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SDT 12. THE ORNL BENCHMARK EXPERIMENT FOR NEUTRON TRANSPORT THROUGH SODIUM

R. E. Maerker

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Neutron Physics Division

SDT 12. The ORNL BENCHMARK EXPERIMENT FOR NEUTRON TRANSPORT THROUGH SODIUM

R. E. Maerker

SEPTEMBER 1974

Reference: R. E. Maerker, F. J. Muckenthaler, R. L. Childs, and M. L. Gritzner, "Final Report of the ORNL Benchmark Experiment for Neutron Transport Through Thick Sodium," ORNL-4880 (1974).

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Abstract

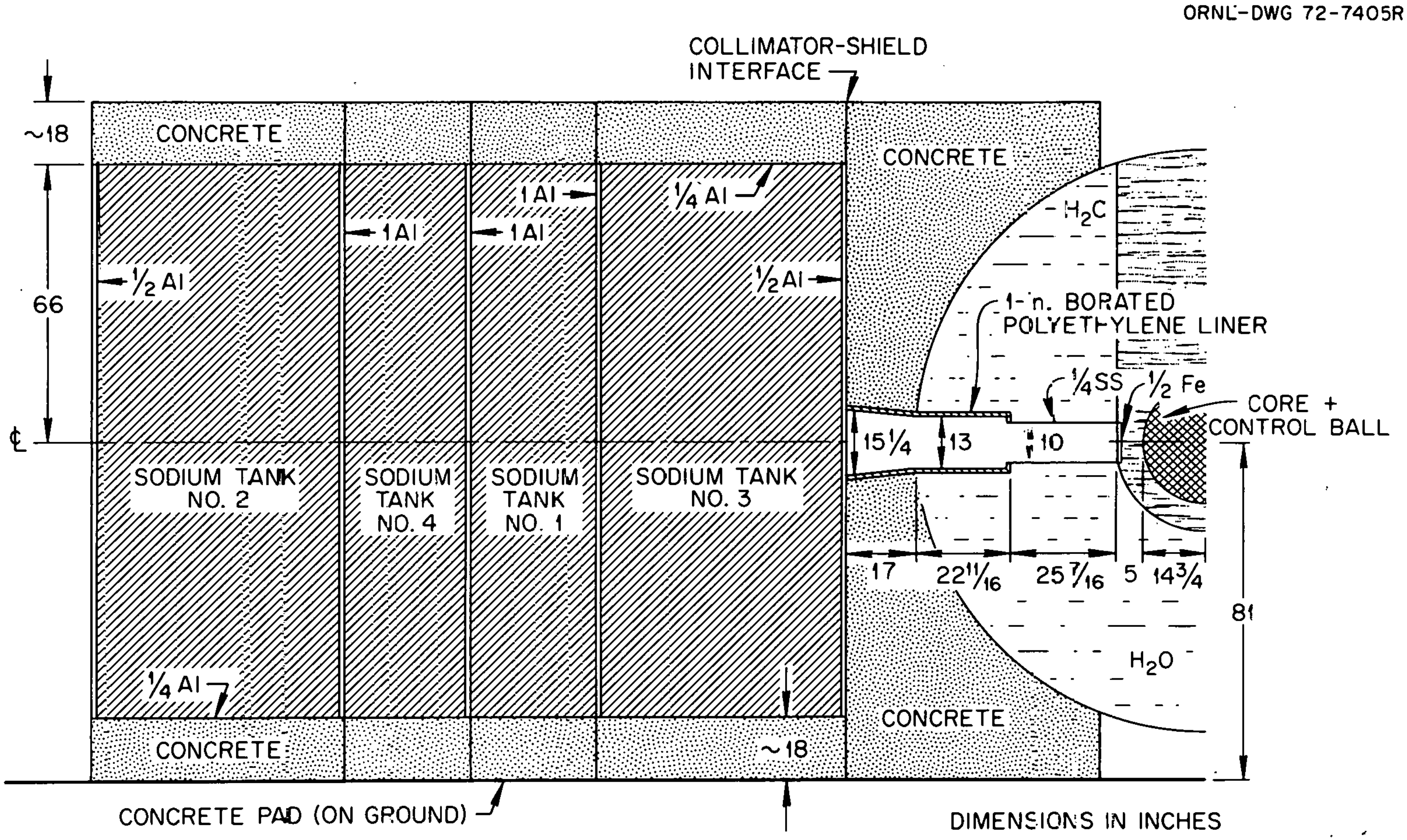
An experiment concerning deep neutron penetration in sodium is described, and experimental results in a format for CSEWG shielding integral data testing are presented. These results provide a basis for verification of the accuracy of sodium cross sections used in transport calculations. The experiment was performed at the Tower Shielding Facility of ORNL and included measurements of both the neutron fluence and neutron spectra behind tanks of sodium up to 15 ft thick.

Description

The sodium coolant which surrounds a fast reactor core constitutes a major portion of the neutron shield. It is therefore essential that accurate experimental results be available to verify the accuracy of transport calculations for deep penetration of neutrons through sodium. Since the thickness of sodium above the fuel elements in the FTR 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.

Consequently, a series of transmission measurements of neutrons above thermal energies through various thicknesses of sodium cylinders have been performed at the Tower Shielding Facility 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 obtained behind sodium thicknesses of approximately 2.5, 5, 10, 12.5, and 15 ft. Concrete at least 1.5 ft thick surrounded the tanks to reduce the effects of transverse leakage from the thicker slabs. Figure 1 shows a schematic of the experimental geometry for the 15-ft case. Figure 2 is a photograph of the cylindrical sodium tanks with some of the concrete collars attached.

The thickness and average sodium density of each of the sodium tanks were determined at eight locations in each tank. The sodium density was determined by placing the tank between a 3-in. sodium iodide detector and a ^{24}Na source and accurately determining the counting rate in the uncollided gamma-ray peak at 2.76 MeV. From the ratio of this counting rate to the counting rate in the peak with no slab present and the previously measured thickness of the sodium, the sodium density could be determined. The average thicknesses of the four tanks (including 1/2 in. of aluminum on each side) are shown in Table 1. The average sodium density was sensibly constant over each tank and from tank to tank as well, and the averaged value of 0.945 grams/cm^3 should be accurate to better than 1%.



Side View of Reactor

Figure 1. Experimental Configuration of the Reactor, the 15 1/4-in. Collimator, and the Sodium Tank Geometry.

