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Analysis of the Thorium Axial Blanket Experiments in the Proteus Reactor

J. R. White
D. T. Ingersoll

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DEPARTMENT OF ENERGY

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IN THE PROTEUS REACTOR

J. R. White* and D. T. Ingersoll

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*UCND Computer Sciences Division.

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ABSTRACT

Detailed analysis has been completed for the ThO_2 and Th-metal axial blanket experiments performed at the Swiss PROTEUS critical facility. The purpose of the analysis was to compare reaction rates and neutron spectra measured in prototypic GCFR configurations with results calculated utilizing various computational methods and cross-section data libraries, including ENDF/B-V thorium data. The comparisons were intended to verify the adequacy of available thorium data for use in accurate fast reactor alternative fuel cycle studies.

The PROTEUS configurations allowed the analysis of infinitely dilute thorium data in a PuO_2/UO_2 fast lattice spectrum at core center as well as the analysis of resonance self-shielding effects in the thorium-bearing axial blankets. The results of these comparisons, although inconclusive in the axial blanket regions, indicate that significant deficiencies still exist in the latest evaluated infinitely-dilute thorium data file. Specifically, the analysis showed that the ^{232}Th capture is underpredicted by ENDF/B-IV data, and the discrepancies are further exaggerated by ENDF/B-V data. On the other hand, ENDF/B-V ^{232}Th fission data appear to be significantly improved relative to ENDF/B-IV data, while discrepancies are extremely large for the $(n,2n)$ process in both data files. Finally, the (n,n') cross sections for thorium also appear improved in ENDF/B-V, except for a small energy range just above the 50 keV threshold. Therefore, these combined data deficiencies suggest that relatively large uncertainties should be associated with many of the results obtained from recent fast reactor alternate fuel cycle analyses.

I. INTRODUCTION

The current interest in proliferation-resistant fuel cycles has generated several questions concerning the adequacy of the basic nuclear data available for the alternate ^{232}Th and ^{233}U fuels. Several recent studies¹⁻³ have attempted to quantify the effect of data uncertainties [particularly for ^{232}Th (n, γ) data] on the performance characteristics of several alternate-fueled fast breeder reactors. In general, these investigations have shown that potential changes^{4,5} in the nuclear data relative to ENDF/B-IV data can significantly impact the reactivity and breeding ratio (or breeding gain) of $^{233}\text{U}/^{232}\text{Th}$ -fueled systems. Thus, these studies tend to indicate that relatively large uncertainties must be associated with many of the results obtained from a variety of recent alternate fuel cycle studies.^{2,6}

A cooperative program between the U.S. and Switzerland is currently attempting to answer some of the questions concerning the adequacy of the nuclear data available for the more important ^{232}Th and ^{233}U neutron reactions. The U.S. program includes postanalyses of a series of Swiss integral experiments⁷⁻⁹ designed to validate neutron physics data and methods for thorium-bearing GCFR lattices. These integral experiments were performed at the PROTEUS zero-power facility located at the Swiss Federal Institute for Reactor Research (EIR) in Würenlingen, Switzerland.

The PROTEUS critical facility is a hybrid reactor consisting of a central GCFR-type pin lattice which is driven critical by annular thermal drivers. A cross-sectional view of the PROTEUS fast-thermal zero-power reactor is shown in Fig. 1, clearly illustrating the reactor's hybrid structure. Reaction rate and neutron spectrum measurements are made at the center of the test zone core and axial blanket regions. The measurements are then compared to calculated detector responses as a test of the accuracy of the nuclear data, multigroup processing, and calculational methods.

The PROTEUS experiments included several configurations utilizing UO_2 , ThO_2 , and Th-metal pins in prototypic GCFR core and axial blanket

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Fig. 1. Cross-Sectional View of the PROTEUS Fast-Thermal Critical Facility.

mockups. The thorium-bearing configurations, along with their core designation (e.g. Core 12, Core 13, etc.), are listed in Table 1. Due to the nature of the various configurations, the Core 12, Core 13, and Core 15 mockups were well suited for analyses using one-dimensional (1-D) geometries along the radial centerline of the reactor. The axial blanket configurations, on the other hand, required two-dimensional (2-D) modeling. Since 2-D transport methods were not available to the Swiss researchers, ORNL was given the primary responsibility for the analyses of the axial blanket mockups with use of the DOT-IV¹⁰ code as the main calculational tool.

Table 1. PROTEUS thorium-bearing configurations

Designation	Core	Central Column	Axial blanket
Core 11 ^a	PuO ₂ /UO ₂		UO ₂
Core 12	PuO ₂ /UO ₂ and ThO ₂ ^b		UO ₂
Core 13	PuO ₂ /UO ₂	ThO ₂	UO ₂
Core 14	PuO ₂ /UO ₂		ThO ₂
Core 15	PuO ₂ /UO ₂	Th-metal	UO ₂
Core 16	PuO ₂ /UO ₂		Th-metal

^aReference configuration.

^b2/1 ratio.

The results of the ORNL analysis of the ThO₂ axial blanket (Core 14) and the Th-metal axial blanket (Core 16) experiments performed at PROTEUS are reported here. The purpose of the analysis was to compare experimentally determined reaction rates and neutron spectra with results calculated using various computational methods and data libraries (including ENDF/B-V thorium data). In particular, the overall analysis attempted to address the adequacy of the available thorium data for use in accurate fast reactor alternative fuel cycle studies.

The remainder of this report fully documents ORNL's effort and significantly extends related results previously reported.^{11,12} Section II first describes the models, data, and methods utilized in this study. Separate results for the PuO_2/UO_2 core region and axial blanket zones of Core 14 and Core 16 are given in Sections III and IV, respectively. Section V discusses the sensitivity of the calculated results to several modeling variations. Section VI presents a comparison of calculated and experimental neutron spectra at the center of the axial blanket regions. Finally, Section VII summarizes the overall results of the study, with some concluding remarks concerning the adequacy of the nuclear data and methods utilized in this investigation.

II. MODELS, DATA, AND METHODS

The models and reference data utilized in the analysis of the thorium axial blanket experiments were supplied by EIR. Figures 2 and 3 display the actual 2-D models employed. As is apparent, the Core 14 and Core 16 geometric models are very similar with only slight differences in the fast core and axial blanket dimensions (Regions 1 and 2, respectively). Comparison of these models with Fig. 1 allows definition of the remaining zones (except for Zones 3 and 15, which are iron and concrete shields, respectively). Additionally, it should be noted that Zones 6-8 are borated plastic layers that serve to reduce the penetration of low-energy neutrons from the thermal driver zones into and through the relatively inactive buffer and blanket regions.

