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REFERENCE THETA-PINCH REACTOR (RTPR) NUCLEONIC DESIGN SENSITIVITY ANALYSIS

BY PERTURBATION THEORY

by

E. L. Simmons, D. J. Dudziak, and S. A. W. Gerstl

ABSTRACT

Previous system studies for the Reference Theta-Pinch Reactor (RTPR) have included nucleonic calculations for reactions such as tritium breeding, energy deposition, atom displacement, etc. The purpose of the present research was to verify the validity of 25-group cross-section data, along with perturbation theory, to facilitate the above calculations. The effects on these responses due to variations in the Be thickness, choices of Mo, V, or Nb structural material, BeO vs Be, graphite thickness, and ^6Li enrichment were investigated.

Increasing the Be thickness from 0.5-5.5 cm increased the tritium breeding from 0.903-1.097, and the neutron heating from 10.29-12.65 MeV per D-T neutron. Gamma emission increased from 7.96-8.76 MeV per D-T neutron. Perturbation theory results for tritium breeding in this study were accurate to within 0.6% for the entire range of Be thickness variations. BeO was found not to be a viable neutron multiplier in the present design of the RTPR due to the moderation of neutrons by the oxygen. Perturbation theory was accurate to within 0.3% for BeO. Decreases in the outboard graphite thickness up to ~ 7 cm revealed a general slight decrease in tritium breeding, but further decreases to 1.2-cm total thickness resulted in an increase in breeding of ~ 0.6%. However, neutron and gamma-ray heating in the coils rises by ~ 300% when the graphite region is thinned to 1.2 cm. Perturbation theory is found invalid for graphite thickness changes greater than ~ 1.0 cm. Decrease in ^6Li enrichment from 95-80 at.% results in a tritium breeding decrease of only 0.6%.

I. INTRODUCTION

Nucleonic calculations for blanket responses such as tritium breeding, energy deposition, and atom displacements were one of the first steps in determining the feasibility of the Reference Theta-Pinch Reactor (RTPR)¹⁻⁴ as a commercial power plant. The effects on the above responses due to Be thickness, BeO vs Be multipliers, graphite thickness, and ^6Li concentration are of interest to provide guidance for post-design optimization of the RTPR. Performing these calculations usually involves computational methods that are both time-consuming and expensive. The use of cross-section data with fewer groups, and the use of perturbation theory to perform these calculations, is therefore desirable. Thus, the purpose of this paper is threefold:

- (1) provide input to the system studies post-design assessment effort regarding nucleonic trade-offs;
- (2) to show the validity of using 25-group cross-section data for such neutronic computations; and
- (3) to determine the accuracy and limitations of perturbation theory for a variety of RTPR blanket parameter studies.

A complete description of the reactor is given in Ref. 4. The neutronic calculations are made for a one-dimensional cylindrical model which represents the plasma chamber, the 0.39-m-thick blanket, and the 0.46-m-thick magnet coils. An illustration of a reactor module is shown in Figs. 1 and 2. The computational model is composed of 36 regions (Fig. 3), representing a radial traverse through the blanket segment shown in Fig. 2. Niobium is the

Fig. 1. Two-metre-long module of RTPR.

structural material, alumina is used for both thermal and electrical insulators, beryllium is contained in the segment to provide neutron multiplication, and graphite is used mainly to moderate neutrons for absorption (and thus tritium breeding) in the enriched ^6Li region.

Fig. 2. Perspective cross section of the RTPR blanket, magnet coils, and mechanical support ring.

Region	Material	No.	Radius (m)
Plasma		1	0 0
			0150
Vacuum		2	04997
Alumina Liner		3	0500
First Wall-Nb		4	0501
Li Coolant		5	0531
Nb		6	0532
Be		7	0557
Nb		8	0558
Li Coolant		9	0603
Nb		10	0604
Alumina		11	06043
Nb		12	06053
Graphite		13	06487
Nb		14	06497
Alumina		15	0650
Nb		16	0651
Li Coolant		17	0676
Nb		18	0677
Alumina		19	06773
Nb		20	06783
Graphite		21	08257
Nb		22	08267
Alumina		23	0827
Nb		24	0828
Enriched ^6Li (95 a/o)		25	0852
Nb		26	0853
Li Coolant		27	0863
Nb		28	0864
Enriched ^6Li (95 a/o)		29	0888
Nb		30	0889
Alumina		31	0909
Impl Coil		32	0929
Alumina		33	0949
Comp. Coil		34	1349
Ti		35	1400
Alumina		36	1420

Fig. 3. One-dimensional radial traverse of the RTPR -- Neutronic model.

Neutron transport and reaction rates were calculated using the model shown in Fig. 3 and variations of it. To facilitate the analysis, calculations were performed in both cylindrical and slab geometry, depending upon the study involved. Computations were made by both repeated forward calculations and by perturbation theory. Tritium breeding, $(n,2n)$ reactions, and parasitic absorption were monitored in the forward calculations. Neutron and gamma-ray heating, as well as atom displacements, were also ascertained in most cases to provide the

necessary data for judging advantages and disadvantages of deviations from the reference design. Comparisons with perturbation theory were limited to tritium breeding only. The data accumulated thus provided a broad spectrum of information to aid in post-design optimization, as well as verifying applicable domains for perturbation theory.

II. CALCULATIONAL METHODS

A. Nuclear Analysis and Methods

Because of its high aspect ratio ($R/r = 112$), the RTPR can be accurately represented for nucleonic calculations as an infinite cylinder. The torus has low curvature, so there is negligible divergence along the major circumference. Thus, a one-dimensional model as shown in Fig. 3 can reasonably represent the plasma chamber, blanket, and magnet coils. The few two-dimensional effects anticipated are discussed in Ref. 5. The Nb structural walls, Li coolant, Be neutron multiplier, alumina insulators, graphite moderators, and magnet coils are explicitly represented in the model's 36 regions, with a range of 129-135 spatial intervals. The radial walls (1 mm Nb and 0.3 mm Al_2O_3) are homogenized within the various discrete regions and occupy 0.5 vol%. The entire niobium structure is about 6.1 vol% of the blanket. Representing the niobium cylindrical pipes that transport Li coolant through the 95 at.-%-enriched 6Li region as a cylinder annulus should result in a relatively minor error.

Representing the blanket in one-dimensional slab geometry resulted in very little error in the tritium breeding when normalized to the reference cylindrical geometry calculation (i.e., when expressing the change in percentage as a function of perturbation made). Thus, for convenience in some studies the geometry was slab rather than cylindrical.

The neutrons from the D-T thermonuclear burn were assumed to be isotropically emitted from a uniform source 150 mm in radius for the cylindrical geometry and 150 mm thick for the slab geometry. The inhomogeneous Boltzmann equation in a discrete-ordinates formulation was used to calculate the neutron flux spatial-spectral distribution in the 36-region model. Forward calculations were made sometimes with the DTF-IV code⁶ in S_4 - P_3 mode. The

validity of using S_4 quadrature is discussed in detail in Refs. 7 and 8. Neutron and gamma-ray heating, in addition to atom displacement and transmutations, were calculated with TR3.⁹ The latter is a post-processing code that folds the response functions of interest with the scalar fluxes computed by DTF-IV, and performs selected spatial integrations. Perturbation theory calculations, using the forward and adjoint angular fluxes from DTF-IV, were performed with the code SENSIT-1D.¹⁰ All perturbation calculations were performed using the adjoint difference approximation derived in Refs. 11-13;

$$I_p = \langle R, \bar{\phi} \rangle - \langle \bar{\phi}^*, \Delta L \bar{\phi} \rangle.$$

Here I_p denotes any integral response of interest in a perturbed system, such as tritium breeding or heat generation in any zone, and R is the respective response function, $\bar{\phi}^*$ is the adjoint flux in the reference case, $\bar{\phi}$ the forward flux in the reference case, and ΔL is the perturbation of the Boltzmann transport operator associated with a given design change.

Experience has shown that difficulties in convergence of the adjoint flux may arise when using S_4 quadrature, depending upon the type of problem involved. Thus, to help assure that proper convergence has occurred in all cases, a forward reference computation and adjoint calculations were performed in S_8 quadrature. Also each of the above calculations was made in slab geometry due to the fact that the SENSIT-1D code was limited at the time to slab geometry.

