FINAL REPORT ON A
BENCHMARK EXPERIMENT FOR
NEUTRON TRANSPORT IN THICK SODIUM

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R. E. Maerker, F. J. Muckenthaler, R. L. Childs,*
and M. L. Gritzner†

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ABSTRACT

An experiment concerning deep neutron penetration in sodium is described, and experimental results are presented which provide a basis for verification of the accuracy of sodium cross sections to be used in transport calculations. The experiment was performed at the Tower Shielding Facility of ORNL and included measurements of both the neutron fluence and neutron spectra through a large diameter sample of sodium up to 15 ft thick. Calculated results for the experiment are presented for comparison with the experimental measurements. These results were obtained using the multigroup Monte Carlo code, MORSE, and a two-dimensional discrete ordinates code, DOT III. One-hundred group data sets were developed from both a preliminary and the final version of the ENDF/III set (MAT=1156) for sodium for use in the calculations. Comparisons of the calculations with experiment indicate that the preliminary version is slightly superior to the final version and that using the preliminary set the total neutron leakage above thermal energies penetrating up through 15 ft of sodium can be calculated to within $\sim 15\%$ and the absolute spectra penetrating up through 12.5 ft of sodium can be calculated to within 20%. Using the final set, the corresponding comparisons are 30% and 60%.

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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 calculations for deep penetration of neutrons through sodium. Results from earlier experiments,¹ which had been conducted for this purpose, were 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 to 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 an experiment at the Tower Shielding Facility (TSF). Detailed measurements of the transmitted neutron spectra were made for thicknesses varying from 5 to 12.5 ft, generally covering the energy range from 70 keV to 11 MeV. Integral measurements of the neutron fluence were made with Bonner ball detectors behind sodium thicknesses ranging from 2.5 to 15 ft. The experimental results were compared with calculations performed using the MORSE multigroup Monte Carlo code and the DOT-III two-dimensional discrete ordinates code. The comparisons of the calculated results for the different spectrometers, and for the integral detectors having widely varying energy responses, have been utilized to determine the accuracy of the transport calculations in sodium using both a preliminary and the final versions of the ENDF/B-III cross-section set for sodium. Through sensitivity analysis, these results will also be used to predict the dose uncertainty in a calculation for the FTR shield.

DESCRIPTION OF THE EXPERIMENT

Neutron transmission measurements through very thick sodium slabs were made at the TSF using a collimated beam of reactor neutrons as a source. These measurements were made behind various combinations of four 11-ft-diam, cylindrical aluminum tanks filled with solid sodium; measurements were

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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 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 by determining accurately 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 tank present and the mass absorption coefficient for 2.75-MeV gamma rays, the sodium density could be directly determined. The average thicknesses of the four tanks (including 1 in. of aluminum) were 29.91, 60.08, 59.86, and 29.59 in. for tanks 1, 2, 3, and 4, respectively, with maximum deviations from the average of 0.22, 0.52, 0.42, and 0.53 in. The average sodium density was reasonably constant over each tank and from tank to tank as well, and the averaged value of 0.945 grams/cm³ should be accurate to better than 1%. The maximum impurities in the sodium estimated by the vendor are presented in Table I. A previous unpublished study showed that the effect of the impurities on the flux transmitted through a 5-meter radius sphere was to decrease the total flux by about a factor of two, presumably because of the presence of the hydrogen.²

Table I. Maximum Impurities in the Sodium

Element	Concentration in wt%	Element	Concentration in wt%
Hydrogen	60 ppm	Potassium	150 ppm
Oxygen	200 ppm	Calcium	400 ppm

Neutron spectral measurements beyond the sodium sample were taken using two types of spectrometers. These were: (I) an NE-213 scintillator, which determines spectra in the energy range 0.8 to 15 MeV with the aid of the unfolding code FERDoR;^{3,4} and (II) a Benjamin proton recoil spectrom-

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

Fig. 2. Photograph of the Sodium Tanks. The concrete collar had not as yet been affixed to the five fast tank in the background.

eter which determines spectra in the range ~ 70 keV to 1.5 MeV with the aid of the unfolding code SPEC4.⁵ A set of spherical BF_3 detectors surrounded by various thicknesses of polyethylene (0 to 5 in.) and an outside shell of cadmium were also used to obtain integral flux measurements. These "Bonner ball" detectors have response functions 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 A modified Bonner ball was also used which consisted of a ~ 3 -in. shell of ^{10}B surrounding a $1/2$ -in. shell of polyethylene, both of which surround a BF_3 detector. The description of each Bonner ball is listed in Table II. The response function of each Bonner ball was determined as a function of energy prior to this experiment to within a few percent utilizing ANISN adjoint calculations and calibra-

Table II. Bonner Ball Description
(Spherical, 2-in.-diam $^{10}\text{BF}_3$ Proportional Counter Surrounded by Polyethylene and 0.030-in. Cd)

Standard Bonner Ball Designation	Polyethylene Thickness (in.)	Diameter of Ball	Location of Center of Detection Forward from Center of Ball (in.)
Cd	0	2.06	0.6
3	0.47	3.00	0.9
4	0.985	4.03	1.2
5	1.48	5.02	1.5
6	1.97	6.00	1.8
8	2.90	7.86	2.4
10	3.90	9.86	3.0
12	4.89	11.84	3.5

Note: Modified 3-in. Bonner ball consists of the proportional counter surrounded by 0.47 in. polyethylene followed by 2.91 in. ^{10}B . The center of detection is 2.6 in. from the center of the ball. The "bare" Bonner ball is the proportional counter itself.

tions with known sources.^{7,8} It is expressed in units of counts/second per neutron/sec/cm² of energy E uniformly incident over an outside hemispherical surface of the ball.

Measurements of the incident neutron beam were made with each of the above spectrometers, together with a ¹⁰B spectrometer which determined the spectra in the energy range from thermal to ~ 5 keV,⁹ so that an absolute energy spectrum from thermal to 15 MeV was 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 the spectrometer measurements, and verified by the integral measurements, for the centerline point located on the exit plane of the collimator is shown in Fig. 3 for the region $1 \text{ eV} \leq E \leq 15 \text{ MeV}$ and tabulated in Table III for the complete range from thermal energies to 15 MeV.¹⁰ 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 cm².

All of the measurements made behind the sodium tanks are summarized in Table IV. 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 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 this low-energy part of the spectrum.

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

Table III. Source Spectrum at the Exit of the Collimator

Group	Energy Interval	Intensity (neutrons/cm ² min/W)	Group	Energy Interval	Intensity (neutrons/cm ² min/W)
1	13.5-14.9 MeV	14	46	0.150-0.166 MeV	827
2	12.2-13.5	32	47	0.136-0.150	785
3	11.05-12.2	73	48	0.123-0.136	798
4	10.0-11.05	199	49	0.111-0.123	799
5	9.04-10.0	312	50	86.5-111 keV	1870
6	8.19-9.04	545	51	67.4-86.5	1790
7	7.41-8.19	846	52	52.5-67.4	1730
8	6.70-7.41	1375	53	40.9-52.5	1650
9	6.07-6.70	2070	54	31.8-40.9	1590
10	5.49-6.07	2585	55	24.8-31.8	1530
11	4.97-5.49	3180	56	19.3-24.8	1490
12	4.49-4.97	3665	57	15.0-19.3	1440
13	4.07-4.49	4420	58	11.7-15.0	1370
14	3.68-4.07	4880	59	9.12-11.7	1340
15	3.33-3.68	4825	60	7.10-9.12	1310
16	3.01-3.33	5315	61	5.53-7.10	1260
17	2.73-3.01	6570	62	4.31-5.53	1220
18	2.47-2.73	7075	63	3.35-4.31	1200
19	2.23-2.47	6955	64	2.61-3.35	1180
20	2.02-2.23	6190	65	2.03-2.61	1150
21	1.83-2.02	5570	66	1.58-2.03	1120
22	1.65-1.83	5175	67	1.23-1.58	1100
23	1.50-1.65	4200	68	961-1230 eV	1030
24	1.35-1.50	4000	69	749-961	1020
25	1.22-1.35	3170	70	583-749	1010
26	1.11-1.22	2485	71	454-583	990
27	1.00-1.11	2350	72	354-454	970
28	0.907-1.00	2135	73	275-354	960
29	0.821-0.907	2215	74	214-275	940
30	0.743-0.821	2345	75	167-214	920
31	0.672-0.743	2320	76	130-167	900
32	0.608-0.672	1990	77	101-130	900
33	0.550-0.608	1700	78	78.9-101	900
34	0.497-0.550	1425	79	61.4-78.9	900
35	0.450-0.497	1210	80	47.9-61.4	900
36	0.408-0.450	1130	81	37.3-47.9	900
37	0.369-0.408	1170	82	29.0-37.3	900
38	0.334-0.369	1175	83	22.6-29.0	900
39	0.302-0.334	1130	84	17.6-22.6	900
40	0.273-0.302	1055	85	13.7-17.6	900
41	0.247-0.273	955	86	10.7-13.7	930
42	0.224-0.247	837	87	8.32-10.7	960
43	0.202-0.224	777	88	6.48-8.32	990
44	0.183-0.202	926	89	5.04-6.48	1035
45	0.166-0.183	845	90	3.93-5.04	1035

Table III. Source Spectrum at the Exit of the Collimator (continued)

Group	Interval	Intensity (neutrons/cm ² min/W)	Group	Energy Interval	Intensity (neutrons/cm ² min/W)
91	3.06-3.93 eV	1035	96	0.876-1.13 eV	1250
92	2.38-3.06	1035	97	0.683-0.876	1350
93	1.86-2.38	1060	98	0.532-0.683	1565
94	1.44-1.86	1100	99	0.414-0.532	1900
95	1.13-1.44	1170	100	0.000-0.414	9.50 x 10 ⁴
Totals 1-100			0.000-14.9 MeV		2.702 x 10 ⁵

Table IV. Experimental Configurations

Nominal Sodium Thickness (in.)	Tank Numbers	Detector Locations (in.)		Detector Type
		Centerline Distance Behind Slab	Radial Distance from Centerline	
30	1	24 24 166	0 24 0	Bonner balls Bonner balls Bonner balls
60	3	24 24 359 359	0 30 0 96	Bonner balls, Benjamin spectrom- eter Bonner balls Bonner balls, Benjamin spectrom- eter, NE-213 spec- trometer Benjamin spectrom- eter, NE-213 spec- trometer
120	2+3	6-72 2 2* 24	0 0-84 0-84 0	Bonner balls Cadmium and 3-in. Bonner balls Cadmium and 3-in. Bonner balls Benjamin Spectrom- eter, NE-213 spec- trometer
150	1+2+3	24	0	Bonner balls, Ben- jamin spectrometer
180	1+2+3+4	6-72 24 24	0 0-84 (hor.) 0-90 (vert.)	Bonner balls 3-in. and 12-in. Bonner balls 3-in. Bonner ball

*These radial traverses were made with a 5-ft sodium tank immediately behind the detectors

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Fig. 4. Measured Relative Bonner Ball Counting Rates 24 in. Behind the Sodium as a Function of Sodium Thickness. The Counting Rate for each ball 24 in. from the open collimator is arbitrarily normalized to one.

It should be pointed out that all the measurements made behind the tanks were obtained in the absence of any detector collimator. Thus, in order to insure that the neutrons being measured behind 15 ft of sodium had not in some way bypassed the sodium shield by leaking from the side of the sample and scattering from the air or the ground to the back of the sample, several radial traverses were taken using a 3-in. Bonner ball. Figure 5 shows the 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 spikes 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 increase in the centerline counting rate 24 in. behind the sodium from these spikes can be shown to be less than 1%, however, and can be neglected in the calculations. 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 about halfway 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 in most cases 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). For those few cases where the background is important, however, it should be mentioned that it is underestimated by the above measurement procedure because it does not include the effects of air and ground scattering of the transmitted beam after penetrating the tanks.

TABULATED RESULTS OF THE MEASUREMENTS BEHIND THE SODIUM

All measurements have an estimated reproducibility of $\pm 5\%$, due primarily to power calibration uncertainties. All Bonner ball locations are measured to the geometric center of the balls.

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

The results of the Bonner ball measurements made behind 2.5 ft of sodium are presented in Table V.

The results of the Bonner ball measurements made behind 5 ft of sodium are presented in Table VI.

The unfolded results from the Benjamin counter spectral measurements behind 5 ft of sodium are shown in Tables VII-IX, where the standard error is due to counting statistics only. No background was measured at the 24-in location because it is assumed to be negligible but backgrounds at both 359-in. locations were measured and subtracted from the foregrounds prior to obtaining the unfolded spectra presented in Tables VIII and IX. Energy calibrations are estimated to be accurate to within +5%.

The unfolded results from the NE-213 spectral measurements behind 5 ft of sodium are shown in Tables X and XI, where the limits of each spectrum are determined by both counting statistics and unfolding uncertainties. Backgrounds were measured and subtracted prior to unfolding.

The results of the Bonner ball measurements made behind 10 ft of sodium are presented in Tables XII through XIV.

The unfolded results from the Benjamin counter spectral measurement behind 10 ft of sodium are shown in Table XV. Backgrounds were obtained for each of the counters and subtracted from the foregrounds prior to obtaining the unfolded spectrum.

The unfolded results from the NE-213 spectral measurements behind 10 ft of sodium are shown in Table XVI. Background was measured and subtracted prior to unfolding.

The results of the Bonner ball measurements made behind 12.5 ft of sodium are presented in Table XVII.

Table V. Measured Bonner Ball Counting Rates Behind 2.5 ft
of Sodium in counts/min/watt

Bonner Ball	Bare	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.
<u>Detectors on Centerline 24 in. Behind Sodium</u>									
Net*	318	58.5	840	2068	2678	2821	2163	1379	878
<u>Detectors 24 in. Off the Centerline and 24 in. Behind Sodium</u>									
Net*	197	41.0	611	1428	1824	1801	1306	754	422
<u>Detectors on Centerline 166 in. Behind Sodium</u>									
Foreground	39.6	5.45	71.3	164	210	219	178	123	83.2
Background	13.0**	1.38	15.6	35	36	32	19	10	5.7
Net	26.6	4.07	55.7	129	174	187	159	113	77.5

*A measurement of the backgrounds for the 3-in. and 12-in. Bonner balls positioned 24 in. behind the sodium was made and found to be ~3% and ~2% of the foregrounds respectively. The net values presented here are the result of multiplying the measured foreground values by 0.90 for the bare ball and by 0.97 for all the remaining balls.

**The measured background for the bare ball 166 in. behind the sodium is probably too low by about 40% due to inability of the measurement to include effects of air scattering of the transmitted beam.

Table VI. Measured Bonner Ball Counting Rates Behind 5 ft of Sodium in counts/min/watt

Bonner Ball	Bare	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod 3-in.
<u>Detectors on Centerline 24-in. Behind Sodium</u>										
Net*	42.0**	21.4**	295	590	639	551	318	149	71.8	6.94
<u>Detectors 30 in. Off the Centerline and 24 in. Behind Sodium</u>										
Net*	34.2	17.2	228	435	462	389	224	102	46.6	-
<u>Detectors on Centerline 359 in. Behind Sodium</u>										
Foreground	2.72	0.675	7.97	14.32	14.57	12.31	7.03	3.31	1.64	0.132
Background	1.69***	0.303	3.08	5.27	5.25	4.29	2.15	0.94	0.40	0.029
Net	1.03	0.372	4.89	9.05	9.32	8.02	4.88	2.37	1.24	0.103

*The net values presented here are the result of multiplying the measured foreground values by 0.90 for the bare ball and by 0.97 for all the remaining balls except the modified 3-in. ball. The measured background for the latter was 1% of the foreground.

**Average of two runs made several months apart. The individual values varied by about 8%. Backgrounds were measured for one of the runs.

***The measured background for the bare ball 359 in. behind the sodium is probably too low by about 15% due to inability of the measurement to include effects of air scattering of the transmitted beam.

