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ABSTRACT

Tritium breeding calculations for a $Li_{17}Pb_{83}$ benchmark problem that employs steel as structure are presented. Large deviations between the results of continuous energy Monte Carlo and multigroup discrete ordinates are observed when different multigroup libraries are used. Effects of group structure and weighting spectra are explored by collapsing the LANL 80-group library into different broad group structures using different weighting spectra. For a system with natural lithium lead many groups with fine structure in the iron resonance region are required for accurate tritium breeding determination. Fewer broad groups can be used only if an appropriate weighting spectrum representing the spectrum in the $Li_{17}Pb_{83}$ system is used to generate the data. For systems highly enriched in ^{6}Li these effects are less pronounced with fewer groups being adequate.

I. INTRODUCTION

Fusion reactors are required to have a tritium breeding ratio that exceeds unity by a margin that allows for tritium losses and radioactive decay and supplying fuel for startup of other fusion reactors (1). In general, fusion reactor blankets are designed to produce tritium breeding ratios of at least 1.1. This is a difficult requirement to achieve with some breeding materials, especially when various blanket penetrations are taken into account or a nonbreeding inboard blanket is used in a tokamak reactor. On the other hand, larger breeding ratios are not desirable because of the negative impact on blanket energy multiplication. Hence, a breeding ratio in the narrow margin 1.1 - 1.2 is usually required in a fusion reactor. Accurate calculation of tritium breeding is, therefore, of prime importance in a fusion reactor design. It was suggested in the International Working Sessions on Fusion Reactor Technology held in 1971 (2) that a standard blanket model be analyzed by different groups using 100-energy group cross section data based on the same ENDF/B-III evaluation. A natural liquid lithium blanket that utilizes niobium as structural material in which the nuclide number density ratio of ^{6}Li, ^{7}Li, and Nb is 1:12.5:1 was proposed. Excellent agreement between the tritium breeding results of Monte Carlo and discrete ordinates codes was obtained (3).

We have performed calculations for this standard blanket using the continuous energy Monte Carlo code MCNP (4) and the discrete ordinates codes ONEDANT (5) and ANISN (6). While MCNP uses continuous energy cross section libraries processed by NJOY (7), the multigroup discrete ordinates codes utilized 25-, 30-, 46-, and 80- group cross section libraries obtained using different processing codes and weighting spectra. The results given in Table

I agree very well. The MCNP results based on ENDF/B-IV and ENDF/B-V were considered as references. This implies that fewer than 100 energy groups can be used with discrete ordinates codes to determine the tritium breeding ratio in such blankets.

Recently, fusion blankets utilizing the liquid metal eutectic $Li_{17}Pb_{83}$ as the breeding material and steel for structure have drawn more attention (11). $Li_{17}Pb_{83}$ is used because of its large tritium breeding capability and low tritium solubility. Stainless steels replace refractory metals in recent reactor designs primarily due to cost and data base availability considerations. Such blankets have large atom fractions of lead and iron. For example, in WITAMIR (12), a tandem mirror fusion reactor design, the nuclide number density ratio of ^{6}Li, ^{7}Li, Pb, and Fe is 1:12.5:65:16. Because of the large lead atom fraction a much softer neutron energy spectrum is obtained.

Large differences in the calculated tritium breeding ratio for WITAMIR were obtained using different codes with cross section data generated by different processing codes. Table II gives a summary of these results. Deviations up to 20% were observed. However, the different discrete ordinates codes gave similar results when the same multigroup cross section data were used. The differences are, therefore, related to using different group structures, weighting spectra and processing codes to generate the multigroup data. Recently, Pelloni (13) observed discrepancies in the calculated tritium breeding ratio for the European Community International Tokamak Reactor (INTOR-EC). The blanket utilizes $Li_{17}Pb_{83}$ as breeder, water as coolant, and type 316 stainless steel as structure. Discrepancies due to the use of different cross section libraries reached ~ 20%. These discrepancies prompted us to set a benchmark problem for a $Li_{17}Pb_{83}$ blanket system with steel structure. Since

Table I. Tritium Breeding Results for the Lithium-Niobium Standard Blanket

Method	Transport Code	Processing Code	Source of Data	Number of Energy Groups	$^6Li(n, \alpha)t$	$^7Li(n,n'a)t$	Tritium Breeding Ratio
Monte Carlo	MCNP	NJOY	ENDF/B-IV	Continuous Energy	0.974 ± 0.014	0.590 ± 0.009	1.56 ± 0.017
P_3S_4	ANISN	MINX (8) - AMPX (9)	ENDF/B-IV	46	0.969	0.575	1.544
P_3S_4	ONEDANT	NJOY - TRANSX (10)	ENDF/B-IV	30	0.976	0.553	1.529
P_3S_4	ANISN	MINX - AMPX	ENDF/B-IV	25	0.934	0.573	1.507
Monte Carlo	MCNP	NJOY	ENDF/B-V	Continuous Energy	0.961 ± 0.013	0.572 ± 0.009	1.533 ± 0.016
P_3S_4	ONEDANT	NJOY - TRANSX	ENDF/B-V	80	0.955	0.560	1.516

Table II Calculated Tritium Breeding Ratio for WITAMIR

Method	Transport Code	Number of Energy Groups	Source of Data	Tritium Breeding
Monte Carlo	MCNP	Continuous Energy	ENDF/B-IV	0.986 ± 0.008
P_3S_8	ANISN	25	ENDF/B-IV	1.068
P_3S_8	ONEDANT	30	ENDF/B-IV	0.872
Monte Carlo	TARTNP	175	ENDL	0.923 ± 0.009[a]
Monte Carlo	MCNP	Continuous Energy	ENDF/B-V	0.964 ± 0.008
P_3S_8	ONEDANT	30	ENDF/B-V	0.856

[a] This calculation was performed by S. Mortenson at TRW.

the discrepancies are also related to the existence of large atom fractions of lead and iron. A series of calculations on pure lead and iron blankets has also been performed.

II. DESCRIPTION OF THE BENCHMARK PROBLEM

A schematic of the model used in the $Li_{17}Pb_{83}$ benchmark calculations is given in Fig. 1. The blanket is modeled in cylindrical geometry and surrounded by a 0.5 cm thick first wall and a 30 cm thick metallic reflector. The number of intervals in the different zones which we used in the discrete ordinates calculations is indicated. In order to investigate the impact of different design parameters on the accuracy of the calculated tritium breeding ratio, three different blanket thicknesses (60, 80, and 100 cm) and two lithium enrichments (7.42 and 90% ^6Li) were considered. Table III gives the nuclide number densities for the materials used in the benchmark problem. All number densities are given for the natural lithium case with the numbers in parentheses corresponding to the 90% ^6Li case. The P_3S_8 approximation was used in the discrete ordinates computations. The angular quadrature set used in the calculations is given in Table IV. These values correspond to the builtin P_N quadrature set in ONEDANT. The information in Fig. 1 and Tables III and IV enables other researchers to duplicate the calculational model used in the analysis so that the only variable will be the cross section data libaray used.

