CROSS-SECTION SENSITIVITY OF TRITIUM
BREEDING IN A FUSION REACTOR BLANKET:
EFFECTS OF UNCERTAINTIES IN
CROSS SECTIONS OF ${}^6\text{Li}$, ${}^7\text{Li}$, AND ${}^{93}\text{Nb}$

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MASTER

OAK RIDGE NATIONAL LABORATORY

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CROSS-SECTION SENSITIVITY OF TRITIUM BREEDING IN A FUSION REACTOR BLANKET:
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I. INTRODUCTION

A fusion reactor operating on the deuterium-tritium fuel cycle will require a tritium-breeding blanket. Since fusion reactors are anticipated to operate at high specific power, e.g., ~ 500 MW(th) per kg of tritium,⁽¹⁾ a tritium-breeding ratio* only slightly greater than unity (that is, ~ 1.003) will yield a doubling time of $\sim$ ten years.⁽¹⁾ In general, calculated tritium-breeding ratios for alternate blanket models fall in the range 1.1 to 1.5.^(2,3) Although these results suggest that adequate tritium breeding can be achieved in a variety of blanket configurations, it is necessary to investigate the sensitivity of the tritium-breeding calculations to uncertainties in the cross-section data. We have initiated such an investigation as part of the fusion reactor technology studies at ORNL. The objectives of this effort are to identify cross-section uncertainties which either cast doubt on the tritium breeding potential of a blanket model, that is, drive the calculated tritium-breeding ratio below unity, or manifest significant uncertainties, that is, $\sim 5\%$, in the breeding ratio. The identification of such cross-section uncertainties will be used to establish priorities with regard to nuclear data needs for the Controlled Thermonuclear Research (CTR) Program.

* The tritium-breeding ratio is defined as the number of tritons produced in the blanket per fusion neutron, or equivalently, per deuterium-tritium fusion reaction.

This paper, which is the first of a series examining the cross-section sensitivity of tritium-breeding calculations, considers a blanket model exhibiting the following tritium-breeding and neutronic characteristics: (1) liquid lithium of natural isotopic abundance is used for breeding; (2) the tritium-breeding ratio is in the "high" range, ~ 1.5 ; (3) graphite is employed for neutron moderation; and (4) the neutron leakage from the blanket is relatively low, $\sim 4\%$ of the source neutrons. These characteristics are similar to those of several blanket models under current investigation,⁽⁴⁾ and therefore, the cross-section sensitivity exhibited by the blanket model of this paper is representative of a large class of blanket models. The cross-section sensitivity of tritium-breeding calculations in other classes of blanket[†] models will be examined in subsequent papers.

Version 3 of ENDF/B⁽⁵⁾ (ENDF/B-3) is used as the reference for cross-section data. In this paper we examine the effects of uncertainties in the cross sections of ^6Li , ^7Li , and ^{93}Nb . These effects are evaluated by altering the reference data sets in patterns based on our estimates of the cross-section uncertainties.

II. BLANKET MODEL AND CALCULATIONAL PROCEDURE

The blanket model adopted in this study is the bench-mark configuration specified at the Neutronics Session of the International Working Sessions on Fusion Reactor Technology⁽⁶⁾ (held at ORNL, June 1971). The details

[†]For example, blanket models using either liquid lithium enriched in lithium-6 or a lithium-bearing molten salt.

of the model are shown in Fig. 1. The 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.

The neutronics calculations for this study were carried out with the discrete ordinates transport theory code XSDRN⁽⁷⁾ using an $S_4 - P_3$ approximation in cylindrical geometry. A vacuum boundary condition was taken at the right-hand boundary. The fusion-neutron source was idealized as an isotropic source of ~ 14 MeV neutrons distributed uniformly in space throughout the "plasma" region of the blanket model.

The cross-section processing code XLACS⁽⁸⁾ was used to process the ENDF/B-3 data into a broad group energy structure consisting of one-hundred groups with the top ninety-nine groups in the GAM-II⁽⁹⁾ energy group structure and one thermal group (a Maxwellian distribution at 300 K was assumed for the thermal group). Resonance self-shielding of the niobium capture cross section was computed by the method of Nordheim⁽¹⁰⁾ as programmed in the XSDRN code.

Table 3 summarizes the neutron balance and tritium breeding by region of the blanket model for the reference data sets, i.e., the unmodified cross section sets. The values in this table are normalized to a source of one fusion neutron. The "Parasitic Absorptions" are non-breeding absorptions, " T_6 " is the tritium-breeding ratio due to the ${}^6\text{Li}(n,\alpha)t$ reaction, " T_7 " is the tritium-breeding ratio due to the ${}^7\text{Li}(n,n'\alpha)t$ reaction,** and "T" is the sum of T_6 and T_7 . We note the following points with regard to the results of Table 3:

**

Note that this reaction does not result in a neutron loss; the inelastically-scattered neutron is available for additional reactions (even additional ${}^7\text{Li}(n,n'\alpha)t$ reactions).