The cross-section structure consisted of 25 groups, a detailed description of which is given in Ref. 9. Calculations to verify the adequacy of 25 groups were made with Be cross sections from ENDF/B-II in order to be consistent with the original 100-group calculations.⁴ Studies thereafter were made with the more recently evaluated Be file from ENDF/B-III, which has a softer secondary neutron spectrum (cf. Fig. 4). This leads to somewhat lower values of tritium breeding, neutron heating, and other reaction rates.¹⁴ Figure 5 shows schematically the computational system used to determine the reaction rates of interest. Detailed discussions of the code functions, data sources, etc., are given in Ref. 9.

Fig. 4. $^9\text{Be}(n,2n)$ secondary energy distributions from ENDF/B-II and ENDF/B-III.

B. Response Functions

The response functions of interest consisted of the following: tritium production, $(n,2n)$ reactions, parasitic absorption, copper transmutations, atom displacements, kerma factors, and gamma-ray production. Tritium production, $(n,2n)$, and parasitic absorption cross sections¹⁵ were included in the DTF-IV cross-section input, so reaction rates were edited directly in that code. Neutron heating rates were computed from kerma factors generated by the MACK code.¹⁶ The utilization of the more recently available ENDF/B-III Be cross sections and MACK kerma factors results in values of neutron heating that are noticeably lower* than those of previously published data,^{14,17} which were computed with ENDF/B-II Be cross sections and older kerma factors.¹⁷

* These results are given quantitatively in later sections of this report.

Fig. 5. CTR nuclear analysis computational system.

Carbon, Cu, Nb, V, and Mo displacements per atom (dpa) response functions were those described in Ref. 5. Gamma-ray production and interaction cross sections were derived from the IASL/CTR Data Library.¹⁵

III. COMPUTATIONAL RESULTS AND ANALYSIS

A. Validity of the Use of 25-Group Cross-Section Data

It was decided to use 25-group cross-section data in order to expedite the calculations of integral nuclear effects in the RTPR. Therefore, the first step was to determine if the 25-group structure would give accurate answers as compared to published data obtained with a widely used and tested 100-group structure. The model for this study was the reference case (Fig. 3) in cylindrical geometry, with 36 discrete regions, and 133 spatial intervals. Calculations were made with DTF-IV in the forward mode with S_4 quadrature and P_3 Legendre expansion. It was assumed that the blanket up to and including the outermost Nb wall (region 30 in Fig. 3) operated at a temperature of 1 073 K, and the rest of the module operated at a temperature of 373 K. Densities of the various materials were obtained at the above temperatures. The radial walls of Al_2O_3 and Nb were homogenized into each discrete region according to their respective volume fractions. The reaction rates for tritium production, $(n,2n)$ reactions, and parasitic absorption were monitored for all elements contained in the blanket, coils, electrical insulation, and supporting structure. This was followed by post-processing with TR3 to determine energy deposition, copper transmutations, and atom displacements. The effect of Nb resonance self-shielding¹⁸ was not included in the tritium breeding calculations.

All cross sections were ENDF/B-III except the Be secondary neutron spectrum which was ENDF/B-II. This was done for compatibility with the reference 100-group calculations. All kerma factors were derived from the MACK code.

Calculations were made for the reference model and some results are shown in Table I. Total tritium breeding, $(n,2n)$ reactions, and parasitic absorptions were 1.022, 0.472, and 0.631, respectively, per D-T neutron. Table I shows in detail how the 25-group computations compared with published 100-group

TABLE I
COMPARISON OF 100-GROUP AND 25-GROUP NEUTRON BALANCES PER D-T NEUTRON
FOR THE REFERENCE CASE^a

<u>Tritium Production</u>									
	<u>⁶Li</u>	<u>⁷Li</u>	<u>Be</u>	<u>Al</u>	<u>Total</u>				
100-group	8.421-1	1.939-1	5.038-3	9.424-7	1.041				
25-group	8.315-1	1.851-1	5.033-3	8.043-7	1.022				
Difference(%) ^b	- 1.26	- 4.53	- 9.92-2	-14.6	- 1.83				

<u>(n,2n) Reaction</u>									
	<u>⁶Li</u>	<u>⁷Li</u>	<u>Be</u>	<u>Al</u>	<u>Ti</u>	<u>Cu</u>	<u>Nb</u>	<u>Total</u>	
100-group	2.966-3	1.911-2	3.455-1	6.817-4	1.947-6	7.527-3	9.918-2	0.4789	
25-group	2.903-3	1.916-2	3.382-1	5.858-4	3.227-6	1.152-2	9.979-2	0.4723	
Difference(%) ^b	- 2.12	0.262	- 2.11	-14.1	65.7	53.0	0.615	- 1.38	

<u>Parasitic Absorption</u>									
	<u>⁶Li</u>	<u>⁷Li</u>	<u>Be</u>	<u>C</u>	<u>O</u>	<u>Al</u>	<u>Cu</u>	<u>Nb</u>	<u>Total</u>
100-group	1.046-3	3.664-3	3.256-2	9.245-2	1.122-2	1.084-2	9.884-2	3.781-1	0.629
25-group	9.605-4	3.679-3	3.231-2	8.938-2	8.957-3	8.378-3	1.161-1	3.716-1	0.631
Difference(%) ^b	- 8.17	0.409	- 0.768	- 3.32	-23.8	-22.7	17.5	- 1.72	0.318

^a x.xxx-N means x.xxx x 10^{-N}

^b Difference(%) = $\frac{(25\text{-group}) - (100\text{-group})}{(100\text{-group})} \times 100$.

computations,⁴ including percentage differences. While there are a few rather large discrepancies in some region integrals for various reactions, the differences in total reactor integrals of tritium production, (n,2n) reactions, and parasitic absorption are -1.83%, -1.38%, and 0.318%, respectively. Errors of this magnitude are considered quite acceptable in view of other uncertainties inherent in the nuclear analyses, such as those caused by geometric inhomogeneities (cf. Figs. 1 and 2), material density and temperature uncertainties, and S₄-P₃ transport approximations.

The first-wall Nb atom displacements were 18.2 dpa for both the 100-group and 25-group cross-section structure. First graphite region (inboard-region 13) atom displacements were 11.7 and 11.5 dpa for the 100-group and 25-group calculations, respectively. The 25-group computations yielded neutron heating of 12.40 MeV per D-T neutron as compared with 12.48 MeV per D-T neutron from the 100-group computations. Neutron heating in the magnet coils was 1.115 x 10² kW/m and 1.299 x 10² kW/m for 100-group and 25-group calculations,

respectively.* Differences in reaction rates as shown in Table 1 and discussed above are due to two effects: (1) averaging of broad group cross sections when collapsing from 100 groups introduces errors in response functions with strong energy dependences (such as threshold reactions); and (2) errors are introduced because of neutron flux differences between the 25-group and 100-group transport solutions, due to broad group scattering and absorption cross-section averaging. The latter effect is especially pronounced at deep penetrations; e.g., in the magnet coils and titanium support. Reactions of interest in regions near the plasma neutron source show much better agreement between 100- and 25-group calculations.

Further verification of the adequacy of 25-group calculations was obtained by repeating the tritium breeding ratio study in Ref. 4. The Be region (see Fig. 3) was varied from 2.0-3.5 cm in thickness while the adjacent outer Li-coolant region

* The 100-group results here are somewhat different from Ref. 4 because of the adoption of MACK kerma factors for the present study, along with minor model differences.

was decreased. Constant Li thickness was maintained by decreasing the outer graphite and increasing the enriched ^6Li (region 25) thickness. Table II illustrates the fact that the 25-group cross-section data do provide rather accurate integral results despite larger local variations. The differences between all integral results are within ~ 2%. The study was extended to a total Be thickness of 5.0 cm and, as can be seen in Table II (cases 5, 6, and 7), the result is an additional 7% increase in tritium breeding. However, the neutron heating in the copper coils also rises by ~ 9% due to the decrease in the outer graphite and subsequent increase in neutron leakage.

From these two studies it was determined that 25-group cross-section data were adequate for calculating integral effects, especially where trends are of major interest rather than absolute values. Such is the case for our further studies.

B. Nb vs Mo vs V Structure

A previous study⁵ on structural materials has been performed to determine blanket parameters such as atom displacements in the first wall and in-board graphite regions, coil heating, and copper

transmutation. This study was also repeated to provide a more firm base regarding the use of 25-group data.

