ORNL-TM-4177

ANALYSIS OF A BENCH-MARK CALCULATION OF TRITIUM BREEDING IN A FUSION REACTOR BLANKET: THE UNITED STATES CONTRIBUTION

D. Steiner

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION • FOR THE U.S. ATOMIC ENERGY COMMISSION

MASTER
DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ORNL-TM-4177

Contract No. W-7405-eng-26

REACTOR DIVISION

ANALYSIS OF A BENCH-MARK CALCULATION OF TRITIUM BREEDING IN A FUSION REACTOR BLANKET: THE UNITED STATES CONTRIBUTION

D. Steiner

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

APRIL 1973

NOTICE This document contains information of a preliminary nature and was prepared primarily for internal use at the Oak Ridge National Laboratory. It is subject to revision or correction and therefore does not represent a final report.

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ANALYSIS OF A BENCH-MARK CALCULATION OF TRITIUM BREEDING IN A FUSION REACTOR BLANKET: THE UNITED STATES CONTRIBUTION

D. Steiner

INTRODUCTION

A fusion reactor operating on the deuterium-tritium fuel-cycle will require a tritium-breeding blanket. Tritium production in the blanket will be accomplished through interactions between the fusion neutrons and the isotopes of lithium, that is via the $^{6}Li(n,\alpha t)$ and the $^{7}Li(n,n'\alpha t)$ reactions. The tritium breeding performance of conceptual blanket models has been calculated by a number of groups.[1] However, since these calculations have generally been based on different cross section sets, it has been difficult to compare results obtained by different groups. At the Neutronics Session of the International Working Sessions on Fusion Reactor Technology[2] (held at Oak Ridge National Laboratory, June 1971) it was agreed to undertake a bench-mark calculation of tritium breeding using version 3 of ENDF/B[3] (ENDF/B-3) as the reference for cross section data. The purpose of this communication is to describe the bench-mark problem and to discuss the results submitted by the United States participants.*

THE BENCH-MARK PROBLEM

The configuration of the blanket model specified in the bench-mark problem is shown in Fig. 1. The blanket geometry was taken as one-dimensional cylindrical geometry. The fusion-neutron source was idealized

---

*Dr. Stephen Blow of the Harwell Laboratory, England, is analyzing the results submitted by the European participants. An analysis of the combined European and United States results will be issued subsequently.

as an isotropic source of 14-MeV neutrons distributed uniformally in space throughout the "plasma" region of the blanket model. The specified nuclide number densities for each material of the blanket are given in Table 1.

The ENDF/B-3 material identification numbers for the nuclides of interest are given in Table 2. It was specified that the nuclear data given in ENDF/B-3 be processed into a broad-group energy structure consisting of one-hundred groups with the top ninety-nine groups in the GAM-II[4] energy group-structure and one thermal group. In preparing these cross sections the effect of resonance self-shielding would be neglected. It was agreed that either discrete ordinates or Monte Carlo transport codes be used in the calculation. A P_3-S_4 approximation was recommended for those employing a discrete ordinates transport code.

RESULTS OF CALCULATION

The participants in the bench-mark calculation are listed in Table 3. Table 4 specifies (1) the processing code used at each laboratory, (2) the flux weighting employed to obtain group-averaged cross sections in the data processing calculation and (3) the assumption made regarding the thermal group cross sections.

The bench-mark calculations are summarized in Table 5 which gives the system breeding in lithium-6 and lithium-7 normalized to one source neutron. In all cases the calculations were performed with a vacuum boundary condition at the right-hand boundary. Note that higher-order angular-quadrature discrete ordinates calculations were performed in addition to the S_4 calculations.

Table 6 compares the P_3-S_4 calculations of breeding by region. Tables 7, 8, and 9 give the neutron balance and the tritium breeding by region for each of the P_3-S_4 calculations; the BNL, LASL, and ORNL

calculations, respectively. Table 10 compares the LASL discrete ordinates calculations (S_4, S_8, and S_{12}) by region. Tables 11 and 12 compare by region the ORNL discrete ordinates calculations (S_4, S_8, S_{12}, and S_{16}) with the ORNL Monte Carlo calculation; Table 11 summarizes the results for the $^7Li(n,n'\alpha t)$ reaction and Table 12 summarizes the results for the $^6Li(n,\alpha t)$ reaction.