Table VII. Benjamin Counter Spectrum on the Centerline
24 in. Behind 5 ft of Sodium

Energy Interval (keV)	Flux (neuts/cm ² /MeV/min/w)	Standard Error (%)	Energy Interval (keV)	Flux (neuts/cm ² /MeV/min/w)	Standard Error (%)
<u>10 atmosphere counter</u>			<u>1 atmosphere counter</u>		
1186.1 - 1350.0	12.3	6.7	263.5 - 300.0	148	3.6
1039.5 - 1186.1	11.8	7.4	232.5 - 263.5	134	4.7
918.7 - 1039.5	9.9	10.2	203.3 - 232.5	119	5.2
806.5 - 918.7	12.6	7.9	179.6 - 203.3	157	4.7
711.7 - 806.5	9.8	11.0	157.8 - 179.6	181	4.2
625.4 - 711.7	13.7	7.8	139.5 - 157.8	240	3.6
547.8 - 625.4	26.9	4.1	123.1 - 139.5	330	2.8
			106.7 - 123.1	360	2.4
			93.9 - 106.7	355	3.0
			83.0 - 93.9	446	2.7
			73.9 - 83.0	645	2.1
<u>3 atmosphere counter</u>					
613.9 - 700.0	16.9	9.4			
541.4 - 613.9	25.8	7.0			
473.5 - 541.4	52.9	3.4			
419.1 - 473.5	52.8	4.3			
369.3 - 419.1	59.5	3.9			
323.9 - 369.3	85.0	2.9			
283.2 - 323.9	131	2.0			
251.5 - 283.2	138	2.4			
219.7 - 251.5	116	2.7			

Table VIII. Benjamin Counter Spectrum on the Centerline
359 in. Behind 5 ft of Sodium

Energy Interval (keV)	Flux (neuts/cm ² /MeV/min/w)	Standard Error (%)	Energy Interval (keV)	Flux (neuts/cm ² /MeV/min/w)	Standard Error (%)
<u>10 atmosphere counter</u>			<u>1 atmosphere counter</u>		
1180.7 - 1350.0	0.200	11.5	263.3 - 300.0	2.32	11.1
1038.1 - 1180.7	0.180	14.3	232.1 - 263.3	2.21	14.0
913.5 - 1038.1	0.201	13.5	204.6 - 232.1	1.58	21.1
806.4 - 913.4	0.176	16.7	178.9 - 204.6	1.88	17.5
708.4 - 806.4	0.195	14.7	158.7 - 178.9	2.56	16.0
628.2 - 708.4	0.200	16.1	138.5 - 158.7	3.47	10.7
548.0 - 628.2	0.402	7.1	122.0 - 138.5	4.68	9.5
			107.3 - 122.0	5.36	9.0
			94.5 - 107.3	4.86	10.7
<u>3 atmosphere counter</u>			83.5 - 94.5	5.67	10.1
613.9 - 700.0	0.257	22.8	72.5 - 83.5	9.19	5.9
541.4 - 613.9	0.278	23.6			
473.5 - 541.4	0.857	7.8			
419.1 - 473.5	0.617	13.3			
369.3 - 419.1	0.742	11.3			
323.9 - 369.3	1.21	7.2			
283.2 - 323.9	2.02	4.6			
251.5 - 283.2	1.99	6.0			
219.7 - 251.5	1.66	6.7			

Table IX. Benjamin Counter Spectrum 96 in. Off the Centerline
359 in. Behind 5 ft of Sodium

Energy Interval (keV)	Flux (neuts/cm ² /MeV/min/w)	Standard Error (%)	Energy Interval (keV)	Flux (neuts/cm ² /MeV/min/w)	Standard Error (%)
<u>10 Atmosphere counter</u>			<u>1 atmosphere counter</u>		
1186.1 - 1350.0	0.182	10.6	263.5 - 300.0	2.08	13.3
1039.5 - 1186.1	0.141	14.2	232.5 - 263.5	1.58	20.6
918.7 - 1039.5	0.173	13.5	203.3 - 232.5	1.43	22.5
806.5 - 918.7	0.175	13.0	179.6 - 203.3	2.00	19.1
711.7 - 806.5	0.164	15.2	157.8 - 179.6	2.08	18.5
625.4 - 711.7	0.157	15.6	139.5 - 157.8	3.77	11.9
547.8 - 625.4	0.343	7.2	123.1 - 139.5	4.27	11.2
			106.7 - 123.1	4.60	9.7
			93.9 - 106.7	5.09	10.9
			83.0 - 93.9	5.86	10.5
			73.9 - 83.0	8.62	8.3
<u>3 atmosphere counter</u>					
613.9 - 700.0	0.214	26.5			
541.4 - 613.9	0.282	22.7			
473.5 - 541.4	0.654	9.9			
419.1 - 473.5	0.528	15.2			
369.3 - 419.1	0.744	11.1			
323.9 - 369.3	1.00	8.6			
283.2 - 323.9	1.76	5.3			
251.5 - 283.2	1.72	6.9			
219.7 - 251.5	1.49	7.4			

Table X. NE-213 Spectrum on the Centerline 359 in. Behind
5 ft of Sodium

Energy (MeV)	Flux (neuts/cm ² /MeV/min/watt)		Energy (MeV)	Flux (neuts/cm ² /MeV/min/watt)	
	Upper Limit	Lower Limit		Upper Limit	Lower Limit
1.0	2.35(-1) ^a	1.95(-1)	3.0	1.32(-1)	1.22(-1)
1.1	2.38(-1)	2.05(-1)	3.2	1.01(-1)	9.0(-2)
1.2	2.30(-1)	2.08(-1)	3.4	7.7(-2)	6.4(-2)
1.3	2.20(-1)	1.95(-1)	3.6	6.4(-2)	5.2(-2)
1.4	2.25(-1)	2.00(-1)	3.8	7.1(-2)	5.7(-2)
1.5	2.25(-1)	2.05(-1)	4.0	8.4(-2)	7.3(-2)
1.6	2.00(-1)	1.78(-1)	4.2	9.2(-2)	8.0(-2)
1.7	1.73(-1)	1.53(-1)	4.4	9.0(-2)	7.8(-2)
1.8	1.70(-1)	1.40(-1)	4.6	8.5(-2)	7.4(-2)
1.9	1.50(-1)	1.35(-1)	4.8	7.2(-2)	6.2(-2)
2.0	1.24(-1)	1.10(-1)	5.0	6.5(-2)	5.5(-2)
2.1	1.02(-1)	8.7(-2)	5.2	6.2(-2)	5.2(-2)
2.2	8.1(-2)	6.5(-2)	5.4	5.6(-2)	4.7(-2)
2.3	8.3(-2)	6.8(-2)	5.6	5.1(-2)	4.1(-2)
2.4	9.2(-2)	7.8(-2)	5.8	5.3(-2)	4.4(-2)
2.5	9.6(-2)	8.4(-2)	6.0	5.6(-2)	4.7(-2)
2.6	1.03(-1)	9.1(-2)	6.2	5.8(-2)	4.9(-2)
2.7	1.19(-1)	1.06(-1)	6.4	5.4(-2)	4.5(-2)
2.8	1.33(-1)	1.20(-1)	6.6	5.2(-2)	4.4(-2)
2.9	1.37(-1)	1.27(-1)	6.8	4.9(-2)	4.1(-2)

^aRead: 2.35×10^{-1} .

Table X (Cont'd.)

Energy (MeV)	Flux (neuts/cm ² /MeV/min/watt)		Energy (MeV)	Flux (neuts/cm ² /MeV/min/watt)	
	Upper Limit	Lower Limit		Upper Limit	Lower Limit
7.0	4.1(-2)	3.3(-2)	9.2	1.9(-2)	1.47(-2)
7.2	3.6(-2)	2.9(-2)	9.4	1.44(-2)	1.08(-2)
7.4	3.7(-2)	3.0(-2)	9.6	1.22(-2)	9.9(-3)
7.6	3.5(-2)	2.9(-2)	9.8	1.17(-2)	9.1(-3)
7.8	3.0(-2)	2.4(-2)	10.0	1.04(-2)	8.0(-3)
8.0	2.55(-2)	1.95(-2)	10.2	9.0(-3)	5.9(-3)
8.2	2.2(-2)	1.65(-2)	10.4	7.7(-3)	4.7(-3)
8.4	2.15(-2)	1.65(-2)	10.6	6.4(-3)	3.4(-3)
8.6	2.25(-2)	1.8(-2)	10.8	5.7(-3)	2.85(-3)
8.8	2.4(-2)	1.95(-2)	11.0	5.8(-3)	2.9(-3)
9.0	2.3(-2)	1.9(-2)	11.2	5.4(-3)	2.7(-3)

Table XI. NE-213 Spectrum 96 in. Off the Centerline 359 in.
Behind 5 ft of Sodium

Energy (MeV)	Flux (neuts/cm ² /MeV/min/watt)		Energy (MeV)	Flux (neuts/cm ² /MeV/min/watt)	
	Upper Limit	Lower Limit		Upper Limit	Lower Limit
1.0	1.95(-1) ^a	1.65(-1)	5.2	2.15(-2)	1.85(-2)
1.1	1.85(-1)	1.6(-1)	5.4	1.9(-2)	1.5(-2)
1.2	2.0(-1)	1.8(-1)	5.6	1.7(-2)	1.4(-2)
1.3	2.0(-1)	1.85(-1)	5.8	1.75(-2)	1.4(-2)
1.4	1.8(-1)	1.7(-1)	6.0	1.65(-2)	1.4(-2)
1.5	1.65(-1)	1.4(-1)	6.2	1.6(-2)	1.25(-2)
1.6	1.4(-1)	1.25(-1)	6.4	1.55(-2)	1.2(-2)
1.7	1.35(-1)	1.2(-1)	6.6	1.4(-2)	1.08(-2)
1.8	1.3(-1)	1.15(-1)	6.8	1.2(-2)	9.5(-3)
1.9	1.07(-1)	9.9(-2)	7.0	9.5(-3)	7.8(-3)
2.0	9.2(-2)	8.4(-2)	7.2	8.8(-3)	6.4(-3)
2.1	8.1(-2)	7.4(-2)	7.4	8.1(-3)	5.9(-3)
2.2	7.0(-2)	6.3(-2)	7.6	8.0(-3)	5.9(-3)
2.3	6.6(-2)	5.9(-2)	7.8	7.9(-3)	5.8(-3)
2.4	6.7(-2)	6.0(-2)	8.0	7.5(-3)	5.5(-3)
2.5	6.9(-2)	6.2(-2)	8.2	7.0(-3)	5.1(-3)
2.6	6.9(-2)	6.3(-2)	8.4	6.7(-3)	4.9(-3)
2.7	6.6(-2)	6.0(-2)	8.6	6.2(-3)	4.6(-3)
2.8	6.2(-2)	5.7(-2)	8.8	5.8(-3)	4.0(-3)
2.9	5.9(-2)	5.4(-2)	9.0	5.1(-3)	3.8(-3)
3.0	5.6(-2)	5.2(-2)	9.2	4.2(-3)	2.8(-3)
3.2	4.9(-2)	4.4(-2)	9.4	2.9(-3)	1.35(-3)
3.4	3.7(-2)	3.2(-2)	9.6	2.3(-3)	6.7(-4)
3.6	3.6(-2)	3.1(-2)	9.8	2.1(-3)	8.5(-4)
3.8	3.8(-2)	3.2(-2)	10.0	2.5(-3)	1.1(-3)
4.0	4.1(-2)	3.6(-2)	10.2	2.4(-3)	1.07(-3)
4.2	4.0(-2)	3.5(-2)	10.4	1.95(-3)	7.8(-4)
4.4	3.4(-2)	2.9(-2)	10.6	1.75(-3)	7.0(-4)
4.6	2.7(-2)	2.3(-2)	10.8	1.85(-3)	9.0(-4)
4.8	2.3(-2)	1.95(-2)	11.0	2.1(-3)	1.05(-3)
5.0	2.25(-2)	1.9(-2)	11.2	2.1(-3)	1.0(-3)

^aRead: 1.95×10^{-1} .

Table XII. Measured Bonner Ball Counting Rates Behind 10 ft of Sodium in counts/min/watt

Bonner Ball	Bare	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod 3-in.
<u>Detectors on Centerline 6 in. Behind Sodium</u>										
Foreground	6.32	3.14	28.00	40.52	35.98	27.05	12.25	4.974	1.819	
Background*	0.34	0.06	0.45	0.63	0.54	0.39	0.17	0.076	0.035	
Net	5.98	3.08	27.5	39.9	35.4	26.7	12.1	4.90	1.78	
<u>Detectors on Centerline 12 in. Behind Sodium</u>										
Foreground	5.64	2.72	23.93	35.13	31.05	23.25	10.40	4.249	1.541	
Background*	0.36	0.06	0.45	0.64	0.55	0.40	0.17	0.076	0.035	
Net	5.28	2.66	23.5	34.5	30.5	22.8	10.2	4.17	1.51	
<u>Detectors on Centerline 24 in. Behind Sodium</u>										
Foreground**	4.54	2.02	17.72	25.99	22.90	17.07	7.788	3.086	1.125	0.0313
Background	0.38	0.06	0.46	0.65	0.56	0.40	0.174	0.078	0.035	0.0005
Net	4.16	1.96	17.3	25.3	22.3	16.7	7.61	3.01	1.09	0.0308
<u>Detectors on Centerline 36 in. Behind Sodium</u>										
Foreground	3.70	1.56	13.50	19.60	17.40	12.97	5.845	2.338	0.853	
Background*	0.39	0.06	0.46	0.65	0.56	0.41	0.175	0.080	0.035	
Net	3.31	1.50	13.0	18.9	16.8	12.6	5.67	2.26	0.818	
<u>Detectors on Centerline 48 in. Behind Sodium</u>										
Foreground	3.085	1.20	10.54	15.37	13.40	9.933	4.49	1.794	0.651	
Background*	0.415	0.06	0.46	0.66	0.57	0.415	0.18	0.081	0.035	
Net	2.67	1.14	10.1	14.7	12.8	9.52	4.31	1.71	0.616	
<u>Detectors on Centerline 60 in. Behind Sodium</u>										
Foreground	2.59	0.950	8.25	11.97	10.43	7.83	3.50	1.412	0.506	
Background*	0.44	0.062	0.47	0.67	0.58	0.42	0.18	0.083	0.035	
Net	2.15	0.888	7.78	11.3	9.85	7.41	3.32	1.33	0.471	
<u>Detectors on Centerline 72.4 in. Behind Sodium</u>										
Foreground	2.21	0.770	6.54	9.50	8.339	6.21	2.792	1.114	0.403	0.0109
Background	0.46	0.063	0.47	0.68	0.595	0.43	0.185	0.084	0.035	0.0006
Net	1.75	0.707	6.07	8.82	7.74	5.78	2.61	1.03	0.368	0.0103

*Backgrounds based on linear interpolation and extrapolation of the measured values at 24 and 72.4 in. behind the sodium. The measured background for the bare ball is probably too low at 72.4 in. by about a factor of 2 due to inability of the measurement to include effects of air scattering of the transmitted beam.

**Average of two runs several days apart for all but the modified 3-in. Bonner ball.

Table XIII. Cadmium Ball Counting Rates 2 in. Behind 10 ft
of Sodium in counts/min/watt

	Air Backing the Detector		5 ft Sodium Backing the Detector	
	Foreground	Net*	Foreground	Net*
On Centerline	3.610	3.55	9.884	9.88
12 in. off centerline	3.421	3.36	9.536	9.54
24 in. off centerline	3.011	2.95	8.566	8.57
36 in. off centerline	2.448	2.39	6.975	6.97
48 in. off centerline	1.751	1.69	5.123	5.12
60 in. off centerline	0.967	0.909	3.127	3.13
72 in. off centerline	0.141	0.083	0.855	0.855

*The background assumed for the air backed measurements was the value of 0.058 counts/min/watt extrapolated from the measurements at 24 in. and 72.4 in. behind the sodium appearing in Table XII. The background was assumed to be negligible for the sodium backed measurements.

Table XIV. 3-in. Bonner Ball Counting Rates 2 in. Behind
10 ft of Sodium in counts/min/watt

	Air Backing the Detector		5 ft Sodium Backing the Detector	
	Foreground	Net*	Foreground	Net*
On Centerline	31.08	30.6	80.16	80.2
12 in. off centerline	29.28	28.8	77.28	77.3
24 in. off centerline	25.72	25.3	68.79	68.8
36 in. off centerline	20.71	20.3	56.18	56.2
48 in. off centerline	14.47	14.0	40.10	40.1
60 in. off centerline	7.789	7.34	23.92	23.9
72 in. off centerline	1.084	0.64	6.229	6.23

*The background assumed for the air backed measurements was the value of 0.445 counts/min/watt extrapolated from the measurements at 24 in. and 72.4 in. behind the sodium appearing in Table XII. The background was assumed to be negligible for the sodium backed measurements.

Table XV. Benjamin Counter Spectrum on the Centerline 24 in.
Behind 10 ft of Sodium

Energy Interval (keV)	Flux (neuts/cm ² /MeV/min/watt)	Standard Error (%)	Energy Interval (keV)	Flux (neuts/cm ² /MeV/min/watt)	Standard Error (%)
<u>10 atmosphere counter</u>			<u>1 atmosphere counter</u>		
1313.1 - 1500.0	2.88(-2) ^a	13.2	263.1 - 300.0	0.455	12.7
1154.2 - 1313.1	2.77(-2)	15.6	231.7 - 263.1	0.490	14.4
1023.4 - 1154.2	2.50(-2)	20.0	204.0 - 231.7	0.275	27.6
892.5 - 1023.4	3.46(-2)	12.9	180.0 - 204.0	0.489	17.0
789.7 - 892.5	2.87(-2)	18.7	157.8 - 180.0	0.609	13.9
696.3 - 789.7	3.10(-2)	17.2	139.4 - 157.8	0.921	10.8
612.1 - 696.3	5.01(-2)	10.8	122.8 - 139.4	1.33	8.1
537.4 - 612.1	9.17(-2)	6.3	108.0 - 122.8	1.38	8.7
			95.1 - 108.1	1.29	10.1
			84.0 - 95.1	1.86	7.9
<u>3 atmosphere counter</u>			72.9 - 84.0	3.00	4.7
473.5 - 541.4	0.140	10.6			
419.1 - 473.5	0.143	13.1			
369.3 - 419.1	0.160	12.2			
323.9 - 369.3	0.261	8.0			
283.2 - 323.9	0.468	4.9			
251.5 - 283.2	0.436	6.9			
219.7 - 251.5	0.385	7.3			

^aRead: 2.88×10^{-2} .

