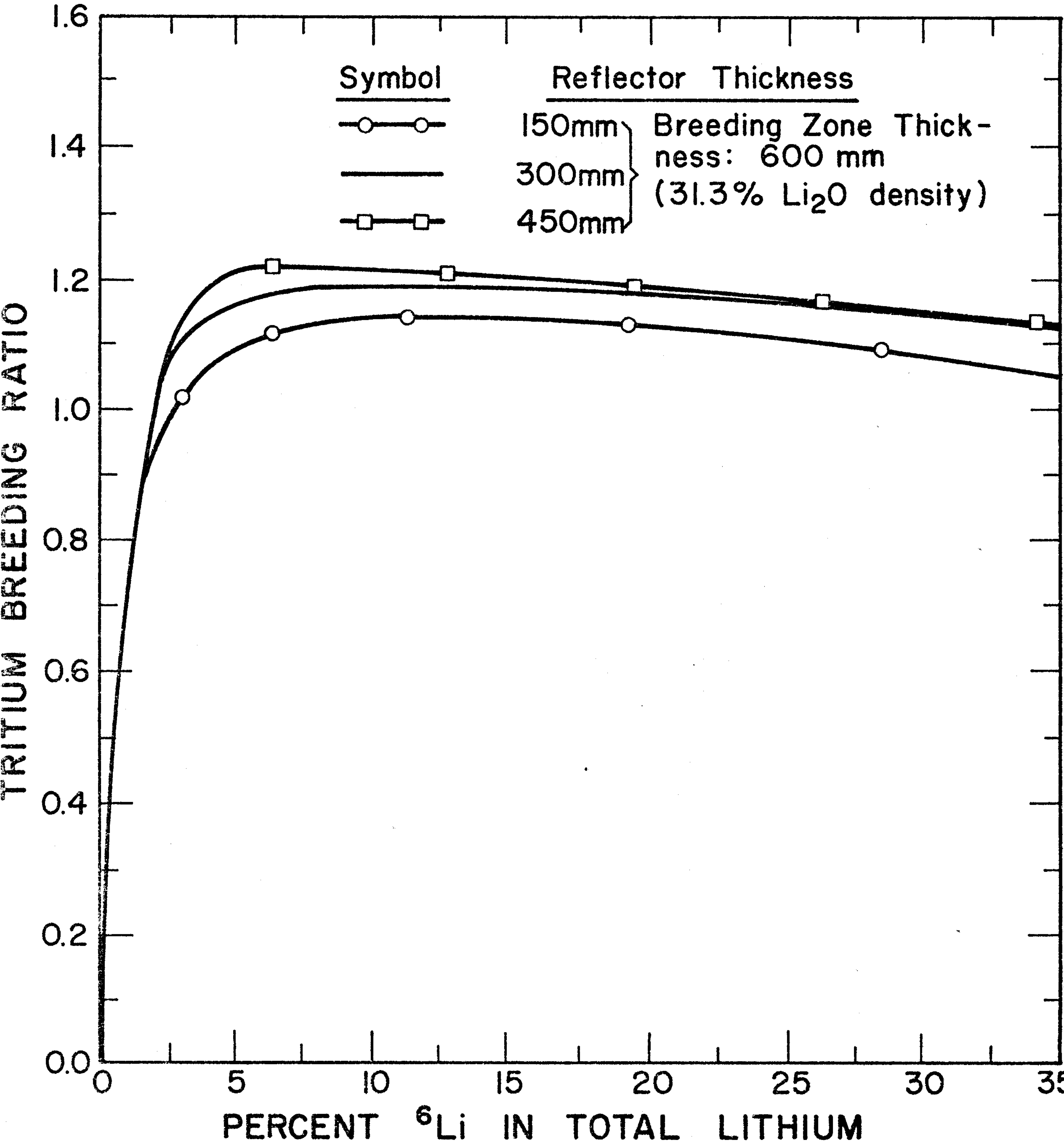
Table III

Nuclear Heating by Zones for the Two-Graphite Reflector Li_2O Blanket (Design C)[a]

(In units of MeV per 14.1 MeV D-T neutron)

