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ADDITIONAL RESULTS CONCERNING CROSS-SECTION SENSITIVITY OF TRITIUM BREEDING IN A FUSION REACTOR BLANKET: EFFECTS OF CROSS SECTIONS OF ^{6}Li, ^{7}Li, AND ^{93}Nb

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ADDITIONAL RESULTS CONCERNING CROSS SECTION SENSITIVITY OF TRITIUM BREEDING IN A FUSION REACTOR BLANKET: EFFECTS OF CROSS SECTIONS OF ^{6}Li, ^{7}Li, AND ^{93}Nb

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Abstract

Previous work concerning cross-section sensitivity of the tritium breeding ratio showed the effects of altering a partial cross section independently of other partial cross sections, permitting the total cross section to rise or fall. The results reported here are mostly for variations made while keeping the total cross section constant. The cases considered were for high and low values of the cross sections for ^{6}Li(n,α)t, ^{7}Li(n,n'α)t, and for ^{93}Nb(n,2n) with compensatory changes in other cross sections. The general conclusions of previous work have been borne out both qualitatively and quantitatively under the present more realistic ground rules. In addition, results are reported for a modified CTR benchmark which has blanket material in place of the graphite reflector. This case shows a drop of 0.13 in ^{6}Li productions, a rise of 0.02 in ^{7}Li productions, and an increase of 0.15 in neutron leakage.

INTRODUCTION

The present study has been conducted by the same methods and on the same CTR configuration as reported in prior reports.[1,2] The earlier work showed the effects of cross section changes made on an individual basis with no compensating changes made in any other cross sections. This approach is not entirely realistic if the aim is to obtain an evaluation of the importance of experimental errors. The total cross section of the nuclides of interest is known with greater certainty than the partial cross sections, some of which are obtained by difference. For instance, the ENDF/B-III[3] data for the scattering cross section of ^{6}Li between 0.7 and 2 MeV is based on the difference between the total and nonelastic cross section, the latter being about 20% uncertain, while the total, judging from the graphs shown by Hibdon and Mooring,[4] shows considerably less dispersion. Similarly, Smith, Whalen, and Guenther[5] in their study of Nb show good to excellent agreement for the total cross section with the ENDF/B-III files but much larger disagreements for the (n,2n) and continuum inelastic cross sections. It was considered worthwhile, therefore, to supplement the previous studies with sensitivity calculations in which compensating changes are supposed. Neutronics calculations have been made with the following changes in cross sections:

a. The $^6Li(n,\alpha)t$ cross section.

Energy Interval (eV)	± Fractional Changes in $^6Li(n,\alpha)t$	Cross Section Changed to Compensate
10^{-5} – 0.1	0.005	σ_T
0.1 – 10^4	0.01	σ_T
10^4 – 10^5	0.01 – 0.02*	σ_s
10^5 – 3×10^5	0.05	σ_s
3×10^5 – 5×10^5	0.05 – 0.1*	σ_s
5×10^5 – 7×10^5	0.1 – 0.15*	σ_s
7×10^5 – 1×10^6	0.15	σ_s
1.0×10^6 – 1.7×10^6	0.15 – 0.1*	σ_s
1.7×10^6 – 2.0×10^7	0.1	σ_s

*Fractional changes in these ranges were made by linear interpolation between the values shown.

(The pattern of cross section changes is that suggested in the ENDF/B documentation as well as by personal discussion with R. J. LaBauve.)

b. The $^7Li(n,n'\alpha)t$ cross section was changed by ±20%. The scattering cross section was changed to compensate, leaving the total cross section unchanged.

c. The niobium (n,2n) cross section was changed by ±25%. The inelastic-to-continuum cross section was changed to compensate, leaving the total cross section unchanged.

d. A "combination" set of cases was run in which changes a, b, and c were made together so as to produce "maximum" and "minimum" tritium breeding rates.

e. The importance of the graphite moderator was examined by replacing it with breeder blanket material in the calculation. Both standard cross sections and the ^{6}Li patterns of a. above were used.

