Comparative One-Dimensional Monte Carlo and Discrete Ordinates Neutronics and Photonics Analysis for a Laser Fusion Reactor Blanket with Li_2O Particles as Coolant and Breeder

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Abstract

Results of an initial neutronics and photonics study for the gravity circulated Li_2O blanket and shield of a laser fusion reactor are discussed. Calculational models for coupled neutron-gamma and neutron-only multigroup Monte Carlo for blanket-shield and blanket only configurations are investigated, and the results are compared with an analogous Discrete Ordinates computation. The capabilities and reliability of the used Monte Carlo code are assessed with regard to the possibility of its future application for two and three-dimensional studies of laser driven fusion reactors. These studies are necessary in the future for the consideration of nonsymmetric effects, penetrations for multiple laser beam ports, shielding of cryogenic fuel-pellet injection and magnetic first wall protection systems, and of beam focusing, diverging, deflection and splitting components.

Monte Carlo results for tritium breeding, neutron and gamma heating, and neutron primary damage effects for a spherical geometry compare satisfactorily with the Discrete Ordinates results, even for small numbers of processed particles. The tritium production per source neutron for 1000 histories is 1.2580 ± 0.0186 as obtained by Monte Carlo, and 1.2534 by Discrete Ordinates. Future studies are recommended to use Monte Carlo for two and three-dimensional realistic models, and one-dimensional discrete ordinates for blanket and shield optimization studies. Coupled pellet-blanket-shield neutronics and photonics studies are also recommended in the future for reliable studies. Monte Carlo may be competitive to discrete ordinates for blanket studies.

1. Introduction

Laser-driven and magnetic plasma-confinement fusion reactor concepts depend on the utilization of the energy of the neutrons generated in the D-T fusion process, which escape from the reaction volume (about 20% of the fusion energy); and the breeding of tritium from these neutrons to replace the consumed fuel. This can be achieved by a breeding blanket that surrounds the reaction volume and acts as an energy dissipation medium for the neutron energy in addition to its breeding function. In previous LCTR's (Laser Controlled Thermonuclear Reactors) studies, circulating liquid lithium was used for cooling and breeding. In our study, the concept of the gravity circulated solid lithium oxide blanket as suggested by Sze et al.[5] and used by Conn et al.[6] for a laser fusion reactor concept is considered.

Structural materials of the fusion reactor blanket system will be damaged by the neutron flux. In LCTR's the cavity can be sized to control the radiation damage. The first walls need not have any particular electrical properties and the cavity need not be highly evacuated. However, because the first wall sustains significant strain under each cycle, its material should possess a high fatigue strength.

Neutronics and photonics studies of LCTR's involve the amount of tritium breeding achieved, the neutron and gamma energy generated and its spacial deposition distribution as an input to the heat transfer calculations, the primary neutron damage effects as an input to the materials and stress analysis calculations, and the neutron and gamma shielding of the reactor components.

Different fusion reactor blanket concepts have been proposed. Among these, the presently analyzed gas-entrained solid lithium oxide concept[5] the liquid lithium-wetted-wall concept[1,2], the magnetically-protected cavity[7], and the BLASCON.[8]

High energy laser beams are necessary for the compression and heating to thermonuclear ignition and burn conditions. The laser beams must be repetitively transported to and accurately focused on a pellet at the center of each reactor cavity. Uniform pellet illumination will require the use of cavities with penetrations for multiple, symmetrically arranged laser beams to ensure efficient pellet compression and burn. As much as 12 laser beams have been suggested in some cases. Cooling ducts will also be present. Radiation streaming and scattering through these ports to the optical system and to the biological shield will be an important shielding consideration. No bending in these ports is possible like in fission reactors ducts and penetrations. One and two dimensional calculations cannot treat that factor, and three-dimensional Monte Carlo calculations will be necessary for adequate neutronics and photonics studies. Time dependence of the occurring phenomena can also be studied by Monte Carlo, as an extra bonus. This will require, however, the processing of a large number of particle histories.

Another problem of a three-dimensional nature is the shielding of cryogenic fuel-pellet injection systems which must be operated in close proximity to relatively hostile cavity radiation environments. This problem is the analogue to the magnets shielding in magnetic confinement fusion reactors. For magnetically protected first walls, the magnets also need to be adequately shielded.

Radiation damage study and shielding of the beam focusing, diverging, and splitting system will also require three-dimensional studies.

So far, only one-dimensional studies have been carried out for laser neutronics and photonics studies. In the future, three-dimensional studies are a necessity. This study is concerned with the comparative assessment of the capabilities of Monte Carlo and discrete ordinates methods for photonics and neutronics studies for LCTR's. A lithium oxide blanket reactor concept is studied. We have chosen the multigroup Monte Carlo Code MØRSE[9] for that study. Coupled neutron-gamma and neutron-only models are considered. The effect of replacing the shield by an albedo surface in approximations used in discrete ordinates calculations is investigated. Monte Carlo results are compared to discrete ordinates results by the ANISN code[10]. This involves tritium breeding, gamma and neutron heating, and neutron primary damage effects including atomic displacements and hydrogen and helium gas production. Computational costs are compared. The same cross-section sets are used for both methods.

Monte Carlo results give a value of tritium production per source neutron of 1.258008 ± 0.018581 (for 1000 histories) and 1.277776 ± 0.056738 (for only 150 histories) compared to a value obtained by discrete ordinates of 1.2534. Total heating in Mev per source neutron is 15.111725 ± 0.177178 (for 1000 histories), and 15.448002 ± 0.700657 (for 150 particle histories) by Monte Carlo and 14.997 by discrete ordinates. Other calculation results also agree satisfactorily.

We conclude by discussing the computational results of the treated models and recommending the future directions of the research.

2. Previous Work on Neutronics and Photonics Studies of Laser Driven Reactors

Discrete ordinates has been used by Frank et al.[2] for laser cavities computations in conjunction with the LASL wetted wall concept. The one-dimensional code DTF-IV was used in these calculations with the P_3S_4 approximation, 100 energy groups cross sections for neutronics calculations, and in the P_3S_4 approximation and 21 energy groups for calculation of secondary γ-Rays distributions.

The basic reactor model is spherical as described in Reference 2. Release of 100 MJ of thermonuclear energy per pellet microexplosion generating $\sim 3.55 \times 10^{19}$ fusion neutrons is assumed. A point source of 14.2 Mev neutrons was included at the center of the calculational model.

A one-dimensional Monte Carlo calculation for the same reactor model has been also reported by Watson[1]. The structure in this calculation was stainless steel. The Los-Alamos code MCH was used in these calculations. The Monte Carlo calculation used the Ritts et al. Kerma factors data[3], whereas the Discrete-Ordinates calculation used the more recent Abdou and Maynard data[4].

3. Computational Models

In the reaction volume of the laser fusion systems, the fusion micro-explosion duration is in the order of tens of picoseconds which is much less than the slowing down time of the neutrons in the blanket medium, i.e., this is a transport problem of time-dependent nature. However, we are here only concerned with the time-integrated quantities such as the tritium breeding ratio, nuclear heating and so on, the transformation of a time-dependent equation into a time-independent form over certain period of time is required. Let

$$\Phi\ (\underline{r},\ E,\ \underline{\Omega}) = \int \phi\ (\underline{r},\ E,\ \underline{\Omega},\ t)\ dt \quad (1)$$

$$S\ (\underline{r},\ E,\ \underline{\Omega}) = \int s\ (\underline{r},\ E,\ \underline{\Omega},\ t)\ dt \quad (2)$$

where $\phi\ (\underline{r},\ E,\ \underline{\Omega},\ t)$ and $s\ (\underline{r},\ E,\ \underline{\Omega},\ t)$ are time-dependent angular flux and source respectively and Φ and S are time integrated angular flux and source, respectively. Performing an integration over a certain interval of time to the time-dependent transport equation itself, we obtain the time-independent form

$$L\ (\underline{r},\ E,\ \underline{\Omega})\ \Phi\ (\underline{r},\ E,\ \underline{\Omega}) = S\ (\underline{r},\ E,\ \underline{\Omega}) \quad (3)$$

The response quantities, $R(\underline{r})$, with which we are concerned can be calculated from the following relation

$$R(\underline{r}) = \int \int \Sigma_R\ (\underline{r},E)\Phi(\underline{r},E,\underline{\Omega})d\underline{\Omega}\ \ dE \quad (4)$$

The neutron source in this investigation is the number of neutrons released in the fusion microexplosions per unit time interval. The total energy released per unit time interval is assumed 3000 MJ, which corresponds to an amount of 1.0639×10^{21} neutrons/sec (17.6 MeV energy is released per fusion reaction).