The geometry of the model, as well as cross-section data, were the same as in Sec. III.A. Studies were carried out for the replacement of Nb by Mo and then by V. DTF-IV was used in the forward S_4 - P_3 mode. Tritium production, (n,2n), and parasitic absorption were again edited. Table III shows the 25-group results. As can be seen, a substitution of Mo for Nb as the structural material renders a lower tritium breeding ratio, and an increase in parasitic absorption. The increase in (n,2n) reactions is not great enough to overcome the increase in parasitic absorption, leading to the decreased tritium breeding. This phenomenon was also observed in Ref. 5. Substitution of V for Nb results in the opposite effect. There is a 25% increase in tritium breeding (1.281 for V vs 1.022 for Nb) due to decreases in low-energy neutron

TABLE II
COMPARISON OF 100-GROUP AND 25-GROUP RESULTS IN REF. 4 BREEDING STUDY

Region (No.)	Case 0	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Lithium Coolant (5)	3.0	2.5	2.5	3.0	3.0	3.0	3.0	3.0
Be (7)	2.5	3.0	3.5	2.0	2.0	4.0	4.5	5.0
Lithium Coolant (9)	4.5	4.5	4.0	5.0	5.0	3.0	2.5	2.0
Second Graphite (21)	14.74	13.74	13.24	13.24	14.74	13.24	12.74	12.24
Enriched ^6Li (25)	2.4	3.4	3.9	3.9	2.4	3.9	4.4	4.9
Lithium Coolant (27)	1.0	0.3	0.3	0.3	1.0	1.0	1.0	1.0
Enriched ^6Li (29)	2.4	3.1	3.1	3.1	2.4	2.4	2.4	2.4
Breeding Ratio (100-group) ^a	1.041	1.08	1.12	1.02	1.01	---	---	---
Breeding Ratio (25-group) ^a	1.022	1.07	1.104	1.013	0.9928	1.124	1.158	1.190
Difference (%) ^b	- 1.83	-0.926	- 1.43	- 0.686	- 1.70	---	---	---

^a Add ~ 0.07 for resonance self-shielding.¹⁸

^b Difference(%) = $\frac{(25\text{-group}) - (100\text{-group})}{(100\text{-group})} \times 100$

TABLE III
REACTION TOTALS FOR Nb, Mo, AND V
STRUCTURAL MATERIAL

Structural Material	Reaction	Total	$\Delta(\%)^b$
<u>Tritium Production</u> ^a			
Nb		1.022	---
Mo		0.871	- 14.8
V		1.281	+ 25.3
<u>(n,2n) Reaction</u>			
Nb		0.472	---
Mo		0.502	+ 6.36
V		0.447	- 5.30
<u>Parasitic Absorption</u>			
Nb		0.631	---
Mo		0.820	30.0
V		0.351	- 44.4
<u>Neutron Energy Deposited/DT Neutron</u>			
Nb		12.40	---
Mo		11.68	- 5.81
V		14.68	+ 18.4
<u>Coil Neutron Heating (W/cm along minor axis)</u>			
Nb		1.299×10^3	---
Mo		1.047×10^3	- 19.4
V		1.332×10^3	+ 2.54

^a Add ~ 0.07 for resonance self shielding.¹⁸

$$^b \Delta(\%) = \frac{(\text{Mo or V value}) - (\text{Nb value})}{(\text{Nb value})} \times 100$$

absorption of about 44%.^{*} While the (n,2n) reactions also decrease by 5%, the decrease in parasitic absorption more than compensates for this

^{*}Vanadium parasitic absorption is highest ($\sigma_{\text{abs}} \approx 2b$) at thermal energies (less than 0.414 eV), and, as shown in Fig. 6, there is a slight increase of flux in that energy range as compared to a Nb structure. The major increases, however, are between the energies of ~ 20 keV and the thermal region, where the V parasitic absorption is low. Neutrons in this energy range are still at low enough energies to be captured readily by ⁶Li, which has an (n, α)T cross section of ~ 1b at an energy of 20 keV, increasing to ~ 400b in the thermal group. The competition between parasitic absorption of V and the ⁶Li(n, α)T reaction is easily dominated by the ⁶Li tritium production and as a consequence the tritium breeding is increased.

Fig. 6. Neutron flux at first mesh point in first enriched ⁶Li region.

effect. Neutron heating in the copper coils increases when V is the structural material due to the increase in leakage of low-energy neutrons from the outer graphite to the coils, while high-energy leakage is practically the same (cf. Fig. 7). Total neutron heating increased from 12.40 MeV per D-T neutron for Nb to 14.68 MeV per D-T neutron using V.

Table IV shows the accuracy of using 25-group cross sections insofar as first wall and first graphite region atom displacements are concerned. The differences are all less than 2%.

Fig. 7. Neutron flux at last mesh point in outer graphite.

TABLE IV
COMPARISON OF MAXIMUM ATOM DISPLACEMENT RATES AT FIRST WALL AND IN GRAPHITE
BETWEEN 100-GROUP AND 25-GROUP ($I_w = 2.0 \text{ MW/m}^2$)

Group	Structural Material	Response Material	Location	Radius (cm)	Displacement (dpa/y)
100	Nb	Nb	1st wall	50.0	18.2
25	Nb	Nb	1st wall	50.0	18.2
Diff(%) ^a					0
100	Nb	Mo	1st wall	50.0	17.5
25	Nb	Mo	1st wall	50.0	17.4
Diff(%)					- 0.571
100	Nb	V	1st wall	50.0	26.0
25	Nb	V	1st wall	50.0	25.7
Diff(%)					- 1.15
100	Nb	C	1st graphite	60.53	11.7
25	Nb	C	1st graphite	60.53	11.5
Diff(%)					- 1.71
100	Mo	Nb	1st wall	50.0	18.6
25	Mo	Nb	1st wall	50.0	18.6
Diff(%)					0
100	Mo	Mo	1st wall	50.0	17.8
25	Mo	Mo	1st wall	50.0	17.7
Diff(%)					- 0.562
100	Mo	V	1st wall	50.0	26.6
25	Mo	V	1st wall	50.0	26.5
Diff(%)					- 0.376
100	Mo	C	1st graphite	60.53	12.0
25	Mo	C	1st graphite	60.53	11.8
Diff(%)					- 1.667
100	V	Nb	1st wall	50.0	---
25	V	Nb	1st wall	50.0	18.1
Diff(%)					---
100	V	Mo	1st wall	50.0	---
25	V	Mo	1st wall	50.0	17.3
Diff(%)					---
100	V	V	1st wall	50.0	---
25	V	V	1st wall	50.0	25.6
Diff(%)					---
100	V	C	1st graphite	60.53	---
25	V	C	1st graphite	60.53	11.1
Diff(%)					---

^a $\text{Diff}(\%) = \frac{(25\text{-group}) - (100\text{-group})}{(100\text{-group})} \times 100.$

C. Be Region Thickness

The thickness of the Be multiplier region is of major interest because of its influence on tritium breeding as well as total energy released per D-T neutron. If the breeding can be enhanced with little change in Be thickness, then the result would be not only increased fusion fuel production, but also an increase in reactor power output for a small increase in the cost of Be. A simple computation has shown that at a thermal conversion efficiency, η^{th} , of 0.4, and electrical energy valued

at 5 m\$/kWh, the enhanced recoverable energy is approximately 1.9×10^7 kWy/kg Be, or 9.6×10^4 \$/kg Be. Here a "kg Be" includes all Be atoms destroyed in nuclear reactions. Thus, Be can in a sense be regarded as a nuclear fuel. Another reason for undertaking such a study is that the present calculations were made in one spatial dimension, with attendant errors caused by heterogeneity and streaming effects. Thus, the Be thickness was varied to provide for more potential margin in the absolute value of the tritium breeding ratio; i.e., assurance

that tritium breeding can be kept greater than 1.0 after accounting for multidimensional effects.