The core zones in both the Core 14 and Core 16 mockups consisted of PuO_2/UO_2 pellets in 7-mm-diameter fuel rods on a 10-mm hexagonal pitch. The ThO_2 blanket in the Core 14 configuration had a similar geometric arrangement but consisted of pins which were loosely filled with sintered particles, giving a relatively low homogeneous thorium density of approximately 6 g/cm^3 in the ThO_2 zones. The Th-metal axial blanket consisted of 19-mm rods on a close 21-mm pitch, yielding a thorium density of 11.3 g/cm^3 . The important difference is that the macroscopic nuclear

Fig. 2. 2-D Reflected Model of the PROTEUS Core 14 Configuration.

properties of the thorium metal blanket are completely dominated by thorium, whereas the nuclear characteristics of the ThO_2 blanket are determined by several other nuclides in addition to thorium. Table 2 illustrates this point with the tabulation of the homogeneous nuclide concentrations for the core, blanket, and iron shield zones of Core 14 and Core 16.

The reference cross-section data utilized in the 2-D computations were supplied by EIR. These 10-group P_0 (P_1 -corrected) libraries for Core 14 and Core 16 were originally derived from the British FGL5¹³ fine-group adjusted data set. However, the ^{232}Th and ^{233}U data (37 groups plus shielding factors) included in the Swiss version of FGL5 were derived

Fig. 3. 2-D Reflected Model of the PROTEUS Core 16 Configuration.

from the ENDF/B-IV-based LIB-IV¹⁴ library. To further address the adequacy of ENDF/B data, fast-region cross sections were generated at ORNL using the AMPX¹⁵ cross-section processing system. Two multigroup data libraries were processed for each experimental configuration, one containing all ENDF/B-IV-derived data¹⁶ and the other containing all ENDF/B-IV data with the exception of ENDF/B-V-derived thorium. (For the remainder of this report, these two multigroup cross-section sets will be identified as ENDF/B-4 and ENDF/B-45, respectively.) These two fast-region data sets were then coupled with EIR 10-group data for the subsequent 2-D DOT-IV calculations.

Table 2. Nuclide concentrations for regions along axial centerline of PROTEUS Cores 14 and 16

Nuclide	Concentration (atoms/barn-cm)			
	PuO ₂ /UO ₂ core	ThO ₂ axial blanket	Th-metal axial blanket	Fe-shield
Th-232		5.7980-3	2.1775-2	
U-233				
U-235	3.3645-5			
U-238	7.9524-3			
Pu-239	1.1155-3			
Pu-240	2.4641-4			
Pu-241	2.9745-5			
Pu-242	5.4304-6			
Am-241	1.1362-5			
Cr	1.7376-3	2.3930-3		
Mo	1.2047-4	1.2318-4		
Mn-55	2.4692-4	2.8587-4		1.1869-3
Ni	1.0046-3	1.2678-3		
Al	1.6642-3	2.1684-4	1.9093-4	
Fe	6.5448-3	8.4474-3		8.2835-2
Si	9.4667-5	1.1993-4		
N-14	1.4746-5	2.0899-5	9.8320-6	
H-2	8.6699-5			
O-16	1.8793-2	1.1602-2	2.6460-6	

The basic calculation scheme utilized to obtain the ORNL-generated cross sections and subsequent broad-group 2-D reaction rates is outlined in Table 3. All of the codes listed, with the exception of the DOT-IV code, are modules of the AMPX modular system. Several of the options utilized during the sequence of calculations are listed in Table 4. The data option included the comparison of ENDF/B-4 and ENDF/B-45 data. Options in the XSDRNPM¹⁵ module allowed the investigation of the sensitivity of the calculated reaction rates to the weighting spectra used in the

Table 3. Basic calculational scheme utilized
in Core 14 and Core 16 analyses

Data Base — 171-group ENDF/B-IV VITAMIN-C library
171-group ENDF/B-V ^{232}Th data

Step	Code name	Function
1	AJAX	Selects appropriate nuclides from master library
	BONAMI	Performs resonance self-shielding using Bondarenko treatment
	NITAWL	Reformats for use in XSDRNPM
2	XSDRNPM	Performs 171-group S_4P_3 transport calculation for slab geometry (axial direction); collapses to 10-group structure using region averaged fluxes
	CONTAC	Creates ANISN formatted cross sections
3	AXMIX	Mixes 10-group macroscopic cross sections for fast regions and combines with EIR supplied data for the remaining regions of the 2-D reflected model
4	DOT-IV	Performs 2-D transport theory calculations and produces desired reaction rate data

Table 4. Options utilized during calculational sequence

Category	Comments
Data base	ENDF/B-IV or ENDF/B-V thorium data
1-D modeling	Options in XSDRNPM include: 1. Infinite slab 2. Buckling search for critical system 3. Buckling correction for finite slab
2-D modeling and theory	Options in DOT-IV include: 1. Diffusion versus transport theory 2. Variable order cross section expansion 3. Variable order quadrature 4. Geometry variations

collapse to a broad-group structure. Finally, choices in the DOT-IV code permitted the examination of theory and modeling approximations in the 2-D reflected model calculations of the Core 14 and Core 16 experimental configurations.

The data base comparisons (ENDF/B-IV-derived versus ENDF/B-V-derived thorium data) form the basis of this report since they are considered to be of greater interest than the remaining parametric calculations performed. However, the latter studies did produce some interesting and useful information and, therefore, are described in some detail in Section V.

For the sake of clarity, it also will be noted here that the spectra from the buckling search 1-D modeling option (option #2 in Table 4) gave the best comparisons between 1-D fine-group and 2-D broad-group spectra and reaction rates at core center. Therefore, the buckling search for a critical system was chosen as reference, and the results tabulated in all sections except Section V were generated using this approximation.

The final point to be discussed in this section is the selection of the 1-D geometric model utilized for the fine-group to broad-group cross-section collapse. In the thorium axial blanket cores, measurements were taken along the axial centerline of the PROTEUS fast zone. Thus, it was highly desirable to account for the axial variation of the broad-group cross sections in the 2-D reflected models. As observed in Figs. 2 and 3, this was accomplished by dividing the PuO_2/UO_2 core and thorium blanket regions into several axial zones and utilizing broad-group cross sections specific to each zone. This fine detail in the fast region is especially important in the vicinity of the Region 1/Region 2 interface (PuO_2/UO_2 core/Th axial blanket) where large changes in spectra and resonance shielding effects occur. Thus, the necessary choice for a 1-D fine-group model was the same configuration as that along the axial centerline of the 2-D Core 14 and Core 16 models. In this way the zone (axial) dependence of the cross sections could be treated in a straightforward manner.

However, the price to pay for this type of modeling is the error introduced by ignoring the effect of the thermal driver regions on the spectra in the central fast zone. Since the PROTEUS central test zone was specifically designed to minimize such effects through the inclusion of the uranium metal buffer zone and borated plastic layers (see Figs. 1-3), it was felt that the 1-D axial model was most appropriate and that modeling errors should be of an insignificant magnitude. (This point will be seen to be a significant factor in the subsequent axial blanket analysis.)