III. CALCULATIONS AND DISCUSSION OF THE RESULTS OBTAINED USING AVAILABLE CROSS SECTION DATA LIBRARIES

Calculations for the benchmark problem have been performed using the different available cross section data libraries. A comparison between the tritium breeding ratio results obtained using data based on ENDF/B-IV is given

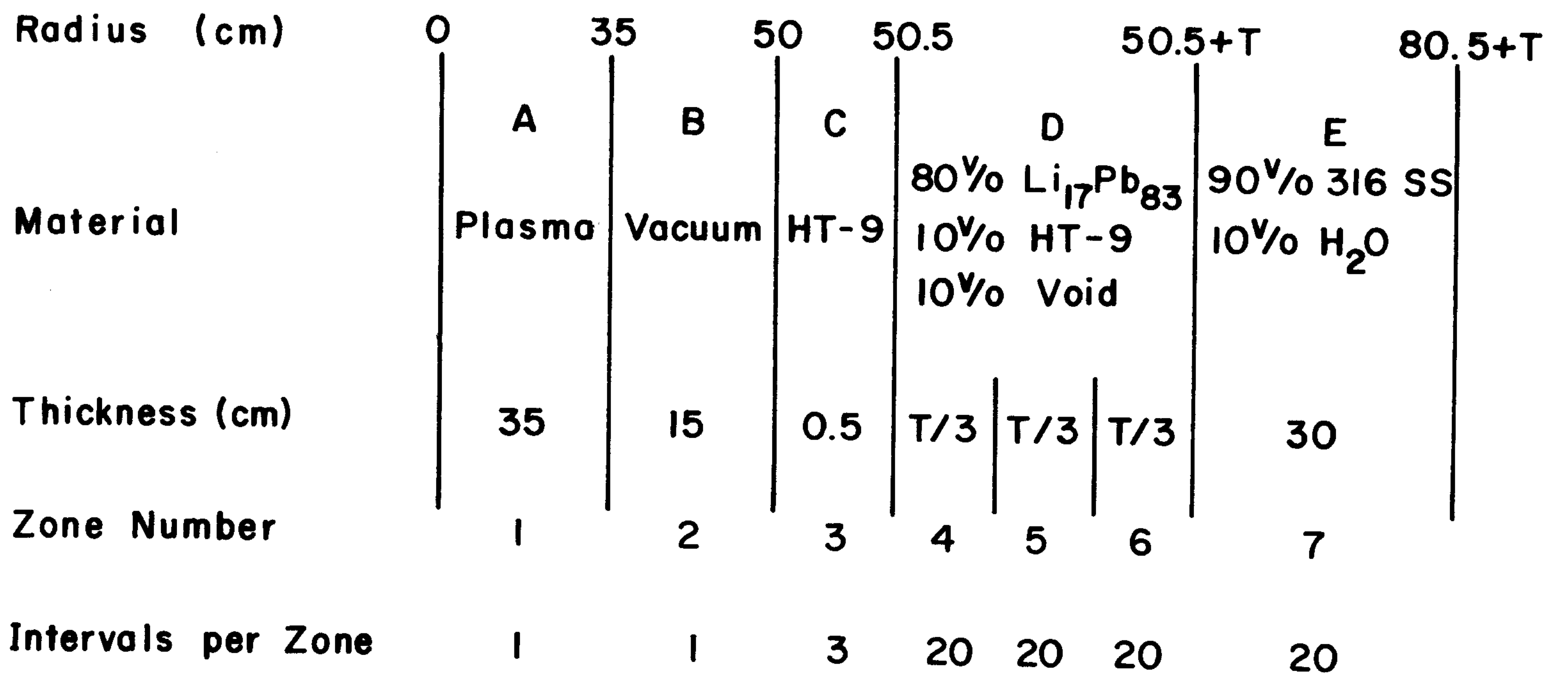

Fig. 1 A schematic of the $Li_{17}Pb_{83}$ benchmark problem.

Table III Nuclide Number Densities for the Materials of the Benchmark Problem

Material	Constituent Elements	Nuclide Density (nuclei/b•cm)
A	Isotropic neutron source in vacuum	
B	Vacuum	
C	Iron	.07678
	Chromium	.01019
D	^{6}Li	.00033 (.00400)[a]
	^{7}Li	.00412 (.00044)
	Lead	.02172
	Iron	.00768
	Chromium	.00102
E	Iron	.05396
	Chromium	.01418
	Nickel	.00886
	Molybdenum	.00068
	Hydrogen	.00667
	Oxygen	.00334

[a] Nuclide density for the 90% ^{6}Li case.

Table IV The S_8 Angular Quadrature Set Adopted in This Study

Cosine	Weight
-0.983032	0.0
-0.960290	0.050614
-0.796667	0.055595
-0.525532	0.052284
-0.183435	0.045335
0.183435	0.045335
0.525532	0.052284
0.796667	0.055595
0.960290	0.050614
-0.850774	0.0
-0.796667	0.055595
-0.525532	0.052284
-0.183435	0.045335
0.183435	0.045335
0.525532	0.052284
0.796667	0.055595
-0.604419	0.0
-0.525532	0.052284
-0.183435	0.045335
0.183435	0.045335
0.525532	0.052284
-0.279004	0.0
-0.183435	0.045335
0.183435	0.045335

in Table V. The results are shown for different blanket thicknesses and lithium enrichments. Because of the continuous energy treatment used in MCNP, the MCNP computation is considered as the reference case for comparing the accuracy of the results obtained with the different multigroup libraries. The large differences between the results particularly for the natural lithium case are consistent with the discrepancies observed in Table II for WITAMIR.

The 25- and 46- group libraries were generated by collapsing the 171 groups in VITAMIN-C (14) using 1/E spectrum. While the response cross sections in the 46-group library are based on the most recent version of the MACKLIB response library (15), the 25-group library (16) includes response functions from an earlier version of MACKLIB (17). The LANL 30-group library has both transport and response cross sections generated using NJOY. The library utilizes the standard Los Alamos group structure. Table VI gives the energy boundaries for the different multigroup libraries used. Comparing the 25- and 46- group structures we notice that while they are identical above 5.5 MeV, each group in the 25-group library below this energy is divided into two to three finer groups in the 46-group library. However, both libraries utilize the same single thermal group. The LANL 30-group library has broader groups in the MeV region and finer groups at lower energies compared to the 25-group library. The group size is similar to that of the 46-group library in the intermediate and low energy region. While both the 25- and 46- group libraries use a single thermal group, two thermal groups are used in the 30-group library.

