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SCOPING NUCLEONIC STUDIES FOR THE RIGGATRON FUSION REACTOR CONCEPT

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Results of S_N and Monte Carlo one-dimensional neutron/gamma-ray transport calculations for conceptual designs of the INESCO RIGGATRON, a Tokamak device using ohmic heating to induce fusion, are detailed. Using various plasma, coil, and blanket configurations, a comparative analysis of cross-section sets is first performed. Scoping calculations of tritium breeding ratios, absorptions, leakages, and neutron/gamma-ray heating are detailed using both multigroup discrete-ordinates and Monte Carlo techniques. Results of this analysis not only serve to provide preliminary design parameters, but also indicate relative degree of consistency among various cross-section sets. Consistency between S_N and Monte Carlo techniques is similarly demonstrated. Results of this one-dimensional compilation also suggest a two-dimensional RIGGATRON model for related study.

INTRODUCTION

We have undertaken a series of one- and two-dimensional neutron/gamma-ray transport calculations for the INESCO RIGGATRON, a small Tokamak device employing high field, ohmic heating to induce deuterium-tritium fusion. As seen in Fig. 1, the RIGGATRON consists of a small, offcenter, D-T plasma zone surrounded by essentially concentric void, copper coil, lithium blanket, and graphite reflector regions. Of conceptual design interest are the blanket tritium breeding ratios, [i.e., $^6Li(n,t)$, $^7Li(n,n't)$] leakages, absorptions, and neutron/gamma heating in various regions and materials. In this report, we give only the results of a comparative one-dimensional study of the RIGGATRON for various plasma, coil, blanket, and reflector configurations. Two-dimensional calculations are under way and will be reported later. The one-dimensional calculations were performed with the diffusion synthetic, S_N code, ONETRAN-DA,[1] and the corresponding two-dimensional calculations with the triangular mesh, S_N code, TRIDENT-CTR.[2]

One task consisted of evaluation of various coupled neutron/gamma-ray cross-section sets and choice of an adequate file from among them to be

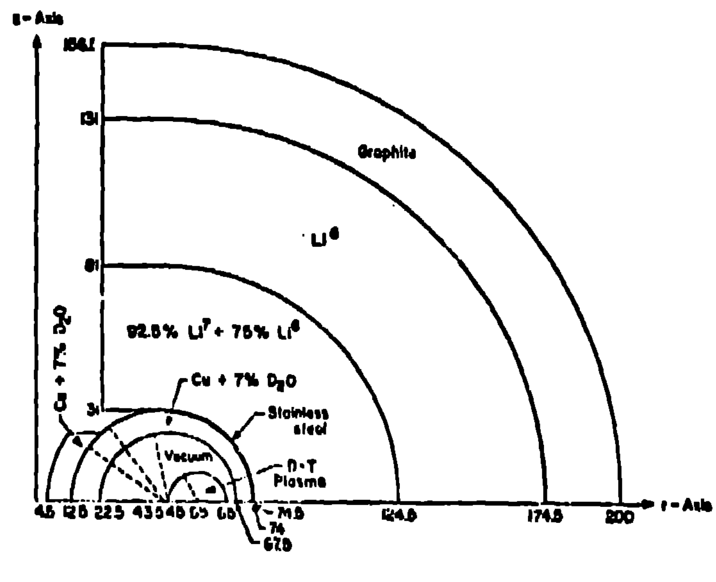

Fig. 1. Two-dimensional RIGGATRON (dimensions in cm).

*Work performed under the auspices of the U. S. Department of Energy.

used in subsequent one- and two-dimensional transport calculations. Libraries tested included the LASL-SAND (30 x 12)[3] set, the CTR (101 x 21)[4] set [collapsed from the VITAMIN-C (171 x 36)[5] file], the LASL-NJOY (30 x 12)[6] set, and the new MATXS (30 x 12)[7] set. Choice of the MATXS set was eventually made following overlapping calculations with other sets.