DISCUSSION OF RESULTS

The results presented in Tables 5 through 12 can be summarized as follows:

1. The Discrete Ordinates P_3-S_4 Results. The BNL system value for breeding in lithium-7 is $\sim$ 1% greater than the LASL system value; the ORNL system value for breeding in lithium-7 is $\sim$ 2% greater than the LASL system value. The differences observed among the region values for breeding in lithium-7 do not exhibit a consistent trend, that is, the BNL and ORNL region values are not consistently higher than the LASL region values. The ORNL system value for breeding in lithium-6 is $\sim$ 5% higher than both the BNL and the LASL system values. The ORNL region values for breeding in lithium-6 are consistently higher than both the BNL and the LASL region values.

2. Higher Order Discrete Ordinates Results. The agreement between the LASL and the ORNL results for breeding in lithium-7 improves considerably as one moves from the S_4 results to the S_8 and S_{12} results. The results for breeding in lithium-6 are relatively insensitive to the order of the angular quadrature. The differences between the ORNL S_{12} and S_{16} results are insignificant.

3. The ORNL Discrete Ordinates and Monte Carlo Calculations. All the ORNL calculations were performed with the same set of multigroup cross sections. Thus, the ORNL discrete ordinates and Monte Carlo results can be compared on the basis of identical input cross sections. Each of the discrete ordinates system values for breeding in lithium-6 is in good agreement with the Monte Carlo system value. The largest discrepancy among the region values for breeding in lithium-6 occurs in the S_4 region-4 value which is $\sim$ 3% higher than the Monte Carlo region-4 value. The S_4 system value for breeding in lithium-7 differs from the Monte Carlo system value by only $\sim$ 1%, however, the S_4 region-4 value is $\sim$ 7% higher than the Monte Carlo region-4 value. The S_8 results for breeding in lithium-7 are in good agreement with the Monte Carlo results in all regions but region-4 where the S_8 result is $\sim$ 4% higher than the Monte Carlo result. The S_{12} results are in good agreement with the Monte Carlo results.

In order to identify the sources of the discrepancies among the P_3-S_4 results, the input multigroup cross sections and the details of the calculations were analyzed. These analyses are discussed below.

Multigroup Cross Section Sets

An examination of the multigroup cross section sets revealed differences in (1) the elastic scattering matrices of all the nuclides, (2) the resonance capture cross sections of niobium, and (3) the thermal group absorption cross section of all the nuclides.

The nature and magnitude of the differences observed in the elastic scattering matrices are illustrated in the first three columns of Table 13. This table compares the lithium-7 within-group scattering cross sections[†]

[†]Note that only the P-0 components, that is, the isotropic components of the Legendre expansion of the scattering matrices, are being compared.

for the top five energy groups and for energy group 60 which is typical of the energy range in which neutron scattering with lithium-7 is isotropic in the center-of-mass system. The first column of Table 13 gives the LASL values for the within-group scattering cross section (in barns) while columns two and three give the BNL and ORNL values relative to the LASL values. It is noted that, while the elastic transfer elements exhibited differences which ranged from $\sim$ 1% to 7%, the total elastic scattering cross sections varied by less than $\sim$ 0.05%. The nature of the differences illustrated for lithium-7 in Table 13 was also observed in the other nuclides, however, the magnitude of these differences was smallest in the case of the niobium elastic transfer matrices.

As specified in Table 4, the BNL and ORNL multigroup cross sections were based on a 1/E flux weighting while the LASL values were based on a constant flux weighting. To examine the effect of the flux weighting assumption, the ENDF/B data for lithium-7 was reprocessed at BNL and ORNL using a constant flux weighting. These results appear in columns four and five of Table 13, again, relative to the LASL values. The following observations are made on the basis of the preceding results:

1. The differences in the elastic scattering matrices were a result of differences in the flux weighting function in the case of the LASL and ORNL results. Moreover, using the same flux weighting function, ETOG at LASL and SUPERTOG at ORNL yield identical results for the elastic scattering matrices.
2. The current version of ETOG at BNL appears to contain an error in the calculation of the elastic scattering matrices. This apparent error was observed in all energy groups from 1 through 59.

The magnitude of the differences observed in the niobium resonance capture cross sections is demonstrated in Table 14. This table compares the BNL and ORNL values relative to the LASL values for energy groups 60 through 70; the LASL values (in barns) are given in column one of the table. It is noted that ∿ 90% of the parasitic absorptions in the system are associated with capture in niobium and that ∿ 40% of the niobium capture events occur in the energy range defined by groups 60 through 70.