Computations of time-integrated results were carried out using a source term of 1.06394×10^{21} (source neutrons/sec) to represent a laser event.

We considered four different computational models in our calculations. The geometries are all spheres and the blanket material compositions are shown schematically in Figures 1 to 4 and tabulated in Table 1. They basically treat a gas-entrained solid lithium oxide cooling/breeding blanket reactor concept. The breeding region in all models is 50 cm thick and divided into three zones, followed by a 20 cm thick graphite reflector.

A 1.5 cm thick carbon liner protecting the first wall was considered in the four models. The first wall in Models I and IV consist of three zones (zone 5, 6 and 7) to simulate the tubing used in the mechanical design. In Models II and III that zone was taken as 1.0 cm thick, and of stainless steel.

The characteristics of the different models are summarized in Table 2. Models I to III were treated by Monte Carlo while Model IV is solved by discrete ordinates. In model II we included a B_4C and stainless steel shield of 40 cm thick in the calculation, while in the three other models the shield region was replaced by a 30% albedo surface. Our aim was to test the effect of such an approximation as used in blanket studies by discrete ordinates, when a shield study is not needed during the initial optimization stages of a blanket design study.

In the three Monte Carlo models, a point isotropic source was considered at the origin of the sphere with a source strength of 1.06394×10^{21} neutron/sec, whereas in the discrete ordinates calculation a volumetric source of 0.1 cm radius (as required by the code input) was considered.

Models II and III were neutron-only problems, and 25 neutron groups were used. Models I and IV were coupled neutron-gamma models with 25 neutron groups and 21 gamma groups. The group structure is a collapsed set from a larger interval group set as given in reference 10. The new group set is displayed in Table 3.

Tables 4 and 5 show the used material densities and region volumes.

Models II and III were each run with 10 batches with 50 particles processed per batch. Model I was considered in two cases: case (a) with only 150 particles histories over 3 batches, and case (b) with 1000 particle histories over 10 batches. Both show the astonishingly (unexpected) good results which can be obtained by Monte Carlo for a one-dimensional problem. Case (a) particularly shows how such results can be obtained at a modest expense in computer time. For one-dimensional blanket studies Monte Carlo is competitive to discrete ordinates as displayed in Table 2. Table 6 shows the computation statistics for the treated Monte Carlo cases. A leakage of 0.1363% is obtained when the boron carbide and stainless steel shield is included.

Russian Roulette was used in the Monte Carlo calculation for particles weight reduced to 1/1000 in all neutron and gamma groups and all material regions. Other particles termination parameters were the subject of a subsequent study.

The combinatorial geometry of the MORSE code(7) was used to represent the reactor geometry.

The albedo routine was modified to allow the assumed 30% albedo when necessary.

To reduce the computation cost, region detectors were used rather than point detectors.

The results reported depend on the collision estimator. Unit weights were assigned to the generated secondary particles in all groups.

Discussion of the obtained results follows in the next sections.

Results from the Monte Carlo calculations are quoted as:

$$Z \pm A,$$

where

Z = estimated mean value, and

A = standard deviation associated with Z.

Statistics are based on the batch concept in the Monte Carlo calculations.

The same sets of cross-sections were used for both the discrete ordinates and Monte Carlo calculation as a basis for the comparison of the quantities of interest.

4. Tritium Breeding

Results for the computation of tritium breeding per source neutron is shown in Table 7 for both the lithium-6 and lithium-7 components. All results compare favourably with the discrete ordinates results. Models II and III, it should be remembered, have a slight excess of stainless steel in the first wall, compared to models I and IV. The difference in the final results was negligible, and did not justify repeating the calculations.

Comparison of models II and III reveals the interesting fact that the 30% albedo approximation overestimates the neutron reflection from the shield, since the inclusion of the shield reduces the estimate for tritium breeding. Inclusion of the shield in future studies will provide the right albedo. That inclusion will not affect drastically the computation costs in Monte Carlo, but may increase the cost in discrete ordinates calculations.

Model I computations are shown for both cases (a) and (b) with 150 and 1000 histories respectively. We show the results of case (a) to demonstrate the interesting result that one obtains a value of 1.277776 ± 0.056738 for tritium breeding per source neutron with only 150 histories, compared to 1.2534 as obtained by discrete ordinates. A computation with 1000 histories gives a value of 1.258008 ± 0.018581. This leads to the interesting (unexpected) conclusion that Monte Carlo can be competitive to discrete ordinates in one dimensional calculations for blanket studies, for a given statistical error. Scoping and survey blanket studies appear as an interesting application for Monte Carlo, but three dimensional studies remain our main objective.

That value of the tritium breeding per source is rather high, even if one accounts for losses in the heat transfer cycle and during reprocessing. A high tritium inventory causes problems of safety and storage. The blanket and shield should be optimized to obtain just the needed excess amount of breeding to account for losses in the system. That optimization in the actual reactor depends on the reaction chamber shape, and an overall average must be estimated. Future two and three dimensional studies should consider these factors.

5. Neutron and Gamma Energy Deposition

For the coupled neutron-gamma calculations of Models I and II, results of neutron and gamma heating are displayed in Table 8 in units of (MeV/ source neutron) for the Monte Carlo and discrete ordinates results.

Case (a) (150 histories) gives a total heating of 15.448002 ± 0.700657, and case (b) (1000 histories) gives a total of 15.111725 ± 0.177178 compared to 14.997 by discrete ordinates.

Both the gamma and neutron heating seem to be very slightly overestimated by the Monte Carlo calculations.

The results of Table 8 are converted to volumetric heating rate values in the blanket and reflector regions in units of (Watts/cm^3) and are displayed in Table 9. They are then compared in Figures 5 to 7 to the results obtained by discrete ordinates. These results show how results agree so well between Monte Carlo and discrete ordinates, even for a small number of histories.

About 82% of the heating is contributed by neutrons, and about 90% of the total is deposited in the blanket zone and carried away by the solid lithium oxide solid particles[12].

6. Neutron Primary Damage Effects

Neutron primary damage effects will be severe for the walls surrounding the central cavity. These effects were calculated for the carbon liner and the first stainless steel walls.

The number of atomic displacements per atom, the amounts of hydrogen and helium produced were calculated and displayed in Tables 10 and 11.

Since we are using a collision estimator, and since the regions concerned are optically thin, few collisions happen there and the Monte Carlo statistics have a large standard deviation. One must recourse to a large number of histories to obtain answers with smaller statistical bars. In that case, as shown in the results of case (b) of Model I, compared to the discrete ordinates results, acceptable results are obtained.

Helium production in the carbon liner is $\sim 4 \times 10^{-4}$ appm per second while it is $\sim 3 \times 10^{-4}$ appm per second in the stainless steel first wall. Hydrogen production is $\sim 8 \times 10^{-5}$ appm per second in the stainless steel wall.

The dpa in the carbon liner and in the stainless steel first wall is $\sim 1.5 \times 10^{-6}$ per second.

7. Neutron and Gamma Fluxes

The scalar neutron and gamma fluxes for case (b) of Model I are shown in Table 12 in the carbon liner, stainless steel walls, blanket and shield, for both the track length and the collision estimators. The same result obtained by both estimators for the first blanket region is just a "rare" occurrence according to the laws of probability. In optically thin regions, the track length per unit volume estimator gives better results than the collision estimator. In either case, large numbers of histories are needed for narrower confidence intervals. For that kind of optically thin regions, dicrete ordinates may be superior to Monte Carlo. On the other hand Monte Carlo gives a confidence interval for the result; but an estimate of the error cannot be obtained in discrete ordinates. In any case, the strength of both methods must be used judiciously: Discrete ordinates is better applied for optically thin regions, as well as for shield studies, while Monte Carlo can be very efficient and economical in blanket studies. In three-dimensional, and three-dimensional-time-dependent studies, Monte Carlo is the only possible recourse. For comparison, several arbitrary group fluxes obtained from Model I and Model IV in the carbon liner, breeding zone and reflector are given in Table 13.