Examining the results of Table V, we notice that the multigroup libraries tend to overestimate the tritium breeding ratio for the thin blanket with the exception of the 30-group library when used for the natural lithium case. As

Table V Tritium Breeding Results Obtained Using Available Cross-Section Data Based on ENDF/B-IV

Lithium Enrichment (% ^6Li)	Blanket Thickness (cm)	CODE	MCNP	ANISN	ONEDANT	
		Number of Energy Groups	Continuous Energy	25	30	46
Natural (7.42% ^6Li)	60	^6Li (n,α)t	0.766 ± 0.014	0.885	0.700	0.793
		^7Li (n,n'α)t	0.024 ± 0.0006	0.023	0.023	0.023
		Total	0.790 ± 0.014	0.908 (14.9)[a]	0.723 (-8.5)	0.816 (3.3)
	80	^6Li (n,α)t	0.972 ± 0.016	1.051	0.841	0.968
		^7Li (n,n'α)t	0.024 ± 0.0006	0.023	0.023	0.023
		Total	0.997 ± 0.016	1.074 (7.7)	0.864 (-13.3)	0.991 (-0.6)
	100	^6Li (n,α)t	1.124 ± 0.017	1.151	0.932	1.080
		^7Li (n,n'α)t	0.024 ± 0.0005	0.023	0.023	0.023
		Total	1.148 ± 0.017	1.174 (2.3)	0.955 (-16.8)	1.103 (-3.9)
90% ^6Li	60	^6Li (n,α)t	1.430 ± 0.016	1.448	1.461	1.449
		^7Li (n,n'α)t	0.003 ± 0.0005	0.002	0.003	0.003
		Total	1.433 ± 0.016	1.450 (1.3)	1.464 (2.2)	1.452 (1.3)
	80	^6Li (n,α)t	1.548 ± 0.016	1.546	1.580	1.560
		^7Li (n,n'α)t	0.003 ± 0.0006	0.002	0.003	0.003
		Total	1.551 ± 0.016	1.548 (-0.1)	1.583 (2.1)	1.563 (0.8)

a Percentage deviation from MCNP result.

Table VI Group Upper Boundaries (eV) for the Different Multigroup Libraries

Group Number	UW 25-Group Structure	LANL 30-Group Structure	ANL 46-Group Structure
1	1.4918 (+7)[a]	1.700 (+7)	1.4918 (+7)
2	1.3499 (+7)	1.500 (+7)	1.3499 (+7)
3	1.2214 (+7)	1.350 (+7)	1.2214 (+7)
4	1.1052 (+7)	1.200 (+7)	1.1052 (+7)
5	1.0000 (+7)	1.000 (+7)	1.0000 (+7)
6	9.0484 (+6)	7.790 (+6)	9.0484 (+6)
7	8.1873 (+6)	6.070 (+6)	8.1873 (+6)
8	7.4082 (+6)	3.680 (+6)	7.4082 (+6)
9	6.7032 (+6)	2.865 (+6)	6.7032 (+6)
10	6.0653 (+6)	2.232 (+6)	6.0653 (+6)
11	5.4881 (+6)	1.738 (+6)	5.4881 (+6)
12	4.4933 (+6)	1.353 (+6)	4.9659 (+6)
13	3.6788 (+6)	8.230 (+5)	4.4933 (+6)
14	3.0119 (+6)	5.000 (+5)	4.0657 (+6)
15	7.4660 (+6)	3.030 (+5)	3.6788 (+6)
16	1.3534 (+6)	1.840 (+5)	3.3287 (+6)
17	7.4274 (+5)	6.760 (+4)	3.0119 (+6)
18	4.0762 (+5)	2.480 (+4)	2.7253 (+6)
19	1.6573 (+5)	9.120 (+3)	2.4660 (+6)
20	3.1828 (+4)	3.850 (+3)	1.8268 (+6)
21	3.3546 (+3)	1.235 (+3)	1.3534 (+6)
22	3.5358 (+2)	4.540 (+2)	1.0026 (+6)
23	3.7267 (+1)	1.670 (+2)	7.4274 (+5)
24	3.9279 (+0)	6.140 (+1)	5.5023 (+5)
25	4.1399 (-1)	2.260 (+1)	4.0762 (+5)
26		8.320 (+0)	3.0197 (+5)
27		3.060 (+0)	2.2371 (+5)
28		1.130 (+0)	1.6573 (+5)
29		4.140 (-1)	1.2277 (+5)
30		1.520 (-1)	6.7379 (+4)
31			3.1828 (+4)
32			1.5034 (+4)
33			7.1017 (+3)
34			3.3546 (+3)
35			1.5846 (+3)
36			7.4852 (+2)
37			3.5358 (+2)
38			1.6702 (+2)
39			7.8893 (+1)
40			3.7267 (+1)
41			1.7603 (+1)
42			8.3153 (+0)

Table VI (Continued)

Group Number	UW 25-Group Structure	LANL 30-Group Structure	ANL 46-Group Structure
43			3.9279 (+0)
44			1.8554 (+0)
45			8.7643 (+0)
46			4.1399 (-1)

[a] Reads 1.4918×10^7

the blanket thickness increases all multigroup libraries result in less overestimate or more underestimate of the tritium breeding ratio. This indicates that there are two competing effects one tends to overestimate the results while the other tends to underestimate them. The first effect dominates for thin blankets while the other dominates for thicker blankets. Much lower discrepancies are observed for the highly enriched case.

In order to understand the reasons for these deviations, a series of calculations was performed for a 75 cm thick lead and a 30 cm thick iron blanket. The calculated neutron leakage and absorption in the pure lead blanket per 14.1 MeV source neutron are given in Table VII. The results were obtained using the same codes and cross section libraries used to generate the results in Table V for the $Li_{17}Pb_{83}$ benchmark problem. These results in Table VII reveal that the absorption obtained using the LANL 30-group library is extremely large. Examining the absorption in the different energy groups, we notice that the absorption in the 20th group (1.235 $\leq$ E $\leq$ 3.35 keV) represents ~ 45% of the total absorption. The absorption cross section in this group is a factor of ~ 50 higher than that in the VITAMIN-C library. This was attributed to an error in the Doppler broadening module (BROADER) of the NJOY code used to generate the 30-group library at 300 K. This error gives pathological results for cross sections containing sharp steps or resonances represented as triangles and was corrected in later versions of NJOY (18). We observed the same problem for the MCNP data for lead processed at 300 K leading to results similar to those of the 30-group library. Using a corrected lead data file for MCNP at 300 K, we obtained results that agree with the MCNP results with data processed at 0 K given in Table V. We conclude from this analysis that the fictitious large lead absorption cross sections in the energy range 1-100

Table VII Neutron Leakage and Absorption in a 70 cm Thick Lead Blanket

	MCNP Continuous Energy ENDF/B-IV Library	ANISN UW 25-Group Library	ONEDANT LANL 30-Group Library	ONEDANT ANL 46-Group Library
Leakage	1.356	1.266	1.061	1.312
Absorption	0.555	0.660	0.859	0.613
Total	1.911	1.926	1.920	1.925

keV of the LANL 30-group library are responsible for the underestimate of the tritium breeding ratio for the natural lithium case. This effect disappears in the highly enriched case as ^6Li dominates absorption in the low keV range. Recently, Pelloni et al. (19) obtained good agreement between the breeding ratios calculated using the VITAMIN-C and LANL 30-group libraries for the INTOR-EC design that utilizes $Li_{17}Pb_{83}$ as breeder and water as coolant. The problem with the lead data in the LANL 30-group library does not influence their results due to the existence of water which helps slow down the neutrons to energies below the range of concern for the lead data. Furthermore, while about half of the tritium breeding in INTOR-EC occurs in the thermal group, half of the breeding occurs in the range 0.1-100 keV in our benchmark problem in which the $Li_{17}Pb_{83}$ acts as both the coolant and breeder.