1. Approximately 76% of the (n,2n) events occur in niobium.
2. In this blanket model the major parasitic absorber is niobium. Approximately 88% of the parasitic absorptions result from capture in niobium and over 90% of these capture events occur in the resonance region of niobium.
3. If resonance self-shielding of the niobium capture cross section is neglected, the number of parasitic absorptions increases by $\sim 16\%$ and T_6 decreases by $\sim 4\%$.

From the neutronics details of the reference case we conclude that the most significant cross sections for this study are those for the ${}^6\text{Li}(n,\alpha)t$ reaction, the ${}^7\text{Li}(n,n'\alpha)t$ reaction, the ${}^{93}\text{Nb}(n,2n)$ reaction, and the ${}^{93}\text{Nb}(n,n')$ reaction. The ${}^{93}\text{Nb}(n,\gamma)$ reaction is also important but will be considered in a subsequent study.

III. RESULTS OF THE SENSITIVITY CALCULATIONS

The sensitivity of the calculated tritium-breeding ratio to uncertainties in cross sections of ${}^6\text{Li}$, ${}^7\text{Li}$, and ${}^{93}\text{Nb}$ was examined by varying the reference data sets for these nuclides. The techniques employed to effect these variations are described in detail in Ref. 11 and are not discussed here. Since the ENDF/B-3 compilations do not currently contain evaluations of the uncertainties in the data files, the assignment of variations to the reference data sets is subjective. In assigning cross-section variations for this study, we attempted to reflect conservative estimates of the uncertainties in the ENDF/B-3 data.

A. Sensitivity to the ${}^6\text{Li}(n,\alpha)t$ Cross Section

The ${}^6\text{Li}(n,\alpha)t$ cross section (1) increases from ~ 0.02 barns to ~ 0.2 barns in the energy range 15 MeV to 2 MeV (the upper limit of the top-energy group in the GAM-II structure is ~ 15 MeV), (2) exhibits a resonance at ~ 0.25 MeV, and (3) at lower energies (below ~ 0.01 MeV) varies inversely with neutron velocity attaining a value of ~ 940 barns at a velocity of 2200 m/sec. For the reference case, $\sim 1\%$ of the ${}^6\text{Li}(n,\alpha)t$ reactions occur in the energy range 15 MeV to 2 MeV, $\sim 57\%$ of the reactions occur in the energy range 2 MeV to 0.01 MeV, and $\sim 42\%$ of the reactions occur below 0.01 MeV. The ${}^6\text{Li}(n,\alpha)t$ reaction competes with the parasitic absorption reactions, the most important of which is the niobium capture reaction.

Two patterns of variation were adopted for the ${}^6\text{Li}(n,\alpha)t$ cross sections. In one patterns, designated the "low-pattern," the reference set was lowered 10% in the range 15 MeV to 2 MeV, 5% in the range 2 MeV to 0.01 MeV, and 3% for all energies below 0.01 MeV. In the "high-pattern" the reference set was raised by the same percentages in the corresponding energy ranges. In both patterns of variation the total cross section of ${}^6\text{Li}$ was adjusted by the amount of the variations in the $(n,\alpha)t$ cross section.

The effects of the variations in the ${}^6\text{Li}(n,\alpha)t$ cross sections are summarized in Tables 4, 5, and 6. Table 4 gives (1) the tritium-breeding ratios, T_6 , T_7 , and T ; (2) the fractional change in T relative to the value for the reference case; (3) the components of the neutron balance (including the number of absorptions in niobium); and (4) the number of scattering events in the graphite region. Table 5 gives T_6 and the fractional change in T_6 (relative to the reference value) for the energy

ranges defined in the patterns of variation. Table 6 gives the tritium-breeding ratios by region.

We note the following points with regard to the results in Table 4:

1. The tritium-breeding ratio, T , is relatively insensitive to the variations in the ${}^6\text{Li}(n,\alpha)t$ cross section. These variations produced a change of $\sim 0.5\%$ in the calculated breeding ratios (relative to the value for the reference case). The observed change was in the same direction as the cross-section changes, that is, the tritium-breeding ratio increased for the high-pattern variation and decreased for the low-pattern variation.

2. The changes in T reflect changes in T_6 ; T_7 remains essentially unaffected. The changes in T_6 are accompanied by a $\sim 3\%$ change in the number of niobium absorptions and a $\sim 2\%$ change in the neutron leakage.

We note the following points with regard to the results in Tables 5 and 6.