Table XVI. NE-213 Spectrum on the Centerline 27 in. Behind
10 ft of Sodium

Energy (MeV)	Flux (neuts/cm ² /MeV/min/watt)		Energy (MeV)	Flux (neuts/cm ² /MeV/min/watt)	
	Upper Limit	Lower Limit		Upper Limit	Lower Limit
1.1	4.0(-2) ^a	3.4(-2)	4.8	4.3(-3)	2.8(-3)
1.2	4.2(-2)	3.7(-2)	5.0	4.7(-3)	3.2(-3)
1.3	4.55(-2)	4.1(-2)	5.2	3.65(-3)	2.15(-3)
1.4	4.4(-2)	4.0(-2)	5.4	2.15(-3)	7.4(-4)
1.5	3.7(-2)	3.3(-2)	5.6	2.35(-3)	1.0(-3)
1.6	3.2(-2)	2.75(-2)	5.8	3.4(-3)	2.05(-3)
1.7	2.8(-2)	2.45(-2)	6.0	3.3(-3)	2.05(-3)
1.8	2.45(-2)	2.0(-2)	6.2	2.0(-3)	7.4(-4)
1.9	2.3(-2)	1.9(-2)	6.4	1.0(-3)	<1.0(-4)
2.0	2.05(-2)	1.7(-2)	6.6	1.65(-3)	4.5(-4)
2.1	1.55(-2)	1.23(-2)	6.8	2.5(-3)	1.35(-3)
2.2	1.28(-2)	9.6(-3)	7.0	2.5(-3)	1.45(-3)
2.3	1.37(-2)	1.08(-2)	7.2	2.3(-3)	1.25(-3)
2.4	1.44(-2)	1.17(-2)	7.4	2.3(-3)	1.33(-3)
2.5	1.42(-2)	1.17(-2)	7.6	1.87(-3)	9.5(-4)
2.6	1.27(-2)	1.04(-2)	7.8	1.04(-3)	1.65(-4)
2.7	1.04(-2)	8.3(-3)	8.0	6.25(-4)	<1.0(-4)
2.8	9.4(-3)	7.2(-3)	8.2	7.2(-4)	<1.0(-4)
2.9	1.0(-2)	8.0(-3)	8.4	9.8(-4)	1.83(-4)
3.0	1.1(-2)	9.0(-3)	8.6	1.25(-3)	4.7(-4)
3.2	9.2(-3)	7.3(-3)	8.8	1.31(-3)	5.9(-4)
3.4	7.4(-3)	5.4(-3)	9.0	1.22(-3)	5.4(-4)
3.6	6.0(-3)	4.0(-3)	9.2	1.13(-3)	4.4(-4)
3.8	7.2(-3)	5.2(-3)	9.4	1.07(-3)	4.0(-4)
4.0	7.0(-3)	5.0(-3)	9.6	9.6(-4)	3.66(-4)
4.2	4.8(-3)	3.1(-3)	9.8	8.25(-4)	2.1(-4)
4.4	4.3(-3)	2.6(-3)			
4.6	4.3(-3)	2.75(-3)			

^aRead as 4.0×10^{-2} .

Table XVII. Measured Bonner Ball Counting Rates on the
Centerline 24 in. Behind 12.5 ft of Sodium
in counts/min/watt

Bonner Ball	Bare	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod 3-in.
Foreground	0.9365	0.3562	2.57	3.47	2.977	2.16	0.974	0.367	0.1446	1.83(-3) ^a
Background	0.0715	0.0076	0.06*	0.07*	0.063	0.05*	0.024*	0.008*	0.0034	0.06(-3)
Net	0.865	0.349	2.51	3.40	2.91	2.11	0.950	0.359	0.141	1.77(-3)

^aRead as 1.83×10^{-3} .

*Estimated values.

The unfolded results from the Benjamin counter spectral measurement behind 12.5 ft of sodium are shown in Table XVIII. Backgrounds were obtained and subtracted prior to unfolding.

The results of the Bonner ball axial traverse measurements made behind 15 ft of sodium are presented in Table XIX. The net values appearing in the table are based on an assumed constant background between 2 in. and 74 in. behind the sodium for each Bonner ball. This assumption is based on the results of background measurements at several locations behind 15 ft of sodium for the 3-in. and 12-in. balls, and on the background measurements for all the balls behind 10 ft of sodium.

The results of the 3-in. Bonner ball radial traverses made at 24 in. behind 15 ft of sodium are presented in Table XX. These are foreground values only, and are plotted in Fig. 5.

The results of the 12-in. Bonner ball radial traverse made at 23 in. behind 15 ft of sodium are presented in Table XXI. These are foreground values only.

ANALYSIS

The calculations performed for this experiment are summarized in Table XXII.

The calculations with MORSE, a multigroup Monte Carlo transport code,¹¹ consistently used a 100-group GAMII structure expanded through P_3 in the angular distribution of elastic scattering and P_0 in the angular distribution of inelastic scattering. Thermal fluxes were not calculated, however. The basic sodium cross-section set used to derive this multigroup set was a preliminary version of the ENDF/B-III set provided by T. A. Pitterle.^{12,13} It was the latest evaluation for sodium available at the time the calculations were initiated. The point data were processed with SUPERTOG¹⁴ using $1/E\sigma_T$ weighting. Maximum allowable impurity concentrations shown in Table I were included in the sodium set using ENDF/B data.

Table XVIII. Benjamin Counter Spectrum on the Centerline 24 in.
Behind 12.5 ft of Sodium

Energy Interval (keV)	Flux (neuts/cm ² /MeV/min/w)	Standard Error (%)	Energy Interval (keV)	Flux (neuts/cm ² /MeV/min/w)	Standard Error (%)
<u>10 atmosphere counter</u>			<u>1 atmosphere counter</u>		
1313.1 - 1500.0	1.97(-3) ^a	16.0	263.7 - 300.0	1.93(-2)	26.3
1154.2 - 1313.1	1.69(-3)	22.1	231.1 - 263.7	2.45(-2)	22.9
1023.4 - 1154.2	1.31(-3)	33.2	203.9 - 231.1	1.92(-2)	34.8
892.5 - 1023.4	8.92(-4)	42.8	178.5 - 203.9	2.15(-2)	31.0
789.7 - 392.5	1.11(-3)	40.6	158.6 - 178.5	2.42(-2)	34.3
696.3 - 789.7	1.43(-3)	31.0	138.7 - 158.6	3.92(-2)	19.6
612.1 - 696.3	2.08(-3)	21.5	122.4 - 138.7	6.04(-2)	15.5
537.4 - 612.1	4.28(-3)	11.1	107.9 - 122.4	8.24(-2)	12.6
			95.2 - 107.9	6.47(-2)	17.9
			82.5 - 95.2	7.18(-2)	14.9
			73.4 - 82.5	1.56(-1)	9.6
<u>3 atmosphere counter</u>					
477.6 - 538.6	5.16(-3)	28.3			
416.5 - 477.6	6.98(-3)	19.5			
368.5 - 416.5	6.65(-3)	25.9			
324.9 - 368.5	1.13(-2)	16.0			
285.7 - 324.9	1.91(-2)	10.4			
250.8 - 285.7	2.35(-2)	9.5			
220.2 - 250.8	1.78(-2)	13.8			
194.1 - 220.2	1.97(-2)	13.8			

^aRead as 1.97×10^{-3} .

Table XIX. Measured Bonner Ball Net Counting Rates Behind 15 ft of Sodium in counts/min/watt

Bonner Ball	Bare	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod 3-in.
Constant Background	0.035*	0.003*	0.0095	0.015*	0.012	0.010*	0.004*	0.002*	0.00075	2.5(-5) ^a
Centerline Distance Behind Sodium, in.										
2			0.666							
4						0.480	0.208			
5								0.0787		
6	0.225	0.092	0.585	0.773	0.626	0.453	0.199	0.0771	0.0304	
8			0.571							
9								0.0702		
11							0.175			
12	0.193	0.0765	0.507	0.661	0.543	0.392	0.174	0.0664	0.0255	
14			0.493							
18	0.168	0.066	0.438	0.578	0.465	0.337	0.147	0.0561	0.0219	
20			0.418							
23										1.21(-4)
24	0.145	0.057	0.394	0.496	0.405	0.289	0.127	0.0497	0.0189	
26			0.365							
30									0.0163	
36	0.111	0.043	0.285	0.371	0.302	0.221	0.0960	0.0367		
38			0.277							
44									0.0118	
48	0.085	0.033	0.220	0.287	0.232	0.166	0.0745	0.0286	0.0108	
50			0.210							
56									0.0091	
60	0.067	0.0253	0.172	0.222	0.181	0.130	0.0588	0.0230		
62			0.165							
64									0.0079	
72	0.053	0.0202	0.135	0.176	0.143	0.103	0.0466	0.0176	0.0070	
74			0.132							

^aRead as 2.5×10^{-5} .^bEstimated background. The value for the bare ball was chosen to make the axial traverse of the bare ball parallel to those of the other Bonner balls. The bare ball and the modified 3-in. ball are the only balls for which background is important.

Table XX. Measured 3-in. Bonner Ball Foreground Counting Rates
24 in. Behind 15 ft of Sodium

Horizontal Traverse		Vertical Traverse			
Distance from Centerline (in.)	Counts/min/watt	Distance from Centerline (in.)	Counts/min/watt	Distance from Centerline (in.)	Counts/min/watt
84 south	0.0714	65 Down	0.161	17 Up	0.402
72	0.113	64 3/4	0.165	23	0.378
60	0.171	64 1/2	0.170	29	0.353
48	0.235	64 1/4	0.168	35	0.327
36	0.306	64	0.165	41	0.301
24	0.361	63 1/2	0.155	47	0.272
12	0.399	63	0.153	53	0.241
4	0.414	61	0.159	55	0.227
0	0.419	55	0.189	59	0.208
6 North	0.417	49	0.252	63	0.194
12	0.407	43	0.258	65	0.194
24	0.366	37	0.293	66	0.205
36	0.309	31	0.323	66 1/2	0.220
48	0.235	25	0.350	67	0.232
60	0.173	19	0.373	67 1/2	0.231
72	0.113	13	0.395	68	0.227
76	0.0926	7	0.411	69	0.199
		1	0.424	71	0.159
		5 Up	0.424	77	0.118
				83	0.00912
		11	0.416	89	0.00643

Table XXI. Measured 12 in. Bonner Ball Foreground Counting Rates
23 in. Behind 15 ft Sodium

Horizontal Traverse	
Distance from Centerline (in.)	Counts/min/watt
84 South	4.04(-3) ^a
72	5.75(-3)
60	8.69(-3)
48	1.36(-2)
36	1.69(-2)
24	1.82(-2)
12	2.05(-2)
0	2.16(-2)
12 North	2.34(-2)
24	1.87(-2)
36	1.57(-2)
48	1.24(-2)
60	8.61(-3)
72	5.64(-3)
84	3.87(-3)

^aRead: 4.04×10^{-3} .

Table XXII. Summary of Calculations Performed

Nominal Sodium Thickness (in.)	MORSE*	DOT-III**		
	Preliminary Set, $\rho_{Na} = 0.918$	Preliminary Set		ENDF/B-III Set
		$\rho_{Na} = 0.918$	$\rho_{Na} = 0.945$	$\rho_{Na} = 0.945$
30	Most Bonner Ball Counting Rates	Most Bonner Balls	None	None
60	Most Bonner Ball Counting Rates	Most Bonner Balls		
		Benjamin Spectra	None	All Benjamin Spectra
	All NE-213 Spectra	All NE-213 Spectra		All NE-213 Spectra
120	Most Bonner Ball Counting Rates	All Bonner Balls at 24 in.	All Bonner Balls at 24 in.	All Bonner Balls at 24 in.
	Benjamin Spectrum	Benjamin Spectrum	Benjamin Spectrum	Benjamin Spectrum
	NE-213 Spectrum	NE-213 Spectrum	NE-213 Spectrum	NE-213 Spectrum
150	Most Bonner Ball Counting Rates	None	All Bonner Balls at 24 in.	All Bonner Balls at 24 in.
	Benjamin Spectrum		Benjamin Spectrum	Benjamin Spectrum
180	Most Bonner Ball Counting Rates	None	All Bonner Balls at 24 in. on Centerline	All Bonner Balls at 24 in. on Centerline

*All MORSE calculations were cut off at 0.414 eV so that no thermal group fluxes were calculated. The calculations used the preliminary set and were performed for a sodium density of 0.918, but were corrected to the proper density of 0.945. A 100 GAMII group structure with expansion through P_3 was used.

**All DOT-III calculations except for $\rho = 0.918$ behind 2.5 and 5 ft of sodium used a 100-group GAMII structure with a sliding P_3 to P_0 expansion. For the exceptions, 50-group P_3 calculations were made.

A 100-group set was also generated for aluminum from ENDF/B data in order to treat the neutron transport in the walls of the sodium tanks. Although the MORSE calculations were accidentally performed for a sodium density of 0.918 grams/cm^3 , the results can be adjusted to conform to a density of 0.945 grams/cm^3 by a simple scaling procedure that introduces little error which has been proved accurate by comparison of ANISN and DOT III calculations performed at both the densities.

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. A separate biasing set was used for each of two ranges of transmitted energies - neutrons above 0.11 MeV and neutrons below 0.11 MeV. No biasing was required for the calculation of neutron transmission through the 2.5- and 5-ft thicknesses. The approximate effect 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 for two cases. In the first case, the concrete was considered to be a perfect absorber; in the second case, the concrete was considered to be a reflecting medium having albedo properties closely approximating those derived several years ago.¹⁵ A comparison of the two cases showed that the flux above thermal energy incident on the detectors arising from neutrons that had been reflected by the concrete collar comprised only about 25% of the total flux, and hence the concrete was treated in the subsequent calculations simply as a reflecting medium. An implication to be drawn from the small effect of the concrete, which is an excellent reflector, is that most of the neutrons that succeed in penetrating 15 ft of sodium and remain above thermal energies in this experiment do not migrate trans-

versely the 5.5 ft or so from their point of injection to the concrete and then return to the vicinity of the centerline through the sodium.

The calculations with DOT-III, a two-dimensional discrete ordinates transport code,¹⁶ used both the preliminary and final versions of the ENDF/B-III cross-section set for sodium (MAT=1156). The calculations through 2.5 and 5 ft of sodium using the preliminary set for $\rho_{\text{Na}} = 0.918$ grams/cm³ employed a 50-group GAMII structure with expansion through P_3 . The remaining calculations used a 100-group GAMII structure. Bartine, Oblow, and Mynatt¹⁷ determined the order of the Legendre expansion of the scattering cross section required to accurately calculate neutron transport through sodium by means of a sensitivity procedure. From their results, a P_3 expansion was used for groups 1-24 (14.9 to 1.35 MeV), a P_2 expansion for groups 25-52 (1.35 MeV to 52.5 keV), a P_1 expansion for groups 53-60 (52.5 to 7.12 keV), and a P_0 expansion for groups 61-100 (7.12 keV through thermal) for the 100-group calculations. R-Z geometry was used to describe the last 9 inches of the reactor collimator, the concrete surrounding the collimator, the aluminum tanks containing the sodium, and the concrete collar surrounding the tanks. (Therefore, in these calculations the concrete reflection was treated explicitly in all cases.) Cross-section sets based on ENDF/B data were generated for aluminum, concrete, and the borated polyethylene liner in the collimator as well as the two sodium sets with maximum impurities shown in Table I. In order to avoid ray effects, an analytic first collision source was used. An S_8 symmetric quadrature (48 angles) was used in the discrete ordinates calculation which calculates the collided flux. The flux at points of interest outside the DOT-III geometry was determined by calculating the uncollided adjoint flux in each group due to a unit isotropic source at the point and then integrating the product of the volume source distribution and the adjoint uncollided flux over the entire system. This latter calculation is performed by the FALSTF¹⁸ code and is equivalent to the analytic last flight calculation used in the statistical estimation procedure in MORSE. First and last collisions were thus completely analytic and discrete ordinates was used for the second to next to last collision and transport.

Uncollided fluxes at each detector centerline location were calculated by hand and added to the scattered fluxes computed using MORSE or DOT-III. These calculations were based on the measured axial variation of the beam emanating from the collimator, and involved evaluation of the following equation:

$$\phi_{g,unc} = \phi_{og} \times \left(\frac{59.5}{59.5+z} \right)^2 \times \exp \left(- \int_0^T \Sigma_{g \text{ total}}[Z'] dZ' \right), \quad (1)$$

where z is the centerline distance in inches between the detector and the exit of the collimator, ϕ_{og} is taken from Table III, $\Sigma_{g \text{ total}}(Z')$ is the total macroscopic cross section at a point within the sodium tank in cm^{-1} and T is the average thickness of the sodium tank, including the aluminum walls, in cm.

The source was mocked up as a point anisotropic source located 59.5 in. along the axis inside the collimator from the exit plane emitting neutrons isotropically over the polar angle range zero to $\tan^{-1} (15.25/2 \times 59.5) = 7.30^\circ$ measured from the centerline, of total intensity $4\pi(59.5 \times 2.540)^2 \times 2.702 \times 10^5 = 7.76 \times 10^{10}$ neutrons/min/watt, and of zero intensity for polar angles greater than 7.30° . The group source intensities were taken from the entries in Table III multiplied by the factor $4\pi(59.5 \times 2.54)^2 = 2.87 \times 10^5$.

Bonner ball counting rates were calculated by integrating the fluxes incident upon the center of detection of each ball (see Table II) with the corresponding response function for each ball. These response functions are presented in Figs. 6 through 14 and are the values tabulated in ref. 8 with a constant 20% decrease below 100 eV in the 3-in. Bonner ball responses and a constant 10% decrease below 100 eV in the 4-in. Bonner ball responses. The bare ball counting rates were not calculated directly for those few cases in which thermal flux calculations were made. Rather, the thermal fluxes were compared with the measured value of (Bare-Cd) $\times 0.80$, where the factor 0.80 is the calibrated value of $\text{n/cm}^2/\text{min}$ per count/min.

Fig. 6. Response Function for the Cadmium Bonner Ball.

Fig. 7. Response Function for the 3-in. Bonner Ball.

Fig. 8. Response Function for the 4-in. Bonner Ball.

Fig. 9. Response Function for the 5-in. Bonner Ball.

Fig. 10. Response Function for the 6-in. Bonner Ball.

Fig. 11. Response Function for the 8-in. Bonner Ball.

Fig. 12. Response Function for the 10-in. Bonner Ball.

Fig. 13. Response Function for the 12-in. Bonner Ball.

Fig. 14. Response Function for the Modified 3-in. Bonner Ball.

A check of both the response functions and the incident spectrum determined by the spectrometers in Table III is afforded by Bonner ball measurements made in the source beam 196 in. from the exit face of the collimator. The group fluxes were calculated from Eq. (1), using uncollided air attenuation for the exponential term, at points corresponding to the center of detection of each ball. Folding with the response functions provided the comparisons shown in Table XXIII.