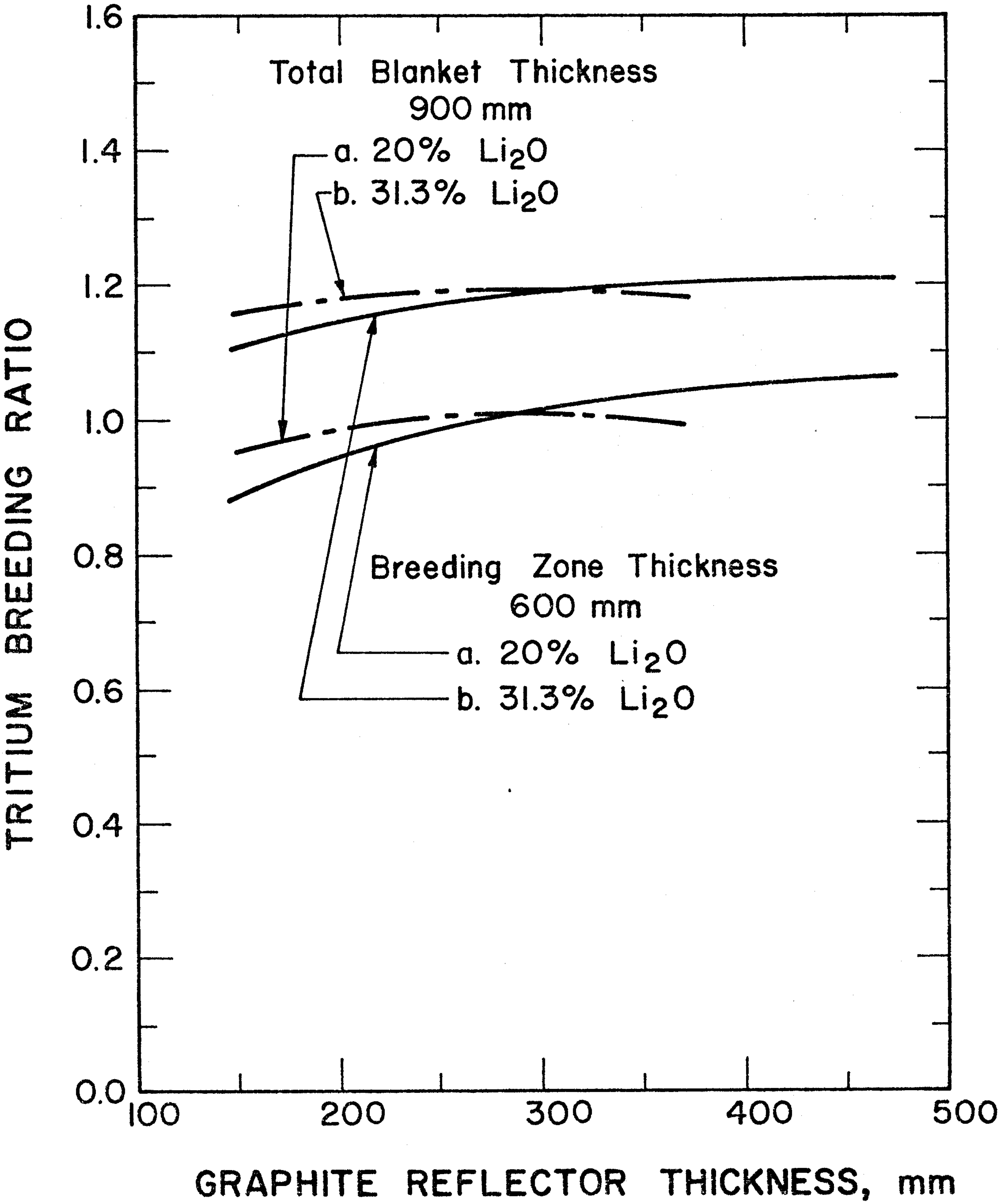
Zone	Thickness (mm)	Composition	Neutron Heating	Gamma Heating	Total Heating
1	5000	Plasma	0.0	0.0	0.0
2	500	Vacuum	0.0	0.0	0.0
3	5	S.S.	0.316	0.378	0.694
4	640	2% S.S. + 31.3% Li_2O + 66.7% He	10.397	2.254	12.651
5	200	Graphite	0.599	0.397	0.996
6	60	2% S.S. + 31.3% Li_2O + 66.7% He	0.565	0.036	0.601
7	200	Graphite	0.117	0.145	0.263
	Sum		11.994	3.210	15.204
Energy Leakage to the Shield			0.051	0.057	0.108

a) A 200 mm graphite zone is attached at the back of the blanket which serves as part of the shield. In this table, this zone is designated as zone 7.