The model of the blanket was a one-dimensional cylinder with 35 discrete regions and 129 spatial intervals (Fig. 8). The Nb wall between the Be region and the adjacent outboard Li-coolant region was removed to simplify the perturbation theory calculations. Table V shows the effect of having the niobium wall included in the model, as was done for the repeated forward calculations. As a first-

Region No.	Region Mat'l	Radius (m)
1	PLASMA	0.0
2	VACUUM	0.150
3	ALUMINA LINER	0.4997
4	FIRST WALL	0.500
5	LI COOLANT	0.501
6	Nb	0.531
7	Be	0.532
8	LI COOLANT	0.557
9	Nb	0.603
10	ALUMINA	0.604
11	Nb	0.6043
12	GRAPHITE	0.6053
13	Nb	0.6487
14	ALUMINA	0.6497
15	Nb	0.650
16	LI COOLANT	0.651
17	Nb	0.676
18	ALUMINA	0.677
19	Nb	0.6773
20	GRAPHITE	0.6783
21	Nb	0.8257
22	ALUMINA	0.8267
23	Nb	0.827
24	ENRICHED	0.828
25	Nb	0.852
26	LI COOLANT	0.853
27	Nb	0.863
28	ENRICHED	0.864
29	Nb	0.888
30	ALUMINA	0.899
31	IMPL. COIL	0.8993
32	ALUMINA	0.929
33	COMP COIL	0.9293
34	Ti SUPPORT	1.349
35	ALUMINA	1.400
		1.420

Fig. 8. One-dimensional RTPR model for the Be-thickness study.

TABLE V
EFFECT OF Nb WALL BETWEEN Be REGION AND
ADJACENT OUTBOARD Li COOLANT REGION

Be Thickness (cm)	Nb Absorption in Wall per D-T Neutron
2.5 (reference)	1.571-2
0.5	9.879-3
1.5	1.292-2
2.0	1.435-2
3.0	1.700-2
3.5	1.823-2
4.0	1.939-2
4.5	2.051-2
5.0	2.160-2
5.5	2.268-2

order approximation the effect of the Nb wall was then subtracted from the forward DTF-IV calculations, to compare with SENSIT-1D results of tritium breeding. All cross sections were 25-group ENDF/B-III. DTF-IV calculations were made in the S_4-P_3 mode. In addition, forward and adjoint (with tritium production as the response function, or adjoint source) calculations were performed in S_8 .^{*} SENSIT-1D calculations were in one-dimensional slab geometry, with 35 discrete regions and 129 spatial mesh points. TR3 was employed to obtain regionwise and overall energy deposition, atom displacement, and copper transmutation.

Figure 9 illustrates the effect of Be thickness on tritium breeding.^{4,11} It is noted that an increase in tritium breeding of ~ 10% can be obtained by increasing the Be thickness from 2.5-5.5 cm. Tritium breeding increases for the obvious reason that an increase in Be leads to an increase in $(n,2n)$ reactions. Table VI shows the increase in total $(n,2n)$ reactions, which is nearly linear from 0.5-3.5 cm of Be. The increase in parasitic absorption is not large enough to overcome the neutron multiplying effect of the $(n,2n)$ reactions in Be. A comparison of Figs. 10 and 11 reveals that an increase in Be thickness from 0.5-5.5 cm greatly increases the neutron flux in the Be region, with a similarly higher leakage flux into the adjacent Li regions. An examination of tritium breeding by

* See Sec. II.A. for discussion of S_8 calculations.

Fig. 9. Comparison of change in tritium breeding as a function of Be thickness for repeated forward calculations and perturbation calculations.

regions reveals that the increased Be thickness attenuates the high-energy neutrons to a greater extent than the displaced Li. Thus, tritium breeding in the enriched ^6Li regions actually decreases with increased Be thickness, but still leaves a net increase when summed over all breeding regions. Figures 12 and 13 show a comparison of neutron flux spectra in the first enriched ^6Li region for the

TABLE VI
NEUTRON BALANCE PER D-T NEUTRON AS A FUNCTION OF
SELECTED Be THICKNESSES
(Slab Geometry)

Be Thickness (cm)	Tritium Production ^a	(n,2n) Reactions	Parasitic Absorption
0.5	0.898	2.106-1	5.211-1
1.5	0.934	3.160-1	5.633-1
2.5 (ref.)	0.969	4.119-1	5.999-1
3.5	1.005	4.943-1	6.302-1
5.5	1.074	6.381-1	6.756-1

^a Not including a correction of ~ 0.07 for resonance self-shielding.¹⁸

Fig. 10. Neutron flux at first mesh point in Be region: Be thickness = 0.5.

two extremes of 0.5- and 5.5-cm Be, respectively. Both the high- and intermediate-energy portions of the flux are lower in magnitude in the 5.5-cm-Be case, since the intermediate-energy flux is predominantly from the slowing down source in the graphite regions (not from the transport of such neutrons which were produced in the Be region).

As expected from previous work,¹⁷ total neutron and gamma-ray heating does rise with increase in Be thickness (Table VII), in this case from 10.29 MeV per D-T neutron and 7.96 MeV per D-T neutron,

Fig. 11. Neutron flux at first mesh point in Be region: Be thickness = 5.5.

Fig. 12. Neutron flux at first mesh point in first enriched ${}^6\text{Li}$ region: Be thickness = 0.5.

respectively, at 0.5-cm-Be thickness, to 12.65 MeV per D-T neutron and 8.76 MeV per D-T neutron at a thickness of 5.5 cm.

Values for Nb atom displacements in the first wall are shown in Table VIII to increase slightly with Be thickness. This minor effect is a consequence of the increase in migration of neutrons generated in the Be region. Graphite displacement rates (Table VIII) and copper transmutation in the

Fig. 13. Neutron flux at first mesh point in first enriched ${}^6\text{Li}$ region: Be thickness = 5.5.

TABLE VII
TOTAL NEUTRON AND GAMMA-RAY HEATING
PER D-T NEUTRON AS A FUNCTION OF
Be THICKNESS

Be Thickness (cm)	Neutron (MeV)	Gamma-ray (MeV)	Total (MeV)
2.5 (ref.)	11.33	8.47	19.8
0.5	10.29	7.96	18.25
1.0	10.57	8.11	18.68
1.5	10.83	8.25	19.08
2.0	11.09	8.37	19.46
3.0	11.56	8.55	20.11
3.5	11.79	8.61	20.4
4.0	12.01	8.67	20.68
4.5	12.23	8.71	20.94
5.0	12.44	8.74	21.18
5.5	12.65	8.76	21.41

compression coil (Table IX) decrease more noticeably as Be thickness increases. As was shown in Figs. 12 and 13, there is a decrease in the high- and intermediate-energy fluxes in the enriched ${}^6\text{Li}$ regions. In general, for regions located as far outboard as the graphite and copper coils, the flux is reduced, resulting in lower atom displacements and copper transmutations. This effect is illustrated in Fig. 14 for the copper compression coil.

TABLE VIII
MAXIMUM ATOM DISPLACEMENTS AS
A FUNCTION OF Be THICKNESS
($I_w = 2.01 \text{ MW/m}^2$)

Be Thickness (cm)	Material	Location	Atom Displacement (dpa/y)
0.5	Nb	1st wall	15.96
	C	1st graphite	10.68
1.5	Nb	1st wall	16.10
	C	1st graphite	10.37
2.5	Nb	1st wall	16.18
	C	1st graphite	10.00
3.5	Nb	1st wall	16.22
	C	1st graphite	9.58
5.5	Nb	1st wall	16.26
	C	1st graphite	8.70

TABLE IX
MAXIMUM COPPER TRANSMUTATION RATES IN
COMPRESSION COIL AS A FUNCTION OF Be THICKNESS
($I_w = 2.0 \text{ Mw/m}^2$)

Be Thickness (cm)	Transmutation Product	Production Rate ^a (ppm/y)
0.5	Ni	173
	$^{60}\text{Co}^b$	2.1
	Zn	165
	He	4.2
	^1H	13.5
1.5	Ni	167
	$^{60}\text{Co}^b$	2.0
	Zn	161
	He	4.0
	^1H	12.1
2.5	Ni	161
	$^{60}\text{Co}^b$	1.9
	Zn	155
	He	3.8
	^1H	11.5
3.5	Ni	153
	$^{60}\text{Co}^b$	1.8
	Zn	149
	He	3.6
	^1H	11
5.5	Ni	140
	$^{60}\text{Co}^b$	1.6
	Zn	126
	He	3.2
	^1H	10

^aFollowing reactions were considered:

^bAssuming ^{60}Co does not decay to ^{60}Ni .

Fig. 14. Neutron flux at first mesh point in copper compression coil, for two thicknesses of Be.