8. Conclusions and Recommendations

The neutronics and photonics of a solid blanket with gravitational flowing lithium oxide particles for a laser-driven fusion reactor has been studied. The results obtained from Monte Carlo and discrete ordinates have been compared and conclusions and recommendations are summarized as follows:

1) The reliability of the used models even for small numbers of treated particles as well as the used Monte Carlo code (MORSE) and the possibility for using it for future two and three dimensional studies.

2) The economical (unexpected) competitiveness of Monte Carlo to discrete ordinate for one-dimensional studies in the blanket part of fusion reactors.

3) Monte Carlo studies can provide the right albedo from the shield without detailed solution in the shield itself. Such quantity is now assumed (based on past experience) in discrete ordinates computations which do not include the shield, and may be an over-, or underestimate.

4) The estimate of the statistical error in Monte Carlo may be advantageous for sensitivity studies. Discrete ordinates doesn't provide an error estimate.

Our future research direction is the treatment of more realistic two and three dimensional reactor models by Monte Carlo, while continuing to use discrete ordinates for one-dimensional optimization studies of the blanket and shield. Coupled pellet-blanket-shield neutronics and photonics are necessary for reliable results in future calculations.

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Table 13 Comparison of some group Neutron and Gamma ray fluxes in different regions for the collision and track length estimators.

Table 1

Material Composition in the Neutronics and Photonics Models

Zone No.	Thickness (cm)	Material Composition			
		Model I	Model II	Model III	Model IV
1	0.1	Vacuum	Vacuum	Vacuum	Source
2	499.9	Vacuum	Vacuum	Vacuum	Vacuum
3	1.5	Carbon Liner	Carbon Liner	Carbon Liner	Carbon Liner
4	1.0	Vacuum	Vacuum	Vacuum	Vacuum
5	0.1	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel
6	0.8	30% Stainless Steel	100% Stainless Steel	100% Stainless Steel	30% Stainless Steel
7	0.1	Stainless Steel	Stainless Steel	Stainless Steel	Stainless Steel
8	50	60% Li_2O+2% S.S.	60% Li_2O+2% S.S.	60% Li_2O+2% S.S.	60% Li_2O+2% S.S.
9	20	Graphite	Graphite	Graphite	Graphite
10	40	(30% albedo)	90% B_4C+10% S.S.	(30% albedo)	(30% albedo)

Table 2

Comparison of the Treated Models

	Model I	Model II	Model III	Model IV
Method of Calculation:	Monte Carlo	Monte Carlo	Monte Carlo	Discrete Ordinates
	P_3	P_3	P_3	P_3-S_8
Source:	point	point	point	volume
Number of Histories:	a: 150, b: 1000	500	500	-
Nature of Problem:	coupled n-γ 25+21=46 groups	n-only 25 groups	n-only 25 groups	coupled n-γ 25+21=46 groups
Shield	not included (30% albedo)	included (B_4C+S.S)	not included (30% albedo)	not included (30% albedo)
First Wall	3 regions	1 region	1 region	3 regions
CPU Time	a) 3 min. 32 sec.	3 min. 19 sec.	3 min. 48 sec.	20 min. 1 sec.
CPU Cost+	a) $5.58, b) $31.97	$5.24	$6.00	$31.55
Memory Usage+	a) $3.42, b) $18.72	$1.92	$2.63	$20.76
Total Tritium Breeding	a) 1.277776 ± 0.056738	1.228411 ± 0.025656	1.250948 ± 0.019740	1.2534
For Source Neutron	b) 1.258008 ± 0.018581			

+Normalized to overnight run rates on the UW-UNIVAC-1110. Some runs were executed on weekend rates and would be a factor of 4/7 cheaper.

Table 3

Coupled Neutron-Gamma Group Parameters

Neutron Groups	Upper Edge (ev)	Gamma Groups	Upper Edge (ev)
1	1.4918+07	26	1.4000+07
2	1.3499+07	27	1.2000+07
3	1.2214+07	28	1.0000+07
4	1.1052+07	29	8.0000+06
5	1.0000+07	30	7.5000+06
6	9.0484+06	31	7.0000+06
7	8.1873+06	32	6.5000+06
8	7.4082+06	33	6.0000+06
9	6.7032+06	34	5.7500+06
10	6.0653+06	35	5.0000+06
11	5.4881+06	36	4.5000+06
12	4.4933+06	37	4.0000+06
13	3.6788+06	38	3.5000+06
14	3.0119+06	39	3.0000+06
15	2.4660+06	40	2.5000+06
16	1.3534+06	41	2.0000+06
17	7.4274+05	42	1.5000+06
18	4.0762+05	43	1.0000+06
19	1.6573+05	44	4.0000+05
20	3.1828+04	45	2.0000+05
21	3.3546+03	46	1.0000+05
22	3.5358+02		Lower edge: 1.0000+03
23	3.7267+01		
24	3.9299+00		
25	4.1399-01		
	Lower edge: 2.2000-02		

Table 4

Materials Compositions Used in the Blanket and Shield Models

Medium	Constituents	Number Density atoms/(barn·cm)
Carbon Liner	C	0.80400-01
First Wall (Stainless Steel)	Cr	0.14500-01
	Ni	0.93800-02
	Fe	0.61410-01
Blanket (Li_2O (60%) + S.S. (2%))	Li^6	0.36507-02
	Li^7	0.45549-01
	O	0.24600-01
	Cr	0.29000-03
	Ni	0.18760-03
	Fe	0.12282-02
Shield (B_4C (90%) + S.S. (10%))	C	0.24705-01
	B^{10}	0.19566-01
	B^{11}	0.79254-01
	Cr	0.14500-02
	Ni	0.93800-03
	Fe	0.61410-02

Table 5

Material Regions Volumes

Carbon Liner	4.726540×10^6 cm^3
Stainless Steel Wall	
1	3.173720×10^5 cm^3
2	2.543524×10^6 cm^3
3	3.185097×10^5 cm^3
Blanket	
1	6.627896×10^7 cm^3
2	7.154175×10^7 cm^3
3	3.780726×10^7 cm^3
Reflector	7.939963×10^7 cm^3
Shield	
1	8.557839×10^7 cm^3
2	9.154490×10^7 cm^3

Table 6

Computation Statistics for the Monte Carlo Models

	Model I		Model II	Model III
Nature of Problem	Coupled n-γ		n-only	n-only
	Case a	Case b		
Particles Processed	150	1000	500	500
Particles/Batch	50	100	50	50
Number of Scatterings				
Carbon (Liner & Reflector)	9534	54600	12789	17259
S.S. Wall	2086	6242	3687	3215
Blanket	26746	181852	31982	32996
Shield	-		1344	-
Total	38366	249546	49802	53440
Particles Killed by Russian Roulette	10493	64598	499	500
Total Weight	2.1884	14.895	0.39215	0.40194
Number Escaped	-	-	1	-
Total Weight	-	-	0.68160	-
Leakage	-	-	0.1363%	-

Table 7

Comparison of Tritium Production Per Source Neutron for the Treated Monte-Carlo Models and the Discrete-Ordinates Calculation

