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TWO-DIMENSIONAL TBR CALCULATIONS FOR CONCEPTUAL COMPACT REVERSED-FIELD PINCH REACTOR BLANKET

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ABSTRACT

A detailed two-dimensional nucleonic analysis was performed for a conceptual first wall, blanket, and shield design for the Compact Reversed-Field Pinch Reactor. The design includes significant two-dimensional aspects presented by the limiter, vacuum ducts, and coolant manifolds; these aspects seriously degrade the tritium-breeding reaction (TBR) predicted by one-dimensional calculations. A range of design change to increase the TBR were investigated within the two-dimensional analysis. The results of this investigation indicated that an adequate TBR could be achieved with a thinner copper first wall, a ^6Li enrichment near 90%, the proper selection of reflector, and a small addition to the blanket thickness, determined by the one-dimensional analysis.

INTRODUCTION

A framework study for the Compact Reversed-Field Pinch Reactor has recently been completed at Los Alamos National Laboratory.^{1,2} This study included the conceptual design for the fusion power core (FPC) of a 1000-MWe (net) reactor, i.e., plasma chambers, first wall, blanket, shield, and coils. Estimates of the nucleonics performance of the first wall, blanket, and shield (FW/B/S) design presented in the original study were based on analyses of the results of a one-dimensional-nucleonics model and parametrics study leading to a "canonical" model. That parameter survey varied the thickness of the blanket and shield as well as the composition of primary materials: PCASS (structure), H_2O (FW/limiter/shield coolant), $\text{B}_4\text{C}/\text{W}$ (shield), and PbLi (enriched to 60% in ^6Li , blanket breeder and coolant). The calculations were performed using the one-dimensional, discrete-ordinates code UNEDANT³ and a 20-neutron/12-gamma-ray group library based on ENDF/B-IV data.⁴

The one-dimensional aspects of the FW/B/S

design are for the most part well represented by the canonical model. Inclusion of the limiter, the vacuum ducts, and the manifolds and headers cooling the limiter, first wall, and second wall, however, give significant two-dimensional characteristics to the FW/B/S model. A two-dimensional-nucleonics analysis, therefore, was performed to assess the effects on the blanket performance predicted by the one-dimensional model. In addition, the effects of using ENDF/B-V cross sections⁵ and other changes in the FW/B/S materials (e.g., HT-9 ferritic steel was substituted for PCASS, and improved shielding materials) could also be assessed.

Of particular interest to this postdesign nucleonics analysis is the tritium-breeding ratio (TBR). The one-dimensional calculation for the canonical FW/B/S model predicted a value of 1.108. Displacement of a portion of the PbLi blanket by the manifold, headers, and vacuum ducts, particularly in regions near the first wall where the greatest contribution to tritium breeding occurs, was expected to degrade the TBR seriously.

After describing the two-dimensional-nucleonics model and the nucleonics codes and cross sections used, the parametric results are given for the referenced FW/B/S model and a range of design changes available to obtain adequate tritium breeding in the highly two-dimensional model that has evolved during the fusion power core (FPC) design integration process. Design directions are indicated to reconcile the blanket performance with the two-dimensional nature of this problem; only tritium breeding is computed. Assessment of other neutronic responses will be reported later.

TWO-DIMENSIONAL MODEL

The CRFPR torus is composed of 24 sectors each forming a portion of the first-wall/second-wall, blanket, shield, and TFC. A half-sector, which is actually wedge shaped, was taken as the unit cell and modeled as a finite cylinder. Because this unit cell is for the most part

poloidally symmetric about the plasma minor axis and toroidally symmetric about the module vertical center plane, the origin for the coordinate system was taken at the intersection of this plane and the plasma centerline. The length of the cylindrical unit cell was taken as one-half the length of the plasma minor axis through the sector. The FW/B/S minor radii were specified at the actual design values. The outer radius of the calculational unit cell was taken as 1.75 m, this value being arbitrarily selected to yield a 0.25-m thickness for the region representing the PFCs. This region is approximately 40% coil and 60% void, and the 0.25-m thickness corresponds to a few neutron mean-free-paths, giving a reasonable cutoff for the purposes of this calculation. The two-dimensional model is depicted in Fig. 1.

NUCLEONICS CALCULATIONS

The nucleonics calculations were performed with a combination of computer codes: the two-dimensional, discrete-ordinates codes TRISM⁶ and TWOANT;⁷ the Monte Carlo code MCNP;⁸ and the one-dimensional, discrete-ordinates code ONEDANT.³ This combination of codes was needed both to benchmark the various calculations against each other and to utilize the particular assets of each (i.e., spatial resolution versus running time).

