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CROSS-SECTION SENSITIVITY OF TRITIUM BREEDING IN FUSION REACTOR BLANKETS*

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Abstract

The objective of the present study is the identification of cross-section uncertainties which might produce uncertainties of the order of several percent in the tritium breeding ratio in fusion reactor blankets. The model chosen was the bench-mark configuration specified at the Neutronics Session of the International Working Sessions on Fusion Reactor Technology. Using ENDF/B version 3 cross sections and an S_4-P_3 transport calculation, calculations of the effects of substantial cross section changes were performed both individually and in selected pairs which would leave the total cross section of an isotope unchanged. The cross sections most worth further study were the $^{7}Li(n,n'\alpha)t$, the $^{93}Nb(n,2n)$ and (n,n') reactions.

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INTRODUCTION

The objectives of this study have been to identify cross-section uncertainties which either cast doubt on the tritium breeding potential of a blanket model or show significant uncertainties in the breeding ratio. The identification of such cross-section uncertainties will be used to establish priorities with regard to nuclear needs for the Controlled Thermonuclear Research Program.

The blanket model adopted is the bench-mark configuration specified at the Neutronics session of the International Working Sessions on Fusion Reactor Technology held at ORNL, June 1971.[1] (Fig. 1). This configuration uses liquid lithium of natural isotopic abundance for breeding and graphite for neutron moderation. Leakage from the blanket is about 4% of the source neutrons and the breeding ratio will be about 1.5.

Version 3 of ENDF/B[2,3] was used as the reference for cross-section data. The cross-section processing code XLACS[4] was used to process the ENDF/B-3 data into a broad group energy structure consisting of 99 fast groups and one thermal group. In this paper we examine the effects of uncertainties in the cross sections of ^{6}Li, ^{7}Li, and ^{93}Nb. These effects were evaluated by making substantial changes in the reference data sets. Changes were made both individually and also in selected pairs which would leave the total cross section of an isotope unchanged as indicated in Table 1. The amounts of the changes were suggested by inspection of the evaluators' reports of ENDF/B data together with the reports of the original measurements when necessary. Techniques used for making the changes are described elsewhere.[5] The neutronics calculations were carried out with the discrete ordinates transport theory code XSDRN[6] using an

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 I

Cross Section Data Changes Studied

Calculation No.	Nuclide	Data Changed	Amount of Change
1	^{6}Li	$\sigma(n,\alpha)t$	± (5–10%) as function of energy
2	^{6}Li	Nuclear temperature for $(n,2n)\alpha$ reaction	±50%
3	^{6}Li	Nuclear temperature for $(n,n'\alpha)d$ reaction	±50%
4	^{7}Li	$\sigma(n,n'\alpha)t$	±20%
5	^{7}Li	Nuclear temperature (θ) for $(n,n'\alpha)t$ reaction	±50%
6	^{7}Li	Nuclear temperature for (n,2n) reaction	±50%
7	^{7}Li	Secondary neutrons from $^{7}Li(n,n'\alpha)t$ suppressed	---
8	^{93}Nb	$\sigma(n,2n)$	±25%
9	^{93}Nb	$\sigma(n,n')$	±25%
10	^{6}Li	$\sigma(n,\alpha)t$; σ_s changed to keep σ_T constant	± (0.5–15%) as function of energy
11	^{7}Li	$\sigma(n,n'\alpha)t$; σ_s changed to keep σ_T constant	20%
12	^{93}Nb	$\sigma(n,2n)$; inelastic-to-continuum changed to keep σ_T constant	25%
13	Li and Nb	Cross sections changed to produce "maximum" and "minimum" breeding ratios	
14	C	Substitution of breeder blanket for graphite reflector	

S_4-P_3 approximation in cylindrical geometry. XSDRN also includes a resonance self-shielding calculation by the method of Nordheim which was applied to the niobium capture cross section. A vacuum boundary condition was taken as the righthand 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.

DISCUSSION OF CALCULATIONS

1. Effect of Varying the ^{6}Li(n,α)t Cross Section

This cross section was varied in high and low patterns suggested in the ENDF/B documentation. These patterns were about ±(10-15%) from 20 MeV down to 0.5 MeV, about ±5% down to 0.1 MeV, declining down to ±0.5% at the lowest energies. The scattering cross section was changed to keep σ_T unaltered.