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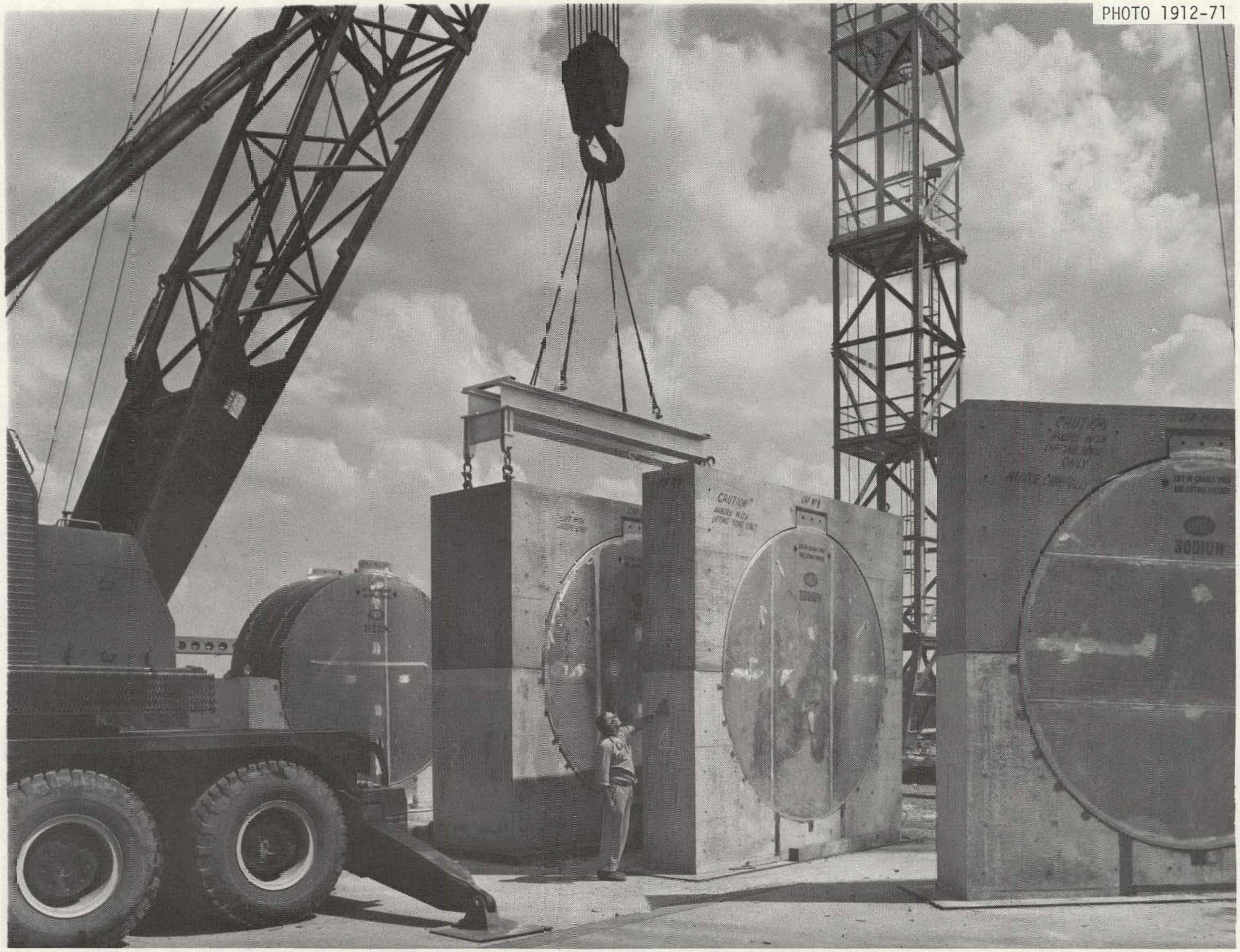

Figure 2. Photograph of the Cylindrical Sodium Tanks Surrounded by the Concrete Collars.

Table 1. Thickness of the Sodium Tanks

Tank Number	Nominal Thickness (including 1 in. of Al)	Average Thickness (including 1 in. of Al)	Average Sodium Thickness	Maximum Sodium Thickness Deviation from Average
1	30 in.	29.91 in.	28.91 in.	0.22 in.
2	60 in.	60.08 in.	59.08 in.	0.52 in.
3	60 in.	59.86 in.	58.86 in.	0.42 in.
4	30 in.	29.59 in.	28.59 in.	0.53 in.

The composition of the sodium can be assumed to be the following (Table 2) based on maximum allowable impurities in reactor grade sodium. The composition of the concrete collar surrounding the sodium tanks is also shown in Table 2.

Table 2. Composition of the Sodium and Concrete Collar Surrounding the Sodium Tanks

Element	Sodium		Concrete Collars	
	Atomic Density (atoms/barn cm)	Partial Density (grams/cm^3)	Atomic Density (atoms/barn cm)	Partial Density (grams/cm^3)
Silicon	- -	- -	3.76×10^{-3}	0.175
Hydrogen	3.39×10^{-5}	5.67×10^{-5}	8.66×10^{-3}	0.015
Oxygen	7.11×10^{-6}	1.89×10^{-4}	4.13×10^{-2}	1.096
Sodium	2.4737×10^{-2}	0.9442	--	--
Carbon	--	--	7.83×10^{-3}	0.156
Potassium	2.19×10^{-6}	1.42×10^{-4}	2.32×10^{-3}	0.159
Calcium	5.68×10^{-6}	3.79×10^{-4}	9.86×10^{-3}	0.655
Magnesium	--	--	1.31×10^{-3}	0.053

Sufficient measurements of the incident neutron beam were made that an absolute energy spectrum from thermal to 15 MeV could be obtained for use in calculations. This incident spectrum is presented in Table 3 in