Symbol
Reflector Thickness
150mm
300mm
450mm
Breeding Zone Thickness: 600 mm
(31.3% Li2O density)
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
TRITIUM BREEDING RATIO
0
5
10
15
20
25
30
35
PERCENT 6Li IN TOTAL LITHIUM

Figure 1



Total Blanket Thickness
900 mm
a. 20% Li2O
b. 31.3% Li2O
Breeding Zone Thickness
600 mm
a. 20% Li2O
b. 31.3% Li2O
TRITIUM BREEDING RATIO
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
100
200
300
400
500
GRAPHITE REFLECTOR THICKNESS, mm

Figure 2

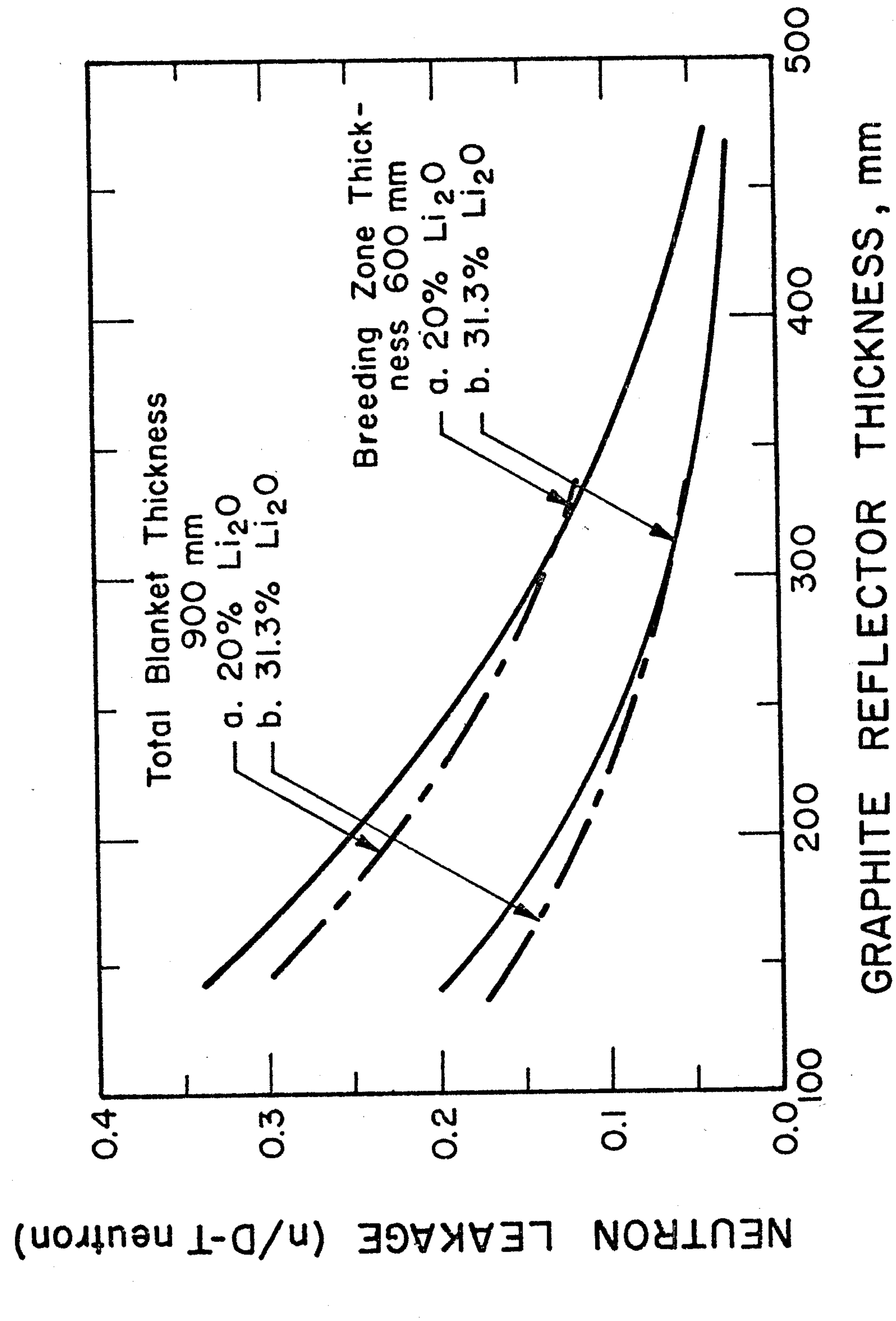

Total Blanket Thickness
900 mm
a. 20% Li2O
b. 31.3% Li2O
Breeding Zone Thick-
ness 600 mm
a. 20% Li2O
b. 31.3% Li2O
0.0
0.1
0.2
0.3
0.4
100
200
300
400
500
GRAPHITE REFLECTOR THICKNESS, mm
NEUTRON LEAKAGE (n/D-T neutron)