Tables 2 and 3 show an almost symmetrical change in the tritium breeding ratio produced by the high and low pattern. Tritium productions from the ^{7}Li(n,n'α)t reaction are only slightly changed, as expected, rising slightly with the low pattern and falling with the high ^{6}Li cross sections. The fractional change in the total is about 0.3%, reflecting the fact that there is a high degree of compensation resulting from slowing down. That is, as Table 3 shows, neutrons which are not absorbed at high energies in lithium are absorbed at lower energies and conversely. This process is assisted by the graphite of region 9.

Table 2. Effects of variations in the $^{6}Li(n,\alpha)t$ cross sections

Reaction*	Low Pattern	Reference Case‡	High Pattern
T_6	0.9638	0.9691	0.9743
T_7	0.5174	0.5172	0.5170
T	1.4812	1.4863	1.4913
Fractional change in T†	−0.0034	--	+0.0034
Total (n,2n)	0.2396	0.2396	0.2396
Niobium absorptions	0.2046	0.2000	0.1954
Total parasitic absorptions**	0.2308	0.2260	0.2215
Neutron leakage	0.0444	0.0440	0.0435
Graphite elastic scattering	18.0501	17.7231	17.4038

*Basis: one fusion neutron.

‡In all tables "reference case" refers to the benchmark calculation of Ref. 2 with standard cross sections.

†Relative to the value for the reference case.

**Includes niobium absorptions.

Table 3. Effects of variations in the $^{6}Li(n,\alpha)t$ cross sections: tritium breeding ratios in ^{6}Li 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	−0.0952	0.0105	0.0116	+0.1019
2 − 0.01	0.5406	−0.0238	0.5538	0.5666	+0.0231
Below 0.01	0.4138	+0.0222	0.4048	0.3961	−0.0215
Total T_6	0.9639	−0.0054	0.9691	0.9743	+0.0054

*Relative to the value for the reference case.

2. Effect of Varying the $^7Li(n,n'\alpha)t$ Cross Section

In this configuration, the production of tritium from ^7Li is half as large as that from ^6Li. Unlike the $^6Li(n,\alpha)t$ reaction, neutrons are not consumed in this reaction but are available for further reactions, to some extent with ^7Li and certainly with ^6Li. The breeding ratio is noticeably more sensitive to this cross section change than to ^6Li changes. A +20% change produces a 4.3% increase in breeding ratio while a -20% change leads to a reduction of 4.9%. (The scattering cross section was changed correspondingly to keep the total cross section unchanged.) The breeding ratio changes decrease with distance fractionally from the center. Table 4 shows that the (n,2n) reaction rate increases as the ^7Li cross section decreases; the same is true for niobium absorptions, parasitic absorptions, leakage and graphite elastic scattering. The most important result is that the breeding rate is noticeably more sensitive to this cross section change than to the ^6Li changes. When uncompensated changes are made in the $^7Li(n,n',\alpha)t$ cross section (k), the effects are somewhat less with respect to breeding reactions, but somewhat greater with respect to (n,2n), parasitic absorptions, leakage, and elastic scattering. The regional distributions of T_6 and T_7 are almost the same.

3. Effect of Varying the Niobium (n,2n) Cross Section

The changes made were ±25%, with compensating changes in the inelastic-to-continnum cross section. The overall change in breeding was ±2.4%. The effect on breeding from ^7Li is much less than when uncompensated changes are made because the ^7Li reaction in the latter case is in direct competition with the (n,2n) reaction. When compensated

Table 4. Effects of variations in the $^{7}Li(n,n'\alpha)t$ cross sections

Reaction*	Cross Section Reduced (−20%)	Reference Case	Cross Section Increased (+20%)
T_6	0.9718	0.9691	0.9665
T_7	0.4414	0.5172	0.5842
T	1.4132	1.4863	1.5507
Fractional change in T†	−0.0491	--	+0.0435
Total (n,2n)	0.2478	0.2392	0.2320
Niobium absorptions	0.2001	0.2000	0.1998
Total parasitic absorptions**	0.2283	0.2260	0.2238
Neutron leakage	0.0472	0.0440	0.0411
Graphite elastic scattering	18.0787	17.7231	17.4002

*Basis: one fusion neutron.

†Relative to the value for the reference case.

**Includes niobium absorptions.

changes are made, the ^{7}Li reaction is affected only by changes in slowing down pattern. The ^{6}Li reaction is affected slightly more than in Ref. 7, increasing with increase in the ^{93}Nb(n,2n) reaction, while the ^{7}Li reaction behaves conversely.