Therefore, one sees that, as discussed above in the case of breeding in the enriched 6,1 regions, Be has a tendency to act as a better shield for the graphite and copper coils than does the displaced Li region.

As shown in Table X and illustrated in Fig. 9, the use of perturbation theory was quite accurate in the case of tritium breeding (differences less than 0.6%). Recall that repeated forward calculations

TABLE X
COMPARISON BETWEEN PERTURBATION THEORY AND
REPEATED FORWARD CALCULATION OF TRITIUM
BREEDING RATIO

Case	Be Thickness (cm)	Forward	Pert	Diff(%) ^a
1	0.5	0.897	0.893	- 0.446
2	1.0	0.914	0.910	- 0.438
3	1.5	0.931	0.928	- 0.322
4	2.0	0.947	0.946	- 0.106
5	3.0	0.981	0.983	+ 0.204
6	3.5	0.998	1.001	+ 0.301
7	4.0	1.015	1.019	+ 0.394
8	4.5	1.033	1.037	+ 0.387
9	5.0	1.049	1.055	+ 0.572
10	5.5	1.066	1.070	+ 0.375

^a Diff(%) = $\frac{(\text{Pert}) - (\text{Forward})}{(\text{Forward})} \times 100$.

were made in cylindrical and slab geometry, while perturbation calculations were made only in slab geometry. Figure 9 shows that when the absolute values for the respective geometries are expressed as percentage change as a function of the perturbation, there is very little difference introduced by the use of two different geometries.

D. BeO vs Be

An alternative blanket material which has been suggested is beryllium oxide, BeO. Among the potential advantages of BeO are its stability at high temperatures, high transport cross section, low parasitic absorption, and low electrical conductivity. These properties make it a candidate for consideration as either a neutron moderator or multiplier, the latter because of the $(n,2n)$ reaction in the Be constituent. Its use as a moderator could potentially allow thinner blankets, with resulting savings of magnetic energy storage and concomitant losses. As a first step in evaluating BeO, its use as a replacement for the Be multiplier was studied in some detail. Some initial analysis of BeO as a moderator has given favorable results, and should be pursued further as time permits.

A simple substitution of BeO for Be in the reference design was first performed, and the thickness of BeO was then perturbed about the reference 2.5-cm thickness. As indicated in Table XI, increasing the BeO region thickness in the range of 0.5-6.5 cm yields increases in Be $(n,2n)$ reactions from approximately 0.044 per D-T neutron to 0.33. The increases in BeO thickness also resulted in an increase in neutron moderation. As a result, over

TABLE XI
Be NEUTRON MULTIPLICATION AND OXYGEN PARASITIC
ABSORPTION PER D-T NEUTRON AS A FUNCTION OF BeO
THICKNESS

BeO Thickness (cm)	Be(n,2n) Reaction	O(absorption)
0.5	4.426-2	1.241-2
1.5	1.170-1	3.167-2
2.5	1.754-1	4.623-2
3.5	2.241-1	5.784-2
4.5	2.656-1	6.742-2
5.5	3.014-1	7.546-2
6.5	3.326-1	8.230-2

the range of thickness studied, the Nb absorption is increased from 0.271-0.390 per D-T neutron due to neutron downscatter by Be and oxygen into the Nb resonance absorption region.

A large fraction of the neutrons is also scattered below the threshold energy of the ${}^7\text{Li}(n,n'\alpha)\text{T}$ reaction, ~ 2.8 MeV (see Fig. 15). Thus, the major contributor to tritium breeding is the ${}^6\text{Li}(n,\alpha)\text{T}$ reaction. Figure 16, giving the component tritium breeding ratios, illustrates the fact that the moderated neutrons in the thermal region, leading to ${}^6\text{Li}(n,\alpha)\text{T}$ reactions, are increasing while the neutrons above 2.8 MeV that result in ${}^7\text{Li}(n,n'\alpha)\text{T}$ reactions are asymptotically decreasing as a function of BeO thickness. The resulting total tritium breeding ratio has a maximum of ~ 0.95 at a minimum BeO thickness of 0.5 cm, reaches a flat minimum at a thickness of 3.5 cm, and then proceeds to increase slowly again with increasing BeO thickness. When BeO is compared with Be as a neutron multiplier (see Fig. 17) it is seen that the tritium breeding with BeO as the multiplier is relatively insensitive to change in multiplier thickness. Figure 18 indicates that, as a function of optical thickness, the $(n,2n)$ reaction rate in the multiplier is progressively lower for BeO, as expected from the added neutron moderation by oxygen. A plausible explanation of why the BeO

Fig. 15. Neutron flux at first mesh point in the Li coolant between the graphite regions, for two thicknesses of BeO.

Fig. 16. Component tritium breeding rates due to $^6\text{Li}(n,\alpha)\text{T}$ and $^7\text{Li}(n,n'\alpha)\text{T}$ reactions for varying thicknesses of BeO in zone 7.

Fig. 18. Comparison of (n,2n) reaction rates in Be and BeO multipliers as a function of Be optical thickness.

Fig. 17. Change in tritium breeding as a function of multiplier thickness (reference = 2.5 cm).

produces more (n,2n) reactions than Be at thin Be optical thickness is as follows. At thin Be optical thicknesses, the high-energy neutrons tend to have more collisions in BeO than in Be (i.e., the mean-free path, γ_t , of BeO $\approx$ 5.11 cm as compared with 10.43 cm in Be). The average fractional energy loss [$\alpha = \frac{(A-1)^2}{A+1}$], is 0.779 for elastic collisions with oxygen; thus, a 14.1-MeV neutron loses $\approx$ 8.91 MeV in the first four elastic collisions, which places it in the energy region (5.0–7.0 MeV) where the Be(n,2n) cross section is at its maximum [i.e., $\sigma_{(n,2n)} \approx$ 0.60b to 0.58b vs 0.50b at 14.1 MeV]. Further increases in optical thickness lead to the moderation of neutrons to energies where the Be(n,2n) cross section suddenly drops below 0.5b. The first four elastic collisions with pure Be will lead to a decrease in energy of 11.7 MeV [$\sigma_{(n,2n)} \approx$ 0.6].

At a pure Be optical thickness equivalent to the BeO reference case, 1.5 cm and 2.5 cm, respectively, Fig. 19 shows the effect of increased moderation by oxygen, where the flux below $\sim$ 1 keV is enhanced in BeO. Also Fig. 19 illustrates the much

Fig. 19. Flux in neutron multipliers Be and BeO at equivalent optical thickness (1.5 cm and 2.5 cm, respectively).

lower flux in BeO above the ${}^7\text{Li}(n,n'\alpha)\text{T}$ threshold energy. This increase in the flux of neutrons in the region < 1 keV yields small changes in tritium breeding; hence the insensitivity of the tritium production with BeO as the multiplier. That is, the lower energy neutrons are absorbed principally in Nb, not in ${}^6\text{Li}$.

From these calculations, it appears that BeO is not a viable material as a neutron multiplier in our present blanket configuration. Maximum tritium breeding is obtained with minimum BeO contained in the blanket, and extending the BeO thickness without changing the blanket structure will not re-acquire that maximum. A further study increasing the BeO region past 7.1 cm and concurrently decreasing the second graphite region, may provide more useful information on tritium breeding using BeO as a neutron multiplier. From the properties of BeO, such as its higher total cross section than graphite, it appears to show promise as a moderator if not as a multiplier. A sample calculation was therefore performed for the reference reactor (i.e., with 2.5-cm-Be multiplier) except that the inboard graphite region (region 13 of Fig. 3) was replaced with BeO. The tritium breeding ratio increased from 1.022 (cf. Table I) to 1.059, while coil heating and transmutation decreased ~ 15%.