Figure 3

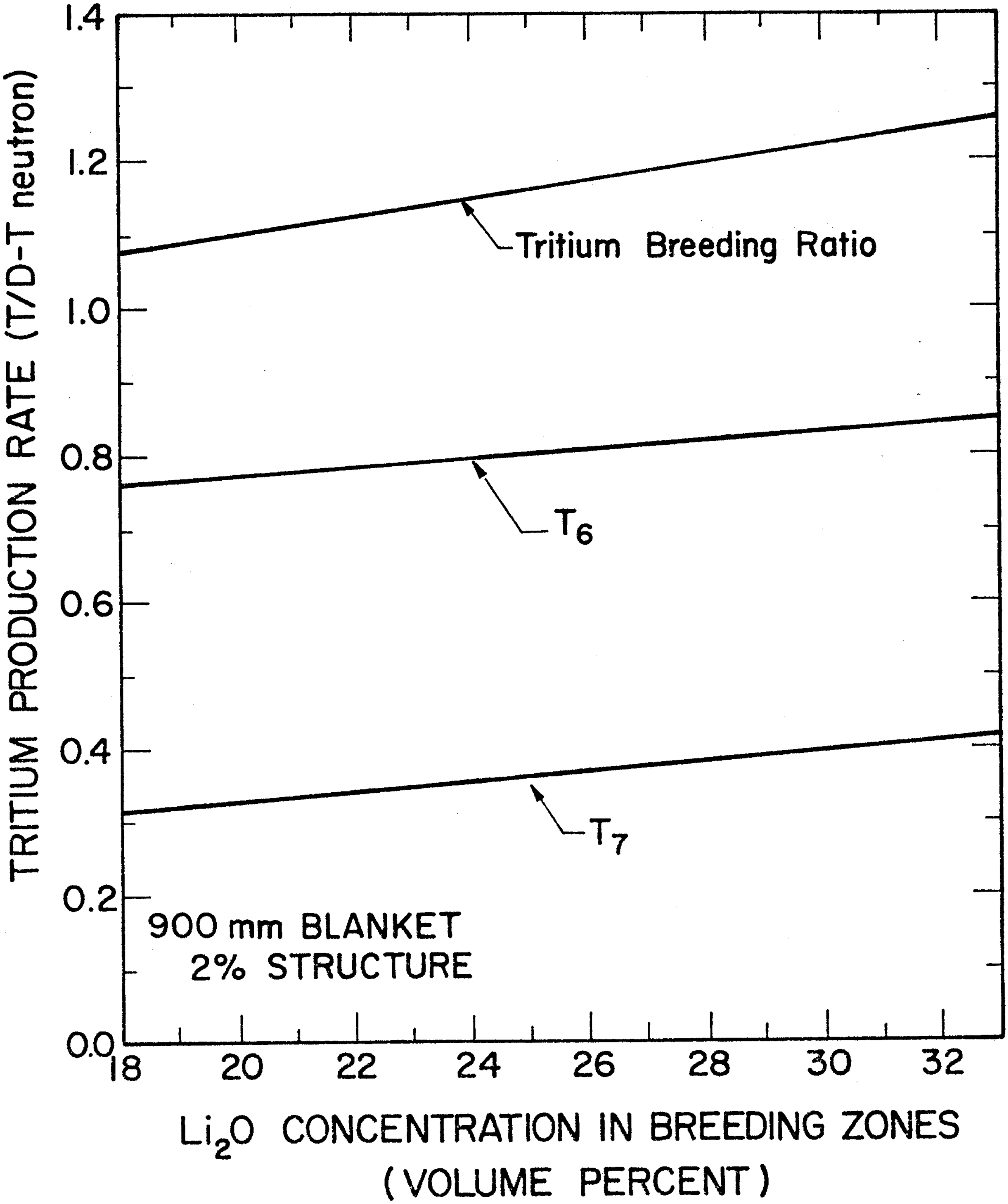

1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
18
20
22
24
26
28
30
32
TRITIUM PRODUCTION RATE (T/D-T neutron)
Tritium Breeding Ratio
T6
T7
900 mm BLANKET
2% STRUCTURE
Li2O CONCENTRATION IN BREEDING ZONES
(VOLUME PERCENT)