DISCUSSION OF CALCULATIONS

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

Table 1 shows an almost symmetrical change in the TBR (Tritium Breeding Ratio) produced by the high and low pattern. As might be expected, the effect on T_7 ($^{7}Li(n,n'\alpha)t$ productions)* is quite small, 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, neutrons which are not absorbed at high energies in lithium are absorbed at lower energies and conversely, as seen in Table 2. A similar point is made by Table 3 where the outer regions 8** and 10 actually have higher (lower) total values of T_6 with lower (higher) cross sections. Part of those neutrons which escaped capture at higher energies in the inner regions have been slowed down and captured in the outer regions. This process is assisted by the graphite of region 9, a subject which will be further discussed below.

While not strictly comparable, the effects produced by the cross section changes here are similar to those obtained earlier[2] where this cross section is altered independently of other cross sections.

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

T_7 is, in this configuration, half as large a source of tritium as T_6. Unlike the $^{6}Li(n,\alpha)t$ reaction, neutrons are not consumed in this reaction but are available for further reactions, to some extent with ^{7}Li, and certainly with ^{6}Li. In the 100-group structure employed in this work, all of this reaction occurs in groups 1-17 (>2.7253 MeV) while about 1 % of the ^{6}Li reaction occurs in this range (see Table 4). The $^{7}Li(n,n'\alpha)t$

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*Correspondingly, $^{6}Li(n,\alpha)t$ tritium productions are labeled T_6.

**See Fig. 1 for identification of regions.

Distances in cm: 0, 150, 200, 200.5, 203.5, 204, 264, 294, 300

Origin → 0

	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

<u>Comment</u>: 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. Effects of variations in the $^6Li(n,\alpha)t$ 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	0.2213
Neutron leakage	0.0444	0.0440	0.0435
Graphite elastic scattering	18.0501	17.7231	17.4038

x 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 2. Effects of variations in the $^6Li(n,\alpha)t$ cross sections: tritium breeding ratios in ^6Li 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	0.9638	−0.0054	0.9691	0.9743	+0.0054

*Relative to the value for the reference case.

Table 3. Effects of variations in the $^6Li(n,\alpha)t$ 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	0.2955	0.2808	0.3011	0.2807	0.3066	0.2806
7	0.2451	0.1096	0.2469	0.1095	0.2486	0.1095
8	0.3102	0.0457	0.3079	0.0457	0.3056	0.0457
10	0.0646	0.0008	0.0635	0.0008	0.0624	0.0008
Totals	0.9638	0.5174	0.9691	0.5172	0.9743	0.5170

Table 4. Energy distribution of $^7Li(n,n'\alpha)t$ reaction (T_7) for the benchmark with standard cross sections

Group	Group Upper Energy (MeV)	Fraction of T_7
1	14.92	0.4373
2	13.5	0.1298
3	12.2	0.0660
4	11.0	0.0741
5	10.0	0.0609
6	9.05	0.0505
7	8.19	0.0445
8	7.4	0.0391
9	6.7	0.0338
10	6.1	0.0286
11	5.49	0.0197
12	4.97	0.0093
13	4.49	0.0036
14	4.06	0.0015
15	3.68	0.0008
16	3.33	0.0003
17	3.01	0.0001
18	2.72	--

cross section variation results are shown in Tables 5 and 6. As with the ^{6}Li changes, the changes in breeding rate are fairly symmetric. Raising the cross section produced an increase of 4.3% in T, while lowering it reduced it by 4.9%. Although the total cross sections are the same, the change in T_7 is less than proportional to the cross section change. The (n,2n) reaction rate increases (decreases) somewhat as the ^{7}Li cross section decreases (increases). The same is true for the niobium absorptions, parasitic absorptions, leakage, and graphite elastic scattering. The most important result, however, is that the breeding rate is noticeably more sensitive to this cross section change than to the ^{6}Li changes. Table 6 shows that the sensitivity decreases percentagewise with distance from the center. It is interesting to note that the T_6 value increases (decreases) with increased (decreased) ^{7}Li cross section in the inner regions, the trend reversing by region 7. This phenomenon is due to alteration in slowing down with changes in the ^{7}Li inelastic cross section. Lowering the ^{7}Li cross section causes an increase in elastic scattering which is less effective than inelastic in reducing neutron energy, but at the same time the (n,2n) reaction in Nb increases. The interplay of these effects produces the results shown. The effects produced by the uncompensated changes in the ^{7}Li(n,n'α)t cross section reported in Ref. 2 are somewhat less as far as T_6 and T_7 are concerned, and 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 results of ±25% changes in the (n,2n) cross section of ^{93}Nb are shown in Tables 7 and 8. To keep the total cross section constant, the inelastic-to-continuum cross section was changed by a compensating amount. Overall, the fractional change in T is ±2.4%. The effect on T_7 is minor, in contrast to the results of Ref. 2. There, the ^{7}Li