With the 1-D and 2-D models clearly defined, a series of 1-D fine-group S_4P_3 transport calculations was performed to produce the broad-group ENDF/B-4 and ENDF/B-45 data libraries for both the Core 14 and Core 16 configurations. These libraries, as well as the full EIR-supplied P_0 10-group set, were then employed in 2-D DOT-IV transport (and diffusion) theory calculations. The 1-D and 2-D computations provided a large calculational data base from which detailed comparisons of calculated and measured reaction rates could be obtained. The next two sections describe the results of these comparisons, first at core center and then in the axial blanket regions.

III. RESULTS AT CENTER OF PuO_2/UO_2 CORE REGION

As mentioned earlier, the primary goal of the ORNL analysis was to address the adequacy of the available thorium data in predicting measured responses. Before presenting the results obtained at the center of the PROTEUS configuration, it should be explicitly noted that at core center thorium is present in only trace amounts (thin activation foils); hence the present analysis is primarily concerned with infinitely dilute thorium data in a PuO_2/UO_2 fast spectrum. Conclusions drawn from the results presented here have this qualifier attached.

A summary of these core-center results for both Core 14 and Core 16 is presented in Tables 5 and 6. These display the calculated-to-measured (C/E) values for some of the more important reaction rate ratios using

Table 5. Comparison of calculated reaction rate ratios at the center of Core 14 and Core 16 using the 2-D 10-group model

Central Ratio	Core 14 Results				Core 16 Results			
	Measured Value	C/E Values			Measured Value	C/E Values		
		EIR Data	ENDF/B-4 Data	ENDF/B-45 Data		EIR Data	ENDF/B-4 Data	ENDF/B-45 Data
C2/F9	$0.2026 \pm 1.7\%$	0.956	0.934	0.868	$0.2001 \pm 1.4\%$	0.964	0.956	0.885
F2/F9	$8.061 \times 10^{-3} \pm 2.0\%$	0.882	0.901	0.952	$8.080 \times 10^{-3} \pm 2.0\%$	0.882	0.873	0.924
C8/F9	$0.1338 \pm 1.0\%$	0.971	1.013	1.015	$0.1334 \pm 1.4\%$	0.981	1.028	1.028
(N2N)2/C2	$6.93 \times 10^{-3} \pm 2.6\%$	0.987	1.287	1.304				

Table 6. Comparison of calculated reaction rate ratios at the center of Core 14 and Core 16 using the 1-D 171-group model

Central ratio	Core 14 C/E values		Core 16 C/E values	
	ENDF/B-4 data	ENDF/B-45 data	ENDF/B-4 data	ENDF/B-45 data
C2/F9	0.928	0.869	0.948	0.879
F2/F9	0.926	0.960	0.906	0.957
C8/F9	1.023	1.033	1.036	1.037
(N2N)2/C2	1.334	1.315		

different data sources for the 2-D 10-group and 1-D 171-group computations, respectively. The frequently used short-hand notation for identifying reaction rates has been used in Tables 5 and 6, and will be used throughout the remainder of this report. The notation is as follows:

- C2 — ^{232}Th neutron capture
- C8 — ^{238}U neutron capture
- F2 — ^{232}Th fission reaction
- F9 — ^{239}Pu fission reaction
- (N2N)2 — ^{232}Th (n,2n) reaction

Several observations from these data tables require further explanation and discussion.

First, it should be emphasized that the 1-D fine-group and 2-D broad-group calculations at core center produce similar C/E values, with the largest deviation being associated with the relatively sensitive high threshold thorium (n,2n) and fission rates. This good agreement is quite significant since it indicates that the fine-group cross-section collapse was performed using a representative weighting spectrum for the center of the PROTEUS test zone.

This point is further magnified in Figs. 4 and 5. Figure 4 first displays the important energy range for the broad-group reaction rate calculation in Core 14, indicating that the energy range below 100 eV can essentially be ignored. Figure 5, which compares the fine-group and broad-group flux spectra at the center of Core 14, shows good agreement above about 100 eV and a relatively poor comparison below this energy. Thus, the 1-D fine-group spectrum, although not completely representative over the entire energy range, does provide an adequate weighting spectrum in the energy range of interest.

It also should be pointed out that this same argument applies to the Core 16 1-D versus 2-D comparison, since, as shown in Fig. 6, the Core 14 and Core 16 flux spectra are very similar in the important energy range. Closer inspection, however, indicates that the Core 14 center spectrum is slightly harder relative to Core 16. This fact accounts for much of the observed shift in the fine-group C/E values. In addition, as indicated in Table 5, the broad-group C/E values for the ORNL-generated data show the same trends as the fine-group results.

The second major point to be noted is the EIR-supplied versus ORNL-generated ENDF/B-4 data comparisons presented in Table 5. Except for the (N2N)2/C2 ratio, fair agreement between the two data sets is achieved. The important C2/F9 and F2/F9 ratios are consistently underpredicted by 4-7% and 10-12%, respectively. In addition, the C8/F9 ratio is underpredicted by about 2% with EIR data and overpredicted by 1-3% with the ORNL ENDF/B-4 library.

These comparisons are more clearly displayed in Table 7, where the percent differences between the individual reaction rates calculated

Fig. 4. ENDF/B-4 Broad-Group Reaction Rates at the Center of Core 14.

Fig. 5. Comparison of Broad-Group and Fine-Group ENDF/B-4 Spectra at the Center of Core 14.

Fig. 6. Comparison of ENDF/B-4 Fine-Group Spectra at the Center of Core 14 and Core 16.

Table 7. Detailed central reaction rate comparisons using EIR and ORNL ENDF/B-4 data

Reaction rate	$\frac{\text{ENDF/B-4} - \text{EIR}}{\text{EIR}} \times 100$	
	Core 14	Core 16
$^{232}\text{Th}(n,\gamma)$	-3.10	-1.50
$^{232}\text{Th}(n,f)$	1.31	1.71
$^{232}\text{Th}(n,2n)$	26.74	20.96
$^{233}\text{U}(n,f)$	-2.23	-1.25
$^{238}\text{U}(n,\gamma)$	2.80	4.16
$^{238}\text{U}(n,f)$	-2.55	-5.43
$^{239}\text{Pu}(n,f)$	-0.85	-0.62

using EIR and ORNL ENDF/B-4 data are tabulated. The good agreement for most of the ^{232}Th and ^{233}U data was expected since, as previously mentioned, the cross sections included in the Swiss version of FGL5 for these nuclides were derived from ENDF/B-IV data. Similarly, the observed differences in the ^{238}U data were anticipated due to the fact that FGL5 is an adjusted data library. However, a slightly higher ENDF/B-IV ^{238}U capture rate was expected since the C8/F9 ratio is known to be well overpredicted with ENDF/B-IV data.¹⁷