1. In the energy range 15 MeV to 2 MeV the $\pm 10\%$ changes in the ${}^6\text{Li}(n,\alpha)t$ cross section produced $\sim \pm 10\%$ changes in T_6 . This direct proportionality is due to the fact that in this energy range the ${}^6\text{Li}(n,\alpha)t$ cross section is small, and therefore, the variations in this cross section do not appreciably alter the neutron transport and slowing down characteristics of the lithium-bearing regions of the blanket. Thus, the calculated fluxes are not sensitive to the cross-section variations and the ${}^6\text{Li}(n,\alpha)t$ reaction rate varies directly in proportion to the change in the reaction cross section.

2. In the energy range 2 MeV to 0.01 MeV the $\pm 5\%$ changes in the ${}^6\text{Li}(n,\alpha)t$ cross section produced $\sim \pm 3\%$ changes in T_6 . In this energy range the value of the cross section is such that the imposed variations

do appreciably alter the calculated fluxes, that is, the neutron transport and slowing down characteristics are appreciably altered. Specifically, the calculated fluxes are somewhat higher in the low-pattern variation than in the reference case and are somewhat lower in the high-pattern variation than in the reference case. These variations in the calculated fluxes tend to compensate for the variations in the cross section.

3. In the energy range below 0.01 MeV the low-pattern variation exhibits an $\sim 3\%$ increase in T_6 while the high-pattern exhibits an $\sim 3\%$ decrease in T_6 , that is, the variation in T_6 is in a direction opposite to the variation in the cross section. This behavior is due to two effects. One effect is associated with the alterations in the neutron transport and slowing down characteristics of the lithium regions of the blanket and affects the calculated fluxes in the same directions as described above in (2). The second effect is associated with the superior neutron-moderating properties of graphite relative to lithium for neutron energies below ~ 0.2 MeV. At such energies neutrons which enter the graphite region are very effectively degraded in energy, and therefore, have a high probability for absorption in ${}^6\text{Li}$ once they leave the graphite region. Thus, most of the neutrons which escape absorption in the energy range 2 MeV - 0.01 MeV are moderated in the graphite and are subsequently absorbed (at lower energies) in the regions adjacent to the graphite, that is, regions 8 and 10 (see Table 6). In the low-pattern variation relatively more neutrons reach the graphite region than in the reference case; in the high-pattern variation relatively fewer neutrons reach the graphite region than in the reference case. The graphite moderating effect is evidenced not only by the results of Table 5, but also by the

results of Table 6 (compare T_6 in regions 8 and 10 among the three cases) and of Table 4 (compare the number of elastic scattering events in graphite).

We emphasize that the relative insensitivity of T_6 to variations in the ${}^6\text{Li}(n,\alpha)t$ cross section is to a large extent due to the moderating characteristics of the graphite region.

B. Sensitivity to the ${}^7\text{Li}(n,n'\alpha)t$ Cross Section

The ${}^7\text{Li}(n,n'\alpha)t$ cross section (1) exhibits a threshold at ~ 3 MeV, (2) attains a maximum value of ~ 0.42 barns at ~ 8 MeV, and (3) decreases slowly above this energy obtaining a value of ~ 0.31 barns at 15 MeV. For the reference case, $\sim 44\%$ of the ${}^7\text{Li}(n,n'\alpha)t$ reactions occur in the top energy group (which covers the energy range ~ 15 MeV - 13.5 MeV), $\sim 77\%$ of the reactions occur above 10 MeV, and $\sim 99\%$ occur above 5 MeV. The ${}^7\text{Li}(n,n'\alpha)t$ reaction competes with other neutron down-scattering reactions, e.g., elastic scattering, inelastic scattering and $(n,2n)$ reactions. The ${}^7\text{Li}(n,n'\alpha)t$ reaction rate depends not only on the value of the reaction cross section but also on the energy distribution of the secondary neutrons produced in the reaction since some of these neutrons will have sufficient energy to undergo ${}^7\text{Li}(n,n'\alpha)t$ reactions. In this section we examine the effects of variations in both the cross section and the secondary-neutron energy distribution of the ${}^7\text{Li}(n,n'\alpha)t$ reaction.

The Cross Section

The reference values for the ${}^7\text{Li}(n,n'\alpha)t$ cross section were varied by $\pm 20\%$ in the energy range of interest (~ 15 MeV to 3 MeV). In this variation the total cross section of ${}^7\text{Li}$ was adjusted by the amount of

the changes in the $(n,n'\alpha)t$ cross section. The effects of the variations in the ${}^7\text{Li}(n,n'\alpha)t$ cross sections are summarized in Tables 7 and 8:

We note the following points with regard to the results in these tables:

1. The tritium-breeding ratio, T , decreases by $\sim 5\%$ for the cross section reduction and increases by $\sim 4\%$ for the cross section increase.
2. The calculated changes in T are due to a small change in T_6 and a large change in T_7 ; T_7 decreases by $\sim 14\%$ for the cross section reduction and increases by $\sim 12\%$ for the cross section increase. The changes in T are accompanied by an $\sim 4\%$ change in the number of $(n,2n)$ reactions, an $\sim 9\%$ change in the neutron leakage, and an $\sim 1\%$ change in the number of parasitic absorptions.
3. The influence of moderating effects in the graphite region are also observed in this case.