For the bare ball, a measured net counting rate of $4828 - 173 = 4655$ counts/min/watt was obtained, leading to a thermal flux of $(4655 - 137) \times 0.80 = 3610$ n/cm²/min/watt. The calculated value is 4170. Thus, the agreement of all the Bonner ball counting rates lies within the uncertainty that the source spectrum is known (10 to 20%).

Some preliminary sodium transport calculations were performed using ANISN, a one-dimensional discrete ordinates transport code,¹⁹ in order to determine the effects of group structure, P_n expansion, cross-section sets, and density on the transmitted fluxes. Table XXIV shows a comparison of the absolute spectra leaking a 5-meter radius sodium sphere due to a point isotropic fission source located at the center using various combinations of two GAM-II structures and P_n expansion all derived from a preliminary version of the ENDF/B-III cross-section set for sodium. The comparisons indicate that the effects of the order of P_n expansion are important for the faster neutrons, as expected, but are negligible for energies below 100 eV, where the bulk of the leaking neutrons lie. The effects of group structure are small for all neutron energies above 1 keV. Below 1 keV, the 50-group set leads to fluxes of the order of 1-1/2 to 2 times higher than the fluxes calculated by the 100-group set. This may be due to the sudden broadening of the energy mesh in the vicinity of 1 keV, even though the total and scattering cross sections are essentially constant from 1 keV down to thermal energies. It is clear that a 100-group set, with P_3 expansion at least for the fast neutrons, is superior to the remaining combinations.

TABLE XXIII. Comparison of Measured and Calculated Bonner Ball Counting Rates in
the Source Beam 196 in. from the Concrete in Counts/min/watt

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod. 3-in.
Measured Fgd.	143	1743	4654	7196	8547	8872	6787	4898	266
Measured Bkgd.	6	15*	50*	120*	149	150*	100*	55	5
Measured Net	137	1730	4600	7080	8398	8720	6690	4843	261
Calculated	135	1850	4800	7320	8650	8640	6800	4830	235
Calculated/Measured	0.99	1.07	1.04	1.03	1.03	0.99	1.02	1.00	0.90

*Estimated.

Table XXIV. Comparisons of Surface Leakages from a 5-Meter Radius Sodium Sphere Calculated by ANISN Due to a Point Fission Source at the Center, in neutrons/source neutron

Group		ΔE	50-Group P_1	50-Group P_3	100-Group P_1	100-Group P_3
100	50					
1,2	1	12.2-14.9 MeV	8.81(-12) ^a	3.16(-11)	8.88(-12)	3.24(-11)
3,4	2	10.0-12.2	3.26(-11)	8.77(-11)	3.34(-11)	9.04(-11)
5,6	3	8.19-10.0	1.07(-10)	2.58(-10)	1.06(-10)	2.56(-10)
7,8	4	6.70-8.10	3.40(-10)	8.32(-10)	3.28(-10)	8.11(-10)
9,10	5	5.49-6.70	4.00(-10)	9.20(-10)	4.16(-10)	9.56(-10)
11,12	6	4.49-5.49	4.53(-10)	9.44(-10)	5.02(-10)	1.05(-9)
13,14	7	3.68-4.49	6.53(-10)	1.26(-9)	6.96(-10)	1.35(-9)
15,16	8	3.01-3.68	1.40(-9)	2.53(-9)	1.37(-9)	2.53(-9)
17,18	9	2.47-3.01	1.66(-9)	2.83(-9)	1.69(-9)	2.93(-9)
19,20	10	2.02-2.47	1.66(-9)	2.74(-9)	1.76(-9)	2.94(-9)
21,22	11	1.65-2.02	3.67(-9)	5.73(-9)	3.78(-9)	6.00(-9)
23,24	12	1.35-1.65	5.61(-9)	8.40(-9)	5.38(-9)	8.21(-9)
25,26	13	1.11-1.35	4.59(-9)	6.75(-9)	4.73(-9)	7.04(-9)
27,28	14	0.907-1.11	3.55(-9)	5.17(-9)	3.52(-9)	5.19(-9)
29,30	15	0.743-0.907	3.38(-9)	4.87(-9)	3.48(-9)	5.08(-9)
31,32	16	0.608-0.743	2.34(-9)	3.36(-9)	2.38(-9)	3.46(-9)
33,34	17	0.497-0.608	6.78(-9)	9.51(-9)	7.20(-9)	1.02(-8)
35,36	18	0.408-0.497	8.60(-9)	1.19(-8)	8.61(-9)	1.20(-8)
37,38	19	0.334-0.408	1.03(-8)	1.39(-8)	1.04(-8)	1.43(-8)
39,40	20	0.273-0.334	1.87(-8)	2.47(-8)	1.85(-8)	2.48(-8)
41,42	21	0.224-0.273	1.20(-8)	1.58(-8)	1.24(-8)	1.65(-8)
43,44	22	0.183-0.224	1.47(-8)	1.91(-8)	1.54(-8)	2.03(-8)
45,46	23	0.150-0.183	2.64(-8)	3.36(-8)	2.62(-8)	3.37(-8)
47,48	24	0.123-0.150	3.06(-8)	3.85(-8)	3.02(-8)	3.84(-8)
49,50	25	0.0865-0.123	7.65(-8)	9.36(-8)	7.11(-8)	8.84(-8)

^aRead: 8.81×10^{-12} .

Table XXIV (Cont'd.)

Group		ΔE	50-Group P_1	50-Group P_3	100-Group P_1	100-Group P_3
100	50					
51,52	26	52.5-86.5 keV	6.96(-8)	8.41(-8)	7.69(-8)	9.37(-8)
53	27	40.9-52.5	6.74(-8)	8.04(-8)	6.96(-8)	8.37(-8)
54	23	31.8-40.9	8.78(-8)	1.03(-7)	8.99(-8)	1.06(-7)
55	29	24.8-31.8	1.02(-7)	1.19(-7)	1.05(-7)	1.23(-7)
56	30	19.3-24.8	1.15(-7)	1.33(-7)	1.18(-7)	1.37(-7)
57	31	15.0-19.3	1.24(-7)	1.42(-7)	1.27(-7)	1.46(-7)
58-60	32	7.10-15.0	3.73(-7)	4.19(-7)	3.41(-7)	3.88(-7)
61,62	33	4.31-7.10	8.67(-8)	9.74(-8)	8.82(-8)	9.97(-8)
63	34	3.35-4.31	5.08(-9)	5.72(-9)	4.81(-9)	5.46(-9)
64	35	2.61-3.35	1.34(-9)	1.65(-9)	1.28(-9)	1.51(-9)
65	36	2.03-2.61	7.97(-9)	9.14(-9)	7.59(-9)	8.67(-9)
66	37	1.58-2.03	5.73(-8)	6.42(-8)	5.63(-8)	6.35(-8)
67	38	1.23-1.58	1.61(-7)	1.79(-7)	1.59(-7)	1.79(-7)
68	39	0.961-1.23	3.04(-7)	3.35(-7)	3.02(-7)	3.35(-7)
69-71	40	454-961 eV	3.53(-6)	3.73(-6)	2.14(-6)	2.31(-6)
72-74	41	214-454	1.03(-5)	1.06(-5)	5.42(-6)	5.70(-6)
75-77	42	101-214	2.39(-5)	2.43(-5)	1.23(-5)	1.27(-5)
78-80	43	47.9 -101	4.70(-5)	4.75(-5)	2.53(-5)	2.58(-5)
81-83	44	22.6-47.9	8.15(-5)	8.21(-5)	4.68(-5)	4.74(-5)
84-86	45	10.7-22.6	1.28(-4)	1.28(-4)	7.89(-5)	7.96(-5)
87-89	46	5.04-10.7	1.79(-4)	1.80(-4)	1.20(-4)	1.20(-4)
90-92	47	2.38-5.04	2.25(-4)	2.26(-4)	1.62(-4)	1.62(-4)
93-95	48	1.13-2.38	2.55(-4)	2.56(-4)	1.96(-4)	1.97(-4)
96-99	49	0.414-1.13	3.47(-4)	3.48(-4)	2.77(-4)	2.78(-4)

Table XXV gives a comparison of ANISN calculations of the effect on the Bonner ball counting rates of using the final and preliminary ENDF/B-III cross-section sets for sodium. The source spectrum for these calculations was identical to that determined for the experiment, and slab geometry was used. The conclusion is that generally speaking the final set leads to more fast neutrons ($E_n > 1$ keV) leaking the slabs than the preliminary set does.

Table XXVI shows the effect of small sodium density changes calculated with ANISN on the Bonner ball counting rates behind 15 ft of sodium using the same experimental source spectrum that was used for the results appearing in Table XXV. The final cross-section set was used in these calculations. These results indicate that the sensitivity of the experiment to sodium density behind 15 ft is approximately a 15% increase in the modified 3-in. Bonner ball counting rate per 1% decrease in the density and an 11% increase in all the remaining Bonner ball counting rates per 1% decrease in the density.

COMPARISON OF CALCULATIONS WITH EXPERIMENT

A. Behind 2.5 ft of Sodium

A comparison of the measured Bonner ball counting rates with the results of the MORSE and DOT-III calculations is shown in Table XXVII. Since both calculations used a sodium density of 0.918, they were corrected to the proper density of 0.945 by scaling each calculated Bonner ball counting rate by the factor appearing in the table. This factor was determined from the measured ratio [counting rate (2.5 ft)/counting rate (2.425 ft)] interpolated from Fig. 4. Both calculations used the preliminary set, and assumed no air attenuation. They should differ only because of the group structures and the treatment of the collimator scattering.

From Table XXVII it is clear that both the MORSE and DOT-III calculations which employed 100-group and 50-group structures respectively agree within 15% of the experimental values, which is estimated to be about as accurate as the source and reproducibility of the measurements can be defined. The DOT-III results are consistently lower than the MORSE results for the 3-in., 4-in., 5-in., and 6-in. balls, but the two are in essential

Table XXV. Comparison of ANISN Calculations of the Sodium
Experiment Using Preliminary and Final Versions
of the ENDF/B-III Evaluations

Sodium Thickness (ft)	Ratio of Results (Final Eval/Prelim Eval)				
	2.5	5	10	12.5	15
Bonner Ball					
Cd	.984	.973	.902	.854	.803
3-in.	.966	.948	.883	.837	.788
4-in.	.986	.962	.884	.834	.784
5-in.	.999	.977	.888	.835	.784
6-in.	1.008	.991	.894	.838	.786
8-in.	1.019	1.012	.904	.844	.789
10-in.	1.028	1.031	.914	.849	.792
12-in.	1.037	1.052	.925	.854	.795
Mod. 3-in.	1.035	1.112	1.320	1.445	1.588

Table XXVI. Sensitivity of the Experiment to Sodium Density
from ANISN Calculations Behind 15 ft of Sodium

Bonner Ball	Ratio of Results	
	[Counting Rate (0.945)/Counting Rate (ρ)]	
	$\rho = 0.957 \text{ grams/cm}^3$ ($\Delta\rho/\rho \approx 1.3\%$)	$\rho = 0.918 \text{ grams/cm}^3$ ($\Delta\rho/\rho = -3.0\%$)
Cd	1.164	0.749
3-in.	1.172	0.742
4-in.	1.176	0.732
5-in.	1.179	0.729
6-in.	1.181	0.727
8-in.	1.182	0.726
10-in.	1.182	0.725
12-in.	1.182	0.725
Mod. 3-in.	1.248	0.651

c/

Table XXVII. Comparison of Calculated and Measured Bonner Ball Counting Rates Behind 2.5 ft of Sodium in Counts/min/watt

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.
Density Correction Factor	0.98	0.98	0.97	0.97	0.97	0.96	0.95	0.94
<u>24 in. Behind, on Centerline</u>								
MORSE, $\rho = 0.918$	54.8	908	2046	2687	2742	2137	1397	884
Corrected MORSE, $\rho = 0.945$	53.7	890	1984	2606	2659	2051	1328	831
DOT-III, $\rho = 0.918$	-	755	1839	2477	2594	2075	1373	879
Corrected DOT-III, $\rho = 0.945$	-	740	1784	2403	2516	1992	1304	826
Measured	58.5	840	2068	2678	2821	2163	1379	878
Calculated/Measured								
Corrected MORSE	0.92	1.06	0.96	0.97	0.94	0.95	0.96	0.95
Corrected DOT-III	-	0.88	0.86	0.90	0.89	0.92	0.95	0.94
<u>24 in. Behind, 24 in. Off Centerline</u>								
MORSE, $\rho = 0.918$	37.6	633	1404	1772	1732	1221	701	388
Corrected MORSE, $\rho = 0.945$	36.9	620	1362	1719	1680	1172	666	365
DOT-III, $\rho = 0.918$	-	533	1255	1644	1649	1200	704	396
Corrected DOT-III, $\rho = 0.945$	-	522	1217	1595	1600	1152	669	372
Measured	41.0	611	1428	1824	1801	1306	754	422
Calculated/Measured								
Corrected MORSE	0.90	1.01	0.95	0.94	0.93	0.90	0.88	0.87
Corrected DOT-III	-	0.85	0.85	0.87	0.89	0.88	0.89	0.88
<u>166 in. Behind, on Centerline</u>								
MORSE, $\rho = 0.918$	3.52	56.6	127	167	176	151	113	79.5
Corrected MORSE, $\rho = 0.945$	3.45	55.5	123	162	171	145	107	74.7
Measured	4.07	55.7	129	174	187	159	113	77.5
Calculated/Measured								
Corrected MORSE	0.85	1.00	0.95	0.93	0.92	0.91	0.95	0.96

agreement for the 8-in., 10-in., and 12-in. balls. Since the effects of the two group structures are most apparent below 1 keV (compare the 50-group P_3 fluxes with the 100-group P_3 fluxes in Table XXIV), and the smaller sized Bonner balls are more sensitive to these low-energy neutrons, one might be tempted to conclude that it is the effect of too coarse a group structure in the DOT-III calculations that is causing the disagreement. If this were true, however, the effect would have to change from an overestimate behind 15 ft of sodium to an underestimate behind 2.5 ft of sodium -- a rather unlikely possibility. It is far more reasonable to conclude that the slight discrepancy in the two calculations of the smaller Bonner ball counting rates lies in the treatment of the collimator effect, which in the MORSE calculations is handled separately but with some simplifying assumptions regarding the magnitude and spectral distribution of the neutrons reflected from the collimator and reincident on the sodium tank. This reflected spectrum is considerably softer than the source spectrum leaking the collimator presented in Table III but contributes appreciably to the transmitted low-energy spectrum behind 2.5 ft of sodium. Thus, the effects of the two-group structures are not considered to be as important in calculating the transmitted fluxes through 2.5 ft of sodium as the effects arising from different treatment of the collimator scattering. Since the DOT-III calculations include the essential features of the collimator in the geometric and cross-sectional description of the experiment, they are considered to be the more realistic.

B. Behind 5 ft of Sodium

A comparison of the measured Bonner ball counting rates with the counting rates calculated by MORSE and DOT-III is shown in Table XXVIII. The two calculations used a sodium density of 0.918 and were corrected to the proper density of 0.945 by multiplying by the factors appearing in the table. These Bonner ball calculations used the preliminary set, but MORSE used 100 groups and DOT-III used 50 groups.

The same general conclusions can be reached from these comparisons that were drawn from the comparisons of the results behind 2.5 ft of sodium. The agreement between the MORSE calculations and experiment is to within ~15%, and between the DOT-III calculations and experiment to within ~20%.

Table XXVIII. Comparison of Calculated and Measured Bonner Ball Counting Rates
Behind 5 ft of Sodium in Counts/min/watt

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod. 3-in.
Density Correction Factor	0.95	0.95	0.94	0.94	0.93	0.93	0.92	0.92	0.88
<u>24 in. Behind, on Centerline</u>									
MORSE, $\rho = 0.918$	20.4	325	608	660	566	324	167	73.7	7.85
Corrected MORSE, $\rho = 0.945$	19.4	308	571	620	527	302	153	67.8	6.91
DOT-III, $\rho = 0.918$	17.0	277	533	593	517	305	148	72.1	-
Corrected DOT-III, $\rho = 0.945$	16.2	263	501	557	481	284	136	66.3	-
Measured	21.4	295	590	639	551	318	149	71.8	6.94
Calculated/Measured									
Corrected MORSE	0.91	1.04	0.97	0.97	0.96	0.95	1.03	0.95	0.99
Corrected DOT-III	0.76	0.89	0.85	0.87	0.87	0.89	0.91	0.92	-
<u>24 in. Behind, 30 in. Off Centerline</u>									
MORSE, $\rho = 0.918$	15.5	240	438	468	392	215	95.9	41.7	-
Corrected MORSE, $\rho = 0.945$	14.7	228	412	440	365	200	88.2	38.4	-
DOT-III, $\rho = 0.918$	12.9	204	380	414	353	198	90.6	40.5	-
Corrected DOT-III, $\rho = 0.945$	12.3	194	357	389	328	184	83.4	37.3	-
Measured	17.2	228	435	462	389	224	102	46.6	-
Calculated/Measured									
Corrected MORSE	0.86	1.00	0.95	0.95	0.94	0.89	0.87	0.82	-
Corrected DOT-III	0.71	0.85	0.82	0.84	0.84	0.82	0.82	0.80	-
<u>359 in. Behind, on Centerline</u>									
MORSE, $\rho = 0.918^*$	0.321	4.87	8.86	9.51	8.07	4.65	2.32	1.21	0.106
Corrected MORSE, $\rho = 0.945^*$	0.305	4.63	8.33	8.94	7.51	4.32	2.13	1.11	0.0929
DOT-III, $\rho = 0.918^*$	0.293	4.48	8.28	8.99	7.70	4.48	2.24	1.17	-
Corrected DOT-III, $\rho = 0.945^*$	0.278	4.25	7.78	8.45	7.16	4.16	2.06	1.08	-
Measured	0.372	4.89	9.05	9.32	8.02	4.88	2.37	1.24	0.103
Calculated/Measured									
Corrected MORSE	0.82	0.95	0.92	0.96	0.94	0.89	0.90	0.90	0.90
Corrected DOT-III	0.75	0.87	0.86	0.91	0.89	0.85	0.87	0.87	-

*Infinite air attenuation effects were calculated using ANISN with the leakage source from DOT-III. The same air attenuation effects were included in the MORSE results presented here.