From Table 14 it is seen that the ORNL niobium resonance capture cross sections are consistently lower than both the BNL and LASL values; in some groups the discrepancy is as much as a factor of three. These discrepancies were identified as arising from differences between the ETOG (BNL and LASL versions) and SUPERTOG (ORNL version) calculations of the resolved resonance contribution to the niobium capture cross section. Further examinations[10,11] substantiated the SUPERTOG results, that is, the lower values of the niobium resonance capture cross sections. In passing, it is noted[10,11] that a more recent version of ETOG (at Westinghouse) appears to yield results in close agreement with the SUPERTOG results.

The BNL and ORNL thermal group absorption cross sections were approximately a factor of two greater than the LASL values. This difference arises from the difference in the assumed Maxwellian temperature (see Table 4); that is, the Maxwellian temperature correction, $(1170K/300K)^{1/2}$, is approximately two. About 7% of the system absorptions (including the $^{6}Li(n,\alpha t)$ reaction) occur in the thermal group and ∿ 96% of these occur in regions 8 and 10, lithium-bearing regions; ∿ 4% of the thermal absorptions occur in the graphite, region 9. There is essentially no thermal group leakage from regions 8 and 10, and, therefore, all thermal sources within and into these regions appear as absorptions. The relative thermal

absorptions in region 8 (and in region 10) depend on the relative macroscopic absorption cross sections of the nuclides in the region. The relative macroscopic absorption cross sections obtain the same value independent of the assumed Maxwellian temperature. Therefore, the difference in the thermal group cross sections has a very small effect on the tritium breeding calculations.* I emphasize that this observation is peculiar to the bench-mark blanket model. Tritium breeding in other blanket models could be quite sensitive to the choice of the thermal group absorption cross section.

Calculational Details

An examination of the details of the discrete ordinates calculations revealed differences in (1) the negative-flux correction algorithm, (2) the number of intervals taken in the plasma region (region 1), (3) the number of intervals taken in the vacuum region (region 2), and (4) the angular quadrature sets. These differences are summarized in Table 15 and 16 and are discussed below.

In regions with coarse mesh spacing the discrete-ordinates-difference approximations can lead to negative values of the angular flux under certain conditions. This difficulty can be eliminated by going to a finer mesh spacing. When negative fluxes are generated, the codes implement corrective measures designated "negative-flux correction algorithms." Different correction algorithms can yield different values of the "corrected" flux. Thus, the discrete ordinates calculations might exhibit discrepancies arising from differences in (1) the mesh size in the plasma and vacuum regions and (2) the negative-flux correction algorithm.

---

*The effect is estimated to be less than 0.2% in the $^{6}Li(n,\alpha t)$ reaction and arises from differences in thermal absorptions in the graphite region.

The presence of sources within a region can prevent negative flux generation even when a coarse mesh spacing is used in that region. This situation obtains in the plasma region, and therefore, the differences in the number of intervals taken in the plasma region did not affect the calculated results. The vacuum region does not contain sources, and the mesh spacing in this region did affect the results. To determine the magnitude of this effect, the ORNL S_4 calculation was repeated with five intervals in the vacuum region (that is, with the same mesh spacing as the BNL calculation) and with ten intervals in the vacuum region. These changes did not alter the values for breeding in lithium-6, but did alter the values for breeding in lithium-7. The results are summarized in Tables 17 and 18. Table 17 compares the original ORNL calculation, the altered ORNL calculations and the BNL calculation. Note that the ORNL results for five intervals and ten intervals are identical. The effect of increasing the number of intervals in the vacuum region is noticeable but small in magnitude; the largest change, $\sim$ 1%, occurred in region 4. Note that the ORNL results move in the direction of the BNL results with this change in mesh size. Table 18 compares the top-energy-group fluxes, that is, energy-group-one fluxes, in the first five intervals of the blanket; the ORNL fluxes for the one interval and five interval cases are given relative to the BNL fluxes. Thus, with the same mesh size in the vacuum region the BNL and ORNL calculations yield top-energy-group fluxes which are essentially the same. This result is consistent with the observation that the BNL and ORNL values for the top-energy-group elastic scattering transfer terms are essentially the same (see Table 13).

On the basis of the calculational comparisons presented in Tables 17 and 18 and the cross section comparisons presented in Tables 13 and 14, the following conclusions are drawn regarding the discrepancies between the BNL and ORNL tritium breeding calculations:

1. The discrepancies in the lithium-7 results are due to differences in both the mesh size taken in the vacuum region and the elastic scattering matrices.
2. The discrepancies in the lithium-6 results are due primarily to the differences in the niobium resonance capture cross sections.