The Secondary-Neutron Energy Distribution

In ENDF/B-3 the energy distribution of the secondary neutrons produced by the ${}^7\text{Li}(n,n'\alpha)t$ reaction is described by an evaporation model with an energy-dependent "nuclear temperature", $\Theta(E)$, where E is the energy of the incident neutron. To examine the effects of uncertainties in the secondary-neutron energy distribution, the reference $\Theta(E)$ values for the ${}^7\text{Li}(n,n'\alpha)t$ reaction were varied by $\pm 50\%$ over the entire energy range of interest. The reduction in $\Theta(E)$ yields a "softer" secondary spectrum than does the reference $\Theta(E)$ value and the increase in $\Theta(E)$ yields a "harder" secondary spectrum than does the reference $\Theta(E)$ value. The extent to which the changes in $\Theta(E)$ modify the secondary spectra is illustrated in Table 9 which gives the probability that the secondary

neutron from the ${}^7\text{Li}(n,n'\alpha)t$ reaction will have an energy greater than 5 MeV (probabilities are given for incident energies of 14 MeV and 12 MeV).

The effects of the variations in the secondary-neutron energy distributions of the ${}^7\text{Li}(n,n'\alpha)t$ reaction are summarized in Table 10.

We note the following points with regard to the results in this table:

1. The tritium-breeding ratio, T , decreases by $\sim 2.5\%$ for the soft spectrum case and increases by $\sim 1\%$ for the hard spectrum case.
2. The changes in T reflect changes in T_7 ; T_6 remains essentially unaffected. The changes in T_7 are accompanied by a change of less than 1% in the number of $(n,2n)$ reactions and by changes of $\sim 1.5\%$ to 4% in the neutron leakage.

The contribution of the ${}^7\text{Li}(n,n'\alpha)t$ secondary neutrons to T_7 is shown in Table 11 which compares T_7 for the hard spectrum case, the reference case, the soft spectrum case, and a case in which the secondary neutron from the ${}^7\text{Li}(n,n'\alpha)t$ reaction is suppressed, in effect treating the ${}^7\text{Li}(n,n'\alpha)t$ reaction as an absorption reaction.^{††} In this table the portion of T_7 due to secondary neutrons from the ${}^7\text{Li}(n,n'\alpha)t$ reaction is defined as the difference between the T_7 value for the given case and the T_7 value for the case in which the secondary neutron is suppressed.

In passing we note that the energy distributions of the secondary neutrons from the ${}^6\text{Li}(n,2n)\alpha$, the ${}^6\text{Li}(n,n'\alpha)d$, the ${}^7\text{Li}(n,2n)$ and the ${}^7\text{Li}(n,2n)\alpha$ reactions are also described by evaporation models in ENDF/B-3. We examined the sensitivity of the breeding ratio to $\pm 50\%$ variations in $\sigma(E)$ for these reactions as well as for the ${}^7\text{Li}(n,n'\alpha)t$ reaction.

^{††}The authors are indebted to Dr. H. Goldstein of Columbia University for suggesting this case.

The results of this examination are summarized in Table 12. The cross sections for the reactions considered are small, and therefore, as anticipated the tritium-breeding ratio was not sensitive to the variations in the secondary-neutron energy distributions.

C. Sensitivity to the $^{93}\text{Nb}(n,2n)$ and $^{93}\text{Nb}(n,n')$ Cross Sections

The $^{93}\text{Nb}(n,2n)$ cross section exhibits a threshold at ~ 9 MeV and attains a value of ~ 1.2 barns at 15 MeV. For the reference case, $\sim 83\%$ of the $^{93}\text{Nb}(n,2n)$ reactions occur in the top energy group (which covers the energy range ~ 15 MeV - 13.5 MeV) and $\sim 97\%$ of the reactions occur above ~ 11 MeV. The $^{93}\text{Nb}(n,2n)$ reaction produces both neutron multiplication and neutron downscattering, and therefore, enhances the $^6\text{Li}(n,\alpha)t$ reaction as well as competes with the $^7\text{Li}(n,n'\alpha)t$ reaction. The $^{93}\text{Nb}(n,n')$ cross section is significant (that is, obtains values ranging between 1 to 2 barns) in the energy range ~ 15 MeV to 1 MeV. For the reference case, $\sim 21\%$ of the $^{93}\text{Nb}(n,n')$ reactions occur in the top energy group, $\sim 50\%$ of the reactions occur above ~ 4.5 MeV, and $\sim 96\%$ of the reactions occur above ~ 1 MeV. The $^{93}\text{Nb}(n,n')$ reaction is a downscattering process, and therefore, competes with the $^7\text{Li}(n,n'\alpha)t$ reaction.