Table 5. 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†	−0.0492	--	+0.0433
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.

Table 6. Effects of variations in the $^{7}Li(n,n'\alpha)t$ cross sections: tritium breeding ratios by region

Region	Cross Section Reduced (−20%)		Fractional Change in	Reference Case		Cross Section Increased (+20%)		Fractional Change in
	T_6	T_7	T_7*	T_6	T_7	T_6	T_7	T_7*
4	0.0494	0.0653	(−0.19)	0.0497	0.0805	0.0500	0.0953	(0.18)
6	0.2998	0.2356	(−0.16)	0.3011	0.2807	0.3023	0.3217	(0.15)
7	0.2473	0.0972	(−0.11)	0.2469	0.1095	0.2465	0.1189	(0.09)
8	0.3107	0.0425	(−0.07)	0.3079	0.0457	0.3052	0.0474	(0.04)
10	0.0645	0.0008	0	0.0635	0.0008	0.0625	0.0009	0
Totals	0.9718	0.4414	(−0.15)	0.9691	0.5172	0.9665	0.5842	(0.13)

*Fractional change in T_7 = [T_7 (perturbed) − T_7 (reference)]/T_7 (reference) by region.

Table 7. 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†	−0.0243	--	+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.

Table 8. Effects of variations in the $^{93}Nb(n,2n)$ 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	0.0474	0.0807	0.0497	0.0805	0.0520	0.0803
6	0.2885	0.2812	0.3011	0.2807	0.3138	0.2802
7	0.2376	0.1096	0.2469	0.1095	0.2562	0.1094
8	0.2972	0.0457	0.3079	0.0457	0.3186	0.0456
10	0.0614	0.0008	0.0635	0.0008	0.0655	0.0008
Totals	0.9322	0.5181	0.9691	0.5172	1.0061	0.5163

reaction was in direct competition with the (n,2n) reaction; here the ^{7}Li reaction rate is affected by the change in slowing down pattern produced by a rise (fall) in the ^{93}Nb inelastic scattering cross section as the (n,2n) cross section falls (rises). The effect on T_6 is slightly larger than before, as are all other reactions beside T_7 in Table 7. Table 8 is quite similar both qualitatively and quantitatively to the corresponding Table 14 in Ref. 2, except for the insensitivity of the ^{7}Li reaction to this change. In every region, the T_6 values increase (decrease) with increase (decrease) in the ^{93}Nb(n,2n) reaction, while the T_7 values behave conversely.

4. The "Combination" Cases – The Effect of Simultaneous Changes

The results of making all the above mentioned changes in ^{6}Li(n,α)t, ^{7}Li(n,n'α)t and ^{93}Nb(n,2n) reactions is displayed in Tables 9 and 10. The fractional change computed is almost the result of combining the three effects independently. That is, from the previous results, one might estimate the result of making the three positive changes simultaneously as

$$(1 + 0.0243)(1 + 0.0433)(1 + 0.0034) - 1 = + 0.0723$$

and of the three negative changes as

$$(1 - 0.0242)(1 - 0.0491)(1 - 0.0034) - 1 = - 0.0753.$$

These are to be compared with the calculated result of +0.0703 and −0.0776 respectively.

Table 10 shows that the effects of the cross-section changes weaken with increasing radius. It is interesting to note that there is a slight decline in T_6 for region 10 for the optimistic (i.e., high) cross-section set.