The LASL and ORNL discrete ordinates calculations (S_4, S_8, and S_{12}) differed in both the angular quadrature sets and the negative-flux correction algorithms. In order to examine the effects of these differences two altered S_4 calculations were performed at ORNL. In the first altered calculation the LASL S_4 angular quadrature set was substituted for the ORNL set. In the second altered calculation the LASL angular quadrature set was used and a negative-flux correction algorithm which approaches the LASL algorithm was substituted for the step function approximation. The results for breeding in lithium-6 were not noticeably affected by these changes, however, the lithium-7 results were affected. Table 19 summarizes the lithium-7 results for the original ORNL calculation, the two altered ORNL calculations, and the LASL calculation. Note that with the LASL angular quadrature set and the altered negative-flux correction algorithm the ORNL results approach the LASL results. On the basis of the calculational comparisons presented in Table 19 and the cross section comparisons presented in Tables 13 and 14 the following conclusions are drawn regarding the discrepancies between the LASL and ORNL S_4 tritium breeding results:

1. The differences in the lithium-7 results are due primarily to differences in the angular quadrature sets and in the negative-flux correction algorithms. The differences in the elastic transfer matrices appear to have a minor effect on the lithium-7 results.

2. The discrepancies in the lithium-6 results are due primarily to the differences in the niobium resonance capture cross sections.

It was noted earlier that the LASL and ORNL discrete ordinates calculations improved in agreement as the order of the angular quadrature increased. Although this trend was not analyzed in detail, it is reasonable to assume that the improved agreement is due to a decrease in the sensitivity of the calculations as one moves from S_4 to higher order angular quadrature, that is, as the order of the angular quadrature increases the calculated results become less sensitive to the differences in the angular quadrature sets and the negative-flux correction algorithms.

CONCLUDING REMARKS

A bench-mark calculation of tritium breeding in a fusion reactor blanket model was performed using ENDF/B-3 as the reference for cross section data. The ENDF/B-3 data was processed into multigroup sets using the ETOG code (at BNL and LASL) and the SUPERTOG code (at ORNL). Calculations were performed using the discrete ordinates codes ANISN (at BNL and ORNL) and DTF-IV (at LASL) and the Monte Carlo code MORSE (at ORNL).

Analysis of the calculations identified deficiencies in the processing codes and differences in calculational details which resulted in discrepancies among the calculated results. Correction of these deficiencies and a more precise specification of calculational details will lead to improved agreement in future fusion bench-mark problems. The following observations are made regarding future calculations.

1. For the assumed blanket geometry, the S_4 approximation gives a system tritium breeding value which is within $\sim$ 0.5% of the Monte Carlo system value. Thus, the S_4 approximation is adequate for survey calculations on system tritium breeding.
2. An S_{12} approximation is recommended in those cases where accurate spatial information is desired.
3. More attention should be given to the choice of mesh spacing. The effect of mesh spacing in the vacuum region was discussed in this paper. However, additional mesh spacing problems are most likely present in the bench-mark model, for example, the mesh spacing in the lithium regions near the graphite may be too coarse.
4. Future bench-mark calculations should involve magnet shield models as well as breeding blanket models.

ACKNOWLEDGEMENTS

The author appreciates the many useful discussions he had with A. L. Aronson (BNL), D. J. Dudziak and D. W. Muir (LASL), and W. W. Engle, Jr., and R. Q. Wright (ORNL). Also, he wishes to acknowledge the efforts of M. B. Emmett and S. K. Penny (ORNL) in carrying out the MORSE calculations.

REFERENCES

1. S. Blow, "The Role of Neutronics Calculations in Fusion Reactor Technology," Proceedings of the International Working Sessions on Fusion Reactor Technology, June 28 - July 2, 1971, Oak Ridge National Laboratory, Oak Ridge, Tennessee, pages 43-65.

2. Proceedings of the International Working Sessions on Fusion Reactor Technology, June 28 - July 2, 1971, Oak Ridge National Laboratory, Oak Ridge, Tennessee, pages 74-76.

3. H. C. Honeck, "ENDF/B Specifications for an Evaluated Nuclear Data File for Reactor Applications," BNL-50066, Brookhaven National Laboratory (1966).

4. G. D. Joanou and J. S. Dudek, "GAMII: A B_3 Code for the Calculation of Fast-Neutron Spectra and Associated Multigroup Constants," GA-4265, General Atomics (1963).

5. D. E. Kunser and R. A. Dannels, "ETOG-1, A Fortran IV Program to Process Data frmm the ENDF/B File to MUFT, GAM, and ANISN Format," WCAP-3845-1, Westinghouse Electric Corporation (1969).