4. Effect of Making Simultaneous Changes

Making all the changes in ^{6}Li(n,α)t, ^{7}Li(n,n$'$,α)t, and ^{93}Nb(n,2n) reactions simultaneously gives a result which can be computed very closely by combining the changes already noted for each separate effect. The most "optimistic" combination produces a fractional rise of 0.0703 in breeding, while the "pessimistic" assumption leads to a decline of −0.0776.

5. Replacement of Graphite with Breeder Blanket Material

In Fig. 1 the graphite zone is seen to lie between radii of 264 and 294 centimeters. As has been pointed out, the graphite blanket effectively moderates fast neutrons enabling them to be captured by ^{6}Li and lower energies. The breeder blanket material, a mixture of lithium and niobium structure, is not as good a moderator as graphite because of its lower scattering cross section. Use of it in place of graphite causes a rise of about 0.02 in the ^{7}Li tritium production rate but the ^{6}Li tritium reaction has fallen about 0.13 due mainly to increased leakage. While the lithium blanket is inferior to graphite, it is still very effective at damping the effects of the cross section changes, much as the graphite does.

6. Secondary Neutron Distribution Results

The energy distributions of the secondary neutrons from ^{6}Li(n,2n)α, ^{6}Li(n,n$'\alpha$)d, ^{7}Li(n,2n), ^{7}Li(n,2n)α, and ^{7}Li(n,n$'\alpha$)t are described by evaporation models in ENDF/B 3. The breeding ratio was generally insensitive to ±50% changes in the "nuclear temperature" $\theta(E)$ except for the $^7Li(n,n\ \alpha)t$ reaction where the breeding ratio fell 2.5% for low θ was raised. Most of the change in breeding occurred in the ^7Li reaction; ^6Li breeding reactions were unaffected.

At the suggestion of Prof. Herbert Goldstein of Columbia,[8] a case was run in which the secondary neutron from the $^7Li(n,n'\alpha)t$ reaction was suppressed, effectively making it an absorption reaction, to show the importance of the secondary neutron to the ^7Li reaction itself. The result was a 15.4% reduction in tritium production from the $^7Li(n,n'\alpha)t$ reaction.

CONCLUSIONS

(1) The status of $^6Li(n,\alpha)t$ cross-section data appears adequate for tritium breeding calculations of about 1% accuracy for the class of blankets considered here. (Calculations 1, 2, 3, 10, of Table 1.)

(2) Uncertainties in the cross-section and secondary-neutron energy distribution of the $^7Li(n,n'\alpha)t$ reaction correspond to breeding ratio uncertainties of about 5%. A re-evaluation of the relevant data in the energy range above 10 MeV is recommended, and additional measurements may be necessary. (Calculations 4, 5, 6, 11.)

(3) The suppression of secondary neutrons in the $(n,n'\alpha)t$ reaction showed the importance of these to tritium productions in ^7Li as well as ^6Li. (Calculation 7).

(4) Uncertainties in the $^{93}Nb(n,2n)$ and (n,n') reactions (calculations 8, 9, 12) attach uncertainties of about 3% to the breeding ratio; new experimental data may reduce this uncertainty.

(5) If all effects due to changes 10, 11, and 12 are combined as in calculation 13, the fractional uncertainty is over ±7%, a result which can be closely predicted by combining the individual changes as though they acted independently.

(6) Calculation 14, in which the graphite reflector was replaced by breeder material, showed a drop of over 7% in the breeding ratio, clearly showing the graphite reflector's importance.

Table 5. Effects of variations in the ^{93}Nb(n,2n) cross section

Reaction*	Cross Section Reduced (−25%)	Reference Case	Cross Section Increased (+25%)
T_6	0.9322	0.9691	1.0061
T_7	0.5180	0.5172	0.5163
T	1.4502	1.4863	1.5224
Fractional change in T†	−0.0242	--	+0.0243
Total (n,2n)	0.1939	0.2392	0.2848
Niobium absorptions	0.1921	0.2000	0.2078
Total parasitic absorptions**	0.2179	0.2260	0.2340
Neutron leakage	0.0433	0.0440	0.0446
Graphite elastic scattering	17.1831	17.7231	18.2630

*Basis: one fusion neutron.

†Relative to the value for the reference case.

**Includes niobium absorptions.

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