Comparisons of the three calculated Benjamin counter spectra and the two NE-213 spectra behind 5 ft of sodium from the two calculations indicate almost perfect agreement in both shape and magnitude, thus verifying that the only significant disagreement in the two calculations lies in the low-energy ($E_n < 1$ keV) region.

A more interesting comparison is between calculations using both the preliminary set and the final ENDF/B-III set in a consistent 100-group structure with measured Benjamin counter and NE-213 spectra. The calculations with the preliminary set were the same ones performed with MORSE of the Bonner ball counting rates presented in Table XXVIII. These spectra were corrected for sodium density by multiplying the sodium scattered contribution by 0.88 and recalculating the uncollided component exactly. The calculations with the ENDF/B-III set were performed with DOT-III at the proper sodium density of 0.945 grams/cm³. Each calculated spectrum was smeared with the resolution function of the spectrometer before comparing with the measured unfolded spectra. The resolution function of the NE-213 spectrometer is shown in Table XXIX. The resolution function of the Benjamin counter is assumed to have a constant value of 10% FWHM independent of energy.

Turning first to the NE-213 results, Fig. 15 shows the comparisons on the centerline 359 in. behind 5 ft of sodium. Air attenuation was calculated in an earlier ANISN run (see footnote to Table XXVIII), with the value 0.96 being a good average over the energy range 1 to 12 MeV for both NE-213 locations. The integral comparisons show that the preliminary set is superior to the final set, although the final set seems to be superior in the energy range 2.5 to 4.5 MeV. Scattered fluxes in the regions 1 to 2.5 MeV are calculated better by the preliminary set. Figure 16 shows the comparisons 96 in. off the centerline 359 in. behind 5 ft of sodium. The integral comparisons again show the preliminary set to be superior, leading to calculated fluxes in the region 1 to 2.5 MeV which agree within several percent of the measurement. Both sets are different in the region centered around 4 MeV, where a measured peak is not predicted by either set, although the final set agrees with the measurement somewhat better.

Table XXIX. Energy Resolution of the NE-213 Spectrometer System

E (MeV)	FWHM (%)	E (MeV)	FWHM (%)	E (MeV)	FWHM (%)
0.5	47.5	3.5	18.2	7.0	12.6
0.6	44	3.6	18.0	7.2	12.4
0.7	41	3.7	17.7	7.4	12.2
0.8	38.5	3.8	17.4	7.6	12.1
0.9	36	3.9	17.1	7.8	11.9
1.0	33.5	4.0	16.9	8.0	11.8
1.2	31	4.2	16.5	8.4	11.5
1.3	30	4.3	16.3	8.6	11.4
1.4	29	4.4	16.1	8.8	11.3
1.5	27.5	4.5	15.9	9.0	11.2
1.6	26.5	4.6	15.7	9.2	11.1
1.7	26	4.7	15.5	9.4	10.9
1.8	25	4.8	15.3	9.6	10.8
1.9	24.5	4.9	15.2	9.8	10.7
2.0	24	5.0	15.1	10.0	10.5
2.1	23.5	5.1	14.9	10.2	10.3
2.2	23	5.2	14.7	10.4	10.2
2.3	22.5	5.3	14.5	10.6	10.1
2.4	22	5.4	14.4	10.8	10.0
2.5	21.5	5.5	14.3	11.0	9.8
2.6	21.2	5.6	14.2	11.4	9.7
2.7	20.8	5.7	14.1	11.8	9.6
2.8	20.4	5.8	13.9	12.2	9.6
2.9	20.1	5.9	13.8		
3.0	19.7	6.0	13.7		
3.1	19.4	6.2	13.5		
3.2	19.1	6.4	13.2		
3.3	18.8	6.6	13.0		
3.4	18.5	6.8	12.8

Fig. 15. Comparison of Measured Spectrum in the Energy Region 1-12 MeV on the Centerline 359 in. Behind 5 ft of Sodium with Calculated Spectra Using Each of the Two Cross-Section Sets.

Fig. 16. Comparison of Measured Spectrum in the Energy Region 1-12 MeV 96 in. Off the Centerline and 359 in. Behind 5 ft of Sodium with Calculated Spectra Using Each of the Two Cross Section Sets.

The comparisons with the Benjamin counter measurements behind 5 ft of sodium are shown in Figs. 17 through 19. In Fig. 17, the comparisons are shown at a point on the centerline 24 in. behind, where air attenuation effects are negligible. The comparisons again favor the preliminary set in the integral and everywhere in the range 74 to 1350 keV with exceptions in the vicinity of 100 keV and 250 keV.

In Figs. 18 and 19 the comparisons are shown at locations on and 96-in. off the centerline 359 in. behind, where air attenuation effects should be considered. Two curves are shown in each figure for each calculation -- one assuming no air attenuation and the other with uncollided air attenuation -- thus bracketing the curve with correct air attenuation. The infinite air attenuation calculated by ANISN in this energy region averages 0.90. Comparison of the calculated integral values with experiment at both locations shows little to choose between the two sets; the preliminary set underpredicting by 8% and the final set overpredicting by about 6%. Spectrum comparisons, however, favor the preliminary set in most energy regions except possibly in the vicinity of 100 keV and 250 keV. Overall, in the region 74 keV to 10 MeV the final set leads to transmitted fluxes through 5 ft of sodium that are slightly higher than experiment, whereas the preliminary set leads to fluxes slightly lower than experiment, with the preliminary set apparently somewhat superior.

C. Behind 10 ft of Sodium

Three sets of calculations were performed using DOT-III, one using the final set and a sodium density of 0.945, and two using the preliminary set with sodium densities of 0.945 and 0.918. Since the MORSE results used the preliminary set and a density of 0.918, the purpose of the 0.918 density DOT-III run was both to verify directly the MORSE results and then to correct the MORSE results to the proper density by the ratio of the DOT-III results at densities of 0.918 and 0.945.

Direct comparisons of the MORSE and DOT-III calculated counting rates at a point on the centerline 24 in. behind 10 ft of sodium, both using the preliminary set and a sodium density of 0.918 grams/cm³ is shown in

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Fig. 17. Comparison of Measured Spectrum in the Energy Region 74 keV-1.35 MeV on the Centerline 24 in. Behind 5 ft of Sodium with Calculated Spectra Using Each of the Two Cross-Section Sets.

Fig. 18. Comparison of Measured Spectrum in the Energy Region 74 keV-1.35 MeV on the Centerline 359 in. Behind 5 ft of Sodium with Calculated Spectra Using Each of the Two Cross-Section Sets.

Fig. 19. Comparison of Measured Spectrum in the Energy Region 74 keV-1.35 MeV 96 in. Off the Centerline and 359 in. Behind 5 ft of Sodium with Calculated Spectra Using Each of the Two Cross-Section Sets.

Table XXX. Also shown in this table is the ratio of the DOT-III calculated counting rates on the centerline 24 in. behind for densities of 0.945 and 0.918 which becomes the correction factor to apply to all the MORSE results behind 10 ft of sodium.

From Table XXX, it is clear that the MORSE and DOT-III calculations are in excellent agreement, and that the small discrepancies in the low-energy fluxes that occurred behind 5 ft of sodium have disappeared, probably because the neutrons that are scattered by the collimator back into the sodium tanks do not contribute more than 5% of the neutrons above thermal energies that are transmitted through 10 ft of sodium. The sensitivity of the experiment to sodium density behind 10 ft from the last line in Table XXX is approximately a 10% increase in the modified 3-in. Bonner ball counting rate per 1% decrease in the density and a 5% increase in the remaining Bonner ball counting rates per 1% decrease in the density. This is to be compared with the sensitivity to sodium density behind 15 ft calculated by ANISN in Table XXVI.

A comparison of the measured Bonner ball counting rates on the centerline 24 in. behind 10 ft of sodium with the counting rates calculated using DOT-III for a density of 0.945 grams/cm³ and density corrected MORSE results is shown in Table XXXI.

An inspection of Table XXXI shows that the preliminary cross-section set is superior to the final set; all the Bonner ball counting rates calculated with the preliminary set agree with the experiment to within 15%, while those calculated with the final set agree to within 20% for the Cd through 12-in. balls but there is poor agreement with the modified 3-in. ball. Since the Cd through the 12-in. balls are responding mostly to the flux below 1 keV but the 3-in. ball is responding only to the flux above 10 keV (see Appendix), it is clear that the final set is overpredicting neutron transmitted fluxes in the region 0.1 MeV to 1 MeV and slightly underpredicting them in the region 1 eV to 1 keV. The measured thermal flux at the above location is (see Table XII):

Table XXX. Direct Comparison of MORSE and DOT-III Calculated Bonner Ball
Counting Rates in Counts/min/watt on the Centerline 24 in.
Behind 10 ft of Sodium and Correction Factors for the
MORSE Counting Rates for a Density of 0.945

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod 3-in.
MORSE, $\rho = 0.918$	1.86	18.8	26.6	24.5	18.1	8.10	2.99	1.05	0.0458
DOT-III, $\rho = 0.918$	1.98	19.6	27.3	25.2	18.3	8.18	3.03	1.09	0.0429
MORSE/DOT-III, $\rho = 0.918$	0.94	0.96	0.97	0.97	0.99	0.99	0.99	0.96	1.07
Statistical Uncertainty, MORSE	± 0.04	± 0.04	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.03	± 0.10
DOT-III [($\rho=0.945$)/($\rho=0.918$)]	0.894	0.874	0.864	0.858	0.856	0.850	0.846	0.841	0.761

Table XXXI. Comparison of Measured and Calculated Bonner Ball Counting Rates
on the Centerline 24 in. Behind 10 ft of Sodium in counts/min/watt

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod. 3-in.
Calculated, DOT-III (prel.)	1.77	17.1	23.6	21.6	15.7	6.95	2.56	0.914	0.0327
Calculated, Corrected MORSE (prel.)	1.66	16.4	23.0	21.0	15.5	6.88	2.53	0.885	0.0349
Calculated, DOT-III (final)	1.63	15.5	21.4	19.8	14.5	6.51	2.44	0.885	0.0422
DOT-III (final/prel.)	0.921	0.906	0.907	0.917	0.924	0.937	0.953	0.868	1.290
Measured	1.96	17.3	25.3	22.3	16.7	7.61	3.01	1.09	0.0308
Calc./Meas. DOT-III (prel.)	0.90	0.99	0.93	0.97	0.94	0.91	0.85	0.84	1.06
Calc./Meas. Corr. MORSE (prel.)	0.85	0.95	0.91	0.94	0.93	0.91	0.84	0.81	1.13
Calc./Meas. DOT-III (final)	0.83	0.90	0.85	0.89	0.87	0.86	0.81	0.81	1.37

$$(4.16-1.96) \times 0.80 = 1.76 \text{ neutrons/cm}^2/\text{min/watt} ,$$

whereas the calculated values using the preliminary and final sets with DOT-III are 1.09 and 1.12 neutrons/cm²/min/watt respectively, yielding calculated to measured ratios of 0.62 and 0.64.

An interesting comparison is to compare the ratio of the DOT-III calculated counting rates using the final and preliminary cross-section sets appearing in Table XXXI with the ANISN calculated ratios behind 10 ft that were presented earlier in Table XXV. The ratios agree very well and slight differences between them can easily be explained in terms of source and sodium tank geometry.

The comparison of measured and calculated Bonner ball counting rates using the density corrected MORSE results along an axial traverse appear in Table XXXII, where air attenuation is assumed negligible for all detectors and locations.

An inspection of Table XXXII shows the agreement between the measured counting rates and the calculated counting rates using the preliminary set is within 20% for all Bonner balls and all locations, and is within the combined errors of the experiment (~ 1% uncertainty in the sodium density, 10 to 20% uncertainty in the absolute source spectrum, and ~ 5% uncertainty in the power calibration of the measured counting rates). There is growing evidence that the 10-in. and 12-in. Bonner ball response functions used may be a little low in the energy region below ~ 100 eV, and this will be discussed further along after more comparisons are made behind the thicker samples of sodium.

The comparison between the transverse profile measurements and the density corrected MORSE calculations of the Cd- and 3-in. Bonner ball counting rates ~ 2 in. behind 10 ft of sodium are presented in Table XXXIII for both the case of air backing the detectors and 5 ft of sodium backing the detectors, the latter geometry closely approximating an "in situ" geometry.

Table XXXII. Comparison of Measured Bonner Ball Counting Rates on the Centerline
with Calculated Values Using Density Corrected MORSE Results
Behind 10 ft of Sodium in Counts/min/watt

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod. 3-in.
<u>6 in. Behind</u>									
Calculated, MORSE	2.73	26.9	37.8	34.4	25.4	11.3	4.15	1.45	
Measured	3.08	27.5	39.9	35.4	26.7	12.1	4.90	1.78	
Calc./Meas.	0.89	0.98	0.95	0.97	0.95	0.93	0.85	0.82	
<u>12 in. Behind</u>									
Calculated, MORSE	2.30	22.6	31.8	29.0	21.4	9.50	3.49	1.22	
Measured	2.66	23.5	34.5	30.5	22.8	10.2	4.17	1.51	
Calc./Meas.	0.87	0.96	0.92	0.95	0.94	0.93	0.84	0.81	
<u>24 in. Behind</u>									
Calculated, MORSE	1.66	16.4	23.0	21.0	15.5	6.88	2.53	0.885	0.0349
Measured	1.96	17.3	25.3	22.3	16.7	7.61	3.01	1.09	0.0308
Calc./Meas.	0.85	0.95	0.91	0.94	0.93	0.91	0.84	0.81	1.13
<u>36 in. Behind</u>									
Calculated, MORSE	1.24	12.2	17.1	15.6	11.5	5.12	1.88	0.658	
Measured	1.50	13.0	18.9	16.8	12.6	5.67	2.26	0.818	
Calc./Meas.	0.83	0.94	0.90	0.93	0.91	0.90	0.83	0.80	
<u>48 in. Behind</u>									
Calculated, MORSE	0.936	9.22	13.0	11.8	8.72	3.87	1.42	0.498	
Measured	1.14	10.1	14.7	12.8	9.52	4.31	1.71	0.616	
Calc./Meas.	0.82	0.91	0.89	0.92	0.92	0.90	0.83	0.81	
<u>60 in. Behind</u>									
Calculated, MORSE	0.720	7.09	9.97	9.09	6.71	2.98	1.10	0.383	
Measured	0.888	7.78	11.3	9.85	7.41	3.32	1.33	0.471	
Calc./Meas.	0.81	0.91	0.88	0.92	0.91	0.90	0.83	0.81	
<u>72.4 in. Behind</u>									
Calculated, MORSE	0.565	5.57	7.83	7.13	5.27	2.34	0.860	0.301	0.0100
Measured	0.707	6.07	8.82	7.74	5.78	2.61	1.03	0.368	0.0103
Calc./Meas.	0.80	0.92	0.89	0.92	0.91	0.90	0.84	0.82	0.97

Table XXXIII. Comparison of Measured and Density Corrected MORSE
Calculated Transverse Absolute Profiles Behind 10
ft of Sodium in Counts/min/watt

	Detector Position Off Centerline (ft)					
	0	1	2	3	4	5
<u>Air Backing the Detectors</u>						
<u>Cd-Bonner Ball</u>						
Calculated, MORSE	3.00	2.75	2.33	1.59	1.03	0.611
Measured	3.55	3.36	2.95	2.39	1.69	0.909
Calc./Meas.	0.85	0.82	0.79	0.67	0.61	0.67
<u>3-in. Bonner Ball</u>						
Calculated, MORSE	30.3	27.8	24.1	17.2	10.2	5.54
Measured	30.6	28.8	25.3	20.3	14.0	7.34
Calc./Meas.	0.99	0.97	0.95	0.85	0.73	0.75
<u>Sodium Backing the Detectors</u>						
<u>Cd-Bonner Ball</u>						
Calculated, MORSE	9.57	9.24	8.31	6.24	3.94	2.25
Measured	9.88	9.54	8.57	6.98	5.12	3.13
Calc./Meas.	0.97	0.97	0.97	0.89	0.77	0.72
<u>3-in. Bonner Ball</u>						
Calculated, MORSE	85.4	83.0	74.2	57.6	35.8	18.7
Measured	80.2	77.3	68.8	56.2	40.1	23.9
Calc./Meas.	1.06	1.07	1.08	1.02	0.89	0.78

The reason for the increasing disagreement at the larger distances off the centerline is undoubtedly due to the replacement in MORSE of the concrete collar by a reflecting medium having the albedo properties of concrete. Thus no transmission through the concrete is calculated, and as the detector approaches the concrete collar at a radius of 5.5 ft an increasing percentage of the counting rate due to neutrons penetrating the concrete is not calculated. For detector positions near the centerline, however, the contribution of the concrete transmitted neutrons is negligible, and out to 2 ft the agreement between the calculations and the measurements is within 20% with air backing and 10% with sodium backing. The calculations assumed that the perturbation of the detectors on the reflected fluxes in the sodium backing case was negligible, which seems to be a reasonable assumption a posteriori if one compares the calculated counting rate enhancements with the measured values. However, the statistical uncertainties of the calculations average about 8% for the detector counting rates for both the air-backed and sodium-backed geometries, and probably obscure any real differences of the order of 10%.