Neutron leakage and absorption per 14.1 MeV source neutron in a 30 cm thick iron blanket obtained using different codes and data libraries are given in Table VIII. Strong iron resonances exist in the energy range 1 keV - 1 MeV. These are mostly elastic scattering resonances. Since smooth standard energy spectra were used to generate the multigroup data from the ENDF files, the resonance self-shielding effects are not included and both the absorption and scattering group cross sections are overestimated. This results in underestimating neutron leakage and overestimating neutron absorption. The largest deviation from the MCNP results occurs in the resonance energy range. This effect is more pronounced for group structures with broad groups in the iron resonance region as is the case for the 25-group library. The effect will be negligible if very fine groups are used in this intermediate energy range. Using ONEDANT with the recent LANL 80-group library (20) gave a value of 0.838 for the total neutron leakage per source neutron while the LANL 30-group

Table VIII Neutron Leakage and Absorption in a 30 cm Thick Iron Blanket

Energy Interval (eV)	Absorption			Leakage		
	MNCP	ANISN		MNCP	ANISN	
	Continuous Energy	25 groups	46 groups	Continuous Energy	25 groups	46 groups
1.00 (+7)[a] - 1.41 (+7)	1.43 (-1)	1.33 (-1)	1.36 (-1)	1.041 (-2)	6.61 (-3)	7.42 (-3)
4.49 (+6) - 1.00 (+7)	8.34 (-3)	8.43 (-3)	8.73 (-3)	1.72 (-3)	1.56 (-3)	1.68 (-3)
2.47 (+6) - 4.49 (+6)	2.70 (-3)	2.54 (-3)	2.60 (-3)	5.57 (-3)	2.72 (-3)	2.89 (-3)
1.35 (+6) - 2.47 (+6)	1.58 (-3)	1.63 (-3)	1.57 (-3)	1.39 (-2)	9.58 (-3)	9.61 (-3)
4.10 (+5) - 1.35 (+6)	2.02 (-2)	1.19 (-2)	1.89 (-2)	2.39 (-1)	8.24 (-2)	1.26 (-1)
1.70 (+5) - 4.10 (+5)	2.78 (-2)	2.61 (-2)	3.42 (-2)	3.35 (-1)	1.27 (-1)	1.93 (-1)
3.50 (+2) - 1.70 (+5)	5.29 (-2)	3.41 (-1)	2.90 (-1)	3.82 (-1)	1.72 (-1)	2.79 (-1)
2.20 (-2) - 3.50 (+2)	4.11 (-2)	3.25 (-1)	1.89 (-1)	5.16 (-3)	3.14 (-2)	2.18 (-2)
Total	0.297 ± 0.008	0.850	0.681	0.993 ± 0.014	0.433	0.641

[a] Reads 1.0×10^7

library gave a value of 0.671.

Since the iron resonances are mainly elastic scattering resonances, the overestimated group scattering cross sections in the resonance region result in underestimating the neutron leakage and overestimating the tritium breeding in a breeding blanket that utilizes steel as structure. This explains the large values for tritium breeding obtained using the 25- and 46- group libraries compared to the MCNP results for the 60 cm thick benchmark problem with natural lithium as shown in Table V. The variation with blanket thickness of the tritium breeding and neutron leakage from the blanket as obtained using MCNP with the continuous energy library and ONEDANT with the 25-group library is shown in Fig. 2. As the blanket thickness increases, the deviation from the MCNP results decreases. The reason is that leakage becomes less significant and the overestimated iron group scattering cross sections will have less impact on the calculated tritium breeding. On the other hand, in thicker blankets with less leakage the overestimated resonance absorption in iron will have an increased impact on tritium breeding resulting in an increased underestimate. These effects result in the observed variation with blanket thickness of the deviation from the MCNP result as shown in Table V. These effects are less pronounced for systems highly enriched in ^{6}Li because of the dominant ^{6}Li absorption in the iron resonance region.

The results of Table V indicate that discrete ordinates calculations using the ANL 46-group library give values for the tritium breeding ratio within ~ 4% of the continuous energy MCNP results. However, larger deviations are expected for thinner blankets with large steel content due to the increased influence of the iron scattering resonances. Because of space limitations such blankets are proposed for use as inboard blankets in the tokamak