The calculations using TRISM took advantage of the triangular mesh capabilities, which allowed detailed modeling of the geometry. In addition, the disk storage system used in TRISM allowed a much larger problem (i.e., finer mesh, higher-order scattering (P_3), and coupled neutrons and gamma rays) than was possible for TWOANT. The restart capabilities of TRISM also allowed the converged fluxes from one case to be used as initial values for subsequent calculations, thereby decreasing the computing time required to converge a new problem.

Although TWOANT calculations were limited to a coarse-mesh, a P_1 -scattering approximation and a number of neutron energy groups established by core storage, this code runs extremely fast relative to pure discrete-ordinates codes, thus allowing a larger number of two-dimensional parametric calculations to be made. Calculations were made only for an integral quantity (tritium-breeding ratio) and no attempt was made to analyze to the spatial variation in the calculated reaction rates.

The use of MCNP allowed the assessment of self-shielding effects, as well as permitting a check on the cross sections and effects of secondary energy and angular distributions. The TWOANT and TRISM codes used the same multigroup cross-section library, while MCNP used a detailed pointwise library. The geometry modeled in MCNP was exactly that used in TRISM (i.e., the surface segments corresponded to the triangular mesh zones specified for TRISM).

The source of the multigroup cross sections used in the TRISM, TWOANT, and ONEDANT calcula-

Fig. 1. Calculation unit cell for two-dimensional CRFPR FW/B/S/C model to reflect in cylindrical geometry the effects of limiter and FW/SW manifolding as well as vacuum ducting.

tions was the MATXS6 library⁹ that was generated from ENDF/B-V data⁵ with the code NJUY.¹¹ The MATXS6 library is an 80/24 group, coupled neutron/gamma-ray set. This library was collapsed to a 30/12 group structure for the calculations performed herein. This approach

also allowed a comparison to be made with the results for the canonical FW/B/S model as well as an assessment of the effects of the weighting spectrum used to collapse the cross-section set. Multigroup libraries were generated using the TRANSX code^{9,10} in which mixing of macro-materials (e.g., H₂O), was performed.

The TRISM mesh used in the calculations included a total of 1 521 triangles. The calculations used S₈P₃ approximations and the 30/12 neutron/gamma-ray group structure described previously. An isotropic 14.1-MeV neutron source was distributed throughout the plasma volume.

The 20 x 24 coarse-mesh boundaries used in the TWODANT calculations coincided with the region boundaries with the exception of the FW/B region behind the limiter. Two fine-mesh intervals were specified for most coarse-mesh intervals with the exception of the broadest coarse-mesh intervals. In this case, up to five fine-mesh intervals were used. The TWODANT calculations were S₈P₃ approximations using only the 30 neutron energy groups. The neutron source was specified as in TRISM, and all calculations were converged to within 10⁻³.

The MCNP calculations were performed in three-dimensional geometry using the identical two-dimensional model specified for TRISM. The tally used was a track length estimate of the flux in the regions containing PbLi multiplied by the ⁶Li and ⁷Li tritium-production cross sections. For this integral tally 10,000 source particles gave relative standard deviations less than 1.0%. The ENDF/B-V cross sections were used.

PARAMETRIC RESULTS

A base-case TRISM calculation for the reference model yielded a TBR of 0.785 compared to the value of 1.108 for the ONEDANT model and the "canonical" blanket. Subbreeding of this magnitude indicated that the blanket design or materials or both would need to be changed. The TRISM calculation of the canonical blanket was used as a benchmark for a TWODANT calculation which gave a TBR of 0.766. A similar MCNP calculation was performed to provide an additional benchmark and gave a value of 0.778 ± 0.006. The fact that the discrete-ordinates and Monte Carlo integral results are the same, within statistics, give added credibility to the detailed TRISM and TWODANT results for this system. Based on these calculations an interim reference TBR of 0.78 was selected to demonstrate the dramatic effects of more realistic two-dimensional designs on this crucial parameter. The intent of the present study is to indicate means by which TBR can be increased above unity while maintaining the essential elements of the FPC design.

The effects of various design and material changes were subsequently examined with a series of TWODANT calculations. Selected TWODANT calculations were benchmarked with a TRISM

calculation. The time investment for the longer-running calculations was minimized by re-starting the code with the specified changes using the converged fluxes for the reference model.