Table XII shows the total neutron and gamma-ray heating per D-T neutron as a function of the BeO

TABLE XII
TOTAL NEUTRON AND GAMMA-RAY HEATING PER D-T NEUTRON
AS A FUNCTION OF BeO THICKNESS

BeO Thickness (cm)	Neutron (MeV)	Gamma-ray (MeV)	Total (MeV)
0.5	10.11	7.90	18.01
2.5	10.46	8.20	18.66
4.5	10.85	8.42	19.27
6.5	11.20	8.53	19.73

thickness when replacing the original Be region with BeO. Even though breeding is not enhanced, recoverable energy per D-T neutron does increase with BeO thickness as a result of the increase in $(n,2n)$ reactions (since even parasitic absorption of the secondary neutron produces usable energy). BeO yields a total energy deposition of 18.7 MeV per D-T neutron for a thickness of 2.5 cm vs that of 19.8 MeV per D-T neutron for Be (cf. Table VII). This occurs partially because of the higher Be atom density in pure Be metal than in BeO. At equivalent optical thicknesses, however, total energy deposition values are much closer. For example, at Be and BeO thicknesses of 1.5 and 2.5 cm, respectively, Tables VII and XII show total heating of 19.1 and 18.7 MeV per D-T neutron, respectively. Still, there is no appreciable advantage to BeO over Be insofar as recoverable energy is concerned.

Values for copper transmutation are given in Table XIII as a function of BeO thickness. Transmutation goes down with increase in BeO thickness because of the effectiveness of BeO as a shield for the copper coils against high-energy neutrons. Comparison with Be shows that copper transmutation in the implosion and compression coils is lower for BeO of either equivalent geometric or optical thickness. Thus, BeO has one neutronic advantage because of its greater moderating power than pure Be. Again its potential value as a moderator is illustrated.

From Table XIV one can see that perturbation theory predicts answers within ~ 0.25% of the repeated forward calculations over the entire range of perturbations. The resulting change in tritium breeding ratio as computed by the two methods is plotted in Fig. 20.

TABLE XIII

MAXIMUM COPPER TRANSMUTATION RATES IN COMPRESSION
COIL AS A FUNCTION OF BeO THICKNESS

$$(I_w = 2.0 \text{ MW/m}^2)$$

BeO Thickness (cm)	Transmutation Product	Production Rate ^a (ppm/y)
0.5	Ni	171
	⁶⁰ Co ^b	2.1
	Zn	163
	He	4.2
	¹ H	12.4
2.5	Ni	150
	⁶⁰ Co ^b	1.7
	Zn	145
	He	3.4
	¹ H	10.7
4.5	Ni	133
	⁶⁰ Co ^b	1.5
	Zn	129
	He	3.0
	¹ H	9.4
6.5	Ni	116
	⁶⁰ Co ^b	1.3
	Zn	114
	He	2.6
	¹ H	8.1

^a Following reactions were considered:

^b Assuming ⁶⁰Co does not decay to ⁶⁰Ni.

E. Graphite Thickness

One of the major concerns in post-design optimization will be the savings in stored magnetic energy and associated joule losses. The amount of magnetic energy loss in the blanket is proportional to the volume of the blanket. Thus, whenever the blanket thickness can be decreased without generating excessive radiation damage and heating in the magnet coils, a large benefit in energy balance

TABLE XIV

DIFFERENCE BETWEEN FORWARD CALCULATIONS AND
PERTURBATION THEORY, USING $\Delta \text{BR}(\%)$ NORMALIZED TO
REFERENCE FORWARD CASE

BeO Thickness (cm)	$\Delta \text{BR}(\%)$ (Pert)	BR ^a (Pert)	BR (Forward)	Diff ^b (%)
2.5	---	0.86028 ^c	0.86028	---
0.5	+1.6705	0.87465	0.87554	-0.102
1.5	+0.58822	0.86534	0.86569	-0.0404
3.5	-0.20143	0.85844	0.85909	-0.0757
4.5	-0.18295	0.85871	0.86078	-0.240
6.5	+0.67309	0.86607	0.86788	-0.209

$$^a \text{BR}(\text{Pert}) = \text{BR}(\text{Forward Ref}) + \frac{\Delta \text{BR}(\%)}{100(\%)} \{ \text{BR}(\text{Forward Ref}) \}$$

$$^b \text{Diff}(\%) = \frac{\text{BR}(\text{Pert}) - \text{BR}(\text{Forward})}{\text{BR}(\text{Forward})} \times 100\%$$

^c Reference tritium breeding ratio for perturbation theory is based upon Eq. (a) for normalization purposes.

accrues. For this reason, the nucleonic effects of changing the outer graphite region thickness were investigated.

Fig. 20. Comparison of change in tritium breeding as a function of BeO thickness for repeated forward calculations and perturbation calculations.

The previous studies (Secs. II.C. and II.D.) demonstrated that the use of slab geometry in predicting tritium breeding gave fairly accurate answers when compared with cylindrical geometry. Although the absolute magnitude may differ considerably, when these values are converted to percentage changes as a function of the perturbation and normalized to the reference case, the difference between the slab and cylindrical representations is negligible. Therefore, the calculations presented in this section were made in slab geometry. The model was a 135-spatial-mesh-point, 36-region slab and the calculations were performed in the S_8-P_3 mode. DTF-IV was used to perform repeated forward calculations, as well as the adjoint calculation with macroscopic tritium breeding cross sections as the adjoint source (response function). All cross sections were ENDF/B-III. TR3 was employed using kerma factors produced by the MACK code, along with other response functions, to obtain energy deposition and atom displacement rates. SENSIT-1D calculations were performed to investigate the range of applicability of perturbation theory to this problem.

All forward calculations were performed by progressively decreasing the outer graphite (region 21 in Fig. 3) thickness and moving all regions outboard of the graphite inward. To model these changes with perturbation theory is more difficult, however, because ϕ and ϕ^* are calculated for the reference 14.74-cm graphite thickness only. Moving all regions outboard of the graphite inward would then involve modifying all these regions -- a major perturbation. Thus, a procedure was adopted which kept the outer graphite region thickness at 14.74 cm while lowering its density to achieve the lesser optical thicknesses.

Figure 21 shows the resulting changes in tritium breeding for the entire range of thicknesses, as computed by the two alternative methods. It is clear that these are major perturbations and hence not amenable to perturbation theory methods. For example, an ~ 1.5 -cm decrease in graphite thickness is represented by a 10% decrease in all cross sections throughout the 14.74-cm-thick graphite region. Figure 22 shows that by this stage perturbation theory is already invalid, having deviated considerably from forward calculations at a decrease of 1 cm. Another interpretation of the perturbation

Fig. 21. Comparison of forward and perturbation theory calculations of tritium breeding for large changes in graphite thickness.

model which demonstrates the severity of this perturbation is to consider a 1-cm slab of graphite replaced by void, with the concomitant large ΔL in this region.

Fig. 22. Comparison of forward and perturbation theory for small changes in outer graphite thickness.

The initial very slight increase in tritium breeding in Figs. 21 and 22 is caused by a small favorable balance between decreasing Nb parasitic absorption (principally in the graphite region which contains 4.4 vol% Nb structure) and increasing blanket leakage. Table XV presents a partial neutron balance, showing the decrease in Nb parasitic absorption and slight increase in (n,2n) reactions as the spectrum hardens; i.e., as the graphite becomes thinner. For similar small decreases in graphite thickness, sensitivity studies⁵ with 100-group P_3 cross sections and cylindrical-geometry S_4 transport showed a slight decrease in tritium breeding. Analysis of neutron balances shows that these differences between 25- and 100-group results are due mainly to a slight variation in Nb absorption (cf. Table I), which is lower in 25-group calculations, and lower leakage in 25-group calculations. As noted earlier, the 25-group calculations generally show the greatest deviation from 100-group results at deep penetrations, where differences are amplified. Further differences are caused by using S_8 in 25-group calculations rather than S_4 as in the 100-group calculations. Thus, the utility of Fig. 22 is principally in demonstrating the applicable range of perturbation theory, rather than in the absolute values computed, since all changes are extremely small.

Most surprising of all, the roughly equal balance between total Nb plus C absorption and blanket leakage persists over more than 13 cm of graphite removal, maintaining tritium production within < 1%

of the reference value. Examination of tritium breeding in the enriched ^6Li regions and associated Li-coolant region (cf. Table XVI) shows a steady increase as the graphite is thinned. The only decrease is in the regions inboard of the graphite, caused by decreased neutron reflection. It is then clear that as far as tritium breeding is concerned the reference graphite thickness is over-moderating the neutrons. Also, the Nb structure in the graphite region is a significant neutron "poison," as can be seen from Table XV. The primary useful function of the thick outboard graphite region is thus to protect the coils from excessive radiation damage and heating, as well as to increase recoverable energy per D-T neutron. All energy deposited outboard of region 30 in Fig. 3 is waste energy and, in fact, requires external energy for coolant flow. One penalty of decreasing the outboard graphite thickness from 14.74-1.228 cm is to increase neutron, gamma-ray, and total heating rates in the coils by factors of 3.61, 3.89, and 3.84, respectively.