A final point of interest in this initial data comparison is the large difference in the calculated thorium (n,2n) reaction rate between the EIR and ENDF/B-4 data. This discrepancy is not clearly understood since the data have the same origin. In spite of this fact, the thorium (n,2n) cross section in the 10-group ENDF/B-4 library was more than 20% larger than the corresponding EIR-supplied data. Since this is a high energy threshold reaction, the calculated thorium (n,2n) reaction rate is very sensitive to data and calculational methods. However, this uncertainty in the (n,2n) reaction rate is an important consideration since the (n,2n) reaction in thorium is a main production route to ^{232}U and its highly radioactive decay chain.⁶

The second data comparison to be made is the contrast between the presently available ENDF/B-IV thorium data and the more recent ENDF/B-V thorium evaluation. This particular comparison is probably the most significant and interesting accomplishment of the present study. Tables 5 and 6 contain the summary results, giving both the 1-D and 2-D central C/E values. The most important observation here is the large decrease in the C/E values for C2/F9 when going from ENDF/B-IV to ENDF/B-V-based thorium data. Since, as shown in Fig. 7, differences in the core center flux spectra are negligible, this decrease is due solely to the reduction of the ^{232}Th capture cross section in the ENDF/B-V data files. Figure 8 displays the normalized capture rate as a function of energy for the 1-D fine-group calculations using ENDF/B data at the center of Core 14. A decrease (about 7% overall) in the ENDF/B-V thorium capture rate is apparent for most of the energies of interest. These results are somewhat disturbing since they seem to question the validity of the new ENDF/B-V infinitely dilute

Fig. 7. Comparison of ENDF/B-4 and ENDF/B-45 Fine-Group Spectra at the Center of Core 16.

Fig. 8. Fine-Group Thorium Capture Rates Versus Energy for ENDF/B-4 and ENDF/B-45 Data at the Center of Core 14.

thorium capture data above 100 eV. Since the C/E values with ENDF/B-IV-based data are already low ($C2/F9 = 0.93 - 0.96$), the new ENDF/B-V data seem to have been evaluated in the wrong direction.

In contrast to the capture cross sections, the recent ENDF/B-V evaluation seems to have improved the thorium fission and $(n,2n)$ data relative to ENDF/B-IV. An increase of approximately 5% in the central ^{232}Th fission rate and a decrease of about 6% in the $(n,2n)$ reaction rate are observed with ENDF/B-V data in the PuO_2/UO_2 fast lattice spectrum. This brings the calculated ^{232}Th fission rate into better agreement with experiment, with C/E values for $F2/F9$ of about 0.92 - 0.95. However, although adjusted in the proper direction, the ^{232}Th $(n,2n)$ reaction rates are still significantly overpredicted with ENDF/B-V-based data.

In summary, the core center results for the Core 14 and Core 16 analyses have shown that ENDF/B-IV infinitely dilute ^{232}Th capture data underpredicts measured values and that these discrepancies are further exaggerated with ENDF/B-V data. On the other hand, ENDF/B-V ^{232}Th fission data appears to be significantly improved relative to ENDF/B-IV-derived data. Lastly, it should be noted that the ^{232}Th $(n,2n)$ cross-section discrepancies in both ORNL-generated ENDF/B data sets appear to be extremely large, although this result is in disagreement with EIR data.

IV. RESULTS IN THE ThO_2 AND Th-METAL AXIAL BLANKET ZONES

The core-center analyses for both the ThO_2 and thorium metal blanket configurations considered thorium only in an infinitely dilute environment, and hence did not include resonance self-shielding effects. To investigate these effects, comparisons were made of reaction rate measurements and calculations in the ThO_2 and Th-metal blankets of Core 14 and Core 16.

It should be noted that the Core 14 - Core 16 similarity mentioned previously (see Fig. 6) applied only to the core region. Although both experiments contained thorium in the axial blanket region, the neutronic characteristics of the ThO_2 and thorium metal blankets are quite different.

Figure 9 emphasizes this point by comparing the Core 14 and Core 16 fine-group spectra at the center of the axial blanket region. The Core 16 fine-group spectrum is determined completely by the neutronic characteristics of thorium, whereas the Core 14 spectrum is affected by several of the nuclides in the ThO_2 blanket. Thus, the Core 14 and Core 16 analyses address the adequacy of thorium data in two quite dissimilar spectral environments.

A summary of the results obtained for the axial blanket reaction rate comparisons in Core 14 and Core 16 is given in Table 8. This displays the C/E values for three important reaction rate ratios at the center of the axial blanket zones. In general, the calculations and measurements show a much larger disagreement in the blanket than at core center. Although improved agreement is obtained for several of the ratios with ORNL-generated data relative to EIR data, the key observation to be made from Table 8 is that the overall results indicate that the data and/or methods utilized in this study are inadequate for the analysis of the PROTEUS axial blanket experiments.

Comparison of the calculated axial profiles of the important ^{232}Th , ^{238}U , and ^{239}Pu capture and fission rates with experiment provide some insight into the discrepancies observed in Table 8. Figures 10-17 display these axial profiles, contrasting the various data sources utilized in the Core 14 and Core 16 analyses.

In general these show that in both cores the calculated and measured profiles agree very well until the core/blanket boundary is approached. At this point the profiles deviate from experiment with varying degrees of magnitude. The ^{232}Th capture rate is overpredicted, the ^{232}Th fission profile falls between the EIR and ORNL-generated data, the ^{238}U capture rate is significantly overpredicted, and lastly, the ^{239}Pu fission rate is greatly underpredicted in the ThO_2 blanket of Core 14. On the other hand, both the ^{232}Th capture and fission rates are overpredicted and the ^{239}Pu fission and ^{238}U capture profiles are underpredicted in the Core 16 thorium metal blanket.

Fig. 9. Comparison of Core 14 and Core 16 Fine-Group ENDF/B-4 Spectra at the Center of the Axial Blanket.

Table 8. Comparison of C/E values for several calculated reaction rate ratios at the center of the axial blanket of Core 14 and Core 16 using the 2-D 10-group model

Reaction rate ratio	Core 14 Results				Core 16 Results			
	Measured Value ^a	C/E Values			Measured Value ^a	C/E Values		
		EIR data	ENDF/B-4 data	ENDF/B-45 data		EIR data	ENDF/B-4 data	ENDF/B-45 data
C2/F9	0.1114	1.31	1.30	1.25	0.1066	1.34	1.20	1.13
F2/F9	1.421×10^{-3}	1.19	0.95	0.96	1.28×10^{-3}	1.34	1.17	1.13
C8/F9	0.2025	1.60	1.42	1.41	0.3969	0.56	0.89	0.75

^aMeasured values were derived from absolute values at core center and relative values at center of axial blanket.

Fig. 10. Core 14 Axial ^{232}Th Capture Rate Profiles Utilizing Various Data Libraries.

