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DEEP PENETRATION INTEGRAL EXPERIMENT FOR A THORIUM BLANKET MOCKUP

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An integral experiment has been performed for verification of radiation transport methods and nuclear data used for design of the radial shield for the gas-cooled fast breeder reactor (GCFR). The experiment included a thorium oxide blanket mockup and several shield configurations. The blanket measurements were needed to reduce uncertainties in the cross-section data used for calculating neutron transmission through a thorium blanket and to bound the uncertainties in calculated gamma-ray heating rates within the blanket.

Measured neutron spectra and integral flux data are compared to 1D calculations of the transmitted flux. Calculations using ENDF/B-IV and ENDF/B-V data for thorium are compared and show the version V data to be superior above 1 MeV. The experiment, which is primarily sensitive to the total removal cross section, also showed V to be an improvement below 1 MeV, but still discrepant from the measurements.

[Thorium, total cross section, integral experiment, GCFR, blanket, neutron transmission.]

Introduction

The design of reactor shielding is a complex effort involving intimate relationships between radiation transport, thermomechanical forces, material properties, and economics. To aid the shield designer in achieving the optimum compromise of these considerations, several analytic tools have been developed such as discrete ordinates and Monte Carlo codes. For advanced reactors, where little operating experience is available, verification of these design methods and the design-based data is important. Integral experiments perform this function by (1) providing data against which the methods and data can be tested or (2) providing direct verification of the effectiveness of the final design.

An integral experiment was designed for the verification of radiation transport methods and nuclear data used for the design of the radial shield for the proposed 300 MW(e) gas-cooled fast breeder reactor (GCFR).[1] The scope of the experiment was chosen to include a thorium oxide radial blanket mockup as well as several shield configurations. The blanket measurements are needed to reduce the large uncertainties which exist in the cross-section data required for calculating neutron transmission through a thorium blanket, hence reducing the uncertainties in the calculated source terms for the radial shield. Similarly, the shield measurements are needed to reduce the uncertainties in the calculated radiation damage to the prestressed concrete reactor vessel. Additionally, the measurements are intended to bound the uncertainties in calculated gamma-ray heating rates within the blanket and shield. Although designed specifically for the GCFR, the experiment provides generic data regarding deep penetration in ThO_2 and common shield materials, which also benefits LMFBR designers.

The experiment is currently being analyzed using primarily one- and two-dimensional discrete ordinates methods. The purpose of this paper is to describe the experiment and measurements, and to present significant results from the analysis of the blanket configurations.

Experiment Design

The experiment was performed at the ORNL Tower Shielding Facility (TSF), and consisted of measurements behind one-dimensional mockups of a GCFR-type radial blanket and radial shield. Both integral and spectral measurements were made of the neutron and gamma-ray flux transmitted through successive material configurations and compared to corresponding calculations of the radiation transport. The collimated neutron source from the TSF reactor[2] was first directed through a spectrum modifier to produce a neutron energy distribution typical of a GCFR. The modified source then penetrated the experimental assemblies which consisted of 150- by 150-cm slabs of blanket and shield material placed perpendicular to the neutron beam centerline. Figure 1 shows the experimental geometry for the case of a three row ThO_2 blanket mockup. One of the three 15-cm-thick slabs of ThO_2 (density of 7.2 g/ml) was fabricated as two 7.5 cm-thick slabs in order to make measurements in 1/2-row increments. The concrete shown in Fig. 1 which surrounds the configuration provides a biological shield for the TSF personnel, while the lithiated paraffin minimizes the contribution of neutrons

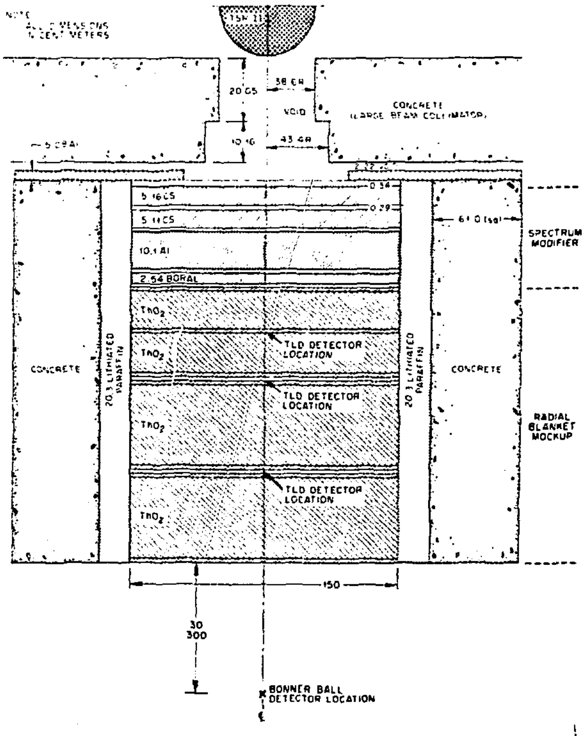

Fig. 1. Plan view of ThO_2 blanket configuration.

which reflect from the concrete back into the test assembly.