Table 3. Source Spectrum at the End of the Collimator

Group	Energy Interval	Intensity (n/cm²/min/watt)	Group	Energy Interval	Intensity (n/cm²/min/watt)
1	13.5-14.9 MeV	14	51	67.4-86.5	1790
2	12.2-13.5	32	52	52.5-67.4	1730
3	11.05-12.2	73	53	40.9-52.5	1650
4	10.0-11.05	199	54	31.8-40.9	1590
5	9.04-10.0	312	55	24.8-31.8	1530
6	8.19-9.04	545	56	19.3-24.8	1490
7	7.41-8.19	846	57	15.0-19.3	1440
8	6.70-7.41	1375	58	11.7-15.0	1370
9	6.07-6.70	2070	59	9.12-11.7	1340
10	5.49-6.07	2585	60	7.10-9.12	1310
11	4.97-5.49	3180	61	5.53-7.10	1260
12	4.49-4.97	3665	62	4.31-5.53	1220
13	4.07-4.49	4420	63	3.35-4.31	1200
14	3.68-4.07	4880	64	2.61-3.35	1180
15	3.33-3.68	4825	65	2.03-2.61	1150
16	3.01-3.33	5315	66	1.58-2.03	1120
17	2.73-3.01	6570	67	1.23-1.58	1100
18	2.47-2.73	7075	68	961-1230 eV	1030
19	2.23-2.47	6955	69	749-961	1020
20	2.02-2.23	6190	70	583-749	1010
21	1.83-2.02	5570	71	454-583	990
22	1.65-1.83	5175	72	354-454	970
23	1.50-1.65	4200	73	275-354	960
24	1.35-1.50	4000	74	214-275	940
25	1.22-1.35	3170	75	167-214	920
26	1.11-1.22	2485	76	130-167	900
27	1.00-1.11	2350	77	101-130	900
28	0.907-1.00	2135	78	78.9-101	900
29	0.821-0.907	2215	79	61.4-78.9	900
30	0.743-0.821	2345	80	47.9-61.4	900
31	0.672-0.743	2320	81	37.3-47.9	900
32	0.608-0.672	1990	82	29.0-37.3	900
33	0.550-0.608	1700	83	22.6-29.0	900
34	0.497-0.550	1425	84	17.6-22.6	900
35	0.450-0.497	1210	85	13.7-17.6	900
36	0.408-0.450	1130	86	10.7-13.7	930
37	0.369-0.408	1170	87	8.32-10.7	960
38	0.334-0.369	1175	88	6.48-8.32	990
39	0.302-0.334	1130	89	5.04-6.48	1035
40	0.273-0.302	1055	90	3.93-5.04	1035
41	0.247-0.273	955	91	3.06-3.93	1035
42	0.224-0.247	837	92	2.38-3.06	1035
43	0.202-0.224	777	93	1.86-2.38	1060
44	0.183-0.202	926	94	1.44-1.86	1100
45	0.166-0.183	845	95	1.13-1.44	1170
46	0.150-0.166	827	96	0.876-1.13	1250
47	0.136-0.150	785	97	0.683-0.876	1350
48	0.123-0.136	798	98	0.532-0.683	1565
49	0.111-0.123	799	99	0.414-0.532	1900
50	86.5-111 keV	1870	100	0.000-0.414	9.50×10^4
			Totals 1-100	0.000-14.9 MeV	2.702×10^5

a 100-group GAM-2 structure. The intensities in Table 3 are for any point on the exit plane of the collimator located within the 15 1/4 in. diameter opening. Mapping of the incident beam along the axial direction established the fact that the collimated source can be represented as a virtual point anisotropic source located 59.5 in. inside the collimator from the exit plane with the beam intensity uniform over the 15 1/4 in. diameter mouth of the collimator and zero elsewhere. The accuracy of the incident absolute spectrum in Table 3 is estimated to be ± 10% down to 200 keV and ± 20% below 200 keV. The ratio of surface-integrated current over the collimator to centerline current is 1200 cm^2.

Neutron spectral measurements beyond the sodium samples were taken using two types of spectrometers. These were: (1) an NE-213 liquid scintillator, which determines spectra in the energy range 0.8-15 MeV with the aid of the unfolding code FERDOR, and (2) a Benjamin proton recoil spectrometer which determines spectra in the energy range ∿50 keV - 1.5 MeV with the aid of the unfolding code SPEC4. Table 4 gives the resolution of the NE-213 as a function of energy. The resolution of the Benjamin spectrometer is 10% FWHM, independent of energy. In addition, a set of spherical BF_3 detectors surrounded by various thicknesses of polyethylene (0-5 in.) and an outside shell of cadmium were used to obtain integral flux measurements. These Bonner ball detectors have response functions which peak in different regions of the spectrum. A modified Bonner ball was also used which consisted of a 3-in. shell of ^{10}B surrounding a 0.5 in. shell of polyethylene, both of which surrounded a BF_3 detector. The composition of each Bonner ball and the location of the center of detection is listed in Table 5. The response functions for the Bonner balls are presented in Tables 6-14. They are expressed in units of counts/sec per unit flux uniformly incident over an outside hemispherical surface of the ball, (the approximate geometry for these measurements) and were obtained by adjoint ANISN calculations normalized to calibration experiments performed at the Tower Shielding Facility. The estimated accuracy of the response functions is also indicated in each of the tables.

Data Obtained Behind the Sodium Tanks

All of the measurements made behind the sodium tanks are summarized in Table 15. The data obtained from these measurements are presented in Tables 16-32. All the data tabulated are with background subtracted except the profile data appearing in Tables 23 and 24, where it is estimated to be less than 10% of foreground. Counting times and operating reactor powers for the Bonner ball measurements were sufficiently large that statistical errors in the Bonner ball counting rates may be assumed to be negligible. The reproducibility of all measurements lies within 5-10% and is due primarily to uncertainties in the power calibration procedure.

The unfolded Benjamin proton recoil spectrometer data are presented in Tables 25-27, where the percent standard error is due to counting statistics only. The absolute energy calibration is accurate to within an estimated ± 5%.

The NE-213 liquid scintillator spectral data are presented in Tables 28-30, where the upper and lower limits indicate the standard error of each unfolded spectrum and are due to combined statistical and unfolding errors.

Table 4. Energy Resolution of the NE-213 Spectrometer System*

E (MeV)	a (E) FWHM (%)	E (MeV)	a (E) FWHM (%)	E (MeV)	a (E) 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
1.1	32.5	4.1	16.7	8.2	11.6
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		

*Interpolation in this table should follow the formula

$$a(E) = \frac{E_2 - E}{E_2 - E_1} a(E_1) + \frac{E - E_1}{E_2 - E_1} a(E_2)$$

where

$E_1 \leq E \leq E_2$.

Table 5. Bonner Ball Description

Spherical, 2-in.-diam $^{10}BF_3$ 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 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 is 2-in.-diam 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 center of detection is displaced in a direction toward the center of gravity of the hemispherical surface upon which the neutrons are incident.