Fig. 11. Core 14 Axial ^{232}Th Fission Rate Profiles Utilizing Various Data Libraries.

Fig. 12. Core 14 Axial ^{238}U Capture Rate Profiles Utilizing Various Data Libraries.

Fig. 13. Core 14 Axial ^{239}Pu Fission Rate Profiles Utilizing Various Data Libraries.

Fig. 14. Core 16 Axial ^{232}Th Capture Rate Profiles Utilizing Various Data Libraries.

Fig. 15. Core 16 Axial ^{232}Th Fission Rate Profiles Utilizing Various Data Libraries.

Fig. 16. Core 16 Axial ^{238}U Capture Rate Profiles Utilizing Various Data Libraries.

Fig. 17. Core 16 Axial ^{239}Pu Fission Rate Profiles Utilizing Various Data Libraries.

The deviations from the measured profiles at the center of the axial blankets are also quantified in Table 9. As indicated, except for the ^{238}U capture rate, the disagreement with experiment is typically between ± 10 -20%. Thus, it is these discrepancies for the individual reaction rates that produce the large range of C/E values observed in Table 8. Although these deviations are not absolute C/E values as in Table 8, Table 9 and the axial profiles do indicate which reaction rates are in error.

A careful investigation of the relatively large discrepancies observed in all of the axial blanket calculations concluded that modeling and methods (rather than nuclear data) uncertainties were the dominant factors, and consequently very little useful information could be obtained from the axial blanket analysis. In particular, it is felt that the procedure for collapsing fine-group cross sections to the broad-group level used in the two-dimensional calculations was inadequate. As at core center, the collapse in the blanket was performed using flux spectra determined from a 1-D calculation in the axial direction along the reactor centerline. While this procedure gives an adequately representative weighting spectrum at the core center, the spectrum computed in the axial blanket lacks a significant low-energy component due to the thermal driver region which surrounds the test zone.

This deviation in the low-energy flux and its importance in the calculation of the Core 14 ThO_2 axial blanket reaction rates are illustrated in Figs. 18 and 19. Figure 18 first contrasts the ENDF/B-4 fine-group and broad-group spectra at the center of the axial blanket, indicating a relatively large disagreement below about 500 eV. Figure 19 then displays the groupwise contribution of several broad-group reaction rates and emphasize that, in contrast to core center, the lower energy groups are quite significant in the axial blanket region. In particular, the ^{238}U capture rate and ^{239}Pu fission rate, which is in the denominator of each reaction rate ratio listed in Table 8, have a significant contribution to the total reaction rate occurring below 500 eV. This large sensitivity of the reaction rates to the low-energy flux and data, combined with the inadequate weighting of the low-energy broad-group cross sections, amply

Table 9. Percent deviation from the measured axial profile
at the center of the axial blankets of Core 14 and Core 16

Reaction rate	Percent deviation $\left(\frac{\text{calc-expt}}{\text{expt}} * 100 \right)$					
	Core 14 ThO ₂ blanket			Core 16 Th-metal blanket		
	EIR data	ENDF/B-4 data	ENDF/B-45 data	EIR data	ENDF/B-4 data	ENDF/B-45 data
²³² Th(n,f)	+12	-17	-20	+23	+18	+5
²³² Th(n, γ)	+14	+10	+14	+12	+11	+10
²³⁸ U(n, γ)	+35	+11	+9	-54	-23	-38
²³⁹ Pu(n,f)	-17	-21	-21	-19	-12	-14

Fig. 18. Comparison of Broad-Group and Fine-Group ENDF/B-4 Spectra
at the Center of the Axial Blanket of Core 14.

Fig. 19. ENDF/B-4 Broad-Group Reaction Rates at the Center of the Axial Blanket of Core 14.

explains the disagreement between the calculated and measured-reaction rates in the axial blanket of Core 14.

Lastly, it should be noted that, in general, the same comments just presented for the Core 14 analysis also apply to the Core 16 thorium metal axial blanket analysis. That is, due to the inadequacy of the fine-group weighting spectra and high sensitivity of the total reaction rates to the low-energy (resonance region) broad-group data, little useful information regarding the adequacy of thorium data in a thorium metal lattice could be extracted. However, for completeness, Figs. 20 and 21 present data for Core 16 similar to that given in Figs. 18 and 19 for Core 14. In addition, comparisons of ENDF/B-4 and ENDF/B-45 fine-group spectra and ENDF/B-45 fine and broad-group spectra are given in Figs. 22 and 23 respectively. These latter two figures indicate that although ENDF/B-V thorium has a large effect on the axial blanket spectra, the discrepancies between the fine- and broad-group spectra still dominate the analysis and thus produce results similar to those obtained with ENDF/B-IV data.

Fig. 20. Comparison of Broad-Group and Fine-Group ENDF/B-4 Spectra at the Center of the Axial Blanket of Core 16.

Fig. 21. ENDF/B-4 Broad-Group Reaction Rates at the Center of the Axial Blanket of Core 16.

Fig. 22. Comparison of ENDF/B-4 and ENDF/B-45 Fine-Group Spectra at the Center of the Axial Blanket of Core 16.

Fig. 23. Comparison of Broad-Group and Fine-Group ENDF/B-45 Spectra at the Center of the Axial Blanket of Core 16.

Therefore, unlike the core center analysis which showed the need for improved thorium capture data, the axial blanket analysis has shown the need for more sophisticated methods and improved modeling of the test reactor. It is expected that the C/E values in the axial blanket could be noticeably improved if either a better procedure were used for cross-section collapsing (e.g. a fine-group 2-D calculation of the weighting spectra) or a finer group structure were used for the broad-group 2-D calculations.

V. SENSITIVITY OF CALCULATED RESULTS TO MODELING APPROXIMATIONS

As indicated in Section II, several theory and modeling options were available in the XSDRNPM¹⁵ and DOT-IV¹⁰ codes. Parametric studies were performed utilizing some of these options to investigate their effect on the calculated reaction rates in the two PROTEUS axial blanket configurations. Of primary concern in this analysis was the validation of the methods utilized to obtain C/E values at core center of the Core 14 and Core 16 mockups since it has already been noted that the axial blanket results did not yield much information concerning the adequacy of the nuclear data. Thus, a sizable effort was made to verify that the observed differences between calculation and experiment at core center were due to data uncertainties rather than methods uncertainties.

The first (and probably most important) parametric investigation was an attempt to quantify the sensitivity of the central reaction rate ratios to the 1-D weighting spectrum utilized in the collapse to a broad-group library. As indicated previously, the XSDRNPM module allows three 1-D model approximations: infinite slab, buckling search for a critical system, or finite buckling correction models. Each of these approximations was utilized in an ENDF/B-4 fine-group calculation of the Core 14 1-D axial representation, with the resultant central flux spectra given in Fig. 24. The finite geometry calculations resulted in an increased fast leakage and a decreased downscatter source, which, when combined, produced

Fig. 24. Comparison of ENDF/B-4 Flux Spectra at Center of Core 14 for Various 1-D Model Approximations.

a harder neutron spectrum relative to the infinite slab geometry. As can be seen in Fig. 24, the buckling correction spectrum varied significantly from the infinite slab calculation. On the other hand, the buckling search and infinite slab computations were quite similar, with the former producing the slightly harder spectrum.