In addition to the ThO_2, measurements were made behind 30 cm of UO_2 and numerous arrangements of shielding material consisting of up to 95 cm of stainless steel, graphite, and boronated graphite. The measurements were made using Bonner balls (BB) for integral neutron flux measurements, NE-213 and hydrogen counters for fast neutron spectra measurements, NE-213 for gamma-ray spectra measurements, and thermoluminescent dosimeters (TLD) for gamma-ray heating measurements. All detectors were positioned on the reactor beam centerline, and were located behind the configurations except for the TLDs which were sandwiched between the blanket and shield slabs.

Analysis

Complete analysis of the blanket and shield measurements will consist of one-dimensional (1D) fine-group and two-dimensional (2D) semifine-group transport calculations of the neutron and gamma-ray fluxes throughout the experimental configurations. The calculated fluxes are used with energy-dependent response functions to predict the observed data from the BB and TLD measurements, and are compared directly to the reduced data from the spectrometer measurements. Since the analysis of the full experiment is currently in progress, results based only on the 1D calculations of the blanket mockups will be presented here. There is much information to be learned from the 1D analysis, however, since the slab design of the experiment intentionally lends itself well to 1-D methods. Also, results from the blanket measurements are of immediate interest since they provide a comparison of the adequacy of thorium data for deep penentration problems typical of reactor physics and shield design calculations.

Analytic Approach

The one-dimensional calculations were performed using the ANISN discrete ordinates transport code.[3] Coupled neutron-gamma-ray cross sections with 171-neutron and 36-gamma-ray energy groups and a P_3 order of expansion were specially prepared for this analysis from the ORNL Vitamin C cross section library[4] and from ENDF/B-V data files for thorium-232. The cross sections were processed using the AMPX-II code system[5] which performed the necessary resonance self-shielding, the neutron-gamma-ray coupling, and the reformatting required to produce an ANISN cross section tape.

The neutron source spectrum was obtained by interpolation of the previously determined 51-group S_{16} angular source[2] on a per unit lethargy basis for each of the 8 forward-directed angles. A similar procedure was used to obtain fine-group response functions from the 51-group Bonner ball responses[6] and the 51, 25-group TLD responses. The experimental configurations were modeled from the TSF boundary source through the spectrum modifier and the blanket slabs. A symmetric S_{16} quadrature was used and mesh intervals were made less than 1 cm.

Calculation of Observed Data

The observed responses of the Bonner balls and the TLDs were determined by folding the calculated fluxes with the corresponding detector response functions. Since the 1D slab geometry does not account for the geometric attenuation of the flux, an absolute comparison between the calculated and measured data can not be made. It is possible, however, to draw several conclusions from the relative comparisons.

The spectrometer pulse height data were converted in a data-reduction process to yield spectra data which could be compared directly to the calculated flux spectra, except for the normalization limitation described above. However, before comparing the calculated and measured spectra, it was appropriate to first smooth the calculation with the approximate resolution of the spectrometer. Also, since the detectors were located several meters behind the configurations, it was felt that the neutron leakage for the forward-most angle at the exit of the calculation was a better approximation to the observed flux. Therefore, all of the calculated results presented below are given as the forward angle leakage.

Results

A comparison of the calculated leakage and the NE-213 neutron flux measurement is given in Fig. 2 for the case of the full UO_2 blanket mockup. With the calculation normalized to give the same integrated flux as the measurement between 3 and 12 MeV, it is apparent that the agreement in the spectral shape is excellent. The only significant discrepancy is between 2 and 4 MeV, but this discrepancy merely suggests that the actual detector had a poorer resolution in this energy range than was used to smooth the calculation. The normalization of the calculated spectrum is substantiated, in part, by a comparison of calculated and measured Bonner ball responses where the detectors were located at the same position as the NE-213 detector. It was found that the calculated-to-measured ratio (C/E) for each of the 3 Bonner balls agreed within 5% with the other balls, and agreed within 25% with the scale factor used to normalize the calculated spectrum in Fig. 2. The fact that the 3 Bonner ball C/E's agreed with each other suggests that the entire energy spectrum was predicted well by the calculations.

