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THE ORNL BENCHMARK EXPERIMENT FOR NEUTRON TRANSPORT IN THICK SODIUM*

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Abstract

The description of an experiment performed at the Tower Shielding Facility (TSF) is presented which provides verification of cross-section accuracy for use in transport calculations of deep penetration of neutrons through 15 ft of sodium. Results of calculations of the experiment are presented which were obtained by using the MORSE multigroup Monte Carlo code to calculate the transport based on an early version of the ENDF/B-III cross-section set for sodium. Comparison of the calculations with experiment indicates that the total neutron leakage above thermal energies penetrating 15 ft of sodium can be calculated to within ~30% and neutrons penetrating up to 10 ft of sodium to within ~10%.

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Introduction

The sodium coolant which surrounds a fast test reactor core constitutes a major portion of the neutron shield. It is therefore essential that accurate experimental results be obtained to verify transport calculation for deep penetration of neutrons through sodium. Results from earlier experiments [1], which have been conducted for this purpose, have been somewhat limited in usefulness because of the small diameter of the sodium samples that were used compared to the total thickness of the sample. Since the thickness of sodium above the fuel elements in the FTR reactor design is approximately 15 ft and the diameter of the pool is approximately 20 ft, an experiment providing confirmation of the transport calculation at a comparable depth with negligible side leakage is necessary. For this reason, a sodium shield 11 ft in diameter and up to 15 ft thick, enclosed in a 1.5-ft concrete collar, was constructed for the experiment at the TSF. Detailed measurements of the transmitted neutron spectra were made for thicknesses varying from 2.5 to 15 ft, covering the energy range from 65 keV to 15 MeV. The experimental results were compared with calculations performed using the MORSE multigroup Monte Carlo code and the latest cross-section data in the ENDF/B library. These comparisons, as well as the comparison of the calculated results for several different integral detectors having widely varying energy responses, have been utilized to determine the accuracy of the transport calculations in sodium. Through sensitivity analysis, these results will also be used to predict the dose uncertainty in a calculation for an FTR shield.

Description of the Experiment

A series of deep-penetration neutron transmission measurements through very thick sodium slabs have been performed at the TSF using a collimated beam of reactor neutrons. These measurements were made behind various combinations of four 11-ft-diam. cylindrical aluminum tanks filled with solid sodium; measurements were obtained behind sodium thicknesses of 2.5, 5, 10, 12.5, and 15 ft. Concrete at least 1.5-ft thick surrounded the periphery of the tanks to reduce the effects of transverse leakage from the slabs. Figure 1 shows a schematic of the experimental geometry for the 15-ft case. Figure 2 is a photograph of the sodium samples.

The thickness and average sodium density of each of the sodium tanks were determined at eight locations in each tank. The sodium density was determined by placing the tank between a 3-in. sodium iodide detector and a ^{24}Na source and accurately determining the counting rate in the uncollided gamma-ray peak at 2.75 MeV. From the ratio of this counting rate to the counting rate in this peak with no shield and the mass absorption coefficient for 2.75-MeV gamma rays, the sodium density could be directly determined to better than 1%. The sodium and the aluminum tank walls were chemically analyzed to determine all impurities.

Neutron spectral measurements beyond the sodium sample were taken using three types of spectrometers. These were: (1) an NE-213 scintillator, which determines spectra in the energy range 0.8-15 MeV with the aid of the unfolding code FERDoR; [2,3] (2) a Benjamin proton recoil spectrometer which determines spectra in the range ~ 50 keV - 1.5 MeV with the aid of the unfolding code SPEC4; [4] and (3) a ^{10}B spectrometer [5] which determines the spectra in the range thermal to ~ 10 keV with the aid of an iterative folding procedure. A set of spherical BF_3 detectors surrounded by various thicknesses of polyethylene (0-5 in.) and an outside shell of cadmium were

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Fig. 1. Side View of Reactor and Sodium Shield Geometry.