A comparison of the measured NE-213 spectrum with spectra calculated with DOT-III using both cross-section sets for a point located on the centerline 24 in. behind 10 ft of sodium is shown in Fig. 20. The integral comparisons again favor the preliminary set, which reflects the better agreement of this set in the region ~ 1 to 2.5 MeV. The two calculated spectra effectively bracket the measured spectrum from 2.5 to 5.2 MeV with the exception of the region 3.8 to 4.0 MeV where both calculated spectra are low. The general features of the comparisons behind 10 ft are similar to those at the two locations behind 5 ft (see Figs. 15 and 16), although the greater errors involved in the measurement behind 10 ft tend to prevent any definitive conclusion from being reached as to the general superiority of one set or the other in the region above 2.5 MeV.

A comparison of the measured Benjamin counter spectrum at the same location as the NE-213 measurement with the two spectra calculated using DOT-III is shown in Fig. 21. Integral comparisons favor the preliminary set, and, indeed, the preliminary set agrees better with the measurement

Fig. 20. Comparison of Measured Spectrum in the Energy Region 1-10 MeV on the Centerline 24 in. Behind 10 ft of Sodium with Calculated Spectra Using Each of the Two Cross-Section Sets.

Fig. 21. Comparison of Measured Spectrum in the Energy Region 70 keV-1.5 MeV on the Centerline 24 in. Behind 10 ft of Sodium with Calculated Spectra Using Each of the Two Cross-Section Sets.

everywhere than does the final set. Both sets overpredict fluxes in the region 0.8 to 1.5 MeV and in the vicinity of 180 keV and 120 keV, but the disagreement is not considered serious.

D. Behind 12.5 ft of Sodium

Flux calculations using both cross-section sets were performed using DOT-III for a point on the centerline 24 in. behind 12.5 ft of sodium with a sodium density of 0.945 grams/cm³. Calculations were also performed with MORSE for the same detector location but using the preliminary set only and for a density of 0.918 grams/cm³. To correct the latter calculations of the Bonner ball counting rates to the proper sodium density, the counting rates of the Bonner balls were decreased by factors linearly interpolated between the density sensitivity effects behind 10 ft of sodium shown in Table XXX and behind 15 ft of sodium shown in Table XXVI. The comparison of the calculated Bonner ball counting rates between DOT-III and density corrected MORSE results both using the preliminary cross-section set is shown in Table XXXIV.

From Table XXXIV, it is clear that the two calculations lie within the statistics of the Monte Carlo calculation, and hence are in agreement.

A comparison of the measured and calculated counting rates is shown in Table XXXV.

The measured thermal flux was $(0.865-0.349) \times 0.80 = 0.413$ neutrons/cm²/min/watt (see Table XVII) while the calculated values using DOT-III are 0.252 and 0.250 neutrons/cm²/min/watt for the preliminary and final cross-section sets respectively, yielding calculated to measured ratios of 0.61 for either set.

An inspection of Table XXXV indicates once again that use of the preliminary set produces results that agree better with experiment. As in the comparison behind 10 ft, the final set produces lower counting rates for the Cd through 12-in. Bonner balls (i.e., lower fluxes below ~1 keV,

Table XXXIV. Comparison of MORSE and DOT-III Calculated Bonner Ball
Counting Rates on the Centerline 24 in. Behind 12.5 ft
of Sodium in Counts/min/watt

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod. 3-in.
DOT-III, $\rho = 0.945$	0.331	2.73	3.46	3.05	2.14	0.915	0.328	0.114	1.67(-3) ^a
MORSE, $\rho = 0.918$	0.422	3.45	4.43	3.93	2.75	1.17	0.422	0.149	1.97(-3)
Density Correction Factor	0.821	0.808	0.798	0.793	0.792	0.788	0.786	0.783	0.706
Corrected MORSE, $\rho = 0.945$	0.346	2.79	3.54	3.12	2.18	0.922	0.332	0.117	1.39(-3)
Corrected MORSE/DOT-III, $\rho = 0.945$	1.04	1.02	1.02	1.02	1.02	1.01	1.01	1.03	0.83
Statistical Uncertainty, MORSE	± 0.06	± 0.05	± 0.04	± 0.04	± 0.04	± 0.04	± 0.04	± 0.04	± 0.16

^aRead: 1.67×10^{-3} .

Table XXXV. Comparison of Measured and Calculated Bonner Ball Counting Rates
on the Centerline 24 in. Behind 12.5 ft of Sodium in Counts/min/watt

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod. 3-in.
Calculated, DOT-III (prel)	0.331	2.73	3.46	3.05	2.14	0.915	0.328	0.114	1.67(-3) ^a
Calculated, Corrected MORSE (prel)	0.346	0.279	3.54	3.12	2.18	0.922	0.332	0.117	1.39(-3)
Calculated, DOT-III (final)	0.292	2.35	2.99	2.65	1.88	0.809	0.292	0.102	2.36(-3)
DOT-III (final/prel)	0.882	0.861	0.864	0.869	0.879	0.884	0.890	0.895	1.413
Measured	0.349	2.51	3.40	2.91	2.11	0.950	0.359	0.141	1.77(-3)
Calc./Meas. DOT-III (prel)	0.95	1.09	1.02	1.05	1.01	0.96	0.91	0.81	0.94
Calc./Meas. Corr. MORSE (prel)	0.99	1.11	1.04	1.07	1.03	0.97	0.93	0.83	0.79
Calc./Meas. DOT-III (final)	0.84	0.94	0.88	0.91	0.89	0.85	0.81	0.72	1.33

^aRead: 1.67×10^{-3} .

see Appendix) and higher counting rates for the modified 3-in. Bonner ball (i.e., higher fluxes above ~ 10 keV). Comparison of the final to preliminary counting rates using DOT-III presented in Table XXXV with the corresponding ratios behind 12.5 ft using ANISN presented in Table XXV shows good agreement, and hence that differences in the source and concrete collar geometry have little importance in gauging the effects of small changes in the sodium cross-section set.

A comparison of the measured and calculated spectra in the Benjamin counter region is shown in Fig. 22. The two calculated spectra shown are the results of DOT-III calculations using each of the cross-section sets. Both integral and shape comparisons favor the preliminary set, with the final set rather seriously overpredicting the measurement. The preliminary set still overpredicts in the same general regions that it did behind 10 ft of sodium, i.e., in the vicinities of 1 MeV, 180 keV, and 90 keV.

Since the modified 3-in. Bonner ball counting rate behind 12.5 ft of sodium arises from almost equal contributions in the energy regions 10 to 100 keV and 100 keV - 1 MeV (see Appendix), there should be a strong correlation between its counting rate and the fluxes measured in the Benjamin counter region 70 keV to 1.5 MeV. Comparing the calculated to measured ratios of the modified 3-in. Bonner ball with those of the integral Benjamin counter results for each cross-section set shows that the Benjamin counter ratios are a little higher than those of the modified 3-in. Bonner ball, whereas they agreed very well behind 10 ft of sodium. This slight incompatibility in the two measurements behind 12.5 ft of sodium suggests that either the Benjamin counter measurements are up to $\sim 20\%$ too low or the modified 3-in. Bonner ball measurement is up to $\sim 20\%$ too high. This discrepancy is still not very serious however.

E. Behind 15 ft of Sodium

Calculations of the Bonner ball counting rates were performed for each cross-section set using DOT-III for a point on the centerline 24 in. behind

Fig. 22. Comparison of Measured Spectrum in the Energy Region 70 keV-1.5 MeV on the Centerline 24 in. Behind 12.5 ft of Sodium with Calculated Spectra Using Each of the Two Cross-Section Sets.

15 ft of sodium with the proper sodium density of 0.945 grams/cm³. The MORSE calculations, as before, assumed a density of 0.918 grams/cm³ and used only the preliminary set, but were more extensive than the DOT-III calculations in that the Bonner ball counting rates were calculated along an axial traverse. The MORSE results were corrected to the proper density by decreasing the calculated counting rates by the density correction factors behind 15 ft calculated by ANISM shown in Table XXVI.

The comparison of the calculated Bonner ball counting rates using DOT-III with the density corrected MORSE counting rates, both using the preliminary cross-section set, is shown in Table XXVI.

From Table XXVI, the agreement of the DOT-III and the MORSE results is seen to lie within the statistics of the Monte Carlo calculation.

A comparison of the measured and calculated counting rates 24 in. behind 15 ft of sodium is shown in Table XXVII.

The measured thermal flux was $(0.145-0.057) \times 0.80 = 7.04 \times 10^{-2}$ neutrons/cm²/min/watt (see Table XIX) while the calculated values using DOT-III are 4.51×10^{-2} and 4.29×10^{-2} neutrons/cm²/min/watt for the preliminary and final cross-section sets respectively, yielding calculated to measured ratios of 0.64 and 0.61 respectively. Since these ratios are essentially unchanged behind 10 ft, 12.5 ft, and 15 ft of sodium, it appears likely that the disagreement is due either to errors in the one-group treatment of the thermal neutrons in the calculations or to insufficient background subtraction in the measurements.

An inspection of Table XXVII shows that use of the preliminary set leads to calculated counting rates for the Cd- through 12-in. Bonner balls that agree more closely with experiment. However, for the modified 3-in. ball, the final set appears to be better. This latter comparison is the only one in the entire series of comparisons presented in this study in which the final cross-section set clearly leads to better agreement with experiment than the preliminary set, and hence it must be regarded with suspicion. The measurement was a very difficult one involving very low

Table XXXVI. Comparison of MORSE and DOT-III Calculated Bonner Ball
Counting Rates on the Centerline 24 in. Behind 15 ft
of Sodium in Counts/min/kilowatt

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod 3-in. ^a
DOT-III, $\rho = 0.945$	46.6	351	426	367	253	106	37.6	12.9	0.0855
MORSE, $\rho = 0.918$	66.2	495	596	520	364	152	54.4	19.1	0.131
Density Correction factor	0.749	0.742	0.732	0.729	0.727	0.726	0.725	0.725	0.651
Corrected MORSE, $\rho = 0.945$	49.5	367	437	379	264	111	39.4	13.8	0.0853
Corrected MORSE/DOT-III, $\rho = 0.945$	1.02	1.05	1.02	1.03	1.04	1.04	1.05	1.07	1.00
Statistical Uncertainty, MORSE	± 0.11	± 0.10	± 0.09	± 0.09	± 0.09	± 0.09	± 0.09	± 0.09	± 0.20

^aThe modified 3-in. Bonner ball counting rate was calculated at a point corresponding to the center of the ball 23 in. behind, to conform to the measurement location.

Table XXXVII. Comparison of Measured and Calculated Bonner Ball Counting Rates
on the Centerline 2 1/2 in. Behind 15 ft of Sodium in Counts/min/KW

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod. 3-in.*
Calculated, DOT-III (prel)	48.6	351	426	367	253	106	37.0	12.9	0.0855
Calculated, Corrected MORSE (prel)	49.5	367	437	379	264	111	39.4	13.8	0.0853
Calculated, DOT-III (final)	40.7	293	350	302	209	88.4	31.5	10.9	0.132
DOT-III (final/prel)	0.837	0.835	0.822	0.823	0.826	0.834	0.838	0.845	1.544
Measured	57.0	394	496	405	289	127	49.7	18.9	0.121
Calc./Meas. DOT-III (prel)	0.85	0.89	0.86	0.91	0.88	0.84	0.76	0.68	0.71
Calc./Meas. Corr. MORSE (prel)	0.87	0.93	0.88	0.94	0.91	0.88	0.79	0.73	0.71
Calc./Meas. DOT-III (final)	0.72	0.74	0.71	0.75	0.72	0.70	0.63	0.58	1.09

*Calculations and measurement were for a distance of 23 in. between the back of the sodium tank and the geometric center of the modified 3-in. Bonner ball.

counting rates, and for this reason it was repeated several times, each for a counting time varying between 2 and 3 hours. The measured value appearing in Tables XIX and XXXVII is an average of the two values 0.119 and 0.123 that lay within the counting statistics (± 0.003). The third value was higher (0.139) and lay outside the counting statistics and hence was discarded. Since background was of the order of 20% of the foreground, it may be part of the problem, as is the response function for the modified 3-in. ball, which is estimated to be accurate to within $\pm 10\%$. Considering the clear superiority of the preliminary set in all the comparisons behind 12.5 ft of sodium and for most of the Bonner balls behind 15 ft of sodium, it is concluded that the measurement behind 15 ft with the modified 3-in. Bonner ball is too high by approximately 30%, and hence the conclusion that the final set is superior in calculating this counting rate is erroneous.

The ratios of the counting rates calculated with DOT-III using the final and preliminary sets appearing in Table XXXVII compare closely with those calculated with ANISN behind 15 ft of sodium shown in Table XXV.

A comparison of the measured Bonner ball counting rates along an axial traverse with values obtained from the density corrected MORSE calculations is shown in Table XXXVIII.

From the comparisons in Table XXXVIII (air attenuation was neglected), the calculated axial profile shapes agree within the statistics of the calculation with all the measured profile shapes. The absolute agreement is to within 15% for the Cd- through 6-in. Bonner balls, but progressively worsens with the 8-in. through 12-in. Bonner balls. Since all the Bonner balls with the exception of the modified 3-in. ball are responding to neutrons only in the energy range 0.4 to 100 eV (see Appendix), it appears the response functions for the larger Bonner balls are low in this energy range, perhaps due to neglect of upscattering effects in their derivation. The response function shapes were calculated by ANISN in the adjoint mode using a single thermal group with no upscattering, calibrated with a ^{252}Cf source, and checked for consistency with an antimony-beryllium source. The

Table XXXVIII. Comparison of Measured Bonner Ball Counting Rates on the Centerline
with Calculated Values Using Density Corrected MORSE Results Behind
15 ft of Sodium, in Counts/min/kilowatt

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod. 3-in.*
<u>6 in. Behind</u>									
Calculated, MORSE	77.9	565	682	571	400	169	58.9	20.2	
Measured	92.0	585	773	626	453	199	77.1	30.4	
Calc./Meas.	0.85	0.97	0.88	0.91	0.88	0.85	0.76	0.66	
<u>12 in. Behind</u>									
Calculated, MORSE	67.5	501	596	514	360	152	53.3	18.3	
Measured	76.5	507	661	543	392	174	66.4	25.5	
Calc./Meas.	0.88	0.99	0.90	0.95	0.92	0.87	0.80	0.72	
<u>24 in. Behind</u>									
Calculated, MORSE	49.5	367	437	379	264	111	39.4	13.8	0.7853
Measured	57.0	394	496	405	289	127	49.7	18.9	0.121
Calc./Meas.	0.87	0.93	0.88	0.94	0.91	0.88	0.79	0.73	0.71
<u>48 in. Behind</u>									
Calculated, MORSE	27.4	205	243	211	148	61.2	21.8	7.47	
Measured	33.0	220	287	232	166	74.5	26.5	10.8	
Calc./Meas.	0.83	0.93	0.85	0.91	0.89	0.82	0.76	0.69	
<u>72 in. Behind</u>									
Calculated, MORSE	16.8	124	147	128	89.1	36.8	13.3	4.57	
Measured	20.2	135	176	143	103	46.6	17.6	7.00	
Calc./Meas.	0.83	0.92	0.84	0.90	0.87	0.79	0.76	0.65	

*23 in. behind.

absolute response functions have thus only been checked down to an energy of ~ 30 keV. Below this energy, upscattering effects may well change the response from the calculated values normalized to the ^{252}Cf source. The Cd ball has no polyethylene and hence no upscattering effect; the 3-in. and 4-in. Bonner ball response functions used have already been corrected for the upscattering effect by measurements on GRELA.²⁰ The latter amounts to a uniform 20% decrease in the response functions below 100 eV for the 3-in. ball and an assumed 10% decrease below 100 eV for the 4-in. ball. It would appear from Table XXXVIII that the upscattering corrections for the 8-in., 10-in., and 12-in. Bonner balls are in the opposite direction, and should be roughly 5%, 15%, and 30% increases in the corresponding response functions below 100 eV. This would make these Bonner ball counting rates consistent with the smaller sized Bonner ball counting rates behind 10 ft, 12.5 ft, and 15 ft of sodium. Such a correction will be incorporated into the response functions for the 8-in., 10-in., and 12-in. Bonner balls for future use.

CONCLUSIONS

With the questionable exception of the modified 3-in. Bonner ball counting rate behind 15 ft of sodium, the preliminary set is superior to the final ENDF/B-III set in comparisons of the calculations with measurements made behind up through 15 ft of sodium (~ 50 mfp). Both sets produce agreement with the measurements well within a factor of two, however. The preliminary set leads to calculated total neutron leakages above thermal energies that lie within $\sim 15\%$ of the measured values and neutron spectra penetrating up to 12.5 ft of sodium that lie within 20% of the measurements. The final set leads to calculated total neutron leakages above thermal energies that lie within $\sim 30\%$ of the measured values and neutron spectra penetrating up to 12.5 ft of sodium that lie within 60% of the measurements. Since the final set overpredicts the neutron leakages above ~ 70 keV behind 5, 10, and 12.5 ft of sodium and underpredicts neutron leakages below ~ 100 eV behind 10, 12.5, and 15 ft of sodium, it appears probable that errors exist in the fast neutron (i.e., $E > 1$ MeV) cross sections. Re-evaluating only these cross sections may well lead to calculated leakages

in adequate agreement with the measurements for all energy regions

Since uncertainties in the calculations include $\pm 10\%$ in the absolute source spectrum, $\pm 5\%$ (excluding the low energy region in the 8-in., 10-in., and 12-in. Bonner balls) in the absolute response functions of the Bonner balls, and $\pm 1\%$ in the sodium density, and the measurements are reproducible to $\pm 5\%$, agreement between measured and calculated values even if there were no cross section errors cannot be expected to be much better than was obtained with the preliminary set, whereas the disagreement with measurement of the calculated spectra using the final set usually exceeds this minimum comparison error. Thus, with rare exceptions, use of the preliminary set leads to calculated quantities that agree with the measurements within the uncertainties of this experiment.