$N^{7}_{Li} = 0.045549$ atoms/(b.cm) Case a: 150 histories

$N^{6}_{Li} = 0.0036507$ atoms/(b.cm) Case b: 1000 histories

Zone	Model I (M.C.)	Model II (M.C.)	Model III (M.C.)	Model IV (D.O.)
		Lithium-7 Contribution		
1	a 0.301097±0.037869 b 0.322341±0.006772	0.307715±0.013718	0.304650±0.007564	-
2	a 0.136374±0.032581 b 0.106612±0.006419	0.086918±0.008886	0.105665±0.008757	-
3	a 0.036428±0.007092 b 0.018789±0.002443	0.017872±0.004207	0.021131±0.003402	-
Subtotal	a 0.473899±0.050457 b 0.447742±0.009645	0.412505±0.016877	0.431446±0.012061	0.4430
		Lithium-6 Contribution		
1	a 0.423445±0.018246 b 0.403001±0.011675	0.421838±0.015945	0.407053±0.011809	-
2	a 0.235452±0.003581 b 0.286153±0.008430	0.271101±0.008805	0.280407±0.005720	-
3	a 0.144980±0.018098 b 0.121112±0.006699	0.122967±0.006452	0.132042±0.008488	-
Subtotal	a 0.803877±0.025948 b 0.810266±0.015882	0.815906±0.019324	0.819502±0.015627	0.8104
Total	a 1.277776±0.056738 b 1.258008±0.018581	1.22841±0.025656	1.250948±0.019740	1.2534

Table 8

Comparison of Nuclear Energy Deposition in Monte Carlo and Discrete Ordinates Coupled Neutron-Gamma Model, (Mev/Source Neutron)

Region		Neutron Heating (M.C.)	(D.O.)	Gamma Heating (M.C.)	(D.O.)	Total Heating (M.C.)	(D.O.)
Carbon Liner	a	0.659730±0.079484	0.592	0.144770±0.010974	0.133	0.804500±0.080238	0.725
	b	0.581020±0.033554		0.124560±0.012541		0.705580±0.035821	
First Wall							
S.S.	a	0.024861±0.012822	0.038	0.034019±0.004894	0.055	0.058880±0.013724	0.093
	b	0.035063±0.006109		0.058186±0.007932		0.093249±0.010012	
S.S. + Vacuum	a	0.110265±0.019716	0.088	0.102267±0.019225	0.131	0.212532±0.027538	0.219
	b	0.109743±0.014188		0.130629±0.011488		0.240372±0.018256	
S.S.	a	0.047628±0.022643	0.042	0.037372±0.013561	0.055	0.085000±0.026393	0.097
	b	0.040834±0.006027		0.065160±0.007899		0.105994±0.000099	
Subtotal	a	0.182754±0.032647	0.168	0.173658±0.024030	0.241	0.356412±0.040537	0.309
	b	0.185640±0.016581		0.253975±0.016040		0.439615±0.023070	
Blanket							
1	a	7.100800±0.474191	-	1.237300±0.250293	-	8.338100±0.536194	-
	b	7.255100±0.109189		1.291000±0.040899		8.546100±0.116594	
2	a	3.288000±0.407087	-	0.721980±0.089042	-	4.009980±0.416711	-
	b	3.169400±0.118282		0.664070±0.017292		3.833470±0.119539	
3	a	1.193600±0.120422	-	0.180440±0.034208	-	1.374040±0.125186	-
	b	0.917930±0.024858		0.194280±0.017036		1.112210±0.030135	
Subtotal	a	11.582400±0.636460	11.286	2.139720±0.267853	2.113	13.722120±0.690524	13.399
	b	11.342430±0.162883		2.149350±0.047560		13.491780±6.169684	
Reflector	a	0.249390±0.025463	0.234	0.315580±0.073262	0.230	0.564970±0.077561	0.464
	b	0.242950±0.025208		0.231800±0.012188		0.474750±0.028000	
Total	a	12.674274±0.642792	12.280	2.773728±0.278945	2.717	15.448002±0.700657	14.997
	b	12.352040±0.169018		2.759685±0.053151		15.111725±0.177178	

Table 9

Volumetric Heating Rates[+] in Breeding and Reflecting Regions
Monte Carlo Results, Model I, Cases a and b

Region		Neutron Heating	Gamma Heating	Total Heating
Blanket				
7	a	18.261580±1.219507	3.182040±0.643690	21.443620±1.378960
	b	18.658400±0.280809	3.320146±0.105182	21.978546±0.199862
8	a	7.833918±0.969917	1.720170±0.212150	9.554090±0.992350
	b	7.551343±0.281816	1.582199±0.041200	9.133542±0.284812
9	a	5.381339±0.542922	0.813510±0.154230	6.194850±0.50440
	b	4.138482±0.12070	0.875910±0.076809	5.014392±0.135865
Reflector	a	0.535386±0.054664	0.677482±0.051353	1.212868±0.075002
	b	0.521561±0.014124	0.497624±0.026165	1.019185±0.029734

[+]Units of Watts/cm^3

$$(\text{Mev/Source Neutron}) \equiv \frac{1.704538\times10^8}{V} \left(\frac{\text{Watts}}{cm^3}\right)$$

where $V \equiv$ volume of region in cm^3

Table 10

Comparison of Gas Production Values+ for the Monte Carlo and the Discrete Ordinates Calculations in Carbon Liner and Stainless Steel First Wall

A. Carbon Liner

		Model I	Model IV
Helium Production	Case a	(3.608259-04)±(0.551775-04)	3.83-04
	Case b	(3.124770-04)±(0.242670-04)	

B. Stainless Steel

		Model I	Model IV
Helium Production	Case a	(1.818742-05)±(1.070257-05)	2.92-05
	Case b	(2.691666-05)±(0.515749-05)	
Hydrogen Production	Case a	(5.966535-05)±(3.251225-05)	8.42-05
	Case b	(7.846504-05)±(1.406093-05)	

+In units of appm per laser fusion event per second. Gas production in appm = $\frac{nR}{V \cdot N} \times 10^6$,
where: N = nuclide number density (atms/cm^3)
n = 1.06394×10^{21} source neutrons/second
R = region integrated response/source neutron
V = region volume

Table 11

Comparison of Atomic Displacement Values for the Monte Carlo and Discrete Ordinates Models in Carbon Liner and Stainless Steel First Wall

a. Carbon Liner[+]

Model I	Model II	Model III	Model IV
a (1.787920-06)±(0.130107-06) b (1.563673-06)±(0.06253-06)	(1.439959-06)±(0.180211-06)	(1.371776-06)±(0.178743-06)	(1.56-06)

b. Stainless Steel Walls

Model I	Model II	Model III	Model IV
a (1.221862-06)±(0.863991-06) b (1.505772-06)±(0.501919-06)	(1.48880-06)±(0.496235-06)	(1.45600-06)±(0.485326-06)	(1.56-06)

[+]In units of dpa per laser fusion event per second. A laser event is considered to release a power of $3x10^3$ MW, equivalent to: $3x10^3 \text{ MW} \times 10^6 \text{ W} \times \frac{1}{1.6021x10^{-13}} \frac{\text{Mev}}{\text{sec}} \times \frac{1}{17.6 \text{ Mev}} = 1.06394x10^{21}$ source neutrons/sec.

Table 12

Scalar Neutron and Gamma Fluxes⁺ in Different Regions for the Collision (C) and Track Length (TR) Estimators

	Neutron Flux		Gamma Flux	
	C	TR	C	TR
Carbon Liner	2.235685+15	2.259995+15	7.070363+14	7.209925+14
Stainless Steel Wall				
1	2.188075+15	2.197126+15	7.914883+14	7.304757+14
2	2.299779+15	2.137899+15	7.307591+14	7.788628+14
3	2.326233+15	2.145519+15	8.163862+14	7.889952+14
Blanket				
1	1.632535+15	1.632535+15	6.083880+14	6.122406+14
2	8.499117+14	8.536296+14	3.085856+14	3.124521+14
3	4.733342+14	4.657361+14	1.662298+14	1.620931+14
Reflector	2.322187+14	2.320847+14	7.655312+14	7.719631+14

⁺In units of particles/(cm^2.sec).
Normalized to a source strength of 1.06394×10^{21} $(\frac{\text{source neutron}}{\text{sec}})$.