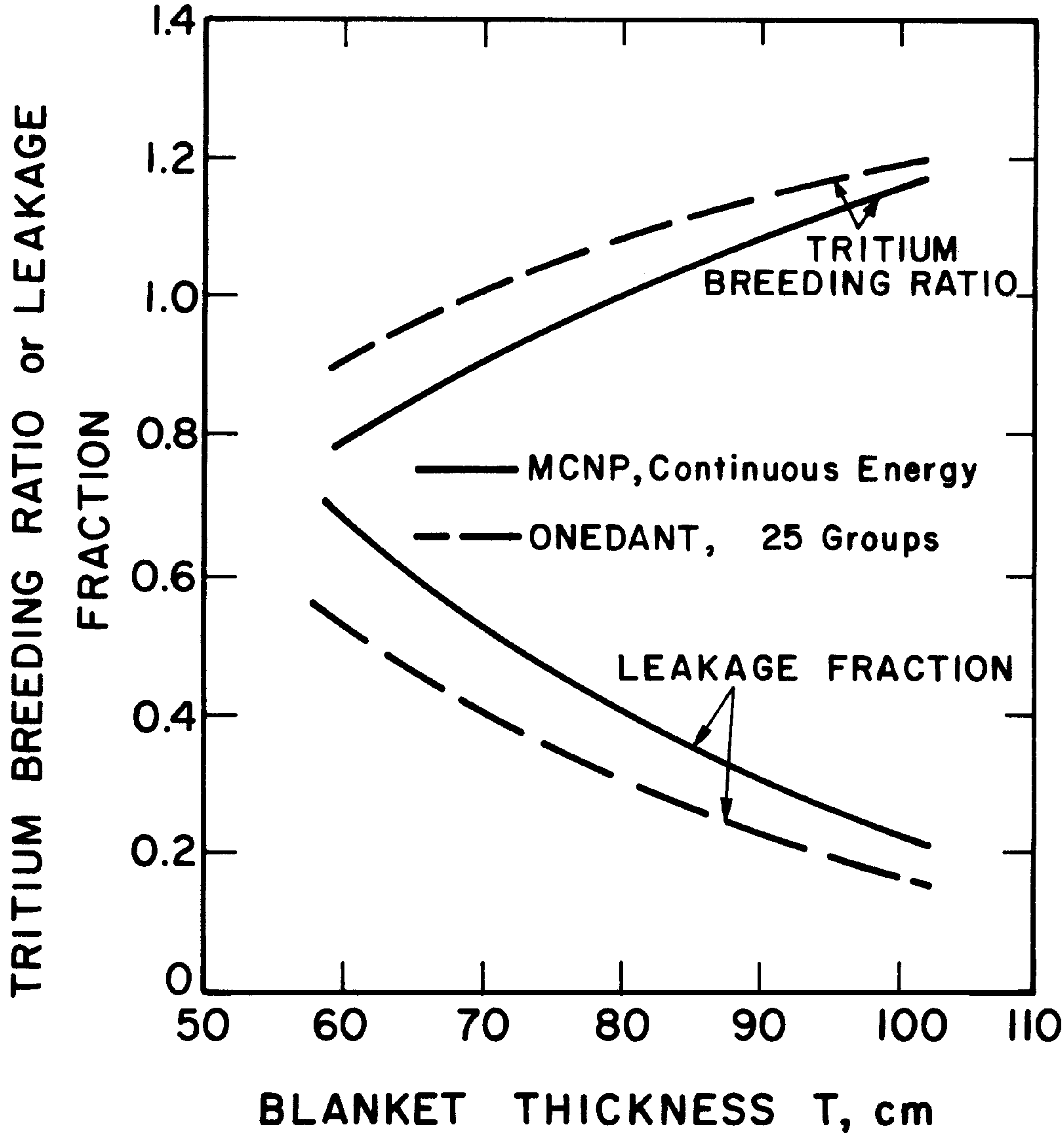

Fig. 2 Variation of tritium breeding and neutron leakage with blanket thickness as predicted by MCNP and ONEDANT with the 25-group library.

reactors. We performed calculations for a 10 cm thick blanket consisting of 80 vol % $Li_{17}Pb_{83}$ with 90% ^6Li, 10 vol % HT-9, and 10 vol % void. A 0.5 cm thick HT-9 first wall was used in front of the blanket at a radius of 50 cm. A 30 cm thick SS-316 reflector cooled by 10 vol % $Li_{17}Pb_{83}$ follows the blanket. The tritium breeding results obtained using MCNP and ONEDANT with the ANL 46-group library are given in Table IX. The P_5S_8 approximation was used in the discrete ordinates calculations. Using the 46-group library gives ~ 10% higher tritium breeding ratio than does MCNP. The values for neutron leakage of this system from MCNP and ONEDANT are 0.5806 and 0.4105, respectively.

IV. EFFECTS OF WEIGHTING SPECTRUM AND GROUP STRUCTURE ON TRITIUM BREEDING

In order to gain further understanding of the effects of weighting spectrum and group structure on the tritium breeding ratio calculated using multigroup cross section data, the TRANSX code was used to collapse the LANL 80-group data (20) into 30- and 21- group data using various weighting spectra. The 80-group library was prepared using the ENDF/B-V evaluated data and the NJOY processing system. The weighting spectrum used is based on the smoothed core spectrum for a typical large LMFBR with a fusion peak at high energies, a 1/E part in the energy range 0.1 - 60 eV, and a thermal tail at lower energies. A part of this spectrum is illustrated in Fig. 3. The group structure has a large number of fine groups in the iron resonance region. The energy boundaries for the 30- and 21- group structures to which we collapsed the 80-group library are given in Table X. The corresponding number of fine groups in each broad group is also indicated. The two broad group structures are similar at energies greater than ~ 1 MeV while the 21-group structure utilizes much broader groups at lower energies. The 30-group structure is similar to

Table IX Tritium Breeding Results for a Thin Blanket With Large Steel Content

	MCNP Continuous Energy ENDF/B-IV Library		ONEDANT ANL 46- Group Library	
	Blanket	Reflector	Blanket	Reflector
^{6}Li (n,α)t	0.456	0.191	0.505	0.208
^{7}Li (n,n'α)t	0.002	0.000	0.002	0.000
Total	0.649 ± .006		0.715	
Neutron Leakage	0.581		0.411	

Table X The 30- and 21- Group Structures

Group Number	30- Group Structure		21- Group Structure	
	Upper Energy Boundary (eV)	Number of Fine Groups from the 80-Group Structure	Upper Energy Boundary (eV)	Number of Fine Groups from the 80-Group Structure
1	2.000 (+7)[a]	2	2.000 (+7)	2
2	1.492 (+7)	1	1.492 (+7)	1
3	1.350 (+7)	1	1.350 (+7)	1
4	1.191 (+7)	1	1.191 (+7)	1
5	1.000 (+7)	1	1.000 (+7)	1
6	7.788 (+7)	1	7.788 (+7)	1
7	6.065 (+6)	2	6.065 (+6)	1
8	3.679 (+6)	1	4.724 (+6)	1
9	2.865 (+6)	1	3.679 (+6)	1
10	2.231 (+6)	1	2.865 (+6)	1
11	1.738 (+6)	1	2.231 (+6)	2
12	1.353 (+6)	4	1.353 (+6)	5
13	8.209 (+5)	4	7.244 (+5)	5
14	4.979 (+5)	3	3.877 (+5)	3
15	3.020 (+5)	2	1.832 (+5)	7
16	1.832 (+5)	4	3.183 (+4)	19
17	6.738 (+4)	6	3.355 (+3)	14
18	2.479 (+4)	8	3.536 (+2)	5
19	9.119 (+3)	8	3.727 (+1)	5
20	3.355 (+3)	8	3.059 (+0)	2
21	1.234 (+3)	5	4.140 (-1)	2
22	4.540 (+2)	3	--	-
23	1.670 (+2)	2	--	-
24	6.144 (+1)	2	--	-
25	2.260 (+1)	2	--	-
26	8.315 (+0)	2	--	-
27	3.059 (+0)	1	--	-
28	1.125 (+0)	1	--	-
29	4.140 (-1)	1	--	-
30	1.523 (-1)	1	--	-

[a] Reads 2.0×10^7

the LANL 30-group structure while the 21-group structure is close to the UW 25-group structure used in the calculations presented in Section II. Three different weighting spectra were used to collapse the 80-group data. These are the spectrum at the blanket midpoint obtained using ONEDANT with the 80-group library, a 1/E spectrum, and the spectrum used to generate the 80-group library. Unlike the other two spectra, the first one is blanket design dependent. This spectrum depends, therefore, on the thickness and enrichment for the blanket under consideration.

Dividing each blanket into three parts, we found that the innermost part is dominant in contribution to tritium breeding. Figure 3 shows the spectra at the midpoint of this part calculated using ONEDANT with the 80-group data and MCNP with the continuous energy data based on ENDF/B-V for the 100 cm thick natural $Li_{17}Pb_{83}$ blanket. The spectrum used to generate the 80-group library is also shown. It is clear that the two calculated spectra agree very well. The valley in the calculated spectra at ~ 250 keV is due to the peak in the ^6Li cross section. The two other dips at ~ 8 and 30 keV are attributed to the iron resonances. The results of Fig. 3 indicate that the spectrum used to generate the 80-group library drops much faster than the calculated one in the low energy region where considerable tritium breeding occurs.