The three spectra displayed in Fig. 24 were then utilized to collapse the 171-group data to 10 groups for the 2-D DOT-IV calculations. This procedure allowed a direct comparison of 1-D and 2-D central reaction rates and also permitted an examination of the influence of the collapsing weight function on the 2-D C/E values. Data from these comparisons are summarized in Table 10.

The first half of Table 10 displays the central C/E values from the three 1-D model approximations. If the 1-D spectra were representative of the 2-D models, good comparisons of 1-D and 2-D reaction rates (and C/E values) should occur. However, the second half of Table 10 indicates quite

Table 10. Sensitivity of important central C/E values
in Core 14 to the ENDF/B-4 1-D weighting spectra

Central ratio	1-D C/E values			2-D C/E values		
	Infinite slab	Buckling search	Buckling correction	Infinite slab	Buckling search	Buckling correction
C2/F9	0.987	0.928	0.722	0.947	0.934	0.884
F2/F9	0.827	0.926	1.386	0.897	0.901	0.915
C8/F9	1.079	1.023	0.808	1.022	1.013	0.975
(N2N)2/C2	1.113	1.334	2.646	1.261	1.287	1.425

poor agreement between the 1-D and 2-D models except for the buckling search case. In this instance (as discussed more fully in Section III), the 1-D weight function was an adequate representation of the 2-D spectrum over the energy range of interest and, therefore, produced good agreement in central C/E values. Thus, the buckling search approximation for a critical system was chosen as the best 1-D weighting function at core center, and the results tabulated in all sections except Section V were generated using this 1-D representation.

The second point to note from Table 10 is the actual variation of the C/E values. As would be expected, the sensitivity of the C/E values to the 1-D weighting spectrum is much greater in the 1-D calculations than the 2-D calculations. However, there is still significant variation among the 2-D results, especially when contrasting the infinite slab and buckling corrected weighting spectra. This fairly large sensitivity emphasizes the importance of having the correct weighting function in the collapse of a fine-group data set to a broad-group library. As shown above with the buckling search results, the weighting spectrum utilized in the cross-section collapse must be properly matched to the calculated broad-group spectrum if realistic results are to be expected.

In addition to the analyses described above, the effect of some theory approximations were also investigated. A comparison of diffusion theory versus transport theory methods showed that the two theories gave

very similar central and axial blanket C/E values. This is illustrated in Table 11, which contrasts diffusion and transport theory methods for calculation of Core 16 reaction rate ratios.

However, more detailed analysis in the axial blanket regions of both Core 14 and Core 16 reveal a higher absolute flux level with diffusion theory relative to the reference transport theory calculations. The effect of this higher flux level in the axial blanket regions is illustrated in Fig. 25 for the ^{232}Th capture rate profile in Core 16. Thus, although not significant compared to other modeling uncertainties, the use of transport theory in the analysis of the axial blanket reaction rates is clearly better than diffusion theory methods.

The effects of the transport scattering and quadrature approximations were also assessed. The reference transport calculations for the Core 14 configuration were performed using a P_0 cross-section expansion and an S_6 symmetric quadrature approximation. However, S_6P_3 and S_4P_3 calculations were also performed. Comparison of the latter two calculations (S_6P_3 versus S_4P_3) showed no observable differences in either the central or axial profile of the calculated reaction rates. Therefore, the C/E values are not sensitive to the quadrature approximation utilized.

On the other hand, the P_3 cross-section expansion showed some interesting differences from the reference P_0 calculation. Although central C/E values were unchanged, the variation in the axial distribution of the reaction rates was quite apparent. A harder flux spectrum as well as an increased flux magnitude relative to core center were observed in the axial blanket region for the P_3 cross-section expansion. These effects are due to increased leakage from the core as a result of the better scattering approximation associated with the P_3 expansion. The effects of the harder spectrum and higher relative flux magnitude on the thorium capture and fission rate profiles in Core 14 are displayed in Figs. 26 and 27, respectively.

The last parametric study to be performed in this analysis was an investigation of the sensitivity of the fast region reaction rates to the boron layers surrounding the ThO_2 and Th-metal blanket regions. As

Table 11. Comparison of transport and diffusion theory
C/E values in Core 16

Reaction rate ratio	Core center C/E values		Axial blanket center C/E values	
	Transport	Diffusion	Transport	Diffusion
C2/F9	0.956	0.955	1.20	1.22
F2/F9	0.873	0.870	1.17	1.19
C8/F9	1.028	1.028	0.89	0.85

Fig. 25. Axial ^{232}Th Capture Rate Profile in Core 16 Using Both Transport and Diffusion Theory Methods.

Fig. 26. Axial Profiles of the ^{232}Th Capture Rate in Core 14 for the S_6P_3 and No-Boron Cases.

Fig. 27. Axial Profiles of the ^{232}Th Fission Rate in Core 14 for the S_6P_3 and No-Boron Cases.

mentioned earlier, the purpose of the boron layers was to shield against leakage from the thermal driver regions to the fast core and blanket zones. Figures 28 and 29, which display the broad-group spectra at the core and axial blanket centers for Core 14 for the reference and no-boron cases, show the effectiveness of such a design. As indicated in Fig. 28, the core center spectrum and resultant reaction rates were essentially unaffected. However, as is apparent in Fig. 29, the softer spectrum in the axial blanket without the boron layers indicates that the measured reaction rates would have been more sensitive to the leakage from the thermal driver regions. In addition, Figs. 26 and 27 show how this spectral change affects the calculated axial ^{232}Th capture and fission rate profiles in Core 14. As observed in these figures (and in Section IV), the axial blanket reaction rates are very sensitive to the low energy component of the neutron flux.

Fig. 28. Broad-Group ENDF/B-4 Spectra at the Center of Core 14 for the No-Boron Case.

Fig. 29. Broad-Group ENDF/B-4 Spectra at the Center of the ThO_2 Axial Blanket in Core 14 for the No-Boron Case.

In summarizing this section, it can be concluded that the central C/E values were insensitive to the theory and modeling approximation investigated. However, it was also shown that the weighting spectrum utilized in the cross-section collapse is a key factor and must be properly matched to the calculated broad-group spectrum. In addition, the calculated results in the axial blankets were found to be quite sensitive to the various approximations utilized, confirming the earlier conclusion that the observed discrepancies in the axial blankets were due to modeling and methods uncertainties rather than data uncertainties.