Table 13

Comparison of Some Group Neutron and Gamma-Ray Fluxes in Different Regions for the Collision and Track Length Estimators

(in units of particles/cm^2-sec-eV per unit D-T neutron)

Region: Carbon Liner

Group No.	Monte Carlo Collision	Monte Carlo Track Length	Discrete Ordinates P_3S_8
1	1.034 (-6)	1.028 (-6)	1.075 (-6)
2	1.887 (-8)	4.607 (-8)	4.442 (-8)
6	8.391 (-8)	1.121 (-7)	1.136 (-7)
11	1.042 (-7)	1.636 (-7)	1.127 (-7)
16	1.259 (-6)	1.362 (-6)	1.076 (-6)
21	2.807 (-4)	2.773 (-4)	2.531 (-4)
24	8.190 (-5)	3.254 (-5)	1.192 (-4)
26	3.166 (-9)	6.629 (-9)	6.329 (-9)
27	1.051 (-8)	1.169 (-8)	1.249 (-8)
31	2.708 (-8)	3.362 (-8)	5.155 (-8)
36	8.763 (-8)	2.129 (-7)	1.295 (-7)

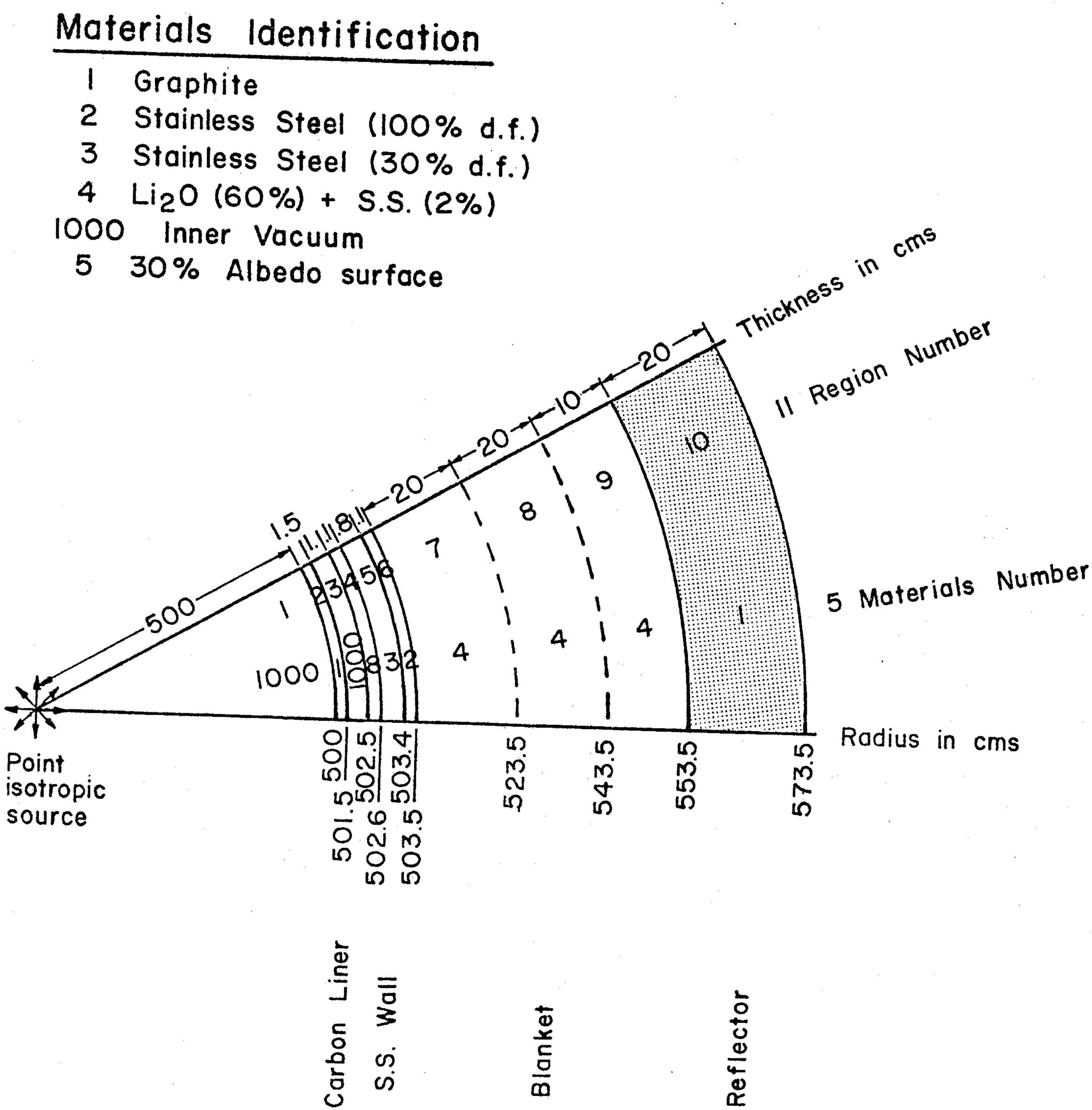
Region: Li_2O Cooling/Breeding Zone

Group No.	Monte Carlo Collision	Monte Carlo Track Length	Discrete Ordinates P_3S_8
1	7.639 (-6)	7.396 (-6)	7.634 (-6)
2	2.734 (-6)	2.533 (-6)	2.874 (-6)
6	1.494 (-6)	2.226 (-6)	1.470 (-6)
11	2.059 (-6)	1.923 (-6)	1.975 (-6)
16	1.789 (-5)	2.626 (-5)	1.838 (-5)
21	5.199 (-3)	5.251 (-3)	5.150 (-3)
24	2.138 (-3)	1.496 (-3)	1.694 (-3)
26	1.566 (-7)	1.579 (-7)	1.534 (-3)
27	3.011 (-7)	3.321 (-7)	3.296 (-7)
31	1.202 (-6)	1.358 (-6)	1.280 (-6)
36	2.145 (-6)	2.916 (-6)	2.848 (-6)

Region: Graphite Reflector

Group No.	Monte Carlo Collision	Monte Carlo Track Length	Discrete Ordinates P_3S_8
1	7.618 (-8)	7.143 (-8)	9.265 (-8)
2	8.411 (-8)	6.220 (-8)	1.027 (-7)
6	6.043 (-8)	8.261 (-8)	7.284 (-8)
11	1.120 (-7)	1.769 (-7)	1.247 (-7)
16	1.163 (-6)	1.149 (-6)	9.305 (-7)
21	1.107 (-3)	1.087 (-3)	1.294 (-3)
24	7.966 (-2)	7.312 (-2)	8.101 (-2)
26	6.332 (-9)	1.159 (-8)	1.428 (-8)
27	4.847 (-8)	4.338 (-8)	3.181 (-8)
31	1.090 (-7)	7.100 (-8)	1.047 (-7)
36	2.207 (-7)	1.983 (-7)	2.100 (-7)

Figure 1


Materials Identification
1 Graphite
2 Stainless Steel (100% d.f.)
3 Stainless Steel (30% d.f.)
4 Li2O (60%) + S.S. (2%)
1000 Inner Vacuum
5 30% Albedo surface
Thickness in cms
11 Region Number
5 Materials Number
Radius in cms
500
1.5
.8
20
20
10
20
1
2
3
4
5
6
7
8
9
10
1000
1000
1
8
3
2
4
4
4
1
500
501.5
502.5
502.6
503.4
503.5
523.5
543.5
553.5
573.5
Point isotropic source
Carbon Liner
S.S. Wall
Blanket
Reflector