The reference values for the $^{93}\text{Nb}(n,2n)$ cross section were varied by $\pm 25\%$ over the energy range of interest (~ 15 to 9 MeV). In these variations the total cross section of ^{93}Nb was adjusted by the amount of the changes in the $(n,2n)$ cross section. The effects of these variations are summarized in Table 13 and 14. We note the following points with regard to the results in these tables.

1. The tritium-breeding ratio, T , is relatively insensitive to the variations in the $^{93}\text{Nb}(n,2n)$ cross section. These variations produced a change of $\sim 0.5\%$ in T and the change was in the same direction as the cross-section variation, e.g., when the $^{93}\text{Nb}(n,2n)$ cross section was lowered, T decreased.

2. The insensitivity of T to changes in the $^{93}\text{Nb}(n,2n)$ cross section resulted from compensating changes in T_6 and T_7 . For example, when the $^{93}\text{Nb}(n,2n)$ cross section was reduced, T_7 increased (relative to the reference case) because of reduced neutron downscattering competition; at the same time, T_6 decreased because of reduced neutron multiplication. The changes in T_6 and T_7 are accompanied by an $\sim 3.5\%$ change in the number of niobium absorptions and by an $\sim 3\%$ change in the neutron leakage.

3. Table 14 shows that for the cross section reduction T_6 is lowered in every region while T_7 is increased in every region (relative to the reference case); the converse is true for the cross section increase.

The reference values for the $^{93}\text{Nb}(n,n')$ cross section were varied by $\pm 25\%$ over the entire energy range of interest (~ 15 MeV to 0.03 MeV). In these variations the total cross section of ^{93}Nb was adjusted by the amount of the changes in the (n,n') cross section. The effects of these variations are summarized in Tables 15 and 16. We note the following points with regard to the results in these tables:

1. The tritium-breeding ratio, T , increased by $\sim 2\%$ for the cross section reduction and decreased by $\sim 2\%$ for the cross section increase.

2. The changes in T are due to a small change in T_6 and a large change in T_7 . For example, for the cross section reduction T_7 increased by $\sim 6\%$ (relative to the reference case) because of reduced neutron downscattering competition and T_6 increased by $\sim 0.4\%$ because of increased neutron multiplication.

3. Table 16 shows that T_7 increases in every region for the cross section reduction and decreases in every region for the cross section increase. On the other hand, T_6 exhibits a strong spatial effect. For example, for the cross section reduction T_6 decreases in the inner regions (regions 4 and 6), but increases in the outer regions (regions 7, 8, and 10) relative to the reference case. This behavior is due both to transport and slowing down effects in the niobium-containing regions and to moderating effects in the graphite region.

In the preceding analysis we neglected possible correlation between uncertainties in the $^{93}\text{Nb}(n,2n)$ and $^{93}\text{Nb}(n,n')$ cross sections. In ENDF/B-3 the niobium inelastic cross section for energies above 2.5 MeV is obtained by subtracting other non-elastic cross sections from the total non-elastic cross sections. According to this procedure an increase in the $^{93}\text{Nb}(n,2n)$ cross section should be accompanied by a reduction in the $^{93}\text{Nb}(n,n')$ cross section; the converse would apply for a decrease in the $(n,2n)$ cross section. From the standpoint of the tritium-breeding ratio, the most deleterious correlation in this study would result from a 25% reduction in the $^{93}\text{Nb}(n,2n)$ cross section with a corresponding increase in the $^{93}\text{Nb}(n,n')$ cross section (such that the total non-elastic cross section remains unchanged). For this case T would be $\sim 3\%$ lower than for the reference case.

IV. CONCLUDING REMARKS

We have examined the cross-section sensitivity of the tritium-breeding ratio in a fusion reactor blanket model which is representative of a large class of blanket configurations under current investigation. The calculated sensitivity of the breeding ratio to estimates of the uncertainties in cross sections of ${}^6\text{Li}$, ${}^7\text{Li}$, and ${}^{93}\text{Nb}$ is summarized in Table 17. We note the following observations with regard to the results of this study.

1. The status of the ${}^6\text{Li}(n,\alpha)t$ cross section data appears adequate for accurate (of the order of $\sim 1\%$) tritium-breeding calculations.

We emphasize that this observation applies to the class of blanket configurations considered here and that other classes must be examined to determine the generality of the observation.

2. Uncertainties in the cross section and secondary-neutron energy distribution of the ${}^7\text{Li}(n,n'\alpha)t$ reaction attach uncertainties in excess of 5% to the tritium-breeding ratio. A re-evaluation of the relevant data in the energy range above ~ 10 MeV might provide a smaller uncertainty, and we recommend that such a re-evaluation be undertaken. Additional measurements may be required to reduce the uncertainty in the tritium-breeding ratio to the order of 1 to 2%.