Fig. 2. Photograph of Sodium Samples.

also used to obtain integral flux measurements. These "Bonner ball" detectors have response functions [7,8] which peak in different regions of the spectrum. They have proven invaluable in providing data for analysis of cross-section problems in an iron benchmark experiment, also recently completed.[6]

Measurements of the incident neutron beam were made with each of the detectors so that an absolute energy spectrum from thermal to 15 MeV, and also the angular distribution of the source, could be obtained for use in the calculations. Mapping of the beam in both transverse and axial directions established the fact that the collimated source could be represented as a virtual point anisotropic source located 59.5 in. from the sodium-concrete interface inside the collimator with the beam intensity uniform over the mouth of the collimator and zero elsewhere.

The absolute source spectrum determined from both the spectrometer and integral measurements for the centerline point located on the exit plane of the collimator is shown in Fig. 3 for the region $1 \text{ eV} \leq E \leq 15 \text{ MeV}$. The region below 1 eV consists of a Maxwellian distribution and a $1/E$ tail, and is unimportant for the calculations reported here. The accuracy of the incident absolute spectrum is estimated to be $\pm 10\%$ down to 200 keV and $\pm 20\%$ below 200 keV. The ratio of surface-integrated current over the collimator to centerline current is 1200 cm^2 .

The Bonner ball data taken at a distance of 2 ft from the back of each sample is shown in Fig. 4, plotted as a function of sodium thickness. The counting rates are normalized to one for the reactor beam measurement 2 ft from the reactor beam port. The difference in the shapes of these curves indicates that the transmitted spectrum is rapidly changing for thicknesses of sodium up to 10 ft as is the spectrally weighted response.

Fig. 3. $E\phi(E)$ on Centerline at Exit Plane of Collimator for
 $1 \text{ eV} \leq E \leq 15 \text{ MeV}$.

Fig. 4. Neutron Attenuation in Sodium, Bonner Ball Count Rate Vs. Sodium Thickness.

of the seven detectors. Beyond 10 ft the spectrum consists primarily of neutrons below 100 eV, in which case all detectors except the modified ball are responding to the low-energy part of the spectrum. In order to insure that the neutrons being measured beyond 15 ft of sodium had not in some way bypassed the sodium shield by leaking from the side of the sample scattering from the air or the ground to the back of the sample, a number of radial traverses were taken using a 3-in. Bonner ball. Figure 5 shows several counting rate profiles made in transverse directions behind the 15 ft of sodium. An inspection of Fig. 5 shows that the effect of any neutron transverse leakage (i.e., leakage from the sides of the concrete and through gaps between the sodium tanks) is small compared with the leakage through the back face. The small peaks in the wings of the vertical traverse result from the presence of gaps between the last sodium tank (#2) and the concrete collar, the gap above the centerline being the wider. The effects of transverse leakage combined with subsequent air and ground scattering were quantitatively measured for several detector locations behind the tanks by placing a 1-ft-thick lithium hydride shield between the detector and the back face of the sodium tanks so that the contribution from direct leakage from the back face was eliminated. This background amounted to only a few percent of the detector response arising from leakage from the back face, and was subtracted from all the measured foreground values (i.e., values obtained in the absence of the lithium hydride shadow shield).

Analysis

Monte Carlo calculations of the transport of neutrons above thermal energies were performed using the multigroup code MORSE[9] in the analysis of the experiment. The basic cross-section data set used for sodium was a preliminary version of the present ENDF/B-III set (MAT = 1156) evaluated and provided by T. A. Pitterle.[10] Only minor differences exist between this set and the final MAT = 1156 evaluation; therefore, the comparisons between the present calculations and measurements should be indicative of the adequacy of the MAT = 1156 set in predicting deep penetration of neutrons through sodium. The point data were processed with SUPERTOG[11] into a 100-group GAM-II structure with a P_3 approximation for the elastic scattering angular distributions. Maximum estimated impurities of 400-ppm calcium, 200-ppm oxygen, 150-ppm potassium, and 60-ppm hydrogen were included in the multigroup set for sodium. A 100-group set expanded through P_3 was also generated for aluminum and its impurities from ENDF/B data. Since the experiment can be adequately represented geometrically as two-dimensional, the calculations employed cylindrical geometry in describing the reactor collimator and the concrete and water shield surrounding it as well as the sodium tanks and the concrete collar. Effects due to multiple reflection between the sodium tanks and the reactor collimator, including the concrete shield surrounding the collimator, were explicitly and separately calculated and are added to the results obtained with a vacuum boundary at the front and back of the sample. For sodium thicknesses of 10 ft or greater, path-length stretching parameters and source energy biasing were determined from adjoint ANISN calculations. No biasing was used for the calculation of neutron transmission through 2.5 and 5 ft. The approximate effect (25%) of the concrete collar surrounding the sodium tanks was assessed a priori by calculating the flux incident on the Bonner balls located on the centerline behind 15 ft of sodium.