Table 6. Response for 2.06 Inch Diameter Bonner Sphere*

Group	Midpoint Energy (eV)	Response (Counts/Incident Neut/cm^2)
1	Thermal	Negligible
2	4.73E-01	1.70E-01
3	6.07E-01	2.40E-01
4	7.79E-01	2.56E-01
5	1.00E-00	2.49E-01
6	1.29E-00	2.30E-01
7	1.65E-00	2.08E-01
8	2.12E-00	1.85E-01
9	2.72E-00	1.65E-01
10	3.49E-00	1.46E-01
11	4.49E-00	1.29E-01
12	5.76E-00	1.14E-01
13	7.40E-00	1.01E-01
14	9.50E-00	8.93E-02
15	1.22E+01	7.89E-02
16	1.57E+01	6.97E-02
17	2.01E+01	6.15E-02
18	2.58E+01	5.16E-02
19	3.31E+01	4.79E-02
20	4.26E+01	4.24E-02
21	5.46E+01	3.74E-02
22	7.02E+01	3.22E-02
23	9.01E+01	2.61E-02
24	1.16E+02	2.42E-02
25	1.49E+02	2.26E-02
26	1.91E+02	1.99E-02
27	2.45E+02	1.75E-02
28	3.14E+02	1.55E-02
29	4.04E+02	1.37E-02
30	5.18E+02	1.20E-02
31	6.66E+02	1.05E-02
32	8.55E+02	9.38E-03
33	1.10E+02	8.28E-03
34	1.41E+03	7.30E-03
35	1.81E+03	6.43E-03
36	2.32E+03	5.62E-03
37	2.98E+03	5.01E-03
38	3.83E+03	4.43E-03
39	4.92E+03	3.91E-03
40	6.32E+03	3.45E-03
41	8.11E+03	3.05E-03
42	1.04E+04	2.70E-03
43	1.34E+04	2.39E-03
44	1.72E+04	2.11E-03
45	2.20E+04	1.86E-03
46	2.83E+04	1.65E-03
47	3.63E+04	1.46E-03
48	4.67E+04	1.29E-03

*Cadmium covered sphere - no polyethylene shell. Estimated accuracy is ± 10% throughout energy range.

Table 6. contd.

49	5.99E+04	1.14E-03
50	7.69E+04	1.02E-03
51	9.88E+04	9.11E-04
52	1.17E+05	8.48E-04
53	1.29E+05	8.14E-04
54	1.43E+05	7.82E-04
55	1.58E+05	7.50E-04
56	1.74E+05	7.20E-04
57	1.93E+05	6.91E-04
58	2.13E+05	6.61E-04
59	2.35E+05	6.26E-04
60	2.60E+05	5.82E-04
61	2.88E+05	5.17E-04
62	3.18E+05	4.47E-04
63	3.51E+05	4.05E-04
64	3.88E+05	3.92E-04
65	4.29E+05	3.87E-04
66	4.74E+05	3.81E-04
67	5.24E+05	3.51E-04
68	5.79E+05	2.99E-04
69	6.40E+05	2.56E-04
70	7.07E+05	2.19E-04
71	7.82E+05	1.89E-04
72	8.64E+05	1.64E-04
73	9.54E+05	1.49E-04
74	1.06E+06	1.42E-04
75	1.17E+06	1.35E-04
76	1.29E+06	1.37E-04
77	1.42E+06	1.51E-04
78	1.57E+06	1.91E-04
79	1.74E+06	2.34E-04
80	1.92E+06	2.50E-04
81	2.13E+06	2.16E-04
82	2.35E+06	1.74E-04
83	2.60E+06	1.68E-04
84	2.87E+06	1.64E-04
85	3.17E+06	1.53E-04
86	3.50E+06	1.54E-04
87	3.87E+06	1.62E-04
88	4.28E+06	1.77E-04
89	4.73E+06	1.84E-04
90	5.23E+06	1.94E-04
91	5.78E+06	1.95E-04
92	6.38E+06	1.69E-04
93	7.06E+06	1.46E-04
94	7.80E+06	1.31E-04
95	8.62E+06	1.20E-04
96	9.52E+06	1.10E-04
97	1.05E+07	1.01E-04
98	1.16E+07	9.21E-05
99	1.29E+07	8.67E-05
100	1.42E+07	3.49E-05

Table 7. Response for 3.00 Inch Diameter Bonner Sphere*

Group	Midpoint Energy (eV)	Response (Counts/Incident Neut/cm^2)
1	Thermal	Negligible
2	4.73E-01	4.99E-01
3	6.07E-01	8.26E-01
4	7.79E-01	1.02E-00
5	1.00E-00	1.13E-00
6	1.29E-00	1.18E-00
7	1.65E-00	1.19E-00
8	2.12E-00	1.18E-00
9	2.72E-00	1.16E-00
10	3.49E-00	1.14E 00
11	4.49E-00	1.11E-00
12	5.76E-00	1.08E-00
13	7.40E-00	1.05E-00
14	9.50E-00	1.01E-00
15	1.22E+01	9.76E-01
16	1.57E+01	9.41E-01
17	2.01E+01	9.04E-01
18	2.58E+01	8.23E-01
19	3.31E+01	8.32E-01
20	4.26E+01	8.01E-01
21	5.46E+01	7.68E-01
22	7.02E+01	7.15E-01
23	9.01E+01	6.25E-01
24	1.16E+02	7.67E-01
25	1.49E+02	7.95E-01
26	1.91E+02	7.67E-01
27	2.45E+02	7.28E-01
28	3.14E+02	6.98E-01
29	4.04E+02	6.69E-01
30	5.18E+02	6.29E-01
31	6.66E+02	6.10E-01
32	8.55E+02	5.83E-01
33	1.10E+03	5.55E-01
34	1.41E+03	5.30E-01
35	1.81E+03	5.05E-01
36	2.32E+03	4.81E-01
37	2.98E+03	4.59E-01
38	3.83E+03	4.37E-01
39	4.92E+03	4.17E-01
40	6.32E+03	3.98E-01
41	8.11E+03	3.80E-01
42	1.04E+04	3.61E-01
43	1.34E+04	3.43E-01
44	1.72E+04	3.26E-01
45	2.20E+04	3.10E-01
46	2.83E+04	2.93E-01
47	3.63E+04	2.77E-01
48	4.67E+04	2.60E-01

*Radial thickness of polyethylene = 0.470 inches;
Density of polyethylene = 0.951 gram/cc;
Estimated accuracy is ± 10% for groups 33-100 and ± 15% for groups 1-32.