Figure 4 gives the spectra calculated by ONEDANT and the 80-group library at the midpoints of the 60 and 100 cm thick natural $Li_{17}Pb_{83}$ blankets. These spectra were used to collapse the 80-group data into broad group libraries to be used in calculations for each of these blankets. Comparing the calculated spectra in Figs. 3 and 4 we notice that even though the spectrum becomes softer as the neutrons penetrate farther in the blanket and as the blanket thickness becomes larger, the shapes of the spectra do not differ very much

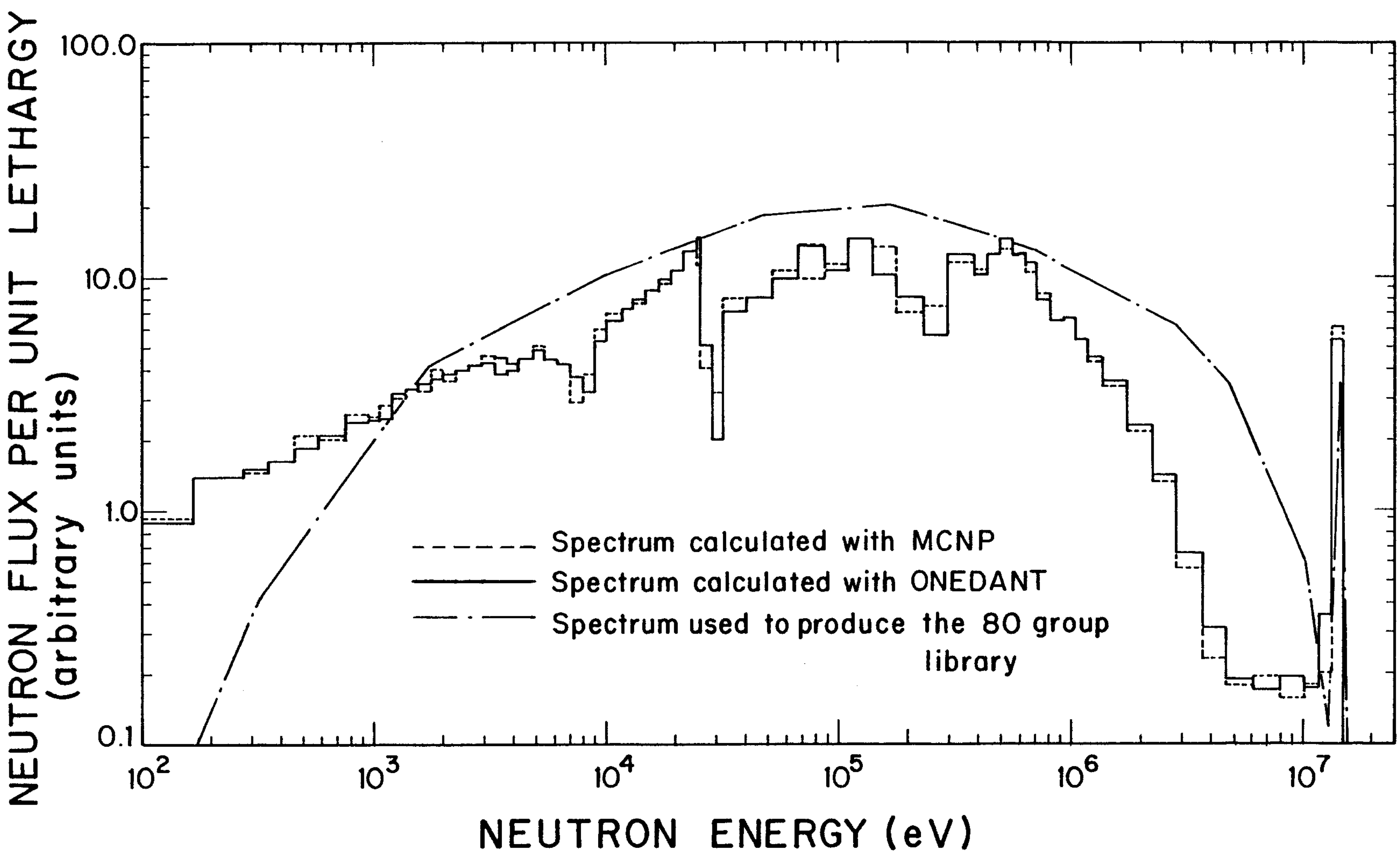

Fig. 3 Neutron spectra at the midpoint of the front third of the 100 cm thick natural $Li_{17}Pb_{83}$ blanket as predicted by MCNP and ONEDANT with the 80-group library. The spectrum used to generate the 80-group library is also shown.