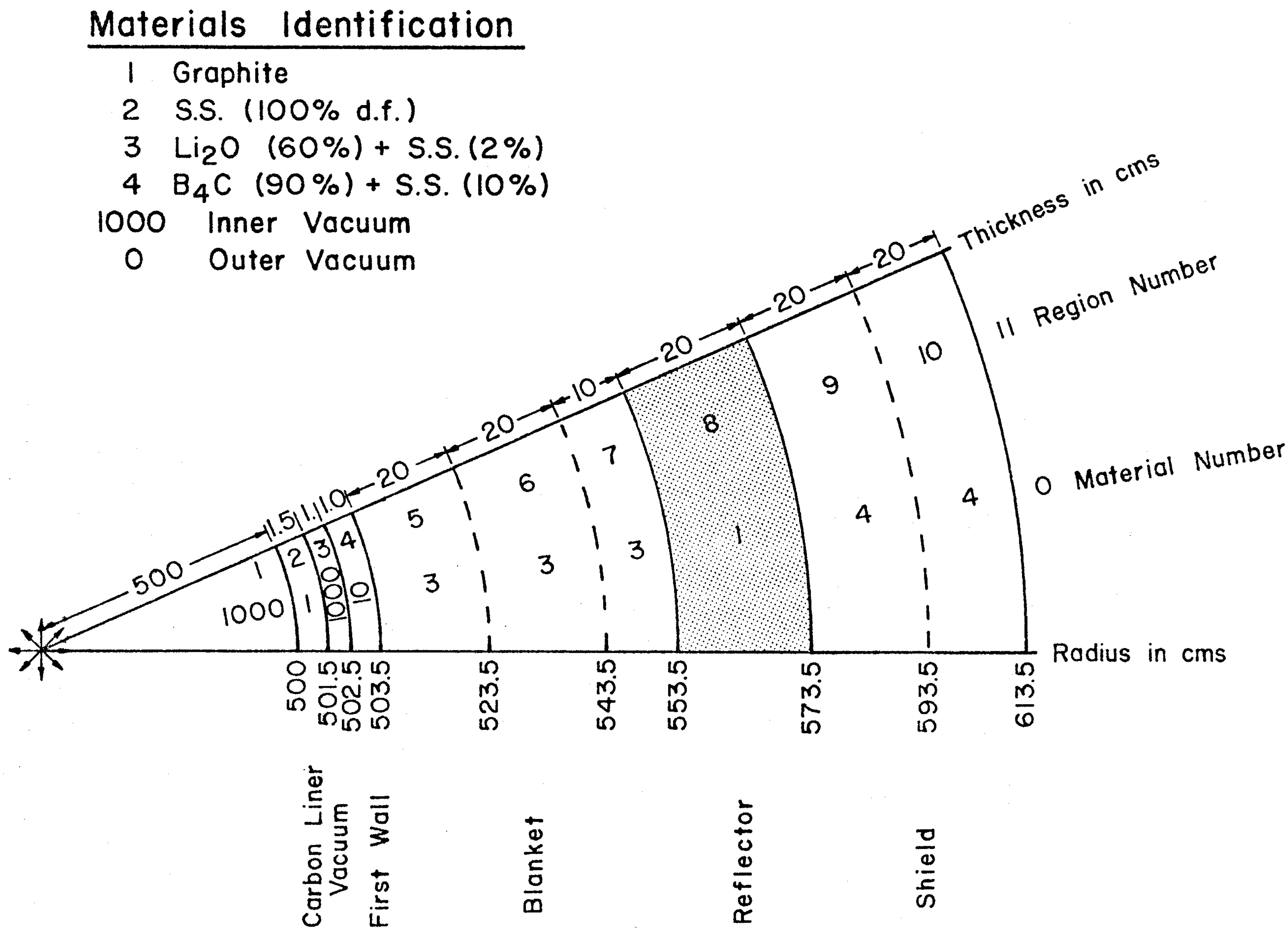

Materials Identification
1 Graphite
2 S.S. (100% d.f.)
3 Li2O (60%) + S.S. (2%)
4 B4C (90%) + S.S. (10%)
1000 Inner Vacuum
0 Outer Vacuum
Thickness in cms
11 Region Number
0 Material Number
Radius in cms
500
1.5
1.1
1.0
20
20
10
20
20
20
1 1000
2 1
3 1000
4 10
5 3
6 3
7 3
8 1
9 4
10 4
500
501.5
502.5
503.5
523.5
543.5
553.5
573.5
593.5
613.5
Carbon Liner
Vacuum
First Wall
Blanket
Reflector
Shield

Figure 2

Materials Identification

1	Graphite
2	Stainless Steel (100% d.f.)
3	Li_2O(60%) + S.S. (2%)
1000	Inner Vacuum
4	30% Albedo surface

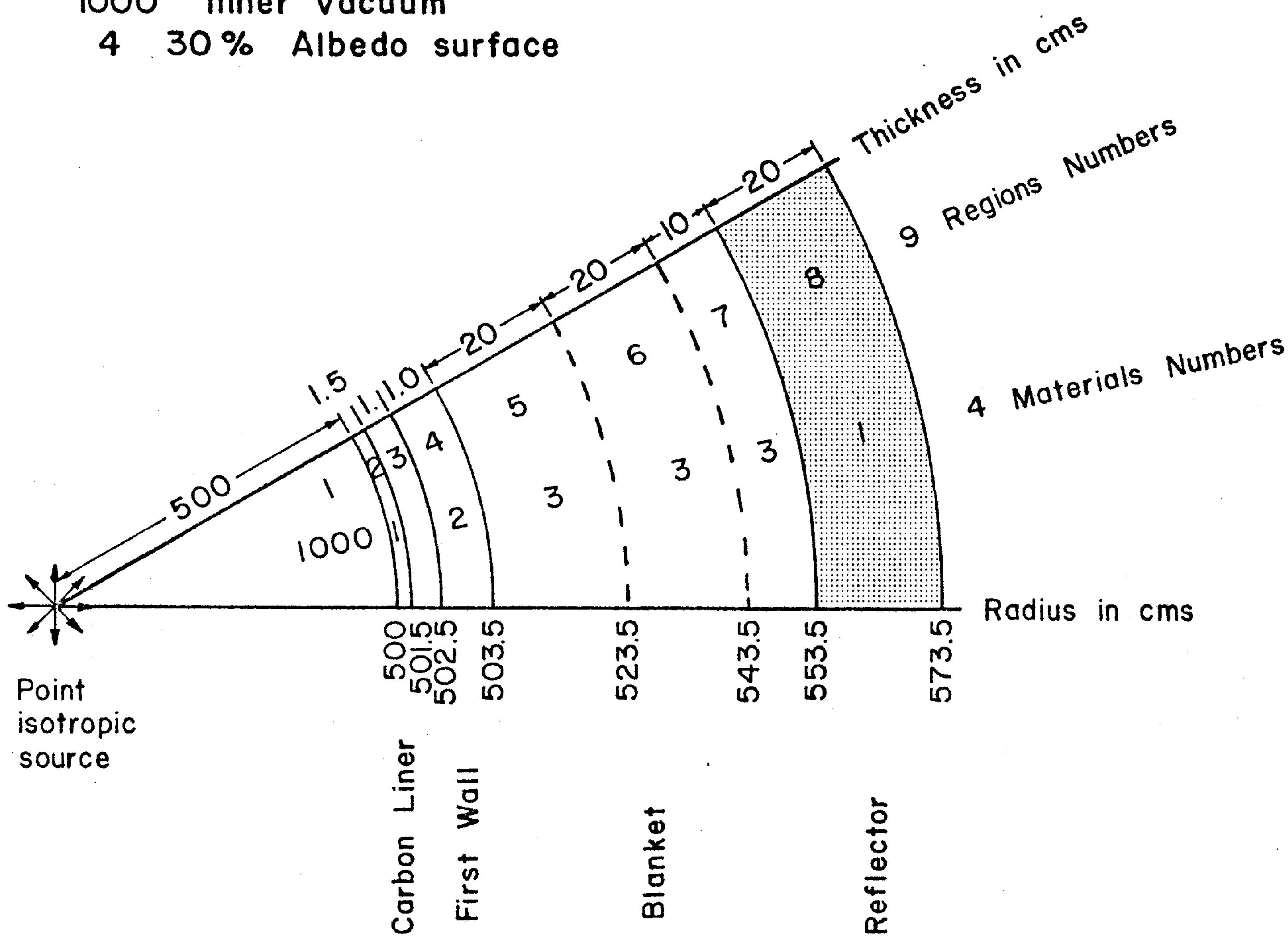
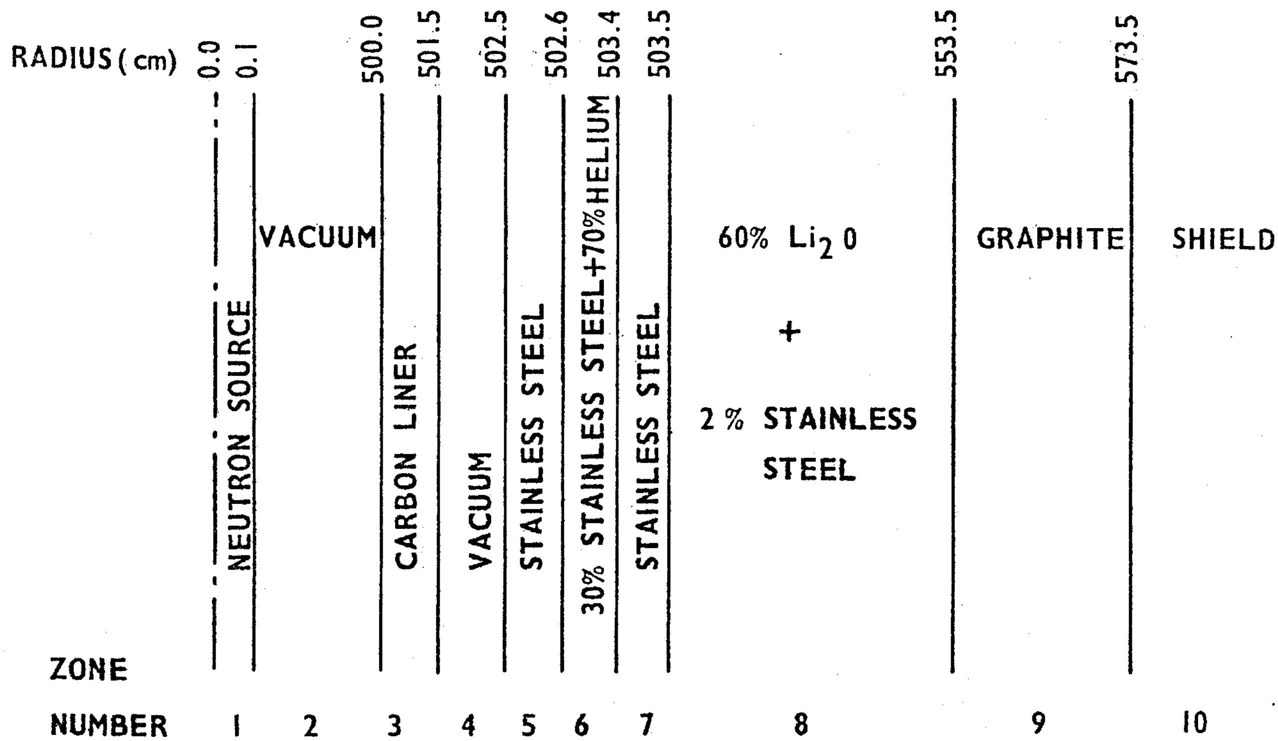