The actual one-dimensional models of the RIGGATRON investigated varied in plasma, coil, and blanket thickness. Additionally, effects of neutron multiplication (n,2n reaction) in a molybdenum liner and coolant effects (7% H_2O and D_2O in copper and molybdenum) on the breeding ratios, leakages, and absorptions were also noted. In further extension, a graphite reflector was added and a void introduced between the coil and the blanket to enhance tritium breeding and reduce neutron leakage. Neutron and gamma-ray heating calculations were performed in the latter design cases. In all cases, an isotropic 14-MeV source of neutrons was assigned to the plasma void region. An S_8 quadrature set and P_3 cross-section expansion were retained consistently for the one-dimensional cylindrical computations. Vacuum boundary conditions were assigned to the blanket or reflector edge and the usual reflective (symmetrical) conditions were applied at the origin. The neutron source in the plasma was normalized to unity.

As a cross check on the S_N approach, a corresponding Monte Carlo calculation was completed for a set of plasma, coil, and blanket parameters. Agreement between one-dimensional Monte Carlo and S_N predictions of breeding and leakage is good, within four percent for the cases considered.

While one-dimensional cylindrical calculations provide good relative estimates of breeding, heating, leakage, etc., they cannot expressly account for toroidal geometric effects and asymmetry in blanket and coil design. For these reasons, a followup two-dimensional toroidal (r,z) calculation is presently under way using the S_N triangular mesh code, TRIDENT-CTR.[2] The two-dimensional model of the RIGGATRON is shown in Fig. 1. Use of a triangular mesh greatly facilitates contouring of material and device boundaries. Our one-dimensional study does indicate feasible breeding ratios in excess of one, so that two-dimensional refinements are additionally warranted.

CROSS-SECTION COMPARISONS

Coupled neutron/gamma-ray cross sections were available from the LASL-SAND (30 x 12),[3] CTR (101 x 21),[4] LASL-NJOY (30 x 12),[6] and MATXS (30 x 12)[7] libraries. The LASL-SAND (30 x 12) set is a number of years older than the other three and is based primarily on ENDF/B-II and ENDF/B-III data. The other three libraries were processed more recently, primarily from ENDF/B-IV data. Because of the importance of tritium breeding in both ^6Li and ^7Li, it was thought that the latest processed cross sections based on ENDF/B-IV evaluations would probably be most desirable, particularly for the lithium. Since the extent of differences in the above libraries was not immediately known, we performed groups of overlapping calculations for fixed RIGGATRON parameters in an attempt to evaluate overall library consistency.

In these comparisons, we fixed the plasma radius at 22.5 cm, coil thickness at 10 cm, and blanket (natural lithium) thickness at either 100 cm or 0 cm (no blanket). Full dense and cooled (7% H_2O) copper coils are also treated. Table 1 lists ^6Li and ^7Li breeding ratios (T_6 and T_7), neutron leakage (L), and copper absorption (A_{Cu}) computed with the LASL-SAND (30 x 12), LASL-NJOY (30 x 12), and CTR (101 x 21) coupled sets. Close agreement is seen in the predictions of the LASL-NJOY (30 x 12) and CTR (101 x 21) sets. Relative consistency between the three libraries is good, with most differences occurring in the ^6Li breeding ratio, T_6. Absorption due to the water produces about a 20% reduction in the sum of breeding plus leakage (T + L) for all sets.

A second comparison of the CTR (101 x 21), LASL-NJOY (30 x 12) and MATXS (30 x 12) cross-section sets was made with the same RIGGATRON parameters used in Table 1, both for full dense