The effect of thickening the blanket was examined by replacing the 50-mm-thick vacuum region behind the blanket with PbLi. Earlier ONEDANT calculations examined the effects of first-wall thickness on TBR and indicated that a substantial enhancement would result by thinning the copper first wall. Based on this assessment, TWODANT and TRISM calculations were performed for the reference 20-mm-thick first wall decreased to 3 mm (2-mm-thick copper and water region followed by 1-mm-thick copper). The effects of relocating the FW/SW coolant manifold was estimated by shifting the homogenized material representing this manifold to the rear of the blanket, locating it in the shield region. The region previously occupied by the manifold was then replaced by PbLi, while conserving the volume of the regions. In addition, the effects of using D₂O as a FW/SW and limiter coolant and increasing the ⁶Li enrichment from 60% to 80% were investigated for the canonical FW/B/S. The values for the TBR calculated by TRISM and TWODANT for these design and material variations on the reference model are summarized in Table 1.

With the exception of adding 50 mm of blanket, all of the design and material variations summarized on Table 1 yielded substantial improvement in the TBR. Only relocation of the FW/SW coolant manifold or changing to D₂O coolant for the FW/SW and limiter give a TBR greater than unity, however. Both of these options were considered less desirable when compared with the more simple design modifications associated with thinning the first wall and using higher ⁶Li enrichments. Specifically, use of D₂O coolant complicates the thermal cycle and is expected to add significant cost, whereas placement of the high-pressure FW/SW coolant manifolds in the shield region requires the use of tube sheets to deliver coolant to the FW/SW region, substantially increasing the number of individual tubes. Such design changes remain as possibilities but are ranked as less desirable relative to other choices.

In each case where the first wall was thinned, an increase of about 14% in the TBR was calculated. It was decided, therefore, to perform a further parametric analysis for a modified reference model which included a thinner first wall.

Based on other engineering considerations, a 5-mm-thick first wall was adopted for the modified reference model; the first wall is modeled as a region of 4-mm-thick copper and water following by a region of 1-mm-thick copper. Although this wall is thicker than that considered in the previous section, the copper volume fraction in the front region is lower, and the performance for the 5-mm-thick first wall is close to that calculated previously for

TABLE 1

TRITIUM-BREEDING RATIOS CALCULATED FOR DESIGN
AND MATERIAL VARIATIONS ON THE REFERENCE MODEL

Coolant	⁶ Li Enrichment (%)	Design Variation	TBR	
			TWODANT	TRISM
H ₂ O	60	Reference	0.786	0.785
H ₂ O	60	Added 50 mm	0.818	-
H ₂ O	60	Relocated manifold to rear of blanket	1.033	-
H ₂ O	60	Reduced to first-wall thickness from 20 mm to 3 mm	0.898	0.901
H ₂ O	80	Reference	0.842	-
H ₂ O	80	Reduce first-wall thickness from 20 mm to 3 mm	0.955	0.959
D ₂ O	60	Reference	0.989	-
D ₂ O	60	Reduce first-wall thickness from 20 mm to 3 mm	1.125	1.113

the 3-mm-thick first wall.

A TRISM calculation for the modified reference model gave a TBR of 0.899, while a value of 0.892 was calculated by TWODANT. MCNP calculations were also performed for this model and yielded a TBR 0.870 ± 0.010 which agrees with the discrete-ordinates calculations. The calculations for both reference models are summarized in Table 2. A new interim reference TBR of 0.88 was selected for this modified reference model as compared with 0.78 for the base reference model.

TABLE 2

CALCULATED TRITIUM-BREEDING RATIO
FOR BASE REFERENCE AND MODIFIED REFERENCE MODELS

	Base Reference Model (20-mm- thick copper)	Modified Reference Model (3-mm- thick copper)
TRISM	0.785	0.899
TWODANT	0.786	0.892
MCNP	0.778	0.870
Selected Interim Reference Value	0.78	0.88

Subsequent parametric calculations were performed with TWODANT and benchmarked with MCNP for selected calculations. To assess the self-shielding effects, a cross-section library with self-shielded cross sections for all materials was generated with TRANSX. A TWODANT calculation was performed for the modified reference model using this library. The TWODANT calculation yielded a TBR of 0.899. This calculation indicated that the TWODANT calculations for a specific case would probably yield slightly higher TBR values if self-shielded cross-section sets were used.