Figure 3



ONE – DIMENSIONAL SCHEMATIC OF THE Li_2O BLANKET

Figure 4

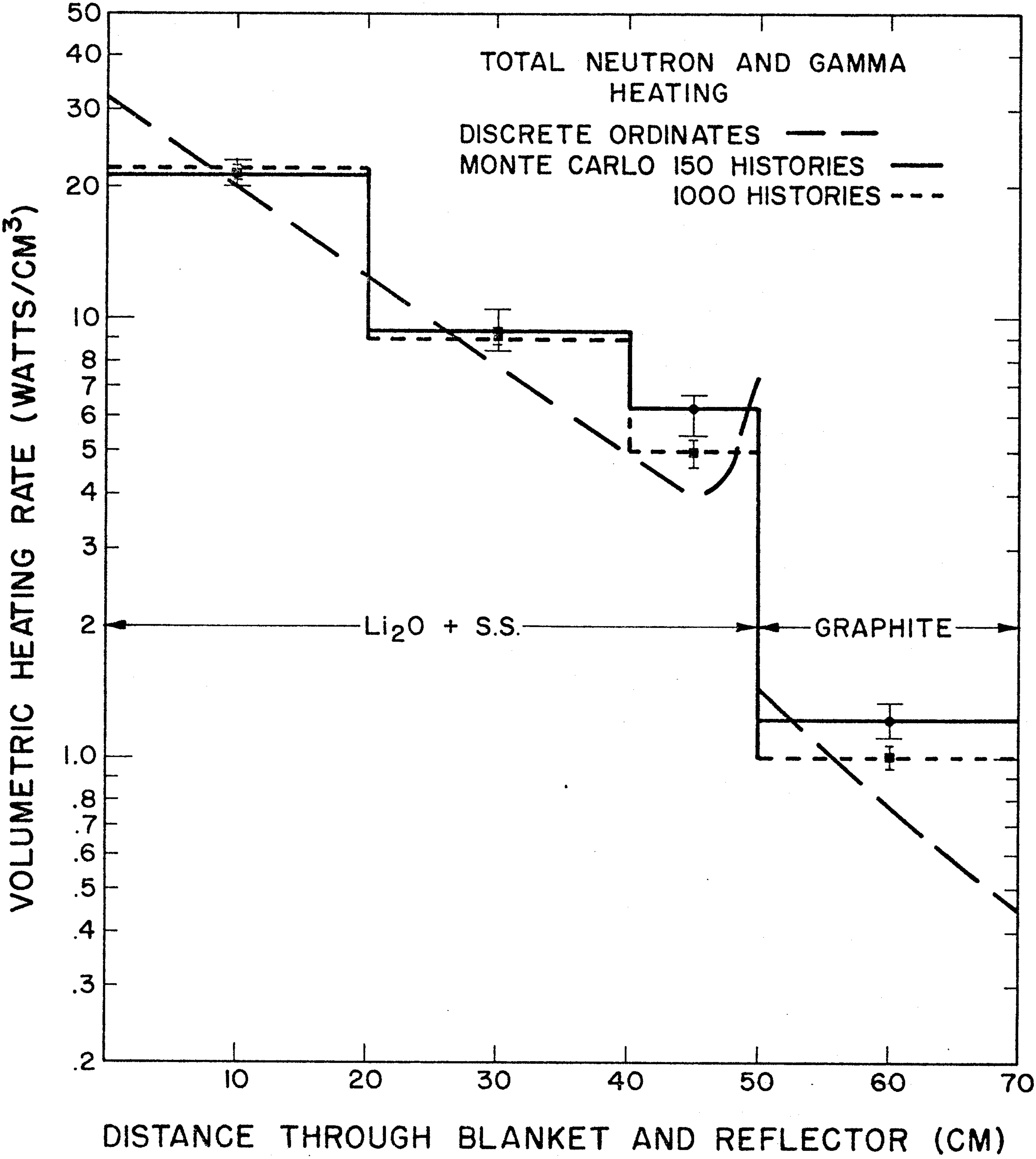

TOTAL NEUTRON AND GAMMA HEATING
DISCRETE ORDINATES
MONTE CARLO 150 HISTORIES
1000 HISTORIES
VOLUMETRIC HEATING RATE (WATTS/CM^3)
50
40
30
20
10
8
7
6
5
4
3
2
1.0
.8
.7
.6
.5
.4
.3
.2
Li_2O + S.S.
GRAPHITE
10
20
30
40
50
60
70
DISTANCE THROUGH BLANKET AND REFLECTOR (CM)