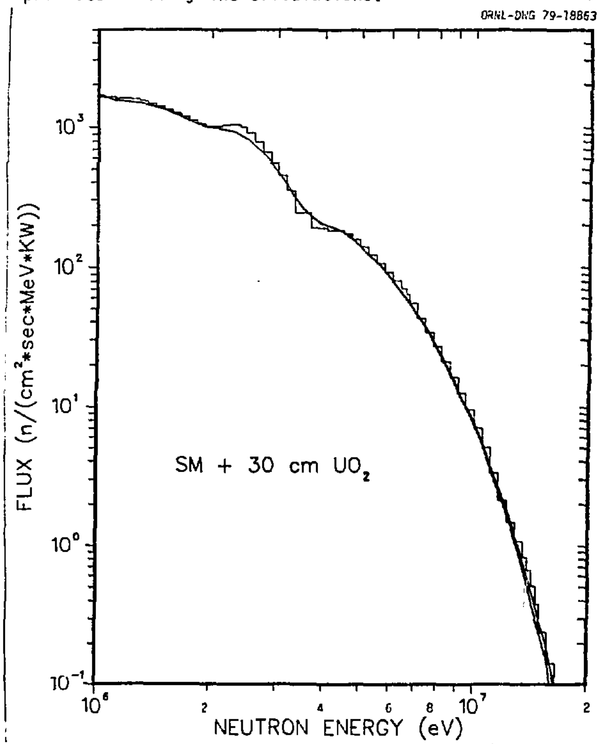

Fig. 2. Comparison of measured (double line) and calculated (histogram) neutron spectrum through a 2-row UO_2 blanket mockup.

Figures 3 and 4 give comparisons of calculated and measured spectra behind a 30-cm-thick ThO_2 blanket mockup. As before, the calculations were normalized based on the integrated flux between 3 and 12 MeV. The calculations shown in Fig. 3 used cross sections which were derived entirely from ENDF/B-IV data, and is in general agreement with the measured spectrum except below 4 MeV. However, the calculation shown in Fig. 4 used thorium data from ENDF/B-V, and predicts the observed spectrum exceedingly well. Similar results, to a greater degree, are shown in Figs. 5 and 6 which compare measurements behind 45 cm of ThO_2 to the corresponding calculations based on ENDF/B-IV and -V thorium data. It is also apparent from the 45-cm case that both sets of data underpredict the observed spectra by 30-40% in the range of 11 to 14 MeV.

As with the UO_2 case presented above, the scale factors used to normalize the calculated spectra in Figs. 3 - 6 were compared to the C/E values determined for the 3 Bonner balls. For the calculations utilizing ENDF/B-V thorium data, the agreement between the scale factors and the C/E's ranged from 10% for the 10" BB to 25% for the 3" BB. The calculations utilizing ENDF/B-IV Th data showed agreements ranging from 15% for the 10" BB to 35% for the 3" BB. The reasonably good agreement between the spectra scale factors and the 10" BB C/E values gives credence to the comparisons in Figs. 3 - 6; however, the disagreement in C/E values among the Bonner balls suggests that the lower energy spectrum is not predicted as well as the higher energies.

One result from the 1D analysis which is independent of the normalization and which also suggests that the low energy neutron transport through ThO_2 is not predicted well, is a comparison of measured and calculated attenuation factors for a single slab of ThO_2. This was determined by calculating the ratio of a detector response for the 30 cm ThO_2 case and the 45 cm case. The results for the Bonner balls and the integrated NE-213 flux are given in Table 1. Also given in Table 1 are the percent differences between the calculated and measured attenuations, which vary from 5% to 18% for calculations utilizing ENDF/B-V thorium, and vary from 11% to 23% for ENDF/B-IV thorium. Both sets of data yield an underprediction of the lower energy neutron attenuation as measured by the 3" BB, but it appears that the ENDF/B-V thorium data reduces the observed discrepancies.

Table 1. Neutron Attenuation Through 15 cm of Thorium Oxide

	ATTENUATION[a]		
DETECTOR	MEASURED	ENDF/B-IV	ENDF/B-V
3" BB (epithermal)	3.70	2.85 (23)[b]	3.04 (18)
6" BB (total)	4.24	3.46 (18)	3.69 (13)
10" BB (fast)	4.39	3.92 (11)	4.19 (5)
NE-213 (3-12 MeV)	6.15	5.10 (17)	5.42 (12)

[a]Ratio of detector response with 30 cm ThO_2 to 45 cm ThO_2.