Figure 4

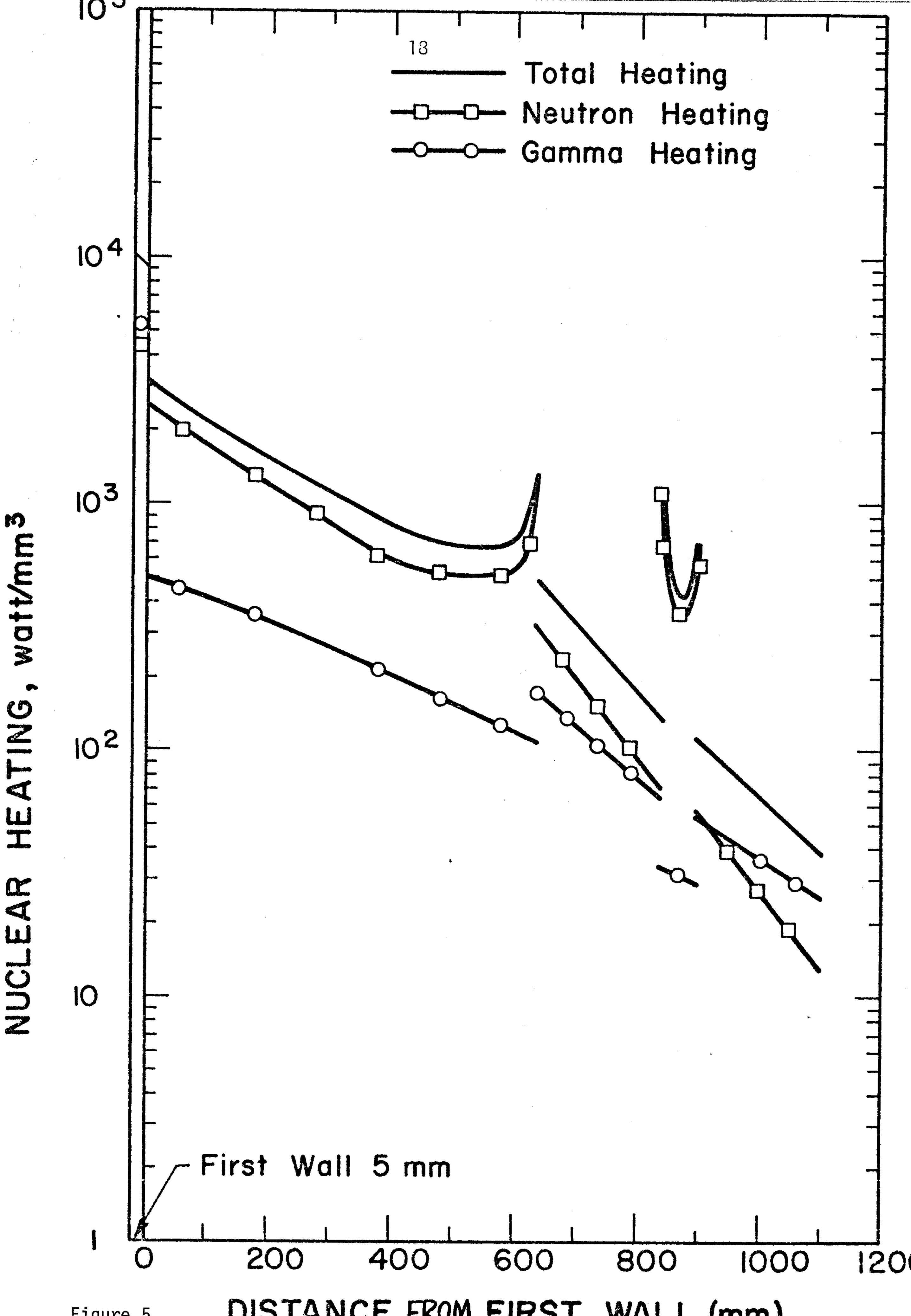

Total Heating
Neutron Heating
Gamma Heating
First Wall 5 mm
NUCLEAR HEATING, watt/mm³
DISTANCE FROM FIRST WALL (mm)
0
200
400
600
800
1000
1200
1
10
10²
10³
10⁴
10⁵