TABLE 1. Cross-Section Comparison of LASL-SAND (30 x 12), LASL-NJOY (30 x 12), and CTR (101 x 21) Sets

r (Plasma) (cm)	Δr (Cu) (cm)	Δr (Li) (cm)	T_6	T_7	T	L	T + L	A_{Cu}	Coolant	Library
22.5	10.0	100.0	0.587	0.128	0.715	0.146	0.861	a	7% H_2O	SAND
			0.714	0.118	0.832	0.191	1.023	a	none	(30 x 12)
			0.643	0.135	0.778	0.182	0.960	a	7% H_2O	NJOY
			0.801	0.126	0.927	0.252	1.177	a	none	(30 x 12)
			0.640	0.138	0.778	0.182	0.960	0.507	7% H_2O	CTR
			0.760	0.128	0.888	0.257	1.145	0.325	none	(100 x 21)
22.5	10.0	-	-	-	-	0.917	-	a	7% H_2O	SAND
			-	-	-	1.110	-	a	none	(30 x 12)
			-	-	-	0.884	-	a	7% H_2O	NJOY
			-	-	-	1.081	-	a	none	(30 x 12)
			-	-	-	0.932	-	0.402	7% H_2O	CTR
			-	-	-	1.119	-	0.231	none	(100 x 21)

[a] Comparative pure absorption cross sections were not available.

and H_2O cooled copper. The entries have been rearranged to permit closer comparison. The overall consistency, as exhibited in Table 2, is excellent, with agreement within 5% for all cases. Since these libraries all represent recent evaluations, agreement is reasonably expected.

The larger CTR (101 x 21) file would afford maximum resolution for these calculations, but this advantage comes at the expense of three to four times increase in actual computing time. Use of theCTR (101 x 21) set in a two-dimensional calculation would be prohibitive. Because of accessibility, timeliness and overall degree of consistency with earlier evaluations, we rely mostly upon the MATXS (30 x 12) neutron/gamma-ray set for the bulk of the one- and two-dimensional calculations.

CONCEPTUAL DESIGN COMPARISONS

For initial analysis, six cylindrical RIGGATRON configurations consisting of a central D-T plasma, water cooled (7%) copper coil, and molybdenum liner (neutron multiplier) and natural lithium (92.5% ^{7}Li + 7.5% ^{6}Li) blanket were chosen. An isotropic source of 14-MeV neutrons, normalized to unity, was placed in the plasma. Vacuum boundary conditions were assigned at the blanket and reflecting boundary conditions at the origin. An S_8 quadrature and P_3 cross-section expansion were employed in the calculations. The LASL-SAND (30 x 12) coupled neutron/gamma-ray set was used in this scoping compilation, shown in Table 3, because it was most readily available at the time. The negative absorptions in molybdenum result from net neutron multiplication via the (n,2n) reaction. The corresponding cross sections, of course, are not pure absorption cross sections.

Although the molybdenum affords net neutron multiplication, it is clear from Table 3 that corresponding increases in copper and molybdenum absorption tend to offset both tritium breeding and leakage, particularly as the thickness of the molybdenum liner increases. The absorptions in both copper and molybdenum increase with thickness. From Table 1, one expects the breeding ratios given in Table 3 to be somewhat low. Nonetheless, Table 3 still provides a base line.

TABLE 2. Cross-Section Comparison of CTR (101 x 21), LASL-NJOY (30 x 12), and MATXS (30 x 12) Sets

r (Plasma) (cm)	Δr (Cu) (cm)	Δr (Li) (cm)	T_6	T_7	T	L	T + L	A_{Cu}	Library	Coolant
22.5	10.0	100.0	0.640	0.139	0.778	0.182	0.960	0.507	CTR (101 x 21)	
			0.637	0.132	0.769	0.182	0.951	a	MATXS (30 x 12)	
			0.638	0.135	0.773	0.182	0.955	a	NJOY (30 x 12)	
22.5	10.0	-	-	-	-	0.932	-	0.402	CTR (101 x 21)	7% H_2O Coil
			-	-	-	0.914	-	a	MATXS (30 x 12)	
			-	-	-	0.884	-	a	NJOY (30 x 12)	
22.5	10.0	100.0	0.760	0.128	0.888	0.257	1.145	0.325	CTR (101 x 21)	
			0.757	0.123	0.880	0.249	1.129	a	MATXS (30 x 12)	
			0.801	0.126	0.927	0.252	1.179	a	NJOY (30 x 12)	none
22.5	10.0	-	-	-	-	1.119	-	0.231	CTR (101 x 21)	
			-	-	-	1.096	-	a	MATXS (30 x 12)	
			-	-	-	1.081	-	a	NJOY (30 x 12)	

[a]Comparative pure absorption cross sections were not available.