3. Correlation between uncertainties in the $(n,2n)$ and (n,n') cross sections of ${}^{93}\text{Nb}$ attach uncertainties of $\sim 3\%$ to the tritium-breeding ratio. New experimental data on the ${}^{93}\text{Nb}(n,2n)$ cross section are available^(12,13) and an evaluation of this data might indicate that the variations adopted here were too conservative. We recommend that such an evaluation be undertaken.

In the subsequent papers we shall examine the cross-section sensitivity of the tritium-breeding ratio in other classes of blanket models.

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Distances in cm	0	150	200	200.5	203.5	204			264	294	300
Origin →	Plasma	Vacuum	Nb	94 % Li 6% Nb	Nb	20 cm	94 % Li 6% Nb 20 cm	20 cm		C	94 % Li 6% Nb
Zone Number	1	2	3	4	5		6		7	8	
Region Number	1	2	3	4	5	6	7	8	9	10	
Material	A	B	C	D	C		D		E	D	
Number of Intervals Per Zone	1	1	3	6	3		30		15	3	
Thickness (cm)	150	50	0.5	3	0.5		60		30	6	

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

Fig. 1. Configuration of the Blanket Model Used in this Study.

Table 1. Nuclide Concentrations for the Materials
of the Blanket Model

Material Code Letter	Constituent	Concentration (atoms/cc)
A	Isotropic source of neutrons	
B	Vacuum	
C	Niobium	0.05556 x 10 ²⁴
	Niobium	0.003334 x 10 ²⁴
D	Lithium-6	0.003234 x 10 ²⁴
	Lithium-7	0.04038 x 10 ²⁴
E	Carbon	0.0804 x 10 ²⁴

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

Nuclide	Identification Number
${}^6\text{Li}$	1115
${}^7\text{Li}$	1116
${}^{93}\text{Nb}$	1164
${}^{12}\text{C}$	1165

Table 3. Neutron Balance and Tritium Breeding by Region of the
Blanket Model for the Reference Cross-Section Data Sets *

Region	(n,2n)	Parasitic Absorptions	T ₆	T ₇	T	System Neutron Leakage
3	0.0574	0.0236				
4	0.0286	0.0105	0.0497	0.0805	0.1302	
5	0.0393	0.0231				
6	0.0800	0.0591	0.3011	0.2807	0.5818	
7	0.0243	0.0488	0.2469	0.1095	0.3564	
8	0.0090	0.0451	0.3079	0.0457	0.3536	
9		0.0149				
10	0.0001	0.0009	0.0635	0.0008	0.0643	
Totals	0.2392	0.2260	0.9691	0.5172	1.4863	0.0440

*Basis: one fusion neutron.

Table 4. Effects of Variations in the
 ${}^6\text{Li}(n,\alpha)t$ Cross Sections

Reaction [*]	Low Pattern	Reference Case	High Pattern
T_6	0.9615	0.9691	0.9764
T_7	0.5174	0.5172	0.5170
T	1.4789	1.4863	1.4934
Fractional Change in $T^{\dagger}$	-0.0050		+0.0048
Total (n,2n)	0.2392	0.2392	0.2390
Niobium Absorptions	0.2067	0.2000	0.1936
Total Parasitic Absorptions ^{**}	0.2328	0.2260	0.2194
Neutron Leakage	0.0447	0.0440	0.0432
Graphite Elastic Scattering	18.1432	17.7231	17.3181

^{*}Basis: one fusion neutron.

[†]Relative to the value for the reference case.

^{**}Includes niobium absorptions.

Table 5. Effects of Variations in the ${}^6\text{Li}(n,\alpha)t$ Cross Sections:
Tritium Breeding Ratios in Lithium-6 by Energy Range

Energy Range (MeV)	Low Pattern		Reference Case	High Pattern	
	T_6	Fractional [*] Change in T_6	T_6	T_6	Fractional [*] Change in T_6
15 - 2	0.0095	-0.095	0.0105	0.0116	+0.105
2 - 0.01	0.5359	-0.032	0.5538	0.5710	+0.031
Below 0.01	0.4161	+0.028	0.4048	0.3938	-0.027
Total T_6	0.9615	-0.008	0.9691	0.9764	+0.008

* Relative to the value for the reference case.