6. R. Q. Wright, et al., "SUPERTOG: A Program to Generate Fine Group Constants and P_n Scattering Matrices from ENDF/B," ORNL-TM-2679, Oak Ridge National Laboratory (1969).

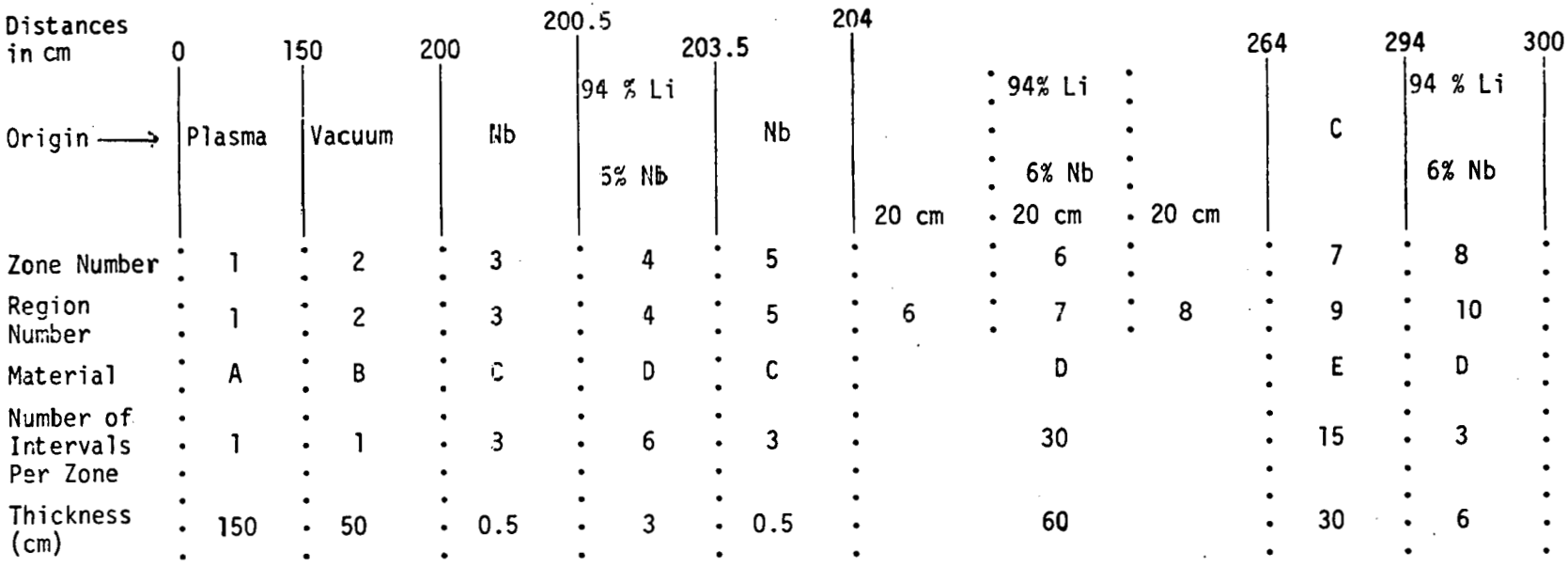
7. W. W. Engle, Jr. "A User's Manual for ANISN," K-1693, Oak Ridge Gaseous Diffusion Plant (1967).

8. K. D. Lathrop, "DTF-IV, A Fortran Program for Solving the Multigroup Transport Equation with Anistropic Scattering," LA-3373, Los Alamos Scientific Laboratory (1965).

9. E. A. Straker, et al., "The MORSE Code - a Multigroup Neutron and Gamma-Ray Monte Carlo Transport Code," ORNL-4585, Oak Ridge National Laboratory (1970).

10. A. L. Aronson, Brookhaven National Laboratory, Personal Communication (January, 1973).

11. D. W. Muir, Los Alamos Scientific Laboratory, Personal Communication (January, 1973).



Comment: The intervals in each zone are of equal step length. There are 62 intervals all together.