Figure 5

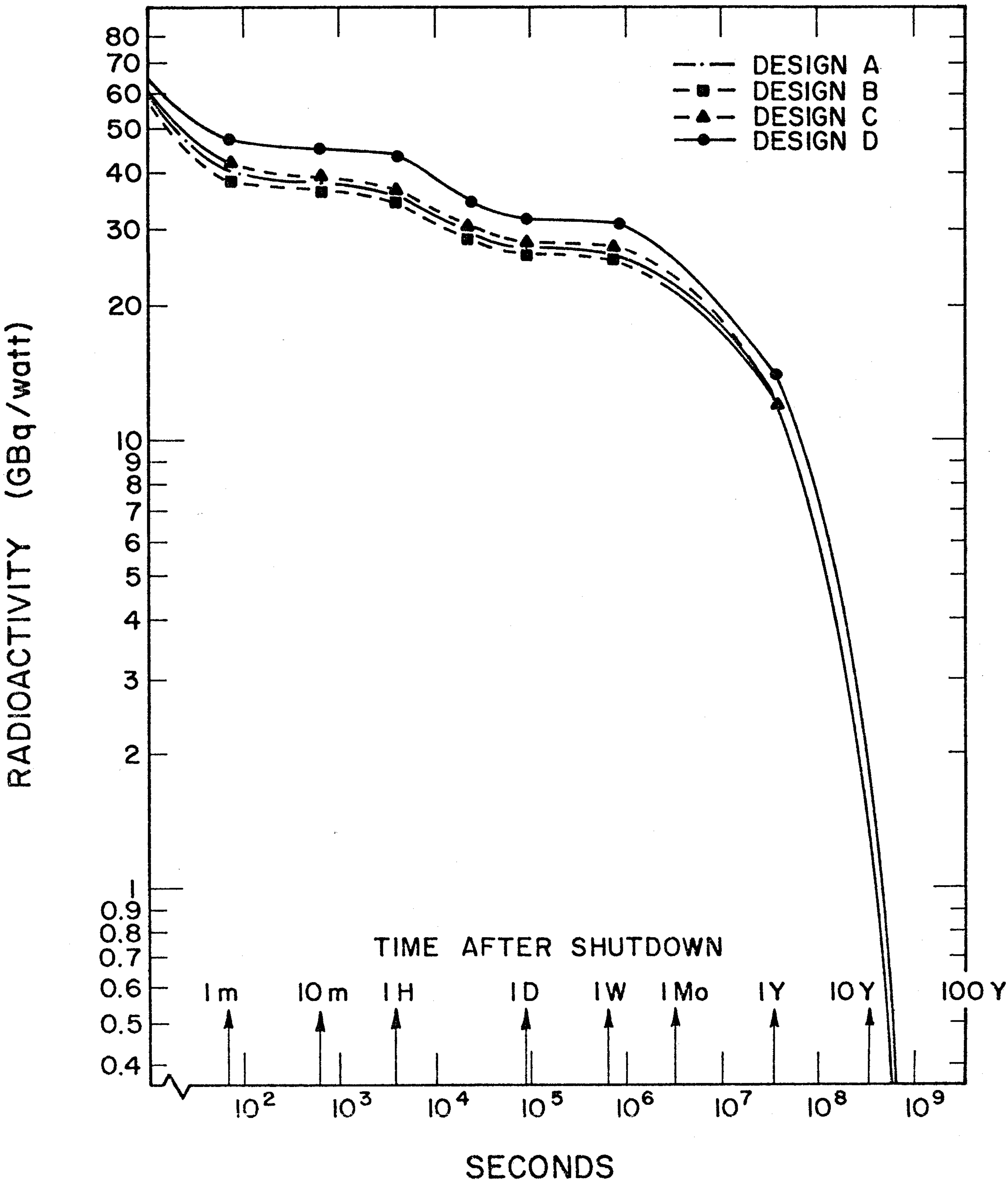

DESIGN A
DESIGN B
DESIGN C
DESIGN D
RADIOACTIVITY (GBq/watt)
80
70
60
50
40
30
20
10
9
8
7
6
5
4
3
2
1
0.9
0.8
0.7
0.6
0.5
0.4
TIME AFTER SHUTDOWN
1m
10m
1H
1D
1W
1Mo
1Y
10Y
100Y
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
SECONDS