Table 7. contd.

49	5.99E+04	2.44E-01
50	7.69E+04	2.27E-01
51	9.88E+04	2.10E-01
52	1.17E+05	1.99E-01
53	1.29E+05	1.92E-01
54	1.43E+05	1.84E-01
55	1.48E+05	1.77E-01
56	1.74E+05	1.70E-01
57	1.73E+05	1.63E-01
58	2.13E+05	1.55E-01
59	2.35E+05	1.48E-01
60	2.60E+05	1.41E-01
61	2.88E+05	1.34E-01
62	3.18E+05	1.27E-01
63	3.51E+05	1.20E-01
64	3.88E+05	1.13E-01
65	4.29E+05	1.06E-01
66	4.74E+05	9.91E-02
67	5.24E+05	9.26E-02
68	5.79E+05	8.62E-02
69	6.40E+05	8.01E-02
70	7.07E+05	7.43E-02
71	7.82E+05	6.87E-02
72	8.64E+05	6.33E-02
73	9.54E+05	5.82E-02
74	1.06E+06	5.34E-02
75	1.17E+06	4.89E-02
76	1.29E+06	4.46E-02
77	1.42E+06	4.07E-02
78	1.57E+06	3.70E-02
79	1.74E+06	3.36E-02
80	1.92E+06	3.04E-02
81	2.13E+06	2.75E-02
82	2.35E+06	2.47E-02
83	2.60E+06	2.22E-02
84	2.87E+06	2.00E-02
85	3.17E+06	1.79E-02
86	3.50E+06	1.60E-02
87	3.87E+06	1.43E-02
88	4.28E+06	1.27E-02
89	4.73E+06	1.12E-02
90	5.23E+06	1.08E-02
91	5.78E+06	9.80E-03
92	6.38E+06	8.69E-03
93	7.06E+06	7.16E-03
94	7.80E+06	6.57E-03
95	8.62E+06	5.80E-03
96	9.52E+06	5.21E-03
97	1.05E+07	4.65E-03
98	1.16E+07	4.09E-03
99	1.29E+07	3.66E-03
100	1.42E+07	3.23E-03

Table 8. Response for 4.03 Inch Diameter Bonner Sphere*

Group	Midpoint Energy (eV)	Response (Counts/Incident Neut/cm^2)
1	Thermal	Negligible
2	4.73E-01	3.82E-01
3	6.07E-01	6.70E-01
4	7.79E-01	8.68E-01
5	1.00E-00	1.01E-00
6	1.29E-00	1.11E-00
7	1.65E-00	1.17E-00
8	2.12E-00	1.22E-00
9	2.72E-00	1.26E-00
10	3.49E-00	1.29E-00
11	4.49E-00	1.31E-00
12	5.76E-00	1.32E-00
13	7.40E-00	1.33E-00
14	9.50E-00	1.34E-00
15	1.22E+01	1.34E-00
16	1.57E+01	1.34E-00
17	2.01E+01	1.34E-00
18	2.58E+01	1.27E-00
19	3.31E+01	1.32E-00
20	4.26E+01	1.32E-00
21	5.46E+01	1.31E-00
22	7.02E+01	1.26E-00
23	9.01E+01	1.14E-00
24	1.16E+02	1.28E-00
25	1.49E+02	1.37E-00
26	1.91E+02	1.37E-00
27	2.45E+02	1.34E-00
28	3.14E+02	1.32E-00
29	4.04E+02	1.31E-00
30	5.18E+02	1.27E-00
31	6.66E+02	1.27E-00
32	8.55E+02	1.25E-00
33	1.10E+03	1.22E-00
34	1.41E+03	1.20E-00
35	1.81E+03	1.18E-00
36	2.32E+03	1.16E-00
37	2.98E+03	1.13E-00
38	3.83E+03	1.11E-00
39	4.92E+03	1.09E-00
40	6.32E+03	1.07E-00
41	8.11E+03	1.05E-00
42	1.04E+04	1.03E-00
43	1.34E+04	1.01E-00
44	1.72E+04	9.93E-01
45	2.20E+04	9.74E-01
46	2.83E+04	9.55E-01
47	3.63E+04	9.36E-01
48	4.67E+04	9.17E-01

*Radial Thickness of Polyethylene = 0.985 Inches;
Density of polyethylene = 0.951 gram/cc;
Estimated accuracy is ± 10% for groups 33-100 and ± 15% for groups 1-32.

Table 8. contd.

49	5.99E+04	8.97E-01
50	7.69E+04	8.77E-01
51	9.88E+04	8.54E-01
52	1.17E+05	8.38E-01
53	1.29E+05	8.27E-01
54	1.43E+05	8.16E-01
55	1.58E+05	8.04E-01
56	1.74E+05	7.92E-01
57	1.93E+05	7.79E-01
58	2.13E+05	7.65E-01
59	2.35E+05	7.50E-01
60	2.60E+05	7.34E-01
61	2.88E+05	7.18E-01
62	3.18E+05	7.00E-01
63	3.51E+05	6.81E-01
64	3.88E+05	6.63E-01
65	4.29E+05	6.42E-01
66	4.74E+05	6.21E-01
67	5.24E+05	5.99E-01
68	5.79E+05	5.76E-01
69	6.40E+05	5.52E-01
70	7.07E+05	5.29E-01
71	7.82E+05	5.04E-01
72	8.64E+05	4.80E-01
73	9.54E+05	4.55E-01
74	1.06E+06	4.30E-01
75	1.17E+06	4.06E-01
76	1.29E+06	3.81E-01
77	1.42E+06	3.57E-01
78	1.57E+06	3.34E-01
79	1.74E+06	3.11E-01
80	1.92E+06	2.88E-01
81	2.13E+06	2.66E-01
82	2.35E+06	2.46E-01
83	2.60E+06	2.25E-01
84	2.87E+06	2.05E-01
85	3.17E+06	1.88E-01
86	3.50E+06	1.71E-01
87	3.87E+06	1.56E-01
88	4.28E+06	1.41E-01
89	4.73E+06	1.27E-01
90	5.23E+06	1.20E-01
91	5.78E+06	1.11E-01
92	6.38E+06	1.02E-01
93	7.06E+06	8.58E-02
94	7.80E+06	7.93E-02
95	8.62E+06	6.91E-02
96	9.52E+06	6.15E-02
97	1.05E+07	5.46E-02
98	1.16E+07	4.74E-02
99	1.29E+07	4.20E-02
100	1.42E+07	3.71E-02