Fig. 1. Configuration of the Bench-Mark Blanket Model

Table 1. Nuclide Number Densities for the Materials of the Bench-Mark Blanket Model

Material Code Letter	Constituent	Number Density
A	Isotropic flux source of neutrons	
B	Vacuum	
C	Niobium	0.05556×10^{24}/cc
D	Niobium	0.003334×10^{24}/cc
	Lithium-6	0.003234×10^{24}/cc
	Lithium-7	0.04038×10^{24}/cc
E	Carbon	0.0804×10^{24}/cc

Table 2. The ENDF/B-3 Material Identification Numbers for the Nuclides of Interest

Nuclide	Identification Number
^{6}Li	1115
^{7}Li	1116
^{93}Nb	1161
^{12}C	1165

Table 3. Participants in Bench-Mark Calculation

Participant	Affiliation
A. L. Aronson	Brookhaven National Laboratory (BNL)
D. J. Dudziak[a] D. W. Muir[b]	Los Alamos Scientific Laboratory (LASL)
D. Steiner	Oak Ridge National Laboratory (ORNL)

[a]Performed the transport calculations.

[b]Performed the data processing calculations.

Table 4. Information on Processing Codes and Thermal Group Cross Sections

Laboratory	Processing Code	Flux Weighting Used to Obtain Group-Averaged Cross Sections	Assumption Regarding Thermal Group Cross Sections
BNL	ETOG[5]	1/E	Maxwellian at 300 K
LASL	ETOG[5]	Constant	Maxwellian at 1170 K
ORNL	SUPERTOG[6]	1/E	Maxwellian at 300 K

Table 5. Summary of Bench-Mark Calculations

Laboratory	Method of Calculation	Code Used	Breeding in ^{7}Li[a]	Breeding in ^{6}Li[a]	Total Breeding[a]
BNL	Discrete Ordinates P_3-S_4	ANISN[7]	0.512	0.383	1.395
LASL	Discrete Ordinates P_3-S_4	DTF-IV[8]	0.507	0.888	1.395
LASL	Discrete Ordinates P_3-S_8	DTF-IV	0.522	0.891	1.413
LASL	Discrete Ordinates P_3-S_{12}	DTF-IV	0.529	0.892	1.421
ORNL	Discrete Ordinates P_3-S_4	ANISN	0.518	0.933	1.451
ORNL	Discrete Ordinates P_3-S_8	ANISN	0.522	0.934	1.456
ORNL	Discrete Ordinates P_3-S_{12}	ANISN	0.527	0.932	1.459
ORNL	Discrete Ordinates P_3-S_{16}	ANISN	0.526	0.932	1.458
ORNL	Monte Carlo[b]	MORSE[9]	0.523 $\pm$ 0.003	0.932 $\pm$ 0.003	1.455 $\pm$ 0.004

[a] Calculated on the basis of one source neutron.

[b] The Monte Carlo calculations employed the same multigroup cross section sets as were used in the Discrete Ordinates Calculations.

Table 6. Comparison of P_3-S_4 Discrete Ordinates Calculations by Region

Region	$^7Li(n, n'\alpha t)$			$^6Li(n, \alpha t)$		
	BNL	LASL	ORNL	BNL	LASL	ORNL
3						
4	0.0815	0.823	0.0806	0.0471	0.0466	0.0480
5						
6	0.2796	0.2680	0.2812	0.2845	0.2790	0.2912
7	0.1064	0.1070	0.1098	0.2244	0.2230	0.2364
8	0.0434	0.0488	0.0458	0.2691	0.2770	0.2944
9						
10	0.0008	0.0011	0.0009	0.0578	0.0627	0.0634
Totals	0.5117	0.5072	0.5183	0.8829	0.8883	0.9334

Table 7. Neutron Balance and Tritium Breeding Summary

for the BNL P_3-S_4 Discrete Ordinates Calculation

Region	(n,2n)	Parasitic Absorptions	^{7}Li(n,n'αt)	^{6}Li(n,αt)	Total Tritium Breeding	System Neutron Leakage
3	0.0582	0.0296				
4	0.0289	0.0129	0.0815	0.0471	0.1286	
5	0.0395	0.0302				
6	0.0793	0.0818	0.2796	0.2845	0.5641	
7	0.0240	0.0734	0.1064	0.2244	0.3308	
8	0.0086	0.0753	0.0434	0.2691	0.3125	
9		0.0012				
10	0.0001	0.0017	0.0008	0.0578	0.0586	
Totals	0.2386	0.3161	0.5117	0.8829	1.3946	0.0395