An examination of the neutron balance and flux reveals that as the graphite is thinned, the blanket leakage is increased and the backscatter of neutrons due to the outer graphite is reduced. Thus, the regions inboard of the outer graphite will have a reduction in energy deposition which in turn yields a decrease in recoverable energy, while the increase in leakage from the outer graphite will increase the waste energy. This is reflected in Table XVII. The increase in waste energy more than compensates for the decrease in recoverable energy and as a consequence the total heating is increased.

TABLE XV
NB NEUTRON BALANCE AND OUTER GRAPHITE LEAKAGE AS A FUNCTION OF OUTER GRAPHITE THICKNESS

Outer Graphite Thickness (cm)	Total Carbon Absorption	Total Nb(n,2n) Reactions	Nb Absorption in Outer Graphite	Total Nb Absorption	Total (C+Nb) Absorption	Cumulative $\Delta(C+Nb)$ Absorption	Blanket Leakage	Cumulative Δ Leakage
1.228	4.0061-2	1.1253-1	3.4279-3	2.8897-1	3.2903-1	- 1.5940-1	2.4579-1	1.7844-1
3.685	4.8742-2	1.1161-1	1.3500-2	3.2808-1	3.7682-1	- 1.1165-1	1.9652-1	1.2917-1
7.37	5.7883-2	1.1072-1	3.3143-2	3.7027-1	4.2815-1	- 6.0320-2	1.37626-1	7.0280-2
11.055	6.3952-2	1.1018-1	5.4143-2	3.9904-1	4.6299-1	- 2.5480-2	9.9054-2	3.1708-2
14.617	6.8073-2	1.0986-1	7.3312-2	4.1965-1	4.8772-1	- 7.5000-4	6.8144-2	7.9800-4
14.74 (Ref.) ^a	6.8194-2	1.0985-1	7.3941-2	4.2028-1	4.8847-1	---	6.7346-2	---

^a This reference case used the ENDF/B-III Be secondary energy spectrum.

TABLE XVI
TRITIUM PRODUCTION AS A FUNCTION OF GRAPHITE THICKNESS

Region	Region No.	Outer Graphite Thickness (cm)					
		1.228	3.685	7.37	11.055	14.6172	14.74 (ref.)
Li Coolant	5	2.5856-1	2.6758-1	2.7570-1	2.7979-1	2.8166-1	2.8170-1
Be	7	5.4586-3	5.4580-3	5.4576-3	5.4575-3	5.4574-3	5.4574-3
Li Coolant	9	2.5234-1	2.7280-1	2.9401-1	3.0676-1	3.1350-1	3.1366-1
Li Coolant	17	7.2028-2	9.6970-2	1.3323-1	1.6881-1	2.0037-1	2.0138-1
Enrich ⁶ Li	25	2.6478-1	2.3918-1	2.1436-1	1.9782-1	1.8513-1	1.8469-1
Li Coolant	27	1.0793-2	8.8904-3	6.6458-3	4.9101-3	3.6362-3	3.5971-3
Enrich ⁶ Li	29	2.0499-1	1.7188-1	1.3041-1	9.6928-2	7.2564-2	7.1788-2
Total ^a		1.0689	1.0628	1.0598	1.0605	1.0623	1.0623

^a Add ~ 0.07 for resonance self-shielding.

TABLE XVII
NEUTRON AND GAMMA-RAY HEATING, RECOVERABLE AND WASTE ENERGIES, AND TOTAL ENERGY
AS A FUNCTION OF OUTER GRAPHITE THICKNESS ^a
(MeV/D-T Neutron)

Graphite Thickness (cm)	Neutron Heating in Copper Coils	Gamma Heating in Copper Coils	Recoverable Energy	Waste Energy	Total Energy
1.228	0.5601	3.0572	16.9760	3.6189	20.5949
3.685	0.4343	2.4170	17.6803	2.8526	20.5329
7.37	0.2978	1.6971	18.4493	1.9957	20.4450
11.055	0.2047	1.1879	18.9955	1.3932	20.3887
14.74	0.1549	0.7861	19.4162	0.9416	20.3578

^a Slab geometry calculations, not normalized to cylindrical geometry reference case. Therefore, only relative changes.

The increase in flux in the copper coils also causes a major enhancement of the copper transmutation. As shown in Table XVIII a decrease in graphite thickness from 14.74-1.228 cm causes an increase in copper transmutation by a factor of ~ 3.

A general conclusion is that while the decrease in graphite has very little effect on tritium breeding, it does contribute greatly to the increased radiation effects in the copper coils. Thus, the advantages of the savings in magnetic energy storage and loss in the blanket must be weighed against greatly enhanced damage to the coils and some reduction in recoverable energy. If blanket thinning appears desirable, some of the reduction in

recoverable energy can be regained by high-Z materials (e.g., tungsten) at the outer edge of the blanket. A thin region of such material would recover much of the gamma-ray energy leakage from the blanket. As mentioned in the previous section, BeO should also be considered as a substitute for graphite in order to reduce deleterious radiation effects in the coils. For equivalent thicknesses, the BeO is a considerably better coil shield than graphite.

F. ⁶Li Enrichment

The RTPR contains an enriched ⁶Li region in order to utilize, in the production of tritium, the thermal neutrons that have been moderated by the

TABLE XVIII
MAXIMUM COPPER TRANSMUTATION RATES IN COMPRESSION
COIL AS A FUNCTION OF OUTER GRAPHITE THICKNESS
($I_w = 2.0 \text{ MW/m}^2$)

Graphite Thickness (cm)	Transmutation Product	Production Rate ^a (ppm/y)
1.228	Ni	599
	$^{60}\text{Co}^b$	7.1
	Zn	593
	He	14.2
	^1H	43.6
3.685	Ni	474
	$^{60}\text{Co}^b$	5.4
	Zn	477
	He	10.8
	^1H	33.8
7.37	Ni	332
	$^{60}\text{Co}^b$	3.6
	Zn	341
	He	7.2
	^1H	23.2
11.055	Ni	229
	$^{60}\text{Co}^b$	2.4
	Zn	232
	He	4.8
	^1H	15.9
14.74 (Ref.)	Ni	196
	$^{60}\text{Co}^b$	1.8
	Zn	204
	He	3.6
	^1H	12.3

^a The following reactions were considered:

^b Assuming ^{60}Co does not decay to ^{60}Ni .

graphite. If the enrichment can be lowered without a significant reduction in tritium breeding, then obviously a savings in the cost of ^6Li can be realized.

The geometry of the neutronic model was identical to that which was discussed in Sec. II.E. DTF-IV was employed to perform repeated forward calculations and TR3 was used as a post-processing code to calculate energy deposition and atom displacements. All cross sections were ENDF/B-III.

Table XIX shows the zonewise tritium production as a function of ^6Li enrichment. Reducing the ^6Li enrichment from the reference 95 at.% to 80 at.% resulted in a decrease in total tritium production of $\sim 0.60\%$. One can observe from the table that the total tritium production is relatively insensitive to ^6Li enrichment over this range. As expected, the decrease in tritium production is the result of decreased $^6\text{Li}(n,\gamma)$ reactions, which arise from a high tritium production cross section at thermal energies ($\sim 400\text{b}$), without compensating $^7\text{Li}(n,n')\gamma$ reactions. Increasing the ^6Li enrichment also increases the leakage of neutrons slightly. This is reflected in Table XX. The waste energy in the copper coils is increased due to this increase in leakage. The recoverable energy is similarly decreased. However, the decrease is only 0.015% for a reduction from 95-80 at.% ^6Li .

Table XXI illustrates the fact that copper coil damage is increased as the ^6Li enrichment is decreased. As was stated above, the reason for this is that the leakage of neutrons is being increased. It is interesting to note that the production of He, ^{60}Co , and ^1H are insensitive to the ^6Li enrichment. This is due to the fact that the neutron leakage for energies around 10 MeV is essentially unchanged. Transmutation effects are, however, relatively minor ($< 10\%$) for reactions caused by lower energy neutrons.