Table 6. Effects of Variations in the ${}^6\text{Li}(n,\alpha)t$ Cross Sections:

Tritium-Breeding Ratios by Region

Region	Low Pattern		Reference Case		High Pattern	
	T_6	T_7	T_6	T_7	T_6	T_7
4	0.0484	0.0805	0.0497	0.0805	0.0510	0.0805
6	0.2948	0.2808	0.3011	0.2807	0.3072	0.2807
7	0.2441	0.1096	0.2469	0.1095	0.2496	0.1094
8	0.3095	0.0457	0.3079	0.0457	0.3063	0.0456
10	0.0647	0.0008	0.0635	0.0008	0.0623	0.0008
Totals	0.9615	0.5174	0.9691	0.5172	0.9764	0.5170

Table 7. Effects of Variations in the
 ${}^7\text{Li}(n,n'\alpha)t$ Cross Sections

Reaction *	Cross Section Reduced (- 20%)	Reference Case	Cross Section Increased (+ 20%)
T_6	0.9722	0.9691	0.9659
T_7	0.4438	0.5172	0.5812
T	1.4160	1.4863	1.5471
Fractional Change in $T^\dagger$	-0.0473		+0.0409
Total (n,2n)	0.2497	0.2392	0.2296
Niobium Absorptions	0.2001	0.2000	0.1998
Total Parasitic Absorptions **	0.2291	0.2260	0.2234
Neutron Leakage	0.0483	0.0440	0.0403
Graphite Elastic Scattering	18.1808	17.7231	17.3150

* Basis: one fusion neutron.

† Relative to the value for the reference case.

** Includes niobium absorptions.

Table 8. Effects of Variations in the ${}^7\text{Li}(n,n'\alpha)t$ Cross Sections:

Tritium Breeding Ratios By Region

Region	Cross Section Reduced (-20%)		Reference Case		Cross Section Increased (+20%)	
	T_5	T_7	T_6	T_7	T_6	T_7
4	0.0493	0.0650	0.0497	0.0805	0.0501	0.0957
6	0.2993	0.2358	0.3011	0.2807	0.3027	0.3214
7	0.2473	0.0984	0.2469	0.1095	0.2464	0.1174
8	0.3115	0.0438	0.3079	0.0457	0.3045	0.0459
10	0.0648	0.0008	0.0635	0.0008	0.0622	0.0008
Totals	0.9722	0.4438	0.9691	0.5172	0.9659	0.5812

Table 9. Probability that the Secondary Neutron
From the ${}^7\text{Li}(n,n'\alpha)t$ Reaction Will Have an
Energy Greater Than 5 MeV

	Probability That $E' > 5$ MeV	
	$E = 14$ MeV	$E = 12$ MeV
Reference $\Theta(E)$ Value	0.61	0.50
$\Theta(E)$ Decreased by 50%	0.37	0.28
$\Theta(E)$ Increased by 50%	0.68	0.65

E' is the energy of the secondary neutron.

E is the energy of the incident neutron.

Table 10. Effects of Variations in the ${}^7\text{Li}(n,n'\alpha)t$
Secondary-Neutron Energy Distribution

Reaction *	$\Theta(E)$ Decreased By 50%	Reference Case	$\Theta(E)$ Increased By 50%
T_6	0.9694	0.9691	0.9691
T_7	0.4805	0.5172	0.5315
T	1.4499	1.4863	1.5006
Fractional Change in $T^\dagger$	-0.0240		+0.0100
Total (n,2n)	0.2375	0.2392	0.2397
Total Parasitic Absorptions **	0.2261	0.2260	0.2260
Neutron Leakage	0.0421	0.0440	0.0447

* Basis: one fusion neutron.

† Relative to the value for the reference case.

** Includes niobium absorptions.

Table 11. The Contribution of the ${}^7\text{Li}(n,n'\alpha)t$
Secondary Neutron to T_7

	$\theta(E)$ Increased By 50%	Reference Case	$\theta(E)$ Decreased By 50%	Secondary Neutron Suppressed
T_7	0.5315	0.5172	0.4805	0.4377
Fraction of T_7 Due to Secondary Neutrons From ${}^7\text{Li}(n,n'\alpha)t$	0.18	0.15	0.09	0.00

Table 12. Effects of Changing Nuclear Temperatures by $\pm 50\%$ in the
Secondary-Neutron Energy Distributions of Several Reactions in Lithium

Case	Reaction	T_6	T_7	T
Reference		0.9691	0.5172	1.4863
$\Theta(E)$ Increased	${}^6\text{Li}(n,2n)\alpha$	0.9691	0.5174	1.4865
$\Theta(E)$ Decreased	${}^6\text{Li}(n,2n)\alpha$	0.9691	0.5171	1.4862
$\Theta(E)$ Increased	${}^6\text{Li}(n,n'\alpha)d$	0.9691	0.5189	1.4880
$\Theta(E)$ Decreased	${}^6\text{Li}(n,n'\alpha)d$	0.9690	0.5127	1.4817
$\Theta(E)$ Increased	${}^7\text{Li}(n,2n)$	0.9691	0.5174	1.4865
$\Theta(E)$ Decreased	${}^7\text{Li}(n,2n)$	0.9690	0.5171	1.4861
$\Theta(E)$ Increased	${}^7\text{Li}(n,2n)\alpha$	0.9691	0.5172	1.4863
$\Theta(E)$ Decreased	${}^7\text{Li}(n,2n)\alpha$	0.9688	0.5172	1.4860