Table 8. Neutron Balance and Tritium Breeding Summary

for the LASL P_3-S_4 Discrete Ordinates Calculation

Region	(n,2n)	Parasitic Absorptions	$^7Li(n,n'\alpha t)$	$^6Li(n,\alpha t)$	Total Tritium Breeding	System Neutron Leakage
3	0.0611	0.0278				
4	0.0295	0.0123	0.0823	0.0466	0.1289	
5	0.0393	0.0281				
6	0.0764	0.0762	0.2680	0.2790	0.5470	
7	0.0249	0.0697	0.1070	0.2230	0.3300	
8	0.0101	0.0752	0.0488	0.2770	0.3258	
9		0.0112				
10	0.0002	0.0020	0.0011	0.0627	0.0638	
Totals	0.2415	0.3025	0.5072	0.8883	1.3955	0.0487

Table 9. Neutron Balance and Tritium Breeding Summary

for the ORNL P_3-S_4 Discrete Ordinates Calculation

Region	(n,2n)	Parasitic Absorptions	^{7}Li(n,n'αt)	^{6}Li(n,αt)	Total Tritium Breeding	System Neutron Leakage
3	0.0575	0.0258				
4	0.0287	0.0114	0.0806	0.0480	0.1286	
5	0.0394	0.0257				
6	0.0802	0.0670	0.2812	0.2912	0.5724	
7	0.0249	0.0584	0.1098	0.2364	0.3462	
8	0.0091	0.0607	0.0458	0.2944	0.3402	
9		0.0125				
10	0.0001	0.0016	0.0009	0.0634	0.0643	
Totals	0.2399	0.2631	0.5183	0.9334	1.4517	0.0433

Table 10. Comparison of LASL Discrete Ordinates Calculations by Region

Region	$^{7}Li(n,n'\alpha t)$			$^{6}Li(n,\alpha t)$		
	$P_3 - S_4$	$P_3 - S_8$	$P_3 - S_{12}$	$P_3 - S_4$	$P_3 - S_8$	$P_3 - S_{12}$
3						
4	0.0823	0.0773	0.0755	0.0466	0.0458	0.0454
5						
6	0.2680	0.2800	0.2870	0.2790	0.2780	0.2770
7	0.1070	0.1160	0.1180	0.2230	0.2250	0.2260
8	0.0488	0.0480	0.0476	0.2770	0.2800	0.2810
9						
10	0.0011	0.0009	0.0008	0.0627	0.0624	0.0624
Totals	0.5072	0.5222	0.5289	0.8883	0.8912	0.8918

Table 11. Comparison of CRNL Discrete Ordinates and Monte Carlo Calculations by Region: The $^{7}Li(n,n'\alpha t)$ Reaction

	$^{7}Li(n,n'\alpha t)$				
Region	$P_3 - S_4$	$P_3 - S_8$	$P_3 - S_{12}$	$P_3 - S_{16}$	Monte Carlo
3					
4	0.0806	0.0780	0.0762	0.0763	0.0752 ± 0.0009
5					
6	0.2812	0.2813	0.2857	0.2858	0.2847 ± 0.0023
7	0.1098	0.1149	0.1168	0.1165	0.1153 ± 0.0017
8	0.0458	0.0467	0.0472	0.0471	0.0472 ± 0.0011
9					
10	0.0009	0.0008	0.0008	0.0008	0.0009 ± 0.0001
Totals	0.5183	0.5222	0.5267	0.5265	0.5233 ± 0.0032

Table 12. Comparison of ORNL Discrete Ordinates and Monte Carlo Calculations by Region: The $^{6}Li(n,\alpha t)$ Reaction

Region	$^{6}Li(n,\alpha t)$				
	$P_3 - S_4$	$P_3 - S_8$	$P_3 - S_{12}$	$P_3 - S_{16}$	Monte Carlo
3					
4	0.0480	0.0476	0.0471	0.0472	0.0467 ± 0.0004
5					
6	0.2912	0.2895	0.2883	0.2884	0.2880 ± 0.0013
7	0.2364	0.2371	0.2370	0.2369	0.2369 ± 0.0010
8	0.2944	0.2957	0.2960	0.2959	0.2946 ± 0.0020
9					
10	0.0634	0.0639	0.0640	0.0640	0.0655 ± 0.0012
Totals	0.9334	0.9338	0.9324	0.9324	0.9317 ± 0.0028

Table 13. The BNL and ORNL Lithium-7 Within Group Scattering Cross Sections Relative to the LASL Values

Laboratory (*) (**) Energy Group Index	LASL (ETOG) (Constant) (In Barns)	BNL (ETOG) (1/E) (Relative)[a]	ORNL (SUPERTOG) (1/E) (Relative)[a]	BNL (ETOG) (Constant) (Relative)[a]	ORNL (SUPERTOG) (Constant) (Relative)[a]
1	0.5001	0.9871	0.9882	0.9989	1.000
2	0.5184	0.9333	0.9881	0.9440	1.000
3	0.5344	0.9451	0.9882	0.9560	1.000
4	0.5443	0.9561	0.9883	0.9671	1.000
5	0.5537	0.9662	0.9883	0.9774	1.000
60	0.2861	0.9615	0.9615	1.000	1.000

*Processing code.