Typical comparisons of the measured Bonner ball counting rates with counting rates obtained by folding the calculated spectral fluxes incident

Fig. 5. Measured Profiles 24 in. Behind 15 ft of Sodium With 3-in. Bonner Ball.

on the balls with the Bonner ball response functions are shown in Figs. 6-9 for the case where the detectors are located on the centerline 24 in. behind the sodium tanks. The response functions for each of the Bonner balls are also presented in these figures. The relative contribution of the calculated Bonner ball counting rates from different energy regions of the transmitted spectra are shown in Table 1 together with the transmitted spectra. It is seen that the counting rates behind 10 and 15 ft of sodium of all of the Bonner balls with the exception of the ^{10}B -modified 3-in. ball are primarily determined by the flux below 1 keV, where the vast majority of the leaking neutrons lie.

The only significant disagreement with the measurements is a calculated moderate excess ($\sim 50\%$) of neutrons detected by the ^{10}B -modified 3-in. Bonner ball behind 10 ft of sodium (i.e., neutrons of several hundred keV energy) and a somewhat smaller excess ($\sim 30\%$) detected by the smaller size Bonner balls behind 12.5 and 15 ft of sodium (i.e., neutrons up to ~ 100 eV energy). Thus, the calculations slightly overpredict the leakage of neutrons through 10 ft of sodium or more, the excess apparently occurring in progressively lower energy regions as the thickness increases.

The above conclusion is further substantiated by comparisons of calculated spectra with experiment. Figure 10 shows a comparison of the measured NE-213 spectra with smoothed (i.e., smeared with the detector resolution) calculated spectra on the centerline behind 5 and 10 ft of sodium, and Fig. 11 shows similar comparisons for the energy region measured by the proton recoil counters. The agreement in the overall proton recoil counter region behind 5 ft of sodium is excellent, but behind 10 ft of sodium the calculations overpredict the measurement by a factor of approximately 1.5, which is consistent with the ^{10}B -modified 3-in. Bonner ball results. Even though the calculations tend to agree with both the proton recoil counter and ^{10}B -modified 3-in. Bonner ball measurements behind 12.5 ft of sodium, the Monte Carlo statistical errors ($\sim 15\%$ in the counting rate and worse in the group fluxes) are sufficiently poor that no definitive conclusions should be drawn. The same applies to the agreement of the calculations with the measured ^{10}B -modified 3-in. Bonner ball counting rate behind 15 ft of sodium, where the Monte Carlo statistical error in the counting rate approaches 25%. Since over 99% of the non-thermal neutrons leaking 12.5 or 15 ft of sodium have final energies between 0.4 eV and 1 keV, the predominant contribution of these fluxes results in small Monte Carlo statistical errors in the predicted counting rates for all the other Bonner balls.