In order to assess the effects of ⁶Li enrichment, TWODANT calculations also were made for 80% and 90% ⁶Li enrichments. In the case that a larger TBR margin might be required, calculations also were performed with D₂O coolant as well as 60, 80, and 90% ⁶Li enrichments. An approximate linear variation in the TBR with ⁶Li enrichment for both H₂O and D₂O coolant yield substantial margins. The H₂O/90% ⁶Li case was also calculated with MCNP, which gave a TBR of 0.939 ± 0.005 . This latter case appeared attractive for further parametric analysis in search of further TBR improvement.

The W/B₄C/H₂O shield located behind the blanket in the reference FW/B/S model was designed to optimize the total blanket energy recovery. This 0.10-m-thick shield consists of alternating 25-mm-thick layers of 80% tungsten and 80% B₄C; each layer also contains 10% PCASS structure and 7.9% H₂O coolant. It appeared that a better reflector in this region could also enhance the TBR.

Calculations were then performed with 90% enriched ^6Li in which all four shield layers were a) taken as the W/PCASS/ H_2O mixture as described above; b) replaced with pure tungsten; or c) replaced with 90% PCASS and 10% H_2O . The TBRs calculated using TWOJANT for these three cases are 0.979, 0.992, and 1.006, respectively. The results for the PCASS reflector prompted an MCNP calculation; a TBR value of 0.978 ± 0.009 resulted. These results indicate that even high-enrichment, well-reflected blanket designs do not provide the TBR margins required.

In order to investigate the possibility of providing a TBR margin with a slightly thicker blanket, TWOJANT calculations were performed for the 90% enriched, PCASS-reflected model with 50 mm and 100 mm of additional PbLi in the blanket region. All radii behind the blanket were correspondingly increased. These calculations yielded TBR values of 1.033 and 1.058, respectively. An almost linear increase in the TBR with increased blanket thickness in this range was observed, indicating a design option

for achieving the desired TBR margin. The latter case was also calculated with MCNP giving a TBR of 1.035 ± 0.008 which is consistent with previous results. The results for these design changes are summarized in Table 3.

CONCLUSIONS AND RECOMMENDATIONS

The effects of more detailed two-dimensional effects on the breeding potential of the canonical, one-dimensional-nucleonics model can be significant. A range of relatively minor FW/B/S material and design changes have been examined as means to increase the TBR above unity using fully two-dimensional models. These changes include a) increase the blanket thickness; b) decrease the first-wall thickness; c) relocate the FW/SW water coolant manifold to the rear of blanket; d) increase the ^6Li enrichment in the self-cooled PbLi blanket; e) replace H_2O with D_2O in the FW/SW and limiter coolant loops; and f) emphasize the reflecting role over shield role of a thin shield/reflector placed

TABLE 3
TRITIUM-BREEDING RATIOS CALCULATED FOR DESIGN
AND MATERIAL VARIATIONS ON THE MODIFIED REFERENCE MODEL

Coolant	^6Li Enrichment (%)	Design Variation	TBR	
			TWOJANT	MCNP
H_2O	60	Modified Reference	0.892	0.870
H_2O	60	Modified Reference	0.899*	-
H_2O	80	Modified Reference	0.947	-
H_2O	90	Modified Reference	0.971	0.939
D_2O	60	Modified Reference	1.123	-
D_2O	80	Modified Reference	1.189	-
D_2O	90	Modified Reference	1.211	-
H_2O	90	All Shield Layers W/PCASS/ H_2O of Modified Reference	0.979	-
H_2O	90	All Shield Layers Pure Tungsten	0.992	-
H_2O	90	All Shield Layers 90% PCASS-10% H_2O	1.006	0.978
H_2O	90	Shield PCASS/ H_2O (above) with 50 mm added PbLi Blanket	1.033	-
H_2O	90	Shield PCASS/ H_2O (above) with 100 mm added PbLi Blanket	1.058	1.035

*All Cross-Sections Self-Shielded

between the blanket and TFC.

It appears that for a thinner copper first wall and high ^6Li enrichments (~90%), adequate tritium-breeding ratios could be achieved with the proper selection of reflector and a small addition to the blanket thickness. These changes preserve the FPC design and are considered minor. An alternative approach would relocate the FW/SW coolant manifold to the rear of the blanket. This option should present a cost issue. If further design modifications are anticipated which would have a strong negative impact on the TBR (i.e., increased FW or limiter thickness, increased FW/SW or limiter manifold size at the first-wall location, reduced ^6Li enrichment, etc.), changing the FW/SW and limiter coolant from H_2O to D_2O presents an option with substantial TBR margins. Finally, if a thicker copper first wall should be required, an attractive combination of the above alternatives could be selected which would yield an adequate margin for the tritium-breeding ratio.

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