Table 9. Response for 5.02 Inch Diameter Bonner Sphere*

Group	Midpoint Energy (eV)	Response (Counts/Incident Neut/cm^2)
1	Thermal	Negligible
2	4.73E-01	2.78E-01
3	6.07E-01	4.95E-01
4	7.79E-01	6.50E-01
5	1.00E-00	7.68E-01
6	1.29E-00	8.54E-01
7	1.65E-00	9.18E-01
8	2.12E-00	9.70E-01
9	2.72E-00	1.01E-00
10	3.49E-00	1.05E-00
11	4.49E-00	1.09E-00
12	5.76E-00	1.12E-00
13	7.40E-00	1.14E-00
14	9.50E-00	1.17E-00
15	1.22E+01	1.19E-00
16	1.57E+01	1.21E-00
17	2.01E+01	1.23E-00
18	2.58E+01	1.18E-00
19	3.31E+01	1.25E-00
20	4.26E+01	1.27E-00
21	5.46E+01	1.28E-00
22	7.02E+01	1.25E-00
23	9.01E+01	1.15E-00
24	1.16E+02	1.19E-00
25	1.49E+02	1.29E-00
26	1.91E+02	1.30E-00
27	2.45E+02	1.30E-00
28	3.14E+02	1.30E-00
29	4.04E+02	1.31E-00
30	5.18E+02	1.29E-00
31	6.66E+02	1.31E-00
32	8.55E+02	1.31E-00
33	1.10E+03	1.30E-00
34	1.41E+03	1.30E-00
35	1.81E+03	1.29E-00
36	2.32E+03	1.29E-00
37	2.98E+03	1.28E-00
38	3.83E+03	1.27E-00
39	4.92E+03	1.27E-00
40	6.32E+03	1.27E-00
41	8.11E+03	1.26E-00
42	1.04E+04	1.26E-00
43	1.34E+04	1.25E-00
44	1.72E+04	1.25E-00
45	2.20E+04	1.24E-00
46	2.83E+04	1.24E-00
47	3.63E+04	1.24E-00
48	4.67E+04	1.24E-00

*Radial thickness of polyethylene = 1.480 inches;
Density of polyethylene = 0.951 gram/cc;
Estimated accuracy is ± 10% for groups 33-100
and ± 15% for groups 1-32.

Table 9. contd.

49	5.99E+04	1.24E-00
50	7.69E+04	1.24E-00
51	9.88E+04	1.24E-00
52	1.17E+05	1.24E-00
53	1.29E+05	1.24E-00
54	1.43E+05	1.24E-00
55	1.58E+05	1.24E-00
56	1.74E+05	1.24E-00
57	1.93E+05	1.24E-00
58	2.13E+05	1.23E-00
59	2.35E+05	1.23E-00
60	2.60E+05	1.22E-00
61	2.88E+05	1.21E-00
62	3.18E+05	1.20E-00
63	3.51E+05	1.19E-00
64	3.88E+05	1.18E-00
65	4.29E+05	1.17E-00
66	4.74E+05	1.15E-00
67	5.24E+05	1.13E-00
68	5.79E+05	1.11E-00
69	6.40E+05	1.09E-00
70	7.07E+05	1.06E-00
71	7.82E+05	1.03E-00
72	8.64E+05	1.00E-00
73	9.54E+05	9.72E-01
74	1.06E+06	9.38E-01
75	1.17E+06	9.03E-01
76	1.29E+06	8.66E-01
77	1.42E+06	8.28E-01
78	1.57E+06	7.88E-01
79	1.74E+06	7.48E-01
80	1.92E+06	7.07E-01
81	2.13E+06	6.63E-01
82	2.35E+06	6.25E-01
83	2.60E+06	5.82E-01
84	2.87E+06	5.37E-01
85	3.17E+06	5.02E-01
86	3.50E+06	4.59E-01
87	3.87E+06	4.27E-01
88	4.28E+06	3.96E-01
89	4.73E+06	3.62E-01
90	5.23E+06	3.40E-01
91	5.78E+06	3.20E-01
92	6.38E+06	2.98E-01
93	7.06E+06	2.57E-01
94	7.80E+06	2.39E-01
95	8.62E+06	2.10E-01
96	9.52E+06	1.87E-01
97	1.05E+07	1.67E-01
98	1.16E+07	1.44E-01
99	1.29E+07	1.28E-01
100	1.42E+07	1.13E-01

Table 10. Response for 6.00 Inch Diameter Bonner Sphere*

Group	Midpoint Energy (eV)	Response (Counts/Incident/Neut/cm^2)
1	Thermal	Negligible
2	4.73E-01	1.78E-01
3	6.07E-01	3.18E-01
4	7.79E-01	4.19E-01
5	1.00E-00	4.97E-01
6	1.29E-00	5.55E-01
7	1.65E-00	5.99E-01
8	2.12E-00	6.36E-01
9	2.72E-00	6.69E-01
10	3.49E-00	6.98E-01
11	4.49E-00	7.25E-01
12	5.76E-00	7.51E-01
13	7.40E-00	7.75E-01
14	9.50E-00	7.97E-01
15	1.22E+01	8.19E-01
16	1.57E+01	8.39E-01
17	2.01E+01	8.57E-01
18	2.58E+01	8.30E-01
19	3.31E+01	8.90E-01
20	4.26E+01	9.10E-01
21	5.46E+01	9.25E-01
22	7.02E+01	9.14E-01
23	9.01E+01	8.48E-01
24	1.16E+02	8.80E-01
25	1.49E+02	9.66E-01
26	1.91E+02	9.86E-01
27	2.45E+02	9.90E-01
28	3.14E+02	1.00E-00
29	4.04E+02	1.02E-00
30	5.18E+02	1.01E-00
31	6.66E+02	1.04E-00
32	8.55E+02	1.05E-00
33	1.10E+03	1.05E-00
34	1.41E+03	1.06E-00
35	1.81E+03	1.07E-00
36	2.32E+03	1.07E-00
37	2.98E+03	1.08E-00
38	3.83E+03	1.08E-00
39	4.92E+03	1.09E-00
40	6.32E+03	1.10E-00
41	8.11E+03	1.11E-00
42	1.04E+04	1.11E-00
43	1.34E+04	1.12E-00
44	1.72E+04	1.13E-00
45	2.20E+04	1.14E-00
46	2.83E+04	1.15E-00
47	3.63E+04	1.17E-00
48	4.67E+04	1.18E-00

*Radial thickness of polyethylene = 1.970 inches;
Density of polyethylene = 0.951 gram/cc;
Estimated accuracy is ± 10% for groups 33-100 and ± 15% for groups 1-32.