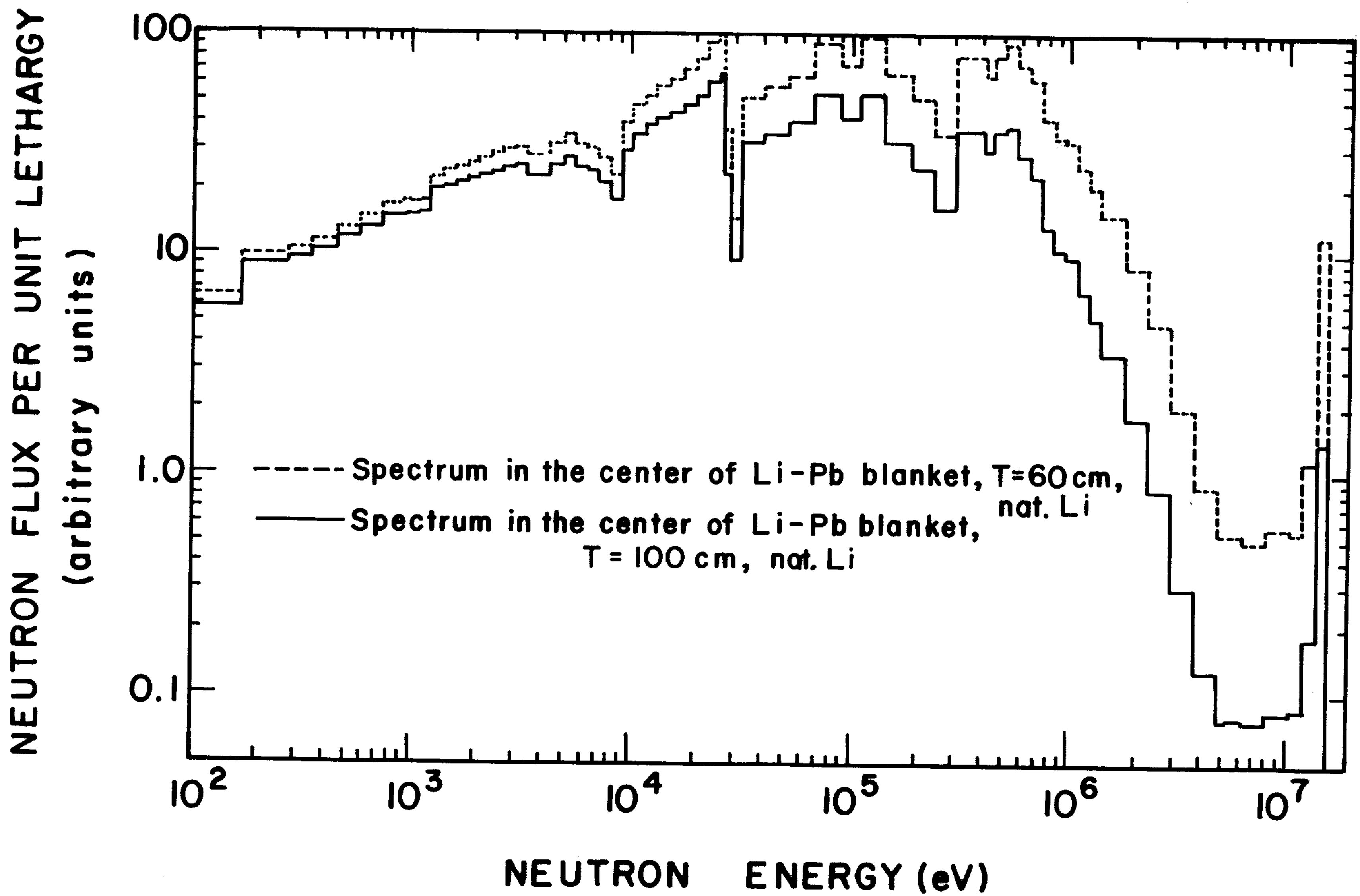

Fig. 4 Neutron spectra calculated by ONEDANT with the 80-group library at the midpoints of the 60 and 100 cm thick natural $Li_{17}Pb_{83}$ blankets.

except for the energy range above ~ 5 MeV. Since the broad group cross sections are sensitive only to the variation of the weighting spectrum within each broad group, using these calculated spectra to collapse the 80-group data will result in similar broad group data provided that these groups are not too broad and no collapsing is used for the few high energy groups. This is important as it implies that regardless of the spatial variation of spectrum, a spectrum representative of the blanket system under consideration can be used to generate an appropriate multigroup library from the ENDF data provided that fine enough groups are used in the high energy region as is the case in all currently used group structures.

Table XI gives a summary of the tritium breeding results obtained using MCNP with the ENDF/B-V continuous energy data and ONEDANT with multigroup libraries generated using the different group structures and weighting spectra. The 80-group library was generated from ENDF/B-V data using spectrum 3. The 30-group data generated from the 80-group data using spectrum 3 are equivalent to being generated directly from ENDF/B-V data using the same weighting spectrum. Comparing the 80-group results to the MCNP results for the natural lithium case, we notice that the 80-group library gives lower values for tritium breeding. This is related to the fact that spectrum 3 is much harder than the actual spectrum in the blanket as indicated by the results of Fig. 3. We notice also that the deviation increases as the blanket thickness increases as a result of the increased spectrum softening. The results of the 30-group library generated using the same weighting spectrum show the same trend with larger deviations from the MCNP results. A deviation of 14% was obtained for the 100 cm thick blanket compared to a deviation of 6% obtained with the 80-group library. The larger deviation results from using much

Table XI Tritium Breeding Results Obtained Using Different Group Structures and Weighting Spectra

Lithium Enrichment (% ^{6}Li)	Blanket Thickness (cm)	Continuous Energy MCNP	Discrete Ordinates ONEDANT					
			80-Group Library	30-Group Data			21-Group Data	
				Spectrum 1[a]	Spectrum 2[b]	Spectrum 3[c]	Spectrum 1	Spectrum 2
7.42	60	0.792 (0.011)[d]	0.771	0.777	0.783	0.716	0.804	0.883
	80	0.985 (0.011)	0.948	---	0.955	0.870	---	1.051
	100	1.130 (0.011)	1.066	---	1.069	0.974	1.085	1.153
90	60	1.389 (0.009)	1.393	---	1.399	1.399	---	1.431
	80	1.512 (0.008)	1.508	---	1.510	1.510	---	1.532

[a] Calculated spectrum at blanket midpoint

[b] 1/E spectrum

[c] The spectrum used to generate the 80-group library

[d] Fractional standard deviation

broader energy groups below ~ 2 MeV where iron resonances exist and the bulk of tritium breeding occurs. These results imply that in order to get an accurate estimate of tritium breeding in a natural $Li_{17}Pb_{83}$ system more than 80 fine groups are needed unless an appropriate weighting spectrum representative of the actual shape of the spectrum in the blanket is used.

For the highly enriched case the results are less sensitive to the weighting spectrum and group structure. In this case a much harder spectrum is obtained. The spectrum at the midpoint of the front part in the 90% ^6Li enriched 80 cm thick blanket is illustrated in Fig. 5 in comparison with the spectrum in the Li-Nb benchmark problem. These spectra were calculated using the 80-group library. Compared to the natural $Li_{17}Pb_{83}$ case these spectra are much harder and closer to the weighting spectrum used to generate the 80-group data. This explains the rather good agreement with the MCNP results indicated in Table XI. Furthermore the large ^6Li content in such blankets results in more high energy neutrons absorbed in ^6Li with much less neutron interaction with iron. Therefore, as long as the high energy groups are fine enough to yield accurate estimate of neutron multiplication few energy groups can be used to analyze highly enriched $Li_{17}Pb_{83}$ systems.

Further insight can be gained by comparing the results obtained using the different weighting spectra with the 80-group calculation considered as a reference. Using the 30-group data generated with spectrum 3 results in less accurate results compared to using a 1/E spectrum since the actual spectrum is closer to 1/E in the low energy region. Using the 1/E spectrum tends to overestimate tritium breeding while using the LMFBR spectrum (spectrum 3) tends to underestimate the results since these spectra are softer and harder than the actual spectrum respectively. When the midpoint spectrum calculated using the