Table 3. Comparative Breeding, Leakage, and Absorption for RIGGATRON (7% H_2O Coolant)

r (Plasma) (cm)	Δr (Mo) (cm)	Δr (Cu) (cm)	Δr (Li) (cm)	T_6	T_7	T	L	T + L	A_{Mo}	A_{Cu}
22.5	-	10.0	100.0	0.587	0.128	0.715	0.146	0.861	-	0.208
22.5	2.0	10.0	100.0	0.550	0.094	0.644	0.127	0.771	-0.075	0.343
22.5	4.0	10.0	100.0	0.483	0.070	0.553	0.105	0.658	-0.032	0.395
22.5	4.0	15.0	100.0	0.240	0.025	0.265	0.060	0.325	-0.015	0.619
15.0	2.0	7.0	100.0	0.690	0.159	0.849	0.185	1.034	-0.109	0.164
15.0	2.0	10.0	100.0	0.569	0.098	0.667	0.138	0.805	-0.090	0.326

As an alternative to H_2O as coolant, D_2O absorbs fewer neutrons. Quantitatively, Table 4 exhibits the comparative effects of using H_2O, D_2O, and no coolant in the copper coil and molybdenum liner. As expected, significant decreases in absorption and increases in blanket breeding (10%-15%) are effected by substituting D_2O for H_2O as coolant.

Introduction of a void between the coil and blanket conceivably enhances the blanket reabsorption probability for neutrons initially backscattered from the blanket. Without a streaming void, a larger percentage of backscattered neutrons would be absorbed in the copper coil. To demonstrate this effect, a void of 300 cm is introduced between coil and blanket. Table 5 lists the corresponding predictions. Gains in the tritium breeding ratios and losses in leakage are apparent. An overall gain of approximately 15% in the sum of breeding plus leakage is noted in both cases (7% H_2O coolant, no coolant).

Lastly, we consider the effects of a graphite reflector outside the blanket. The central plasma is now taken to be 22.5 cm, the copper coil 7 cm and 10 cm thick, the void 200 cm thick, the blanket 100 cm thick, and the graphite reflector 25 cm thick. The S_8 quadrature and P_3 cross sections are again used from the MATXS file. Table 6 gives the results, assuming 5% D_2O coolant in the copper. Neutron (n) and gamma (γ) heating in the copper, lithium and carbon are also listed in the last six columns (MeV). Fairly large (greater than 1.10) breeding ratios are seen. The bulk of the neutron heating occurs in the blanket, while most of the gamma-ray heating takes place in the copper coil. The neutron/gamma-ray kerma factors account for both neutron/gamma-ray energy deposition. Effectively, in the two cases seen, graphite enhances breeding by reduction of leakage.

This one-dimensional study indicates possible tritium breeding ratios in the neighborhood of 1.10, realistically using D_2O as coolant. Introduction of a void space between the coil and blanket, and a graphite reflector, considerably enhances computed breeding ratios. The calculations are sensitive to the thickness of the copper coil, presence or nonpresence of H_2O or D_2O coolant, and thickness of molybdenum multiplier. Plasma radii ranged from 15 cm to 22.5 cm, copper coil thicknesses from 7 cm to 15 cm, molybdenum liners from 2 cm to 4 cm, and coil-blanket voids from 200 cm to 300 cm. The blanket thickness was fixed at 100 cm and the reflector thickness at 25 cm.