Table 10. contd.

49	5.99E+04	1.20E-00
50	7.69E+04	1.23E-00
51	9.88E+04	1.26E-00
52	1.17E+05	1.27E-00
53	1.29E+05	1.29E-00
54	1.43E+05	1.30E-00
55	1.58E+05	1.31E-00
56	1.74E+05	1.32E-00
57	1.93E+05	1.34E-00
58	2.13E+05	1.35E-00
59	2.35E+05	1.36E-00
60	2.60E+05	1.37E-00
61	2.88E+05	1.38E-00
62	3.18E+05	1.39E-00
63	3.51E+05	1.39E-00
64	3.88E+05	1.40E-00
65	4.29E+05	1.40E-00
66	4.74E+05	1.40E-00
67	5.24E+05	1.40E-00
68	5.79E+05	1.40E-00
69	6.40E+05	1.39E-00
70	7.07E+05	1.38E-00
71	7.82E+05	1.37E-00
72	8.64E+05	1.35E-00
73	9.54E+05	1.33E-00
74	1.06E+06	1.31E-00
75	1.17E+06	1.28E-00
76	1.29E+06	1.25E-00
77	1.42E+06	1.21E-00
78	1.57E+06	1.17E-00
79	1.74E+06	1.13E-00
80	1.92E+06	1.09E-00
81	2.13E+06	1.03E-00
82	2.35E+06	9.91E-01
83	2.60E+06	9.37E-01
84	2.87E+06	8.70E-01
85	3.17E+06	8.30E-01
86	3.50E+06	7.62E-01
87	3.87E+06	7.22E-01
88	4.28E+06	6.84E-01
89	4.73E+06	6.34E-01
90	5.23E+06	5.99E-01
91	5.78E+06	5.67E-01
92	6.38E+06	5.35E-01
93	7.06E+06	4.71E-01
94	7.80E+06	4.39E-01
95	8.62E+06	3.91E-01
96	9.52E+06	3.51E-01
97	1.05E+07	3.14E-01
98	1.16E+07	2.73E-01
99	1.29E+07	2.43E-01
100	1.42E+07	2.16E-01

Table 11. Response for 7.86 Inch Diameter Bonner Sphere*

Group	Midpoint Energy (eV)	Response (Counts/Incident Neut/cm^2)
1	Thermal	Negligible
2	4.73E-01	7.04E-02
3	6.07E-01	1.26E-01
4	7.79E-01	1.66E-01
5	1.00E-00	1.98E-01
6	1.29E-00	2.21E-01
7	1.65E-00	2.39E-01
8	2.12E-00	2.55E-01
9	2.72E-00	2.68E 01
10	3.49E-00	2.81E-01
11	4.49E-00	2.93E-01
12	5.76E-00	3.04E-01
13	7.40E-00	3.15E-01
14	9.50E-00	3.25E-01
15	1.22E+01	3.36E-01
1	1.57E+01	3.46E-01
17	2.01E+01	3.55E-01
18	2.58E+01	3.45E-01
19	3.31E+01	3.73E-01
20	4.26E+01	3.84E-01
21	5.46E+01	3.93E-01
22	7.02E+01	3.91E-01
23	9.01E+01	3.65E-01
24	1.16E+02	3.82E-01
25	1.49E+02	4.22E-01
26	1.91E+02	4.35E-01
27	2.45E+02	4.40E-01
28	3.14E+02	4.51E-01
29	4.04E+02	4.61E-01
30	5.18E+02	4.62E-01
31	6.66E+02	4.78E-01
32	8.55E+02	4.88E-01
33	1.10E+03	4.96E-01
34	1.41E+03	5.05E-01
35	1.81E+03	5.12E-01
36	2.32E+03	5.21E-01
37	2.98E+03	5.29E-01
38	3.83E+03	5.37E-01
39	4.92E+03	5.46E-01
40	6.32E+03	5.57E-01
41	8.11E+03	5.67E-01
42	1.04E+04	5.78E-01
43	1.34E+04	5.89E-01
44	1.72E+04	6.03E-01
45	2.20E+04	6.19E-01
46	2.83E+04	6.36E-01
47	3.63E+04	6.56E-01
48	4.67E+04	6.79E-01

*Radial thickness of polyethylene = 2.900 inches;
Density of polyethylene = 0.951 gram/cc;
Estimated accuracy is ± 10% for groups 33-100
and ± 20% for groups 1-32.

Table 11. Contd.

49	5.99E+04	7.06E-01
50	7.69E+04	7.40E-01
51	9.88E+04	7.79E-01
52	1.17E+05	8.09E-01
53	1.29E+05	8.29E-01
54	1.43E+05	8.50E-01
55	1.58E+05	8.73E-01
56	1.74E+05	8.96E-01
57	1.93E+05	9.22E-01
58	2.13E+05	9.48E-01
59	2.35E+05	9.75E-01
60	2.60E+05	1.00E-00
61	2.88E+05	1.04E-00
62	3.18E+05	1.06E-00
63	3.51E+05	1.09E-00
64	3.88E+05	1.13E-00
65	4.29E+05	1.16E-00
66	4.74E+05	1.19E-00
67	5.24E+05	1.22E-00
68	5.79E+05	1.25E-00
69	6.40E+05	1.28E-00
70	7.07E+05	1.31E-00
71	7.82E+05	1.34E-00
72	8.64E+05	1.36E-00
73	9.54E+05	1.38E-00
74	1.06E+06	1.39E-00
75	1.17E+06	1.40E-00
76	1.29E+06	1.41E-00
77	1.42E+06	1.41E-00
78	1.57E+06	1.41E-00
79	1.74E+06	1.40E-00
80	1.92E+06	1.38E-00
81	2.13E+06	1.34E-00
82	2.35E+06	1.33E-00
83	2.60E+06	1.29E-00
84	2.87E+06	1.21E-00
85	3.17E+06	1.19E-00
86	3.50E+06	1.10E-00
87	3.87E+06	1.08E-00
88	4.28E+06	1.06E-00
89	4.73E+06	1.01E-00
90	5.23E+06	9.69E-01
91	5.78E+06	9.28E-01
92	6.38E+06	8.87E-01
93	7.06E+06	8.14E-01
94	7.80E+06	7.59E-01
95	8.62E+06	6.99E-01
96	9.52E+06	6.35E-01
97	1.05E+07	5.74E-01
98	1.16E+07	5.05E-01
99	1.29E+07	4.55E-01
100	1.42E+07	4.09E-01