VI. AXIAL BLANKET NEUTRON SPECTRUM CALCULATIONS

In addition to the reaction rate measurements, neutron spectrum measurements were made at the center of the ThO_2 and Th-metal axial blankets. The spectra were measured using gas-filled proportional counters placed in the axial blankets via a cylindrical hole which extended through the upper half of the blankets and the iron block. Five spherical counters (40 mm o.d.) with filling pressures of 1/2, 1, and 3 atm of hydrogen and 5 and 10 atm of argon-hydrogen mixtures were used to cover the energy range from 10 keV to 2.3 MeV.¹⁸ The measured proton-recoil distributions were unfolded using the SPEC-4¹⁹ code to provide the resulting neutron energy distributions for comparison with calculated flux spectra.

The relatively fine energy resolution of the measured spectra (10-14%) warranted using a finer energy group structure for the spectra calculations than was used for the 10-group reaction rate calculations. The 126-group CLEAR cross-section library¹⁶ selected is a subset of the VITAMIN C library and contains 75 energy groups between 10 keV and 2 MeV. As with the VITAMIN C library, the CLEAR library is derived from ENDF/B-IV, so that a special cross-section set for Th-232 needed to be prepared to investigate the effects of ENDF/B-V thorium data. This was done by collapsing the locally-prepared 174-group ENDF/B-V Th-232 cross sections using a standard Maxwellian-1/E-fission spectrum weighting function.

Since a one-dimensional calculation could not give sufficiently accurate results in the axial blanket and since a fine-group 2-D calculation of the full geometry was not economically feasible, a compromise approach was used. Figure 30 shows the basic method used for the fine-group 2-D spectrum calculations including the cross-section processing. The AMPX-II modules MALOCS, AJAX, BONAMI, NITAWL, and AXMIX¹⁵ were used to prepare the cross sections, while DOT-IV performed the 2-D transport calculations. The spatial fission sources produced in the 10-group 2-D calculations described earlier were folded with 126-group zone-dependent fission-neutron energy distributions to yield a distributed source for the fine-group calculations. The axial space mesh for the 10-group and 126-group calculations were identical, while the radial mesh for the fine-group

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Fig. 30. Flow Diagram Showing Cross-Section Processing and Computational Approach for Fine-Group Two-Dimensional Calculation of Neutron Flux in the Axial Blanket.

calculations was truncated beyond the uranium buffer region. This reduced the space mesh to an economical size while also eliminating upscatter considerations and hence the need for multiple source iterations. Figure 31 shows the R-Z model used for the spectrum calculation of the ThO₂ axial blanket (Core 14).

A comparison of the neutron spectrum calculated and measured at the center of the ThO₂ axial blanket is illustrated in Fig. 32. The measurement has been normalized to the calculated flux over the full energy range of the measurement. The calculated spectrum, which is based on all ENDF/B-IV data, agrees reasonably well with the measurement between 30 and 500 keV while overpredicting at higher energies and underpredicting at lower energies. A similar comparison is shown in Fig. 33 for the Th-metal axial blanket (Core 16) and shows the same type of disagreement as with the ThO₂ blanket case.

Although the cause for the overpredictions above 500 keV was not known, it was felt that the underpredictions below 30-40 keV might be due to the finite-model approximation. It had been noted for the reaction rate calculations that the 1-D calculations (used to collapse the 171-group cross sections) produced a significantly softer energy spectrum in the axial blanket when a finite buckling was used instead of the infinite lattice approximation. To further investigate this, a 10-group calculation was performed using the same reduced geometry and fission source as used in the 126-group Core 14 calculation, but using the same 10-group cross sections as used in the full-geometry calculation. Even though the 10-group cross sections had been collapsed using an infinite lattice approximation, the 10-group reduced-model calculation gave C/E values for most of the reaction rate ratios that were closer to the 126-group values than to the 10-group full-model values. These results are summarized in Table 12 and provide sufficient data to conclude that at least part of the underprediction of the lower-energy spectra in the axial blankets is due to the finite geometric model approximation.

The neutron spectrum in the Th-metal axial blanket (Core 16) was further investigated to determine the effects of k_{eff} and the spectrometer

Fig. 31. Two-Dimensional Model Used for Fine-Group Calculation of Neutron Spectrum at the Center of the Axial Blanket.

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Fig. 32. Comparison of Measured and Calculated Spectra in the ThO₂ Axial Blanket of Core 14. Calculated spectrum used all ENDF/B-IV-derived data.

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Fig. 33. Comparison of Measured and Calculated Spectra in the Th-Metal Axial Blanket of Core 16. Calculated spectrum used all ENDF/B-IV-derived data.

Table 12. Calculated-to-experimental ratios at the center of Core 14 (ThO₂ axial blanket)

Ratio	C/E values			
	10-grp. full model (infinite lattice) ^a	10-grp. full model (finite buckling) ^a	126-grp. reduced model	10-grp. reduced model
C2/F9	0.947	0.884	0.884	0.887
C8/F9	1.022	0.975	0.949	0.981
F2/F9	0.897	0.915	0.964	0.939
(N2N)2/C2	1.261	1.425	1.276	1.406

^aApproximation used in the 1-D calculation to collapse cross sections from 171 to 10 groups.

gap. Since the measurements were actually performed with the PROTEUS reactor in a slightly subcritical configuration, it was important to know if this had a significant spectral effect. Therefore, the 10-group full-geometry calculation for Core 16 was redone with the critical radius reduced from 77.876 cm to 75.246 cm, which caused k_{eff} to drop from 0.994 to the desired 0.970. The subcritical fission source was then used as a distributed source for a 126-group 2-D calculation. In Fig. 34 the resulting spectrum is compared to the reference critical case and is shown to be indistinguishable from the critical case. Actual group fluxes differed by only 1-2% between the critical and subcritical calculations.

Also shown in Fig. 34 is the neutron spectrum in the Th-metal blanket when the spectrometer gap is ignored. The gap has very little effect on the spectrum, except to harden the spectrum slightly due to the removal of some blanket material and steel reflector material.

Finally, Core 16 was recalculated using cross sections for thorium based on ENDF/B-V. The version V data was incorporated into both the 10-group full-model calculation used to produce the fission source and the 126-group reduced-model calculations; all other materials used the version IV data. In Fig. 35 the resulting spectrum in the Th-metal axial blanket is compared to the measured neutron spectrum. Agreement between the calculated and measured spectra is significantly better above 500 keV than with ENDF/B-IV thorium. However, below 200 keV the new data yields substantial discrepancies.

Fig. 34. Calculated Neutron Spectra in the Core 16 Th-Metal Axial Blanket.

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Fig. 35. Comparison of Measured and Calculated Spectra in the Th-Metal Axial Blanket of Core 16. ENDF/B-V-derived ^{232}Th data were used for the calculation.