Conclusions

The preliminary ENDF/B-III cross-section set for sodium used in the calculations, when expanded through P_3 in the scattering angular distributions and averaged over the 100-group GAM-II group structure with a $1/E \sigma_T$ weighting function, yields calculated energy-integrated neutron fluxes above 0.4 eV behind up to 15 ft of sodium that agree with experiment to within $\sim 30\%$. Estimating errors in the experiment (i.e., the source term and reproducibility of the measurements), in the absolute response functions of the detectors, and in the Monte Carlo transport calculations each to be of the order of 10% means that approximately half of the maximum disagreement may be due to other than cross-section error. The agreement of the spectral fluxes above 0.4 eV is to within $\sim 50\%$, and seems to be poorest in the region of a few hundred keV behind 10 ft of sodium, where 3% of the transmitted neutrons lie. While the comparison of calculations with this experiment show that no serious cross-section errors are observed, sensitivity analyses must be performed to determine the importance of these comparisons on sodium shielding problems.

Fig. 6. Comparison of Calculated and Measured Counting Rates for the 3-in. Bonner Ball.

Fig. 7. Comparison of Calculated and Measured Counting Rates for the 6-in. Bonner Ball.

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Fig. 8. Comparison of Calculated and Measured Counting Rates for the 12-in. Bonner Ball.

Fig. 9. Comparison of Calculated and Measured Counting Rates for the ^{10}B -Modified 3-in. Bonner Ball.

Table 1. Percentage of Calculated Counting Rates and Fluxes Leaking the Sodium Due to Neutrons in Various Energy Groups (Detectors are on the Centerline 24 in. Behind the Sodium)

ΔE /Bonner Ball	Cd	3-in.	5-in.	6-in.	8-in.	12-in.	$^{10}\text{B-mod.}$ 3-in.	Relative Flux
<u>Sodium thickness = 0 ft</u>								
1.0-15 MeV	1	5	34	44	62	88	55	51
0.11-1.0 MeV	0	8	22	23	20	9	32	17
11.7-111 keV	1	10	12	11	6	1	12	8
0.96-11.7 keV	2	13	10	8	4	1	1	7
101-961 eV	5	15	7	5	3	1	0	5
10.7-101 eV	14	17	7	4	2	0	0	5
1.13-10.7 eV	44	23	6	4	2	0	0	5
0.414-1.13 eV	33	9	2	1	1	0	0	2
<u>Sodium thickness = 5 ft</u>								
1.0-15 MeV	0	0	4	6	13	42	13	6
0.11-1.0 MeV	0	3	12	16	23	20	47	12
11.7-111 keV	0	7	16	18	17	11	38	15
0.96-11.7 keV	1	6	8	8	7	4	2	7
101-961 eV	12	32	29	26	21	12	0	27
10.7-101 eV	25	27	20	17	12	7	0	19
1.13-10.7 eV	44	21	9	8	6	3	0	11
0.414-1.13 eV	18	4	2	1	1	1	0	3
<u>Sodium thickness = 10 ft</u>								
1.0-15 MeV	0	0	0	0	1	5	5	0
0.11-1.0 MeV	0	0	2	3	4	8	38	2
11.7-111 keV	0	0	3	4	6	6	53	3
0.96-11.7 keV	0	1	2	3	3	3	4	2
101-961 eV	4	16	22	23	24	22	0	19
10.7-101 eV	20	33	38	36	34	32	0	34
1.13-10.7 eV	54	41	29	27	25	22	0	32
0.414-1.13 eV	22	9	4	4	3	2	0	8
<u>Sodium thickness = 15 ft</u>								
1.0-15 MeV	0	0	0	0	0	1	4	0
0.11-1.0 MeV	0	0	0	0	0	1	41	0.1
11.7-111 keV	0	0	0	0	0	1	52	0.4
0.96-11.7 keV	0	0	0	0	1	4	3	0.3
101-961 eV	1	5	10	11	12	10	0	7
10.7-101 eV	12	28	33	35	38	37	0	31
1.13-10.7 eV	51	49	45	43	38	37	0	42
0.414-1.13 eV	36	18	12	11	11	9	0	19

Fig. 10. Comparison of Measured NE-213 and Smoothed Calculated Fluxes on the Centerline Behind 5 and 10 ft of Sodium.

Fig. 11. Comparison of Measured Hydrogen Counter and Smoothed Calculated Fluxes on the Centerline Behind 5 and 10 ft of Sodium.

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