MONTE CARLO COMPARISONS

As an additional check on the cross sections as well as the discrete-ordinates calculational model, a continuous energy Monte Carlo calculation (NCMP code)[8] was performed. This Monte Carlo calculation duplicated the one-dimensional discrete-ordinates calculation for a 22.5-cm radius plasma, 7-cm-thick

TABLE 4. Comparative Breeding, Leakage, and Absorption for RIGGATRON (7% H_2O, D_2O, and No Coolant; MATXS Library)

r (Plasma) (cm)	Δr (Mo) (cm)	Δr (Cu) (cm)	Δr (Li) (cm)	T_6	T_7	T	L	T + L	A_{Mo}	A_{Cu}	Coolant
22.5	-	10.0	100.0	0.587	0.128	0.715	0.146	0.861	-	0.208	7% H_2O
				0.658	0.128	0.786	0.172	0.958	-	0.097	7% D_2O
				0.714	0.118	0.832	0.191	1.023	-	0.012	none
22.5	2.0	10.0	100.0	0.550	0.094	0.644	0.127	0.771	-0.075	0.343	7% H_2O
				0.649	0.095	0.744	0.158	0.902	-0.127	0.243	7% D_2O
				0.734	0.087	0.821	0.184	1.005	-0.169	0.166	none
15.0	2.0	7.0	100.0	0.690	0.159	0.849	0.185	1.034	-0.109	0.154	7% H_2O
				0.773	0.160	0.933	0.216	1.149	-0.159	0.086	7% D_2O
				0.828	0.150	0.978	0.236	1.214	-0.159	0.038	none

TABLE 5. Comparative Breeding, Leakage, and Absorption for RIGGATRON with Void Between Coil and Blanket (7% H_2O, No Coolant; MATXS Library)

r (Plasma) (cm)	Δr (Coil) (cm)	Δr (Void) (cm)	Δr (Blanket) (cm)	T_6	T_7	T	L	T + L	Coolant
22.5	10.0	-	100.0	0.643	0.135	0.778	0.182	0.960	
		300.0	100.0	0.739	0.139	0.878	0.159	1.037	7% H_2O
		-	-				0.914		
22.5	10.0	-	100.0	0.757	0.123	0.880	0.248	1.129	
		300.0	100.0	0.874	0.129	1.003	0.205	1.200	none
		-	-				1.096		

copper coil, and a 1-m-thick natural Li blanket. All calculations of tritium breeding and neutron leakage were performed to a relative standard deviation of 1%. Table 7 shows results of comparisons among various cross-section sets, where the MATXS library was processed from ENDF-IV. Here we have a direct comparison of the MATXS library with a calculation using its progenitor ENDF-IV pointwise library. The comparison includes errors due to more than just cross-section processing, such as those inherent in the discrete ordinates approximation, and the statistical error in the Monte Carlo results. However, the net result in all cases agrees to within 4% for both tritium breeding and leakage. We thus adopted the 30 x 12-group MATXS library for all further multigroup analysis.

TABLE 6. Comparative Breeding, Leakage, Absorption, and Heating for RIGGATRON with Void and Reflector (7% D_2O Coolant; MATXS Library)

r (Plasma) (cm)	Δr (Coil) (cm)	Δr (Void) (cm)	Δr (Blanket) (cm)	Δr (Graphite) (cm)	T_6	T_7	T	L	T + L
22.5	7.0	200.0	100.0	25.0	1.081	0.229	1.310	0.004	1.314
22.5	10.0	200.0	100.0	25.0	0.969	0.139	1.108	0.003	1.111

Q^n_{Cu}	Q^γ_{Cu}	Q^n_{Li}	Q^γ_{Li}	Q^n_C	Q^γ_C
1.09	6.11	7.69	1.03	0.03	0.16
1.34	8.55	6.22	0.75	0.02	0.13

TABLE 7. Comparison of Monte Carlo Results with Discrete-Ordinates Calculations for 7-cm Coil (7% D_2O) and 1-m Blanket ^nLi)

Calculational Method	Cross-Section Set	Leakage	% Difference from Monte Carlo	T	% Difference from Monte Carlo
Monte Carlo, MCNP	ENDF-IV Pointwise	0.267	-	1.097 4	-
S_8 P_3, ONETRAN-DA	LASL-SAND (30 x 12)	0.277	3.74	1.054 5	-3.91
S_8 P_3, ONETRAN-DA	MATXS (30 x 12)	0.275	3.00	1.056 5	-3.73

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