Blanket and coil sensitivities to ^6Li enrichment are clearly quite dependent upon the graphite thickness discussed in the previous section. Indications of this are observed from the large neutron spectrum shifts in the leakage from graphite to ^6Li regions. Thus, blanket optimization must consider these two classes of modifications in series. Consequently, no further ^6Li enrichment studies were performed.

TABLE XIX
TRITIUM PRODUCTION AS A FUNCTION OF ^6Li ENRICHMENT

Region	Region (No.)	^6Li Enrichment (at.%)					
		80	85	90	95 (ref.)	97	99
Li Coolant	5	0.2818	0.2818	0.2817	0.2817	0.2817	0.2817
Be	7	5.4574-3	5.4574-3	5.4574-3	5.4574-3	5.4574-3	5.4574-3
Li Coolant	9	0.3140	0.3139	0.3138	0.3137	0.3136	0.3136
Li Coolant	17	0.2023	0.2019	0.2017	0.2014	0.2013	0.2012
Enrich. ^6Li	25	0.1783	0.1806	0.1827	0.1847	0.1854	0.1862
Li Coolant	27	4.0439-3	3.8804-3	3.7325-3	3.5971-3	3.5476-3	3.4990-3
Enrich. ^6Li	29	7.0506-2	7.0986-2	7.1410-2	7.1788-2	7.1923-2	7.2053-2
Total ^a		1.0564	1.0585	1.0605	1.0623	1.0629	1.0637

^a Add ~ 0.07 for resonance self-shielding.¹⁸

TABLE XX
ENERGY DEPOSITION, (MeV/D-T Neutron) AS A FUNCTION OF ^6Li ENRICHMENT

^6Li Enrichment (%)	Neutron Heating in Coils	Gamma-Ray Heating in Coils	Recoverable Energy	Waste Energy	Total Energy
80	0.1576	0.8199	19.4133	0.9781	20.3914
85	0.1567	0.8079	19.4143	0.9651	20.3794
90	0.1558	0.7967	19.4153	0.9530	20.3683
95 (ref.)	0.1549	0.7861	19.4162	0.9416	20.3578
97	0.1546	0.7822	19.4165	0.9374	20.3539

IV. CONCLUSION

The major objective of these post-design assessment studies was to provide basic data for the next iterative design of the Reference Theta-Pinch Reactor. It is these iterations and continual feedback that will lead to the optimization of the reactor. Already this limited research has provided data on nuclear responses that could lead to significant improvement upon the reference blanket design.

A secondary objective of determining the adequacy of using 25-group nuclear data was reached. In summary, it was found that 25-group calculations render total integral effects accurate to within 2% of the 100-group calculations. This accuracy is considered to be sufficient for computations pertaining to the change of nuclear effects due to design changes. Therefore, not only were computer

time savings generated, but also the integrity of the answers was preserved.

The replacement of niobium with molybdenum resulted in an increase in parasitic absorption and subsequent decrease in tritium production of ~ 15%. Since the tritium breeding ratio of the reference case was 1.02, the decrease due to Mo would force the ratio to go well below 1.0, an obviously undesirable effect. However, Mo does have the beneficial effect of a reduction in magnet coil heating of ~ 19%. This indicates that its presence in the blanket provides a better shield for the coils than an equivalent volume fraction of Nb. When vanadium was substituted for niobium as the structural metal, the tritium breeding ratio increased by a sizeable 25%, while the coil heating only increased by ~ 2.5%. Thus, as far as tritium breeding and coil heating

TABLE XXII

MAXIMUM COPPER TRANSMUTATION RATES IN COMPRESSION COIL AS A FUNCTION OF ^6Li ENRICHMENT
($I_w = 2.0 \text{ MW/m}^2$)

^6Li Enrichment (%)	Transmutation Product	Production Rate ^a (ppm/y)	Maximum Neutron Flux ($\times 10^6 \text{ MeV}$) ($\text{cm}^{-2} \text{ s}^{-1}$)
80	Ni	210	5.83×10^{13}
	$^{60}\text{Co}^b$	1.8	
	Zn	222	
	He	3.6	
	^1H	12.4	
85	Ni	205	5.73×10^{13}
	$^{60}\text{Co}^b$	1.8	
	Zn	215	
	He	3.6	
	^1H	12.4	
90	Ni	201	5.64×10^{13}
	$^{60}\text{Co}^b$	1.8	
	Zn	209	
	He	3.6	
	^1H	12.4	
95 (ref.)	Ni	196	5.56×10^{13}
	$^{60}\text{Co}^b$	1.8	
	Zn	204	
	He	3.6	
	^1H	12.3	
97	Ni	194	5.53×10^{13}
	$^{60}\text{Co}^b$	1.8	
	Zn	202	
	He	3.6	
	^1H	12.3	

^a The following reactions were considered:

^b Assuming ^{60}Co does not decay to ^{60}Ni .

are concerned, the use of vanadium appears to be more advantageous. The physical properties of the materials (i.e., creep strength, ease of fabrication, thermal conductivity and expansion, etc.) will have to be considered in order to select the best material. Nevertheless, the performed study does provide a partial neutronic basis for the selection of the structural material.

Increases of the Be-region thickness from 2.5-5.5 cm led to an increase in the tritium breeding ratio of ~ 10%. This provides a rather large margin to assure that the tritium breeding ratio can be kept above 1.0 after accounting for multi-dimensional effects. Also, as Be thickness increases, the flux is reduced in regions as far out as the outer graphite and copper coils; hence, advantageous effects such as the reduction in atom displacements and copper transmutation occur. Therefore, it appears that increases in the Be region thickness will increase the tritium production and also provide better shielding for the magnet coils. One possible drawback to such a design change is the limited availability of beryllium. Cameron¹⁹ states that designers should minimize the use of beryllium in domestic fusion reactors due to the lack of large deposits of Be in the United States. However, considering the tenuous basis for estimating resources, such conclusions are disputable, as by Bass.²⁰

The use of BeO as a neutron multiplier was found to be inadequate for that purpose in the reference configuration. However, due to its moderating properties it is a potential superior neutron moderator; studies with BeO as the moderator should be initiated in a next iterative design of the RTPR blanket.

The graphite thickness study has the most potential impact of all the design modifications investigated. It indicates that the blanket can be decreased by ~ 13 cm, thus resulting not only in a reduction of stored magnetic energy and blanket joule losses, but also in a negligible effect on tritium breeding. The detrimental effects of increase in coil damage and decrease in recoverable energy appear to present no insurmountable problems. These effects could possibly be alleviated to an extent by the use of design modifications proposed in this report; e.g., a high-Z gamma-ray

absorber at the periphery of the blanket. However the main point is that the potential capital savings in the cryogenic and energy storage systems, along with an improved energy balance, that are generated as a result of the decrease in blanket thickness provide a strong incentive to redesign the module.

Over a wide range, the degree of enrichment of ^6Li in the blanket showed little effect upon the tritium breeding, hence a savings in the cost of ^6Li can be realized. Copper transmutation increases (< 10% at 80 at.% ^6Li enrichment vs the reference 95 at.%) are a minor effect. Future studies of the nuclear effects due to concurrent changes in the graphite thickness and ^6Li enrichment may provide more information on how much ^6Li enrichment cost can be saved.

The final purpose of this research was to determine the accuracy and limitations of the use of perturbation theory in the cases investigated. It was determined that perturbation theory was quite accurate in the Be and BeO studies, to within at least ~ 0.6% of the repeated forward calculations. However, it was found that in the graphite study perturbation theory was invalid for decreases in the thickness by more than ~ 1.0 cm. Recall that the assumption made in perturbation theory is that the design change is small; hence, as an approximation one uses the unperturbed forward and adjoint fluxes. However, in the graphite study it was seen that if the outer graphite was decreased by more than ~ 1.0 cm, perturbation theory was no longer applicable (i.e., such a design change must be considered a major perturbation). This confirms^{12,13} that when perturbation theory alone is used to calculate effects, one must carefully assure that design changes performed result in perturbations to the transport operator which are small in magnitude. Indeed, it appears that one must have good intuition as to whether the design changes being made are appropriate for perturbation theory, and if the results are believable. Here, intuition must include a quantitative appreciation of the ΔL term. Overall, it appears that although perturbation theory does have its well-known limitations, in the hands of an experienced reactor nuclear analyst, it is a very useful tool in design sensitivity analyses.

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