APPENDIX

Presented herein are many of the calculated group fluxes obtained from both the MORSE and DOT-III calculations. Following this presentation, tables of the percentage of the calculated Bonner ball counting rates behind the various thicknesses of sodium due to neutrons in various broad energy groups are given. The prefix A in these table numbers refers to Appendix.

Table AI. Total Calculated Group Fluxes on the Centerline 24 in.
Behind 2.5 ft of Sodium ($\rho = 0.918$, preliminary set) in
neutrons/cm²/min/watt, Using MORSE

Group*	Flux	Group*	Flux	Group*	Flux	Group*	Flux	Group*	Flux	Group*	Flux
1	0.159	19	31.9	37	25.6	55	52.9	73	37.3	91	18.7
2	0.830	20	23.6	38	35.3	56	43.6	74	37.9	92	18.0
3	1.04	21	43.3	39	29.8	57	37.2	75	36.0	93	16.3
4	3.27	22	33.6	40	37.4	58	31.7	76	33.8	94	15.4
5	5.02	23	35.2	41	29.2	59	25.6	77	30.7	95	15.2
6	9.56	24	41.6	42	23.4	60	18.7	78	28.3	96	14.5
7	12.7	25	28.5	43	17.0	61	10.8	79	27.8	97	14.0
8	21.4	26	26.9	44	31.7	62	6.78	80	25.1	98	13.3
9	26.7	27	21.9	45	29.6	63	1.59	81	24.6	99	12.9
10	32.9	28	23.4	46	21.7	64	0.258	82	23.6		
11	31.5	29	19.8	47	24.2	65	1.98	83	22.5		
12	32.2	30	16.0	48	33.1	66	11.7	84	21.8		
13	33.8	31	12.5	49	27.1	67	24.7	85	20.4		
14	35.8	32	15.3	50	45.9	68	36.0	86	20.1		
15	30.2	33	17.6	51	69.0	69	29.2	87	19.7		
16	49.2	34	36.7	52	18.2	70	47.1	88	18.7		
17	36.9	35	28.4	53	46.4	71	46.8	89	19.5		
18	33.5	36	27.1	54	25.8	72	41.8	90	19.2		

*See Table III for the GAM-II group structure.

Table AII. Total Calculated Group Fluxes on the Centerline 24 in.
Behind 5 ft of Sodium ($\rho = 0.918$, preliminary set) in
neutrons/cm²/min/watt, Using MORSE

Group	Flux	Group	Flux	Group	Flux	Group	Flux	Group	Flux
1	0.003	24	2.15	47	3.80	70	15.7	93	5.93
2	0.012	25	1.98	48	5.36	71	16.9	94	5.36
3	0.032	26	1.84	49	4.11	72	18.3	95	5.00
4	0.10	27	1.53	50	7.56	73	15.8	96	4.71
5	0.19	28	1.72	51	12.6	74	16.4	97	4.13
6	0.43	29	1.46	52	3.58	75	16.0	98	3.55
7	0.56	30	1.16	53	10.1	76	15.5	99	3.16
8	0.96	31	0.81	54	5.47	77	15.3		
9	1.02	32	1.16	55	12.7	78	14.2		
10	1.48	33	1.38	56	11.0	79	14.5		
11	1.46	34	3.20	57	8.88	80	12.6		
12	1.47	35	2.47	58	8.29	81	12.2		
13	0.99	36	2.49	59	6.85	82	11.7		
14	0.99	37	2.38	60	5.66	83	11.0		
15	0.96	38	3.45	61	2.97	84	9.68		
16	2.50	39	2.89	62	2.14	85	9.35		
17	1.55	40	4.22	63	0.463	86	8.73		
18	1.54	41	5.96	64	0.0488	87	8.04		
19	1.29	42	2.63	65	0.556	88	7.80		
20	1.07	43	2.09	66	3.59	89	7.42		
21	2.41	44	3.85	67	7.12	90	7.10		
22	1.68	45	3.83	68	10.8	91	6.97		
23	1.75	46	2.92	69	13.6	92	6.68		

Table AIII. Total Calculated Group Fluxes on the Centerline 24 in.
Behind 10 ft of Sodium ($\rho = 0.918$, preliminary set) in
neutrons/cm²/min/watt, Using MORSE

Group	Flux	Group	Flux	Group	Flux	Group	Flux	Group	Flux
1	5.0(-5) ^a	24	5.51(-3)	47	2.74(-2)	70	2.98(-1)	93	7.35(-1)
2	3.3(-5)	25	4.49(-3)	48	3.77(-2)	71	3.46(-1)	94	6.94(-1)
3	9.0(-5)	26	4.39(-3)	49	2.30(-2)	72	3.54(-1)	95	5.61(-1)
4	1.48(-4)	27	9.07(-3)	50	5.11(-2)	73	3.84(-1)	96	4.97(-1)
5	7.33(-4)	28	6.08(-3)	51	6.76(-2)	74	4.90(-1)	97	4.59(-1)
6	5.16(-4)	29	4.70(-3)	52	1.13(-1)	75	5.21(-1)	98	4.38(-1)
7	6.36(-4)	30	3.14(-3)	53	7.34(-2)	76	6.78(-1)	99	3.61(-1)
8	1.18(-3)	31	2.45(-3)	54	3.02(-2)	77	7.15(-1)		
9	9.58(-4)	32	3.96(-3)	55	6.64(-2)	78	6.86(-1)		
10	9.80(-4)	33	4.66(-3)	56	8.53(-2)	79	7.20(-1)		
11	1.13(-3)	34	1.16(-2)	57	8.63(-2)	80	7.84(-1)		
12	6.96(-4)	35	8.94(-3)	58	8.22(-2)	81	7.79(-1)		
13	1.40(-3)	36	1.03(-2)	59	7.59(-2)	82	8.79(-1)		
14	6.98(-4)	37	1.23(-2)	60	6.17(-2)	83	8.41(-1)		
15	6.83(-4)	38	1.33(-2)	61	2.57(-2)	84	8.38(-1)		
16	2.62(-3)	39	1.03(-2)	62	1.56(-2)	85	8.59(-1)		
17	1.77(-3)	40	2.14(-2)	63	3.57(-3)	86	7.83(-1)		
18	2.05(-3)	41	1.53(-2)	64	3.08(-4)	87	8.07(-1)		
19	2.00(-3)	42	1.28(-2)	65	4.45(-3)	88	7.52(-1)		
20	1.69(-3)	43	1.32(-2)	66	2.98(-2)	89	7.94(-1)		
21	3.46(-3)	44	2.09(-2)	67	7.64(-2)	90	7.48(-1)		
22	2.88(-3)	45	1.96(-2)	68	1.51(-1)	91	7.44(-1)		
23	3.96(-3)	46	1.85(-2)	69	2.00(-1)	92	7.66(-1)		

*F ad as 5.0×10^{-5} .

Table AIV. Total Calculated Group Fluxes on the Centerline Behind
10 ft of Sodium ($\rho = 0.918$, preliminary set) in
neutrons/cm²/min/watt, Using DOT-III

Group	Flux	Group	Flux	Group	Flux	Group	Flux	Group	Flux
1	3.57(-5) ^a	24	8.48(-3)	47	1.94(-2)	70	2.62(-1)	93	7.21(-1)
2	7.85(-5)	25	6.71(-3)	48	3.14(-2)	71	3.25(-1)	94	6.84(-1)
3	1.42(-4)	26	6.63(-3)	49	2.53(-2)	72	3.88(-1)	95	6.38(-1)
4	3.34(-4)	27	5.71(-3)	50	4.94(-2)	73	4.49(-1)	96	5.91(-1)
5	5.76(-4)	28	6.16(-3)	51	8.36(-2)	74	5.07(-1)	97	5.46(-1)
6	1.07(-3)	29	5.48(-3)	52	2.16(-2)	75	5.63(-1)	98	4.99(-1)
7	1.21(-3)	30	4.44(-3)	53	6.62(-2)	76	6.15(-1)	99	4.52(-1)
8	2.12(-3)	31	3.12(-3)	54	3.88(-2)	77	6.64(-1)	100	1.20(0)
9	1.62(-3)	32	4.19(-3)	55	1.01(-1)	78	7.07(-1)		
10	2.00(-3)	33	5.21(-3)	56	9.29(-2)	79	7.46(-1)		
11	1.59(-3)	34	1.26(-2)	57	8.54(-2)	80	7.80(-1)		
12	1.61(-3)	35	1.02(-2)	58	7.93(-2)	81	8.08(-1)		
13	1.54(-3)	36	9.48(-3)	59	7.01(-2)	82	8.30(-1)		
14	1.76(-3)	37	9.60(-3)	60	5.61(-2)	83	8.47(-1)		
15	1.94(-3)	38	1.47(-2)	61	2.95(-2)	84	8.59(-1)		
16	4.23(-3)	39	1.29(-2)	62	2.21(-2)	85	8.64(-1)		
17	3.23(-3)	40	2.06(-2)	63	4.34(-3)	86	8.64(-1)		
18	3.33(-3)	41	1.58(-2)	64	2.13(-4)	87	8.59(-1)		
19	3.69(-3)	42	1.22(-2)	65	4.82(-3)	88	8.48(-1)		
20	3.08(-3)	43	9.28(-3)	66	3.37(-2)	89	8.32(-1)		
21	5.61(-3)	44	2.00(-2)	67	8.33(-2)	90	8.11(-1)		
22	5.11(-3)	45	2.13(-2)	68	1.41(-1)	91	7.86(-1)		
23	6.28(-3)	46	1.58(-2)	69	2.01(-1)	92	7.55(-1)		

*Read as 3.57×10^{-5} .

Table AV. Total Calculated Group Fluxes on the Centerline 24 in.
Behind 10 ft of Sodium ($\rho = 0.945$, preliminary set) in
neutrons/cm²/min/watt, Using DOT-III

Group	Flux	Group	Flux	Group	Flux	Group	Flux	Group	Flux
1	2.71(-5) ^a	24	6.34(-3)	47	1.47(-2)	70	2.08(-1)	93	6.52(-1)
2	5.94(-5)	25	5.01(-3)	48	2.38(-2)	71	2.60(-1)	94	6.20(-1)
3	1.06(-4)	26	4.95(-3)	49	1.92(-2)	72	3.13(-1)	95	5.80(-1)
4	2.49(-4)	27	4.26(-3)	51	6.38(-2)	74	4.15(-1)	98	4.57(-1)
5	4.30(-4)	28	4.60(-3)	51	6.38(-2)	74	4.15(-1)	97	4.99(-1)
6	7.96(-4)	29	4.09(-3)	52	1.65(-2)	75	4.64(-1)	98	4.57(-1)
7	9.00(-4)	30	3.31(-3)	53	5.07(-2)	76	5.11(-1)	99	4.15(-1)
8	1.57(-3)	31	2.33(-3)	54	2.98(-2)	77	5.55(-1)	100	1.09(0)
9	1.19(-3)	32	3.14(-3)	55	7.81(-2)	78	5.96(-1)		
10	1.47(-3)	33	3.89(-3)	56	7.16(-2)	79	6.33(-1)		
11	1.16(-3)	34	9.45(-3)	57	6.62(-2)	80	6.65(-1)		
12	1.18(-3)	35	7.61(-3)	58	6.16(-2)	81	6.94(-1)		
13	1.13(-3)	36	7.11(-3)	59	5.46(-2)	82	7.17(-1)		
14	1.29(-3)	37	7.19(-3)	60	4.37(-2)	83	7.35(-1)		
15	1.43(-3)	38	1.10(-2)	61	2.29(-2)	84	7.49(-1)		
16	3.13(-3)	39	9.69(-3)	62	1.71(-2)	85	7.58(-1)		
17	2.40(-3)	40	1.55(-2)	63	3.36(-3)	86	7.61(-1)		
18	2.48(-3)	41	1.19(-2)	64	1.64(-4)	87	7.60(-1)		
19	2.74(-3)	42	9.18(-3)	65	3.70(-3)	88	7.53(-1)		
20	2.29(-3)	43	6.99(-3)	66	2.62(-2)	89	7.42(-1)		
21	4.10(-3)	44	1.51(-2)	67	6.51(-2)	90	7.26(-1)		
22	3.81(-3)	45	1.61(-2)	68	1.11(-1)	91	7.06(-1)		
23	4.68(-3)	46	1.19(-2)	69	1.59(-1)	92	6.81(-1)		

^aRead as 2.71×10^{-5} .

Table AVI. Total Calculated Group Fluxes on the Centerline 24 in.
Behind 10 of Sodium ($\rho = 0.945$, final set) in
neutrons/cm²/min/watt, Using DOT-III

Group	Flux	Group	Flux	Group	Flux	Group	Flux	Group	Flux
1	4.11(-5) ^a	24	8.05(-3)	47	1.68(-2)	70	2.22(-1)	93	6.10(-1)
2	8.26(-5)	25	6.60(-3)	48	2.75(-2)	71	2.56(-1)	94	5.85(-1)
3	1.48(-4)	26	6.10(-3)	49	2.29(-2)	72	2.90(-1)	95	5.57(-1)
4	3.89(-4)	27	5.31(-3)	50	4.66(-2)	73	3.25(-1)	96	5.24(-1)
5	5.85(-4)	28	4.72(-3)	51	7.97(-2)	74	3.60(-1)	97	4.87(-1)
6	1.07(-3)	29	4.86(-3)	52	2.17(-2)	75	3.94(-1)	98	4.47(-1)
7	1.17(-3)	30	4.11(-3)	53	6.50(-2)	76	4.28(-1)	99	4.07(-1)
8	1.98(-3)	31	2.87(-3)	54	4.09(-2)	77	4.61(-1)	100	1.12(0)
9	1.57(-3)	32	3.97(-3)	55	1.11(-1)	78	4.92(-1)		
10	1.92(-3)	33	4.68(-3)	56	1.03(-1)	79	5.21(-1)		
11	2.05(-3)	34	1.18(-2)	57	9.54(-2)	80	5.49(-1)		
12	2.53(-3)	35	1.19(-2)	58	8.84(-2)	81	5.75(-1)		
13	2.14(-3)	36	9.19(-3)	59	7.75(-2)	82	5.99(-1)		
14	1.94(-3)	37	9.30(-3)	60	6.10(-2)	83	6.20(-1)		
15	1.97(-3)	38	1.41(-2)	61	3.13(-2)	84	6.38(-1)		
16	3.70(-3)	39	1.28(-2)	62	2.30(-2)	85	6.52(-1)		
17	2.96(-3)	40	1.67(-2)	63	4.49(-3)	86	6.64(-1)		
18	3.23(-3)	41	1.41(-2)	64	2.14(-4)	87	6.70(-1)		
19	3.49(-3)	42	1.10(-2)	65	4.76(-3)	88	6.71(-1)		
20	3.00(-3)	43	8.35(-3)	66	3.66(-2)	89	6.67(-1)		
21	6.07(-3)	44	1.79(-2)	67	9.01(-2)	90	6.60(-1)		
22	5.50(-3)	45	1.90(-2)	68	1.39(-1)	91	6.48(-1)		
23	6.62(-3)	46	1.40(-2)	69	1.84(-1)	92	6.31(-1)		

^aRead as 4.11×10^{-5} .

Table AVII. Total Calculated Group Fluxes on the Centerline 24 in.
Behind 12.5 ft of Sodium ($\rho = 0.918$, preliminary set) in
neutrons/cm²/min/watt, Using MORSE

Group	Flux	Group	Flux	Group	Flux	Group	Flux	Group	Flux
1	2.0(-6) ^a	24	3.59(-4)	47	5.38(-4)	70	2.26(-2)	93	1.62(-1)
2	2.2(-6)	25	1.48(-4)	48	6.97(-4)	71	3.64(-2)	94	1.61(-1)
3	2.3(-6)	26	1.66(-4)	49	7.26(-4)	72	3.34(-2)	95	1.57(-1)
4	1.0(-5)	27	4.16(-5)	50	1.61(-3)	73	4.57(-2)	96	1.51(-1)
5	1.2(-5)	28	6.10(-5)	51	2.56(-3)	74	5.55(-2)	97	1.39(-1)
6	1.0(-5)	29	7.40(-5)	52	5.10(-4)	75	6.16(-2)	98	1.33(-1)
7	3.5(-5)	30	1.94(-4)	53	2.73(-3)	76	5.75(-2)	99	1.19(-1)
8	1.9(-5)	31	5.33(-5)	54	1.31(-3)	77	5.75(-2)		
9	3.1(-5)	32	1.19(-4)	55	1.44(-2)	78	7.67(-2)		
10	5.7(-5)	33	1.15(-4)	56	7.62(-3)	79	9.64(-2)		
11	3.0(-5)	34	7.69(-4)	57	4.05(-3)	80	1.04(-1)		
12	3.0(-5)	35	5.19(-4)	58	5.72(-3)	81	1.10(-1)		
13	1.6(-5)	36	2.33(-4)	59	3.87(-3)	82	1.29(-1)		
14	3.4(-5)	37	3.39(-4)	60	2.54(-3)	83	1.23(-1)		
15	4.9(-5)	38	4.62(-4)	61	6.53(-4)	84	1.50(-1)		
16	9.1(-5)	39	4.48(-4)	62	5.59(-4)	85	1.45(-1)		
17	5.5(-5)	40	5.32(-4)	63	9.89(-5)	86	1.48(-1)		
18	7.7(-5)	41	2.36(-4)	64	-	87	1.37(-1)		
19	6.8(-5)	42	1.95(-4)	65	1.74(-4)	88	1.79(-1)		
20	1.9(-5)	43	2.49(-4)	66	9.85(-4)	89	1.75(-1)		
21	3.23(-4)	44	6.17(-4)	67	2.63(-3)	90	1.81(-1)		
22	1.84(-4)	45	6.14(-4)	68	5.43(-3)	91	1.60(-1)		
23	5.29(-4)	46	4.58(-4)	69	1.43(-2)	92	1.69(-1)		

^aRead as 2.0×10^{-6} .