[b]Calculated using leakage for forward-most angle only. Number in parentheses give percent deviation from measured attenuation.

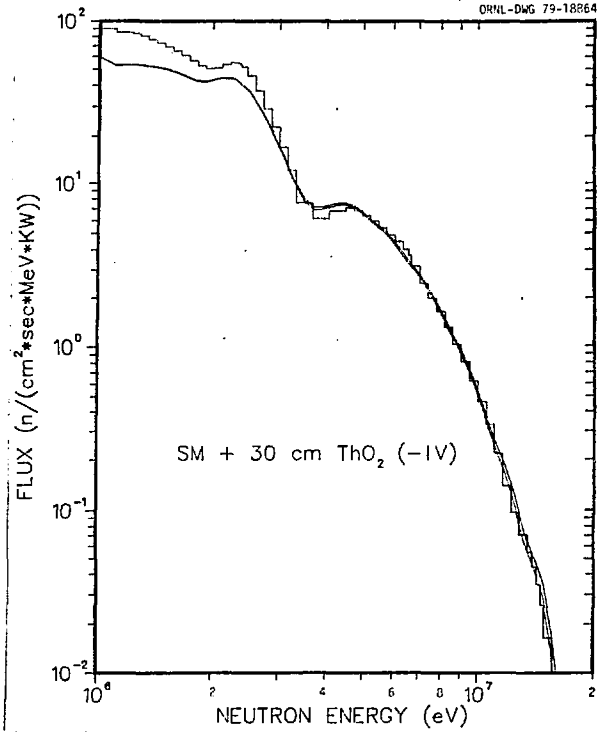

Fig. 3. Comparison of measured and calculated neutron spectrum through a 2-row ThO_2 blanket mockup. Calculation used ENDF/B-IV Th data.

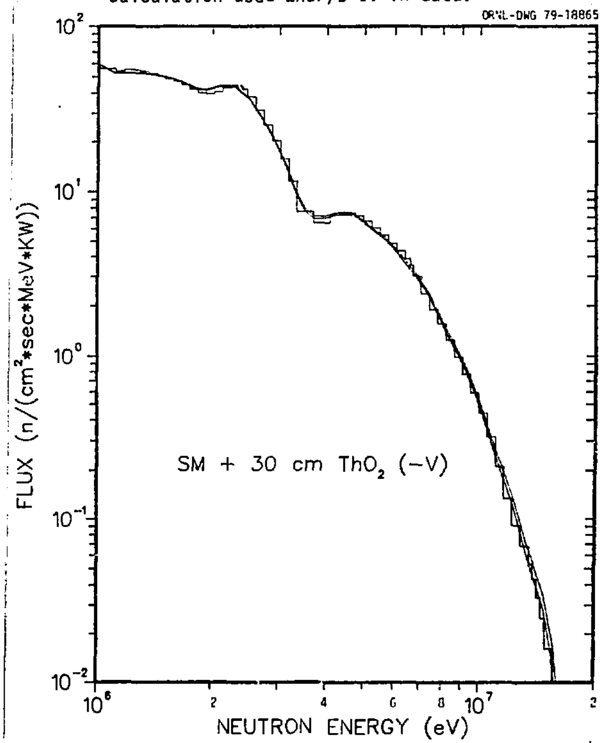

Fig. 4. Comparison of measured and calculated neutron spectrum through a 2-row ThO_2 blanket mockup. Calculation used ENDF/B-V Th data.

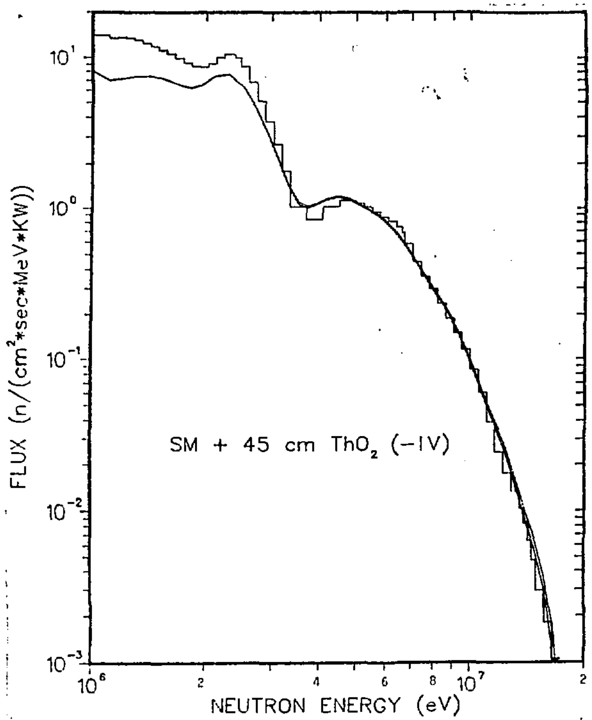

Fig. 5. Comparison of measured and calculated neutron spectrum through a 3-row ThO_2 blanket mockup. Calculation used ENDF/B-IV Th data.