5. Replacement of Graphite with Breeder Blanket Material

Figure 1 shows the blanket model of the CTR benchmark configuration. The graphite zone lies between radii of 264 and 294 centimeters. As has been pointed out earlier,[2] the graphite blanket effectively moderates fast neutrons enabling them to be captured by ^{6}Li at lower energies. The

Table 9. Effects of variations in all cross sections

Reaction*	Cross Section Reduced	Reference Case	Cross Section Increased
T_6	0.9287	0.9691	1.0077
T_7	0.4423	0.5172	0.5831
T	1.3710	1.4863	1.5908
Fractional change in T†	−0.0776	--	+0.0703
Total (n,2n)	0.2008	0.2392	0.2764
Niobium absorptions	0.1965	0.2000	0.2027
Total parasitic absorptions**	0.2247	0.2260	0.2268
Neutron leakage	0.0470	0.0440	0.0413
Graphite elastic scattering	17.8365	17.7231	17.5941

*Basis: one fusion neutron.

†Relative to the value for the reference case.

**Includes niobium absorptions.

Table 10. Effects of variations in all cross sections: tritium-breeding ratios by region

Region	Cross Section Reduced				Reference Case		Cross Section Increased			
	T_6	$\frac{T_6 - T_6^\circ}{T_6^\circ}$	T_7	$\frac{T_7 - T_7^\circ}{T_7^\circ}$	T_6°	T_7°	T_6	$\frac{T_6 - T_6^\circ}{T_6^\circ}$	T_7	$\frac{T_7 - T_7^\circ}{T_7}$
4	0.0458	−0.08	0.0655	−0.19	0.0497	0.0805	0.0536	0.08	0.0951	0.18
6	0.2816	−0.06	0.2361	−0.16	0.3011	0.2807	0.3204	0.06	0.3211	0.14
7	0.2360	−0.04	0.0973	−0.11	0.2469	0.1095	0.2572	0.04	0.1187	0.08
8	0.3018	−0.02	0.0425	−0.07	0.3079	0.0457	0.3131	0.02	0.0473	0.04
10	0.0635	−0.00	0.0008	−0.06	0.0635	0.00085	0.0633	−0.003	0.00086	0.02
Totals	0.9827	−0.014	0.4423	−0.14	0.9691	0.5172	1.0077	0.04	0.5831	0.13

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. At 1 MeV, for instance, $\xi\Sigma_s$ for lithium is about 0.02 while that for graphite is about 0.03.

Tables 11 through 13 indicate the importance of the graphite. In Table 11 it is seen that the elastic scatterings in zone 7 have been reduced about sevenfold. There is a rise of about 0.02 in the ^{7}Li tritium production rate, but the ^{6}Li production of tritium has dropped by ~0.13, due primarily to a neutron leakage increase. Table 12 shows an increase of 0.07 in ^{6}Li absorptions from 15 to 0.01 MeV but below that energy, the rate has been cut in two for a net loss of 0.13. Table 13 shows the effect by regions; regions 8 and 10 which were nearest the graphite have suffered a sharp drop in T_6 not made up by the presence of breeder region 9. The ^{7}Li production in regions 8 and 10 is only slightly affected since the $(n,n'\alpha)t$ reaction is at high energies. The ^{7}Li added by region 9 serves to increase the production but not enough to overcome the drop in T_6.

As for the change in $^6Li(n,\alpha)t$ cross sections, the calculated results show an almost symmetrical variation (Table 11) between 1.37 and 1.38+. The ^{7}Li production is only slightly affected.

The graphite zone clearly improves the blanket neutron economy. The lithium blanket is not quite as good a moderator as the graphite, but still very effective at damping the effects of the cross section changes, much as the graphite does.

CONCLUDING REMARKS

Table 14 gives a summary of all the results for tritium production in the present study. The general conclusions of Ref. 2 have been borne out both qualitatively and quantitatively with the more realistic ground rules used. The ^{6}Li data still appears adequate and the motivation for improving the ^{7}Li and $^{93}Nb(n,2n)$ data still exist.