Table AVIII. Total Calculated Group Fluxes on the Centerline 24 in.
Behind 12.5 ft of Sodium ($\rho = 0.945$, preliminary set) in
neutrons/cm²/min./watt, Using DOT-III

Group	Flux	Group	Flux	Group	Flux	Group	Flux	Group	Flux
1	1.46(-6) ^a	24	2.92(-4)	47	7.33(-4)	70	1.39(-2)	93	1.31(-1)
2	3.14(-6)	25	2.30(-4)	48	1.20(-3)	71	1.84(-2)	94	1.28(-1)
3	5.19(-6)	26	2.28(-4)	49	9.72(-4)	72	2.36(-2)	95	1.23(-1)
4	1.15(-5)	27	1.96(-4)	50	1.93(-3)	73	2.94(-2)	96	1.16(-1)
5	2.01(-5)	28	2.13(-4)	51	3.33(-3)	74	3.58(-2)	97	1.10(-1)
6	3.77(-5)	29	1.89(-4)	52	8.61(-4)	75	4.26(-2)	98	1.03(-1)
7	4.06(-5)	30	1.53(-4)	53	2.68(-3)	76	5.00(-2)	99	9.52(-2)
8	7.19(-5)	31	1.07(-4)	54	1.60(-3)	77	5.77(-2)	100	2.52(-1)
9	5.03(-5)	32	1.45(-4)	55	4.26(-3)	78	6.56(-2)		
10	6.10(-5)	33	1.80(-4)	56	3.97(-3)	79	7.36(-2)		
11	4.83(-5)	34	4.43(-4)	57	3.72(-3)	80	8.15(-2)		
12	4.86(-5)	35	3.57(-4)	58	3.51(-3)	81	8.93(-2)		
13	4.70(-5)	36	3.34(-4)	59	3.13(-3)	82	9.69(-2)		
14	5.40(-5)	37	3.39(-4)	60	2.52(-3)	83	1.04(-1)		
15	6.12(-5)	38	5.23(-4)	61	1.33(-3)	84	1.11(-1)		
16	1.36(-4)	39	4.62(-4)	62	1.00(-3)	85	1.17(-1)		
17	1.06(-4)	40	7.50(-4)	63	1.96(-4)	86	1.22(-1)		
18	1.10(-4)	41	5.75(-4)	64	1.02(-5)	87	1.26(-1)		
19	1.22(-4)	42	4.44(-4)	65	2.16(-4)	88	1.30(-1)		
20	1.02(-4)	43	3.38(-4)	66	1.53(-3)	89	1.32(-1)		
21	1.89(-4)	44	7.38(-4)	67	3.85(-3)	90	1.34(-1)		
22	1.73(-4)	45	7.92(-4)	68	6.75(-3)	91	1.34(-1)		
23	2.14(-4)	46	5.89(-4)	69	1.01(-2)	92	1.33(-1)		

^aRead as 1.46×10^{-6} .

Table AIX. Total Calculated Group Fluxes on the Centerline 24 in.
Behind 12.5 ft of Sodium ($\rho = 0.945$, final set) in
neutrons/cm²/min/watt, Using DOT-III

Group	Flux	Group	Flux	Group	Flux	Group	Flux	Group	Flux
1	2.45(-6) ^a	24	4.07(-4)	47	9.08(-4)	70	1.62(-2)	93	1.16(-1)
2	4.71(-6)	25	3.34(-4)	48	1.50(-3)	71	1.96(-2)	94	1.14(-1)
3	7.80(-6)	26	3.08(-4)	49	1.25(-3)	72	2.33(-2)	95	1.11(-1)
4	1.75(-5)	27	2.69(-4)	50	2.59(-3)	73	2.74(-2)	96	1.07(-1)
5	2.64(-5)	28	2.39(-4)	51	4.50(-3)	74	3.18(-2)	97	1.02(-1)
6	5.51(-5)	29	2.46(-4)	52	1.23(-3)	75	3.66(-2)	98	9.59(-2)
7	5.74(-5)	30	2.08(-4)	53	3.73(-3)	76	4.18(-2)	99	8.90(-2)
8	9.77(-5)	31	1.46(-4)	54	2.38(-3)	77	4.73(-2)	100	2.50(-1)
9	7.29(-5)	32	2.01(-4)	55	6.59(-3)	78	5.30(-2)		
10	8.80(-5)	33	2.37(-4)	56	6.24(-3)	79	5.88(-2)		
11	9.45(-5)	34	6.03(-4)	57	5.87(-3)	80	6.49(-2)		
12	1.16(-4)	35	6.14(-4)	58	5.53(-3)	81	7.10(-2)		
13	1.01(-4)	36	4.73(-4)	59	4.92(-3)	82	7.72(-2)		
14	9.22(-5)	37	4.80(-4)	60	3.90(-3)	83	8.33(-2)		
15	9.55(-5)	38	7.33(-4)	61	2.01(-3)	84	8.92(-2)		
16	1.80(-4)	39	6.68(-4)	62	1.48(-3)	85	9.50(-2)		
17	1.44(-4)	40	8.77(-4)	63	2.88(-4)	86	1.00(-1)		
18	1.59(-4)	41	7.42(-4)	64	1.47(-5)	87	1.05(-1)		
19	1.72(-4)	42	5.80(-4)	65	3.04(-4)	88	1.09(-1)		
20	1.48(-4)	43	4.41(-4)	66	2.35(-3)	89	1.12(-1)		
21	3.02(-4)	44	9.54(-4)	67	5.90(-3)	90	1.15(-1)		
22	2.74(-4)	45	1.02(-3)	68	9.40(-3)	91	1.16(-1)		
23	3.32(-4)	46	7.49(-4)	69	1.29(-2)	92	1.17(-1)		

^aRead as 2.45×10^{-6} .

Table AXI. Calculated* Group Fluxes on the Centerline 24 in. Behind
15 ft of Sodium ($\rho = 0.945$, preliminary set) in
neutrons/cm²/min/watt, Using DOT-III

Group	Flux	Group	Flux	Group	Flux	Group	Flux	Group	Flux
1	8.37(-8) ^a	24	1.39(-5)	47	3.59(-5)	70	8.03(-4)	93	1.99(-2)
2	1.74(-7)	25	1.10(-5)	48	5.91(-5)	71	1.11(-3)	94	2.00(-2)
3	2.60(-7)	26	1.09(-5)	49	4.81(-5)	72	1.48(-3)	95	1.96(-2)
4	5.26(-7)	27	9.39(-6)	50	9.58(-5)	73	1.94(-3)	96	1.91(-2)
5	9.22(-7)	28	1.02(-5)	51	1.67(-4)	74	2.48(-3)	97	1.85(-2)
6	1.70(-6)	29	9.06(-6)	52	4.32(-5)	75	3.12(-3)	98	1.77(-2)
7	1.82(-6)	30	7.33(-6)	53	1.35(-4)	76	3.85(-3)	99	1.67(-2)
8	3.28(-6)	31	5.14(-6)	54	8.11(-5)	77	4.67(-3)	100	4.51(-2)
9	2.29(-6)	32	6.92(-6)	55	2.19(-4)	78	5.59(-3)		
10	2.70(-6)	33	8.61(-6)	56	2.05(-4)	79	6.59(-3)		
11	2.19(-6)	34	2.13(-5)	57	1.93(-4)	80	7.67(-3)		
12	2.20(-6)	35	1.72(-5)	58	1.83(-4)	81	8.81(-3)		
13	2.15(-6)	36	1.61(-5)	59	1.65(-4)	82	1.00(-2)		
14	2.48(-6)	37	1.63(-5)	60	1.33(-4)	83	1.12(-2)		
15	2.83(-6)	38	2.53(-5)	61	7.01(-5)	84	1.24(-2)		
16	6.26(-6)	39	2.24(-5)	62	5.28(-5)	85	1.37(-2)		
17	4.94(-6)	40	3.65(-5)	63	1.03(-5)	86	1.48(-2)		
18	5.16(-6)	41	2.80(-5)	64	5.48(-5)	87	1.59(-2)		
19	5.78(-6)	42	2.16(-5)	65	1.13(-5)	88	1.70(-2)		
20	4.84(-6)	43	1.64(-5)	66	8.11(-5)	89	1.79(-2)		
21	8.96(-6)	44	3.60(-5)	67	2.06(-4)	90	1.87(-2)		
22	8.20(-6)	45	3.88(-5)	68	3.68(-4)	91	1.93(-2)		
23	1.02(-5)	46	2.88(-5)	69	5.62(-4)	92	1.97(-2)		

*Uncollided contributions are neglected as they are completely negligible in all Bonner ball counting rates.

Table AXII. Calculated* Group Fluxes on the Centerline 24 in. Behind
15 ft of Sodium ($\rho = 0.945$, final set) in
neutrons/cm²/min/watt, Using DOT-III

Group	Flux	Group	Flux	Group	Flux	Group	Flux	Group	Flux
1	1.55(-7)	24	2.14(-5)	47	4.86(-5)	70	1.02(-3)	93	1.66(-2)
2	2.80(-7)	25	1.75(-5)	48	8.10(-5)	71	1.27(-3)	94	1.68(-2)
3	4.20(-7)	26	1.62(-5)	49	6.75(-5)	72	1.56(-3)	95	1.68(-2)
4	9.99(-7)	27	1.41(-5)	50	1.40(-4)	73	1.89(-3)	96	1.67(-2)
5	1.50(-6)	28	1.26(-5)	51	2.46(-4)	74	2.28(-3)	97	1.62(-2)
6	2.77(-6)	29	1.29(-5)	52	6.71(-5)	75	2.73(-3)	98	1.56(-2)
7	2.92(-6)	30	1.09(-5)	53	2.05(-4)	76	3.24(-3)	99	1.48(-2)
8	4.93(-6)	31	7.66(-6)	54	1.31(-4)	77	3.82(-3)	100	4.29(-2)
9	3.65(-6)	32	1.06(-5)	55	3.69(-4)	78	4.45(-3)		
10	4.34(-6)	33	1.25(-5)	56	3.52(-4)	79	5.14(-3)		
11	4.71(-6)	34	3.18(-5)	57	3.35(-4)	80	5.90(-3)		
12	5.80(-6)	35	3.24(-5)	58	3.18(-4)	81	6.72(-3)		
13	5.17(-6)	36	2.49(-5)	59	2.84(-4)	82	7.60(-3)		
14	4.75(-6)	37	2.53(-5)	60	2.26(-4)	83	8.52(-3)		
15	4.97(-6)	38	3.88(-5)	61	1.15(-4)	84	9.49(-3)		
16	9.21(-6)	39	3.53(-5)	62	8.49(-5)	85	1.05(-2)		
17	7.50(-6)	40	4.65(-5)	63	1.63(-5)	86	1.15(-2)		
18	8.27(-6)	41	3.05(-5)	64	7.81(-7)	87	1.25(-2)		
19	8.96(-6)	42	3.08(-5)	65	1.73(-5)	88	1.34(-2)		
20	7.72(-6)	43	2.34(-5)	66	1.36(-4)	89	1.42(-2)		
21	1.58(-5)	44	5.08(-5)	67	3.45(-4)	90	1.50(-2)		
22	1.43(-5)	45	5.44(-5)	68	5.59(-4)	91	1.56(-2)		
23	1.74(-5)	46	4.00(-5)	69	7.87(-4)	92	1.62(-2)		

*Uncollided contributions are neglected as they are completely negligible in all Bonner ball counting rates.

Table AX. Calculated* Group Fluxes on the Centerline 24 in.
Behind 15 ft of Sodium ($\rho = 0.918$, preliminary set) in
neutrons/cm²/min/watt, Using MORSE

Group	Flux	Group	Flux	Group	Flux
1-5	2.0(-6)	69	2.26(-3)	92	2.43(-2)
6-10	1.8(-6)	70	1.93(-3)	93	2.46(-2)
11-15	2.7(-5)	71	1.31(-3)	94	2.37(-2)
16-20	3.3(-5)	72	5.25(-3)	95	2.65(-2)
21-25	6.5(-5)	73	3.92(-3)	96	3.20(-2)
26-30	3.9(-5)	74	3.95(-3)	97	2.56(-2)
31-35	5.3(-5)	75	5.52(-3)	98	2.19(-2)
36-40	1.45(-4)	76	5.44(-3)	99	2.05(-2)
41-42	1.4(-4)	77	7.42(-3)		
43-44	5.4(-5)	78	6.58(-3)		
45-46	1.2(-4)	79	8.86(-3)		
47-48	1.65(-4)	80	1.10(-2)		
49-50	3.15(-4)	81	1.50(-2)		
51-52	4.05(-4)	82	1.81(-2)		
53-54	2.85(-4)	83	2.72(-2)		
55-56	6.3(-4)	84	2.74(-2)		
57-58	5.3(-4)	85	2.40(-2)		
59-60	2.85(-4)	86	1.81(-2)		
61-62	7.8(-5)	87	1.84(-2)		
63-64	-	88	2.04(-2)		
65-66	-	89	2.38(-2)		
67	3.9(-4)	90	2.45(-2)		
68	7.0(-4)	91	2.27(-2)		

*Uncollided contributions are neglected as they are completely negligible in all Bonner ball counting rates.

Table AXIII. Percentage of Calculated Bonner Ball Counting Rates
Due to Various Energy Groups in the Source Spectrum
at a Point on the Centerline 24 in. from
the Edge of the Collimator

Bonner Ball	Cd	3-in.	5-in.	6-in.	8-in.	12-in.	Mod 3-in.	Relative Flux
1-15 MeV	1	5	34	44	62	88	55	51
0.11-1 MeV	0	8	22	23	20	9	32	17
0.0117-0.11 MeV	1	10	12	11	6	1	12	8
0.961-11.7 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

Table AXIV. Percentage of Calculated Bonner Ball Counting Rates
Due to Various Energy Groups Leaking 2.5 ft of Sodium at
a Point on the Centerline 24 in. Behind*

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Relative Flux
1-15 MeV	0	2	8	14	25	41	57	74	27
0.11-1 MeV	0	8	20	25	28	30	25	17	22
0.0117-0.11 MeV	1	12	17	20	18	13	9	4	15
0.961-11.7 keV	2	7	8	8	5	3	2	1	6
101-961 eV	10	27	22	16	11	7	4	2	13
10.7-101 eV	19	18	14	9	7	4	2	1	9
1.13-10.7 eV	44	21	9	6	5	2	1	1	6
0.414-1.13 eV	24	5	2	2	1	0	0	0	2

*Group fluxes are presented in Table AI.

Table AXV. Percentage of Calculated Bonner Ball Counting Rates Due
to Various Energy Groups Leaking 5 ft of Sodium at
a Point on the Centerline 24 in. Behind*

Bonner Ball	Cd	3-in.	5-in.	6-in.	8-in.	12-in.	Mod 3 in.	Relative Flux
1-15 MeV	0	0	4	6	13	42	13	6
0.11-1 MeV	0	3	12	16	23	20	47	12
0.0117-0.11 MeV	0	7	16	18	17	11	38	15
0.961-11.7 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

*Group fluxes are presented in Table AII.

Table AXVI. Percentage of Calculated Bonner Ball Counting Rates Due
to Various Energy Groups Leaking 10 ft of Sodium at
a Point on the Centerline 24 in. Behind*

Bonner Ball	Cd	3-in.	5-in.	6-in.	8-in.	12-in.	Mod 3-in.	Relative Flux
1-15 MeV	0	0	0	0	1	5	5	0.4
0.11-1 MeV	0	0	2	3	4	8	38	1
0.0117-0.11 MeV	0	0	3	4	6	6	53	3
0.961-11.7 keV	0	1	2	3	3	3	4	2
101-961 eV	4	16	22	23	24	22	0	18
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	10

*Group fluxes are presented in Table AIV.

Table AXVII. Percentage of Calculated Bonner Ball Counting Rates Due
to Various Energy Groups Leaking 12.5 ft of Sodium at
a Point on the Centerline 24 in. Behind*

Bonner Ball	Cd	3-in.	5-in.	6-in.	8-in.	12-in.	Mod 3-in.	Relative Flux
1-15 MeV	0	0	0	0	0	1	6	0.10
0.11-1 MeV	0	0	0	0	1	2	39	0.38
0.0117-0.11 MeV	0	0	0	1	2	2	50	0.92
0.961-11.7 keV	0	0	1	1	1	1	5	0.73
101-961 eV	2	8	13	14	14	14	0	10
10.7-101 eV	14	28	38	37	36	36	0	31
1.13-10.7 eV	54	50	39	39	38	37	0	42
0.414-1.13 eV	30	14	9	8	8	7	0	15

*Group fluxes are presented in Table AVIII.

Table AXVIII. Percentage of Calculated Bonner Ball Counting Rates Due
to Various Energy Groups Leaking 15 ft of Sodium at
a Point on the Centerline 24 in. Behind*

Bonner Ball	Cd	3-in.	5-in.	6-in.	8-in.	12-in.	Mod 3-in.	Relative Flux
1-15 MeV	0	0	0	0	0	1	4	0.04
0.11-1 MeV	0	0	0	0	0	1	41	0.15
0.0117-0.11 MeV	0	0	0	0	0	1	52	0.37
0.961-11.7 keV	0	0	0	0	1	1	3	0.31
101-961 eV	1	4	8	10	10	10	0	6
10.7-101 eV	10	21	28	29	32	32	0	26
1.13-10.7 eV	54	58	51	49	45	43	0	47
0.414-1.13 eV	35	17	13	12	12	11	0	20

*Group fluxes are presented in Table AXI.

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