Figure 6

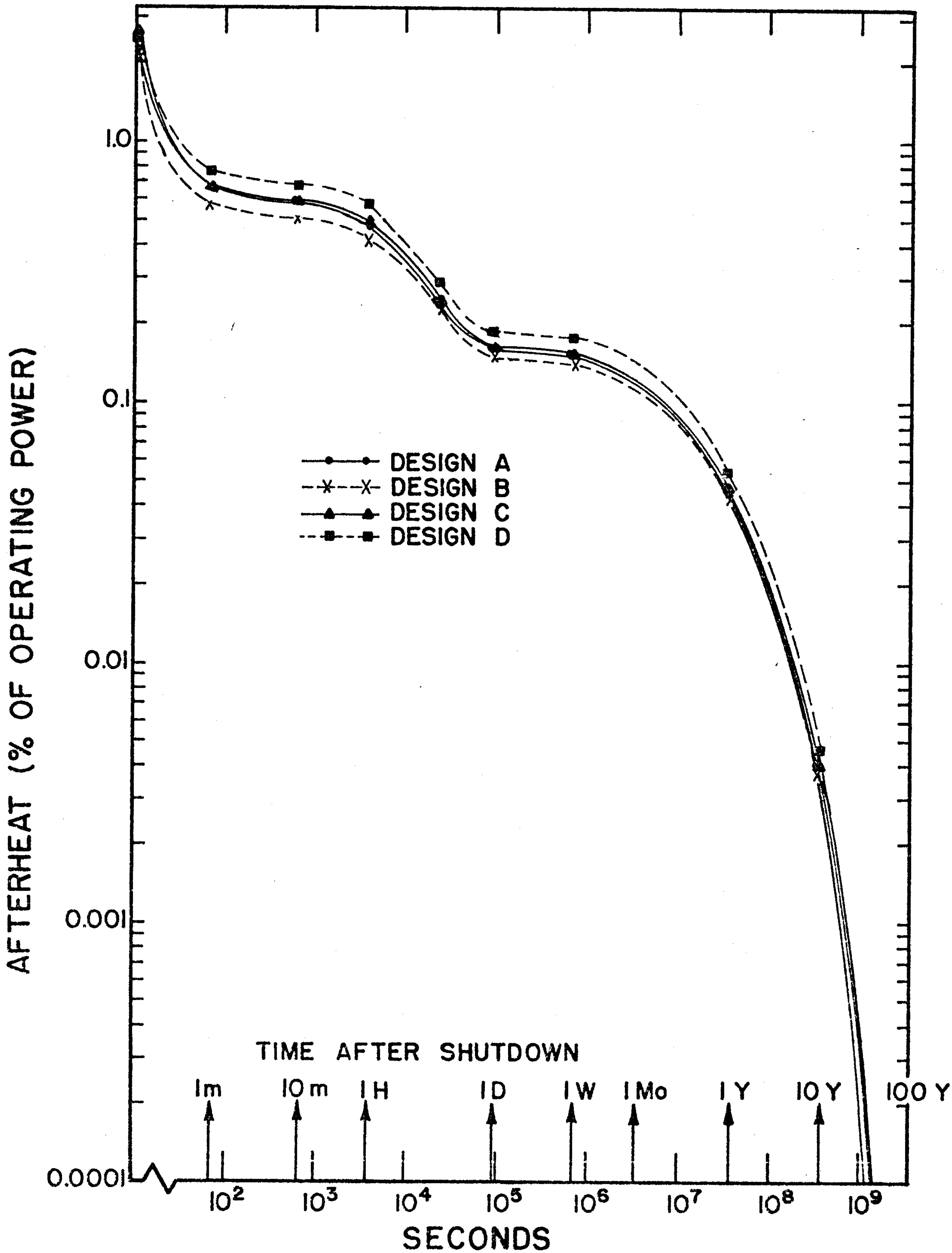

AFTERHEAT (% OF OPERATING POWER)
1.0
0.1
0.01
0.001
0.0001
DESIGN A
DESIGN B
DESIGN C
DESIGN D
TIME AFTER SHUTDOWN
1m
10m
1H
1D
1W
1Mo
1Y
10Y
100Y
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
SECONDS

Figure 7