ORNL-DWG 79-18867

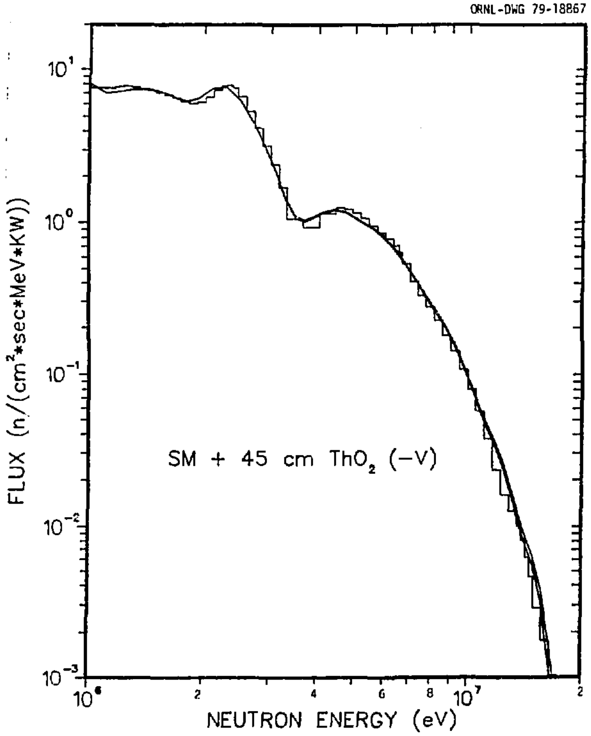

Fig.6. Comparison of measured and calculated neutron spectrum through a 3-row ThO_2 blanket mockup. Calculation used ENDF/B-V Th data.

Conclusions

Any meaningful interpretation of the experimental results which have been analyzed thus far requires a familiarity with the relevant nuclear data: the thorium-232 total neutron cross section. Figure 7 compares the total macroscopic cross section for ThO_2 resulting from ENDF/B-IV-derived data for both thorium and oxygen, and from ENDF/B-V-derived thorium data mixed with version IV oxygen data. Since no significant changes were made to the oxygen evaluation for ENDF/B-V, the two mixtures given in Fig. 7 represent version IV and V, respectively. The most striking difference is the almost uniform 7-9% increase in the total cross section between 1 eV and 100 keV for ENDF/B-V, which largely explains the differences observed in Table 1 between the two calculations. The newer thorium evaluation also increased the total cross section by a few percent between 1 and 3 MeV and between 5 and 8 MeV which contributes to the spectral differences observed in Figs. 3 - 6.

It can, therefore, be concluded that based on the initial results from this integral experiment, the ENDF/B-V evaluation of the thorium-232 total cross section is a significant improvement over the previous ENDF/B-IV evaluation. Furthermore, the new total cross section appears adequate above 1 MeV for calculating deep penetration in ThO_2, which is the dominant concern for most shielding requirements. However, additional investigation of the total cross section at lower energies appears to be needed. It is expected that the remaining analysis of the blanket measurements will better identify the source of the observed discrepancies, and will provide additional information on the adequacy of thorium gamma-ray production cross sections.

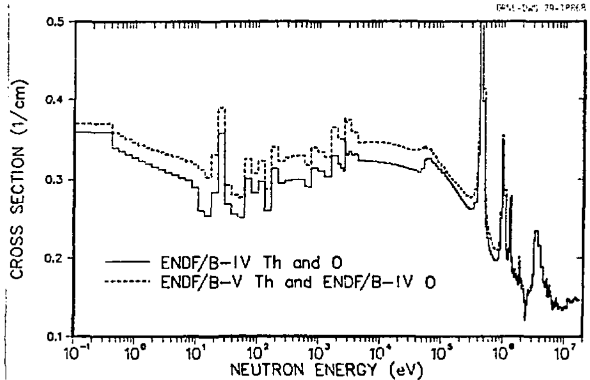

Fig. 7. Comparison of ENDF/B-IV and ENDF/B-V macroscopic total cross section for ThO_2.

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