Table 13. Effects of Variations in the $^{93}\text{Nb}(n,2n)$ Cross Section

Reaction *	Cross Section Reduced (- 25%)	Reference Case	Cross Section Increased (+ 25%)
T_6	0.9359	0.9691	1.0002
T_7	0.5431	0.5172	0.4930
T	1.4790	1.4863	1.4932
Fractional Change in $T^\dagger$	-0.0049		+0.0046
Total (n,2n)	0.2007	0.2392	0.2749
Niobium Absorptions	0.1925	0.2000	0.2069
Total Parasitic Absorptions **	0.2198	0.2260	0.2318
Neutron Leakage	0.0451	0.0440	0.0429
Graphite Elastic Scattering	17.4474	17.7231	17.9769

* Basis: one fusion neutron.

† Relative to the value for the reference case.

** Includes niobium absorptions.

Table 14. Effects of Variations in the $^{93}\text{Nb}(n,2n)$ Cross Sections:

Tritium Breeding Ratios By Region

Region	Cross Section Reduced (-25%)		Reference Case		Cross Section Increased (+25%)	
	T_6	T_7	T_6	T_7	T_6	T_7
4	0.0471	0.0828	0.0497	0.0805	0.0522	0.0783
6	0.2880	0.2942	0.3011	0.2807	0.3135	0.2683
7	0.2386	0.1161	0.2469	0.1095	0.2546	0.1031
8	0.2999	0.0491	0.3079	0.0457	0.3154	0.0425
10	0.0623	0.0009	0.0635	0.0008	0.0645	0.0008
Totals	0.9359	0.5431	0.9691	0.5172	1.0002	0.4930

Table 15. Effects of Variations in the $^{93}\text{Nb}(n,n')$ Cross Sections

Reaction *	Cross Section Reduced (- 25%)	Reference Case	Cross Section Increased (+ 25%)
T_6	0.9728	0.9691	0.9656
T_7	0.5488	0.5172	0.4887
T	1.5216	1.4863	1.4543
Fractional Change in $T^{\dagger}$	+0.0238		-0.0215
Total (n,2n)	0.2464	0.2392	0.2321
Niobium Absorptions	0.1993	0.2000	0.2005
Total Parasitic Absorptions **	0.2267	0.2260	0.2252
Neutron Leakage	0.0469	0.0440	0.0413
Graphite Elastic Scattering	18.1901	17.7231	17.3004

* Basis: one fusion neutron.

† Relative to the value for the reference case.

** Includes niobium absorptions.

Table 16. Effects of Variations in the $^{93}\text{Nb}(n,n')$ Cross Sections:

Tritium Breeding Ratios by Region

Region	Cross Section Reduced (-25%)		Reference Case		Cross Section Increased (+25%)	
	T_6	T_7	T_6	T_7	T_6	T_7
4	0.0489	0.0836	0.0497	0.0805	0.0505	0.0777
6	0.2993	0.2966	0.3011	0.2807	0.3028	0.2663
7	0.2479	0.1177	0.2469	0.1095	0.2458	0.1021
8	0.3118	0.0500	0.3079	0.0457	0.3043	0.0418
10	0.0649	0.0009	0.0635	0.0008	0.0622	0.0008
Totals	0.9728	0.5488	0.9691	0.5172	0.9656	0.4887

Table 17. Summary of Cross-Section Sensitivity of Tritium Breeding Calculations

Case	Reaction	T_6	T_7	T	Fractional Change in T [*]
Reference		0.9691	0.5172	1.4863	
Cross Section Reduced	${}^6\text{Li}(n,\alpha)t$	0.9615	0.5174	1.4789	-0.0050
Cross Section Increased	${}^6\text{Li}(n,\alpha)t$	0.9764	0.5170	1.4934	+0.0048
Cross Section Reduced	${}^7\text{Li}(n,n'\alpha)t$	0.9722	0.4438	1.4160	-0.0473
Cross Section Increased	${}^7\text{Li}(n,n'\alpha)t$	0.9659	0.5812	1.5471	+0.0409
$\Theta(E)$ Reduced	${}^7\text{Li}(n,n'\alpha)t$	0.9694	0.4805	1.4499	-0.0240
$\Theta(E)$ Increased	${}^7\text{Li}(n,n'\alpha)t$	0.9691	0.5315	1.5006	+0.0100
Cross Section Reduced	${}^{93}\text{Nb}(n,2n)$	0.9359	0.5431	1.4790	-0.0049
Cross Section Increased	${}^{93}\text{Nb}(n,2n)$	1.0002	0.4930	1.4932	+0.0046
Cross Section Reduced	${}^{93}\text{Nb}(n,n')$	0.9728	0.5488	1.5216	+0.0238
Cross Section Increased	${}^{93}\text{Nb}(n,n')$	0.9656	0.4887	1.4543	-0.0215

* Relative to value for reference case.

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