**Flux weighting for group averaging.

[a]The ratio of the BNL or ORNL value to the LASL value.

Table 14. The BNL and ORNL Niobium Resonance Capture Cross Sections Relative to the LASL Values

Laboratory	LASL	BNL	ORNL
Energy Group Index	(In Barns)	(Relative)[a]	(Relative)[a]
60	0.5055	1.0045	0.9775
61	2.7184	0.9905	0.3721
62	1.9879	0.9854	0.3315
63	3.0367	0.9988	0.3604
64	1.3695	1.0149	0.6520
65	2.4594	1.0056	0.7185
66	1.6435	0.9881	0.8194
67	2.4654	0.9734	0.7985
68	3.3268	0.9841	0.8815
69	1.8162	0.9145	0.8875
70	2.3787	0.9241	0.8507

[a]The ratio of the BNL or ORNL value to the LASL value.

Table 15. Summary of Differences in the Discrete Ordinates Calculations

Laboratory	Negative-Flux Correction Algorithm	Number of Intervals in Plasma	Number of Intervals in Vacuum	Angular[a] Quadrature Sets
BNL	Step Function Approximation	Ten	Five	Same as ORNL
LASL	Flux Set to Zero	One	One	Different from ORNL
ORNL	Step Function Approximation	One	One	

[a]Table 16 compares the S_4 angular quadrature sets.

Table 16. Comparison of the S_4 Angular Quadrature Sets[a]

BNL and ORNL Set		LASL Set	
Cosine	Weight	Cosine	Weight
- 0.471404	0.0	- 0.426582	0.0
- 0.333333	0.166667	- 0.301639	0.166667
0.333333	0.166667	0.301639	0.166667
- 0.942808	0.0	- 0.953422	0.0
- 0.881917	0.166667	- 0.904449	0.166667
- 0.333333	0.166667	- 0.301639	0.166667
0.333333	0.166667	0.301639	0.166667
0.881917	0.166667	0.904449	0.166667

[a]Sets for cylindrical geometry.

Table 17. The Effect of Differences in the Number of Intervals Taken in the Vacuum Region: Tritium Breeding in Lithium-7

	$^{7}Li(n,n'\alpha t)$			
Region	ORNL One Interval In Vacuum	ORNL Five Intervals In Vacuum	ORNL Ten Intervals In Vacuum	BNL Five Intervals In Vacuum
3				
4	0.0806	0.0813	0.0813	0.0815
5				
6	0.2812	0.2809	0.2809	0.2796
7	0.1098	0.1088	0.1088	0.1064
8	0.0458	0.0453	0.0453	0.0434
9				
10	0.0009	0.0008	0.0008	0.0008
Totals	0.5183	0.5171	0.5171	0.5117

Table 18. The Effect of Differences in the Number of Intervals Taken in the Vacuum Region: The ORNL Top-Energy-Group Fluxes Relative to the BNL Values

	ORNL One Interval In Vacuum	ORNL Five Intervals In Vacuum
Blanket Interval Index	Relative Flux[a]	Relative Flux[a]
1	0.9373	0.9994
2	0.9395	0.9995
3	0.9405	0.9996
4	0.9365	0.9997
5	0.9326	0.9998

[a]The ratio of the ORNL value to the BNL value.

Table 19. Effects of Differences in the Angular Quadrature Sets and the Negative-Flux Correction Algorithms: S_4 Results for Breeding in Lithium-7

Region	$^7Li(n,n'\alpha t)$			
	ORNL No Changes	ORNL LASL A.Q.S.[a]	ORNL LASL A.Q.S.[a] Altered N.F.C.A.[b]	LASL
3				
4	0.0806	0.0856	0.0822	0.0823
5				
6	0.2812	0.2671	0.2685	0.2680
7	0.1098	0.1030	0.1071	0.1070
8	0.0458	0.0466	0.0488	0.0488
9				
10	0.0009	0.0011	0.0011	0.0011
Totals	0.5183	0.5034	0.5077	0.5072

[a]Angular Quadrature Set (A.Q.S.)

[b]Negative-Flux Correction Algorithm (N.F.C.A.)