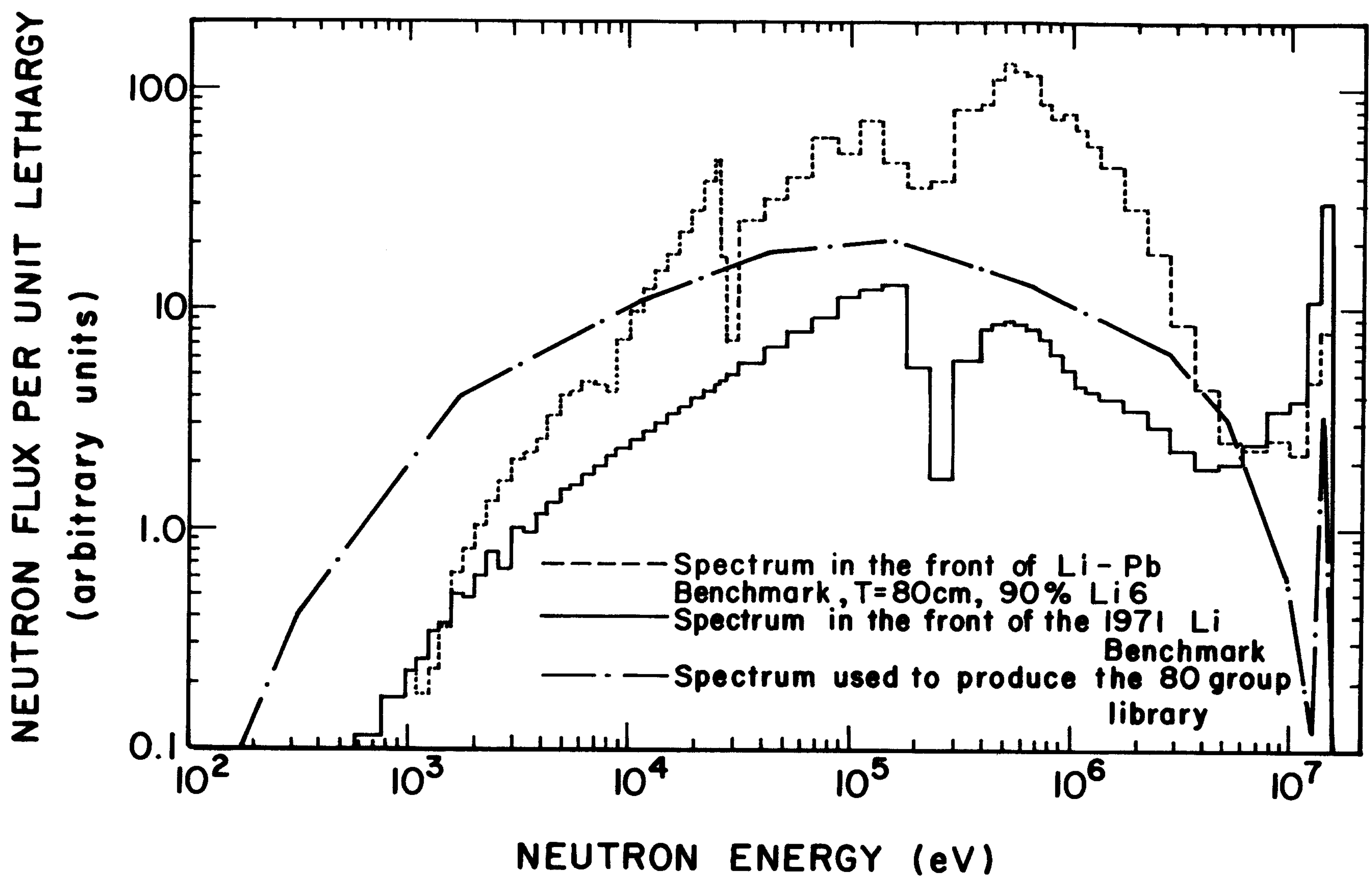

Fig. 5 Comparison between spectra at the midpoint of the front third in the 90% ^6Li enriched 80 cm thick $Li_{17}Pb_{83}$ and the lithium-niobium benchmark problem. The spectrum used to generate the 80-group library is also shown.

80-group library was used to generate the few group data, more accurate results were obtained. There is still a slight deviation in this case due to the spatial variation of the spectrum in the blanket. The 30-group results agree with the 80-group results much better than do the 21-group results. This is due to the significant difference between the two group structures evident in Table X with the 21-group library having extremely broad energy groups at energies lower than ~ 1 MeV. Even if the midpoint calculated spectrum is used to generate the 21-group data, deviations up to ~ 4% from the 80-group results will still be obtained. Again this situation is of less concern in the highly enriched case due to the harder spectrum and the dominating effect of absorption in ^6Li.

V. SUMMARY AND CONCLUSIONS

The tritium breeding results for the standard blanket utilizing liquid lithium as breeder and niobium as structure calculated using different codes and cross section libraries agreed very well. However, large deviations up to 20% were obtained for blankets utilizing $Li_{17}Pb_{83}$ for breeding and steel for structure. In such blankets the spectrum is quite soft and large amounts of lead and iron exist. These discrepancies prompted us to set a benchmark problem for the $Li_{17}Pb_{83}$ blanket system with steel structure. In order to investigate the impact of the different design parameters on the accuracy of the calculated tritum breeding ratio, three different blanket thicknesses and two lithium enrichments were considered. A series of calculations for pure lead and iron blankets has also been performed to gain further understanding of the effects of these species on the accuracy of the calculated tritium breeding ratio.

With the continuous energy MCNP calculation considered as the reference case, the LANL 30-group library was found to underestimate tritium breeding due to significantly large lead group absorption cross sections in the energy range 1-100 keV. On the other hand, the UW 25-group library and to a less extent the ANL 46-group library tend to overestimate tritium breeding. This is attributed to the inadequacy of the broad group structure in properly representing the sharp iron resonances which are mainly elastic scattering resonances. This effect is more pronounced for thin blankets with large leakage. These effects are less pronounced in blankets highly enriched in ^{6}Li due to the dominant ^{6}Li absorption.

The effects of weighting spectra and group structures have also been analyzed. We used different weighting spectra to collapse the LANL 80-group library into different broad group structures. Using the LMFBR spectrum which was used to generate the 80-group library results in less accurate results compared to using a 1/E spectrum since the actual spectrum is closer to 1/E in the low energy region. The deviations increase as the blanket thickness increases due to the increased spectrum softening. Larger deviations are obtained also when group structures with very broad groups in the iron resonance region are used. When the midpoint spectrum was used to generate the few group data, more accurate results were obtained. These effects are less pronounced in highly enriched systems since much harder spectra are obtained and ^{6}Li absorption dominates in the iron resonance region.

We conclude from this study that in a natural $Li_{17}Pb_{83}$ system with steel structure, the neutron spectrum is quite soft and the large amount of iron with its strong resonances will influence the accuracy of tritium breeding. In this case the calculated tritium breeding is sensitive to the energy group structure and weighting spectrum. To accurately determine tritium breeding in such systems, many fine groups (> 80) are required. Fewer groups can be used only if an appropriate group structure with fine enough groups in the iron resonance region is used to generate the data together with an appropriate weighting spectrum representative of the blanket system. Our results imply that regardless of the spatial variation of spectrum and the dependence of spectrum on blanket thickness, a spectrum representative of this kind of blanket system can be used to generate multigroup data from ENDF provided fine enough groups are used in the high energy region. The resulting multigroup data are expected to give quite accurate tritium breeding ratios for this kind of system. For systems which are highly enriched in ^{6}Li less sensitive results are obtained due to the hard spectrum and dominant effect of ^{6}Li. Few groups with fine enough structure in the iron resonance region will be adequate. Calculations by different researchers for this $Li_{17}Pb_{83}$ benchmark problem will help identify specific areas of improvement for the different data libraries and processing codes.

VI. Acknowledgement

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