Figure 5

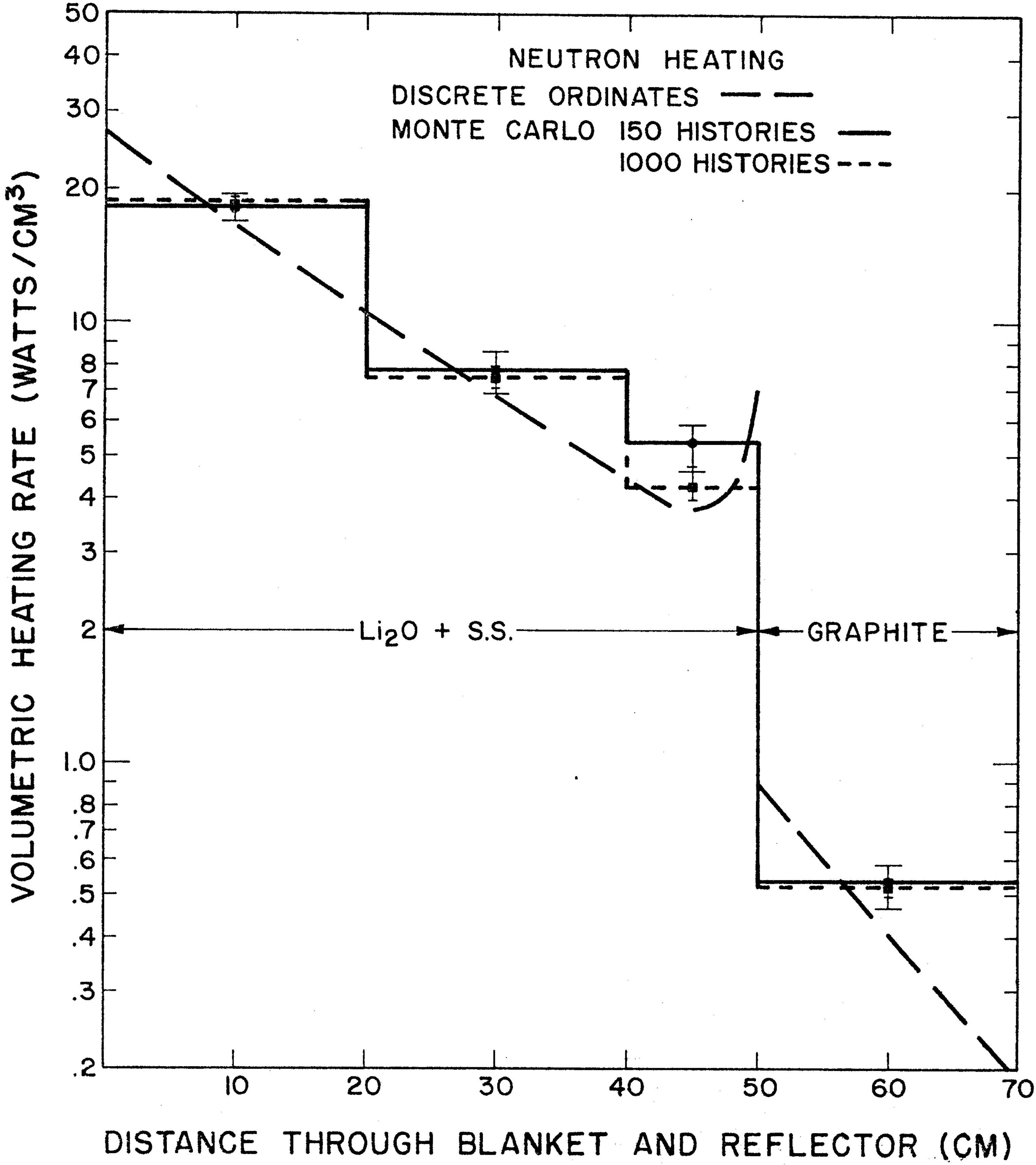

NEUTRON HEATING
DISCRETE ORDINATES
MONTE CARLO 150 HISTORIES
1000 HISTORIES
Li2O + S.S.
GRAPHITE
VOLUMETRIC HEATING RATE (WATTS/CM3)
DISTANCE THROUGH BLANKET AND REFLECTOR (CM)
50
40
30
20
10
8
7
6
5
4
3
2
1.0
.8
.7
.6
.5
.4
.3
.2
10
20
30
40
50
60
70

Figure 6

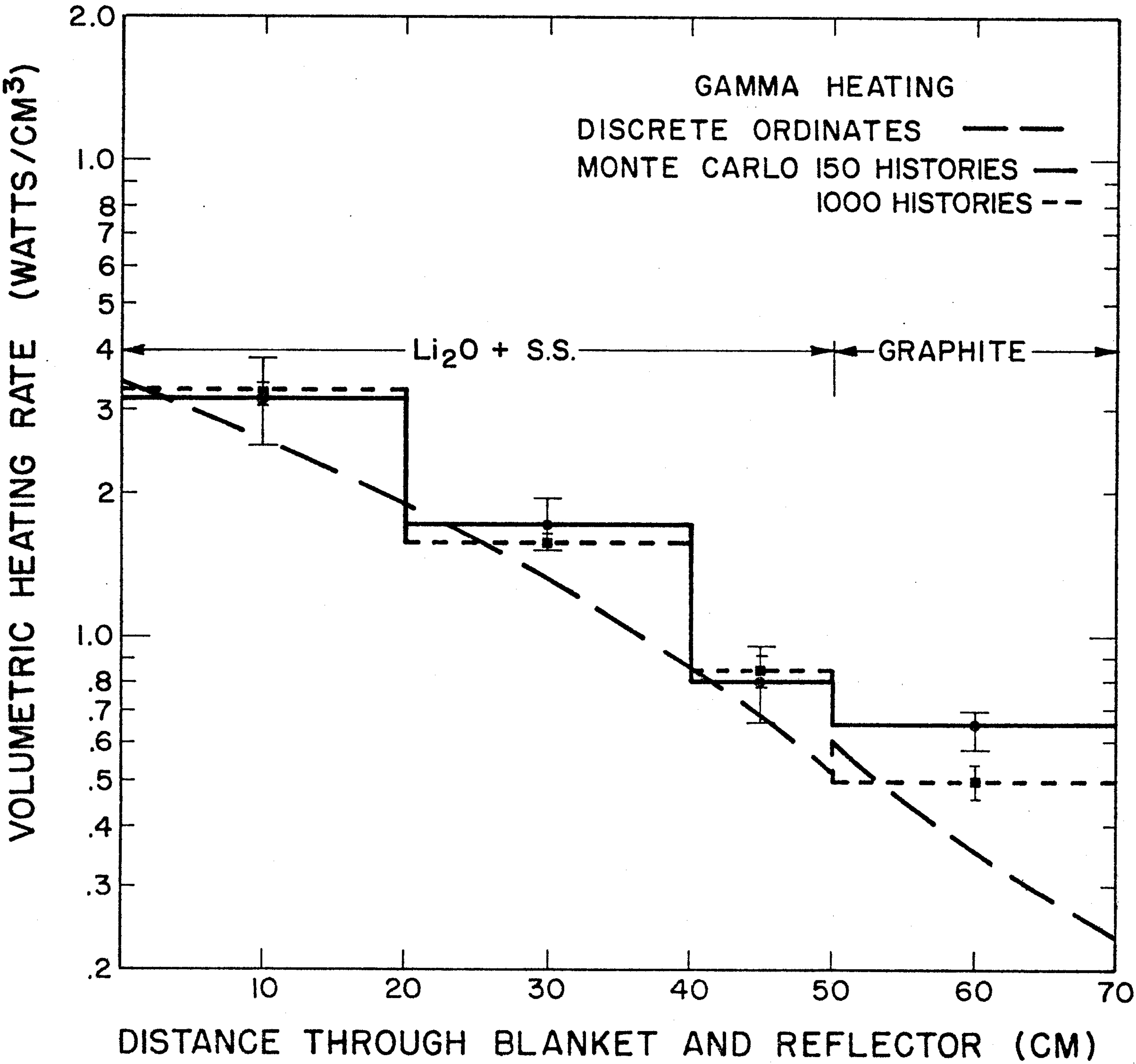

GAMMA HEATING
DISCRETE ORDINATES
MONTE CARLO 150 HISTORIES
1000 HISTORIES
Li2O + S.S.
GRAPHITE
VOLUMETRIC HEATING RATE (WATTS/CM3)
DISTANCE THROUGH BLANKET AND REFLECTOR (CM)
2.0
1.0
8
7
6
5
4
3
2
1.0
.8
.7
.6
.5
.4
.3
.2
10
20
30
40
50
60
70

Figure 7