Table 11. Benchmark without graphite — effects of variations in the $^6Li(n,\alpha)t$ cross sections

Reaction*	Low Pattern	Reference Case: Without Graphite	Reference Case: With Graphite	High Pattern
T_6	0.8274	0.8366	0.9691	0.8456
T_7	0.5402	0.5401	0.5172	0.5399
T	1.3676	1.3767	1.4863	1.3855
Fractional change in T†	−0.0066	--	--	+0.0064
Total (n,2n)	0.2438	0.2438	0.2392	0.2438
Niobium absorptions	0.2084	0.2034	0.2000	0.1985
Total parasitic absorptions**	0.2198	0.2148	0.2260	0.2099
Neutron leakage	0.1961	0.1919	0.0440	0.1877
Elastic scattering in zone 7	--	2.423	17.7231	--

*Basis: one fusion neutron.

†Relative to the value for the reference case without graphite.

**Includes niobium absorptions.

Table 12. Benchmark without graphite — effects of variations in the $^6Li(n,\alpha)t$ cross sections: tritium breeding ratios in ^6Li by energy range

Energy Range (MeV)	Low Pattern: T_6	Low Pattern: Fractional* Change in T_6	Reference Case T_6: Without Graphite	Reference Case T_6: With Graphite	High Pattern: T_6	High Pattern: Fractional* Change in T_6
15 − 2	0.0100	−0.0991	0.0111	0.0105	0.0122	+0.0991
2 − 0.01	0.6054	−0.0221	0.6191	0.5538	0.6323	+0.0213
Below 0.01	0.2120	+0.0266	0.2065	0.4048	0.2011	−0.0262
Total T_6	0.8274	−0.0110	0.8366	0.9691	0.8457	+0.0109

*Relative to the value for the reference case without graphite.

Table 13. Benchmark without graphite — effects of variations in the $^6Li(n,\alpha)t$ cross sections: tritium-breeding ratios by region

Region	Low Pattern		Reference Case				High Pattern	
			T_6		T_7			
	T_6	T_7	Without Graphite	With Graphite	Without Graphite	With Graphite	T_6	T_7
4	0.0472	0.0805	0.0485	0.0497	0.0805	0.0805	0.0498	0.0805
6	0.2844	0.2807	0.2902	0.3011	0.2806	0.2807	0.2958	0.2806
7	0.2184	0.1094	0.2206	0.2469	0.1094	0.1095	0.2227	0.1093
8	0.1503	0.0451	0.1512	0.3079	0.0450	0.0457	0.1515	0.0450
9	0.1176	0.0228	0.1172	--	0.0228	--	0.1168	0.0228
10	0.0090	0.0017	0.0089	0.0635	0.0017	0.0008	0.0089	0.0017
Totals	0.8274	0.5402	0.8366	0.9691	0.5401	0.5172	0.8456	0.5399

Table 14. Summary of all tritium breeding sensitivity results in the present study

Case	Reaction	T_6	T_7	T	Fractional* Change in T
Reference		0.9691	0.5172	1.4863	
Cross section reduced	$^6Li(n,\alpha)t$	0.9638	0.5174	1.4812	−0.0034
Cross section increased	$^6Li(n,\alpha)t$	0.9743	0.5170	1.4913	+0.0034
Cross section reduced	$^7Li(n,n'\alpha)t$	0.9718	0.4414	1.4132	−0.0492
Cross section increased	$^7Li(n,n'\alpha)t$	0.9665	0.5842	1.5507	+0.0433
Cross section reduced	$^{93}Nb(n,2n)$	0.9322	0.5180	1.4502	−0.0243
Cross section increased	$^{93}Nb(n,2n)$	1.0061	0.5163	1.5224	+0.0243
All above cross sections reduced	---	0.9287	0.4423	1.3710	−0.0776
All above cross sections increased	---	1.0077	0.5831	1.5908	+0.0703
Cross section reduced (without graphite)	$^6Li(n,\alpha)t$	0.8274	0.5402	1.3676	−0.0066
Cross section increased (without graphite)	$^6Li(n,\alpha)t$	0.8456	0.5399	1.3855	+0.0064
Reference (without graphite)		0.8366	0.5401	1.3767	--

*Relative to the value for the reference case.

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