The source of the lower energy discrepancies observed in Fig. 35 was suggested by an inspection of the basic nuclear data for thorium. Figure 36 gives a comparison of ENDF/B-IV and -V ^{232}Th cross sections for the inelastic scattering process, (n,n') . Even though the magnitude of the (n,n') cross section is small compared to the total cross section, the differences shown in Fig. 36 correlate closely with the differences in the calculated spectra in Figs. 33 and 35. In order to verify the correlation, a special hybrid 126-group cross-section set was prepared for thorium which was identical to the ENDF/B-IV-based set except that the discrete and continuum inelastic scattering partial cross sections were replaced with ENDF/B-V partials. Figure 37 outlines the computational scheme for creating the hybrid thorium data and calculating a "hybrid spectrum" in the Th-metal axial blanket of Core 16.

The hybrid spectrum is compared to the ENDF/B-IV and -V spectra in Fig. 38, which shows that for the given energy range, the shape of the flux spectrum is largely determined by the (n,n') cross section. With consideration of the measured spectrum (Fig. 33 or 35), it appears that the changes in the (n,n') cross section above 400 keV are appropriate; however, the significant decrease in the data below 200 keV is not supported by this experiment. This decrease apparently causes a reduced flux removal from the corresponding energy groups, which causes the flux to increase relative to the ENDF/B-IV case (see Fig. 38). At lower energies (below 50-60 keV) the flux begins to drop rapidly due to the loss of the downscatter source from the preceding groups. Therefore, the preferred inelastic cross section for thorium would comprise ENDF/B-IV data below 200 to 300 keV and ENDF/B-V data above that energy.

It should be noted that the log-log scaling in Fig. 36 tends to exaggerate the importance of the low-energy differences. A more thorough look at the inelastic scattering cross sections in the ENDF/B-V evaluation⁵ shows that the sub-200 keV differences are mostly confined to the (n,n') to the first excited level, and that the differences are due to the method of interpolation between the 49.5-keV threshold and the first available experimental data at approximately 250 keV. Therefore, the total inelastic cross section between 50 and 200 keV could probably be

Fig. 36. Comparison of ENDF/B-IV and ENDF/B-V Multigroup Cross Sections for the Inelastic Scattering Process (MT4).

restored to the ENDF/B-IV values while still being consistent with the newer experimental data on which the ENDF/B-V evaluation is based.

Although the neutron spectrum in the measured energy range is highly sensitive to changes in the (n,n') cross sections, the total thorium capture reaction rate is decreased only 3% by using the hybrid spectrum rather than the all-ENDF/B-IV case. This is due to compensating positive and negative differences in the spectra. Coincidentally, the "bad" (n,n') changes below 200 keV contribute 1.5% while the apparent cross section improvements above 200 keV contribute the other 1.5%. The total ^{232}Th fission rate, on the other hand, decreased 18% with the hybrid spectrum, which is entirely due to the drop in the flux spectrum above 1 MeV resulting from the increased inelastic cross section. Therefore, the newer (n,n') could have significant impact in some aspects of alternate fuel cycle studies.

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Fig. 37. Flow Diagram Showing Cross-Section Processing Used to Create Hybrid Thorium Data Set from ENDF/B-IV and -V.

Fig. 38. Comparison of Core 16 Axial Blanket Spectra Calculated Using ENDF/B-IV, ENDF/B-V, and the Hybrid IV/V Thorium Data.

In conclusion, it is felt that the spectrum measurements are worthwhile in that they provide a more stringent test of the cross section data and methods than do the integral reaction rates. Also, because of the energy range for the spectrum data, the measurements test different components of the thorium data, i.e., the inelastic process rather than capture or fission. As with the reaction rate measurements in the axial blanket, however, a careful analysis is required to understand and eliminate possible effects of model and methods approximations.

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VII. SUMMARY AND CONCLUSIONS

As mentioned previously, the main goal of the ORNL analyses of the Core 14 and Core 16 PROTEUS thorium-bearing configurations was an assessment of the available thorium data for use in accurate fast reactor alternate fuel cycle studies. From this viewpoint, a summary of the major results of this study is as follows:

1. The EIR- and ORNL-generated ENDF/B-IV ^{232}Th data produced similar central reaction rates (maximum 3% difference) except for the significantly higher ^{232}Th (n,2n) rate obtained using ORNL ENDF/B-IV data.
2. Both ENDF/B-IV-derived libraries underpredicted the central infinitely dilute ^{232}Th capture and fission rates with C/E values of 0.93-0.96 and 0.87-0.90 for C2/F9 and F2/F9, respectively.
3. ENDF/B-V thorium data produced significantly lower capture rates (-7%) and better fission and (n,2n) rates (+5% and -6%, respectively) than did ENDF/B-IV.
4. In the axial blanket analyses, modeling and methods uncertainties were dominant factors for the reaction rate calculations, indicating that more sophisticated methods are needed to properly analyze the PROTEUS axial blanket measurements.
5. The central C/E values were insensitive to the theory and 2-D modeling approximations investigated; however, the 1-D weighting spectrum utilized in the cross-section collapse was a key factor and needed to be properly matched to the calculated broad-group spectrum.
6. The fine-group 2-D calculations of the neutron spectra in the axial blanket were also affected by methods and modeling difficulties; however, some useful conclusions regarding ^{232}Th (n,n') cross sections were obtained.

Based on these results, several concluding remarks concerning the adequacy of present thorium data can be made. First, one can conclude that since the central C/E values were insensitive to theory and modeling approximations, a comparison of calculated and measured reaction rate ratios at the center of the Core 14 and Core 16 configurations was a true

measure of the adequacy of the nuclear data in the energy range of interest. Thus, from the C/E values obtained in this study, one can only conclude that the presently available thorium data appears somewhat inadequate for accurate GCFR fuel cycle analyses. Both ENDF/B-IV and ENDF/B-V ^{232}Th data seem to have significant deficiencies. Although the more recent ENDF/B-V ^{232}Th fission data appears more satisfactory than ENDF/B-IV data, the discrepancies in the observed ENDF/B-IV ^{232}Th capture rate in a PuO_2/UO_2 fast lattice spectrum are greatly exaggerated with ENDF/B-V data. In addition, the ^{232}Th (n,2n) cross-section uncertainties in both ENDF/B data sets appear to be extremely large. This all indicates that relatively large uncertainties must be associated with many of the results obtained from a wide variety of recent fast reactor alternate fuel cycle studies.

Finally, it should be emphasized that the above rather harsh conclusions are based only on the core center results from the Core 14 and Core 16 analyses. These analyses were primarily concerned with infinitely dilute thorium data in PuO_2/UO_2 fast spectrum. Thus the present thorium data assessment is somewhat incomplete, since the axial blanket studies provided little useful information about resonance self-shielded thorium data. Nevertheless, the infinitely dilute thorium results are valid and, therefore, strongly suggest the need for further thorium data analyses and evaluations, both integral and differential.

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