Table 12. Response for 9.86 Inch Diameter Bonner Sphere*

Group	Midpoint Energy (eV)	Response (Counts/Incident Neut/cm^2)
1	Thermal	Negligible
2	4.73E-01	2.43E-02
3	6.07E-01	4.36E-02
4	7.79E-01	5.76E-02
5	1.00E-00	6.85E-02
6	1.29E-00	7.66E-02
7	1.65E-00	8.28E-02
8	2.12E-00	8.81E-02
9	2.72E-00	9.29E-02
10	3.49E-00	9.72E-02
11	4.49E-00	1.01E-01
12	5.76E-00	1.05E-01
13	7.40E-00	1.09E-01
14	9.50E-00	1.13E-01
15	1.22E+01	1.16E-01
16	1.57E+01	1.20E-01
17	2.01E+01	1.23E-01
18	2.58E+01	1.20E-01
19	3.31E+01	1.30E-01
20	4.26E+01	1.34E-01
21	5.46E+01	1.37E-01
22	7.02E+01	1.37E-01
23	9.01E+01	1.28E-01
24	1.16E+02	1.39E-01
25	1.49E+02	1.59E-01
26	1.91E+02	1.53E-01
27	2.45E+02	1.56E-01
28	3.14E+02	1.60E-01
29	4.04E+02	1.64E-01
30	5.18E+02	1.65E-01
31	6.66E+02	1.71E-01
32	8.55E+02	1.75E-01
33	1.10E+03	1.79E-01
34	1.41E+03	1.83E-01
35	1.81E+03	1.86E-01
36	2.32E+03	1.90E-01
37	2.98E+03	1.94E-01
38	3.83E+03	1.98E-01
39	4.92E+03	2.02E-01
40	6.32E+03	2.07E-01
41	8.11E+03	2.12E 01
42	1.04E+04	2.18E-01
43	1.34E+04	2.23E-01
44	1.72E+04	2.30E-01
45	2.20E+04	2.38E-01
46	2.83E+04	2.47E-01
47	3.63E+04	2.57E-01
48	4.67E+04	2.69E-01

*Radial thickness of polyethylene = 3.890 inches;
Density of polyethylene = 0.951 gram/cc;
Estimated accuracy is ± 10% for groups 33-100
and ± 25% for groups 1-32.

Table 12. Contd.

49	5.99E+04	2.84E-01
50	7.69E+04	3.03E-01
51	9.88E+04	3.26E-01
52	1.17E+05	3.44E-01
53	1.29E+05	3.57E-01
54	1.43E+05	3.71E-01
55	1.58E+05	3.86E-01
56	1.74E+05	4.02E-01
57	1.93E+05	4.20E-01
58	2.13E+05	4.39E-01
59	2.35E+05	4.61E-01
60	2.60E+05	4.84E-01
61	2.88E+05	5.10E-01
62	3.18E+05	5.35E-01
63	3.51E+05	5.63E-01
64	3.88E+05	5.97E-01
65	4.29E+05	6.29E-01
66	4.74E+05	6.65E-01
67	5.24E+05	7.03E-01
68	5.79E+05	7.42E-01
69	6.40E+05	7.82E-01
70	7.07E+05	8.25E-01
71	7.82E+05	8.68E-01
72	8.64E+05	9.12E-01
73	9.54E+05	9.56E-01
74	1.06E+06	9.98E-01
75	1.17E+06	1.04E-00
76	1.29E+06	1.08E-00
77	1.42E+06	1.12E-00
78	1.57E+06	1.15E-00
79	1.74E+06	1.18E-00
80	1.92E+06	1.20E-00
81	2.13E+06	1.20E-00
82	2.35E+06	1.22E-00
83	2.60E+06	1.22E-00
84	2.87E+06	1.16E-00
85	3.17E+06	1.19E-00
86	3.50E+06	1.10E-00
87	3.87E+06	1.11E-00
88	4.28E+06	1.14E-00
89	4.73E+06	1.12E-00
90	5.23E+06	1.10E-00
91	5.78E+06	1.06E-00
92	6.38E+06	1.03E-00
93	7.06E+06	9.81E-01
94	7.80E+06	9.13E-01
95	8.62E+06	8.74E-01
96	9.52E+06	8.05E-01
97	1.05E+07	7.40E-01
98	1.16E+07	6.61E-01
99	1.29E+07	6.05E-01
100	1.42E+07	5.52E-01

Table 13. Response for 11.84 Inch Diameter Bonner Sphere*

Group	Midpoint Energy (eV)	Response (Counts/Incident Neut/cm^2)
1	Thermal	Negligible
2	4.73E-01	8.12E-03
3	6.07E-01	1.46E-02
4	7.79E-01	1.93E-02
5	1.00E-00	2.30E-02
6	1.29E-00	2.57E-02
7	1.65E-00	2.78E-02
8	2.12E-00	2.96E-02
9	2.72E-00	3.12E-02
10	3.49E-00	3.26E-02
11	4.49E-00	3.40E-02
12	5.76E-00	3.53E-02
13	7.40E-00	3.66E-02
14	9.50E-00	3.79E-02
15	1.22E+01	3.91E-02
16	1.57E+01	4.03E-02
17	2.01E+01	4.15E-02
18	2.58E+01	4.04E-02
19	3.31E+01	4.37E-02
20	5.26E+01	4.50E-02
21	5.46E+01	4.62E-02
22	7.02E+01	4.60E-02
23	9.01E+01	4.30E-02
24	1.16E+02	4.51E-02
25	1.49E+02	5.01E-02
26	1.91E+02	5.17E-02
27	2.45E+02	5.25E-02
28	3.14E+02	5.40E-02
29	4.04E+02	5.54E-02
30	5.18E+02	5.57E-02
31	6.66E+02	5.79E-02
32	8.55E+02	5.93E-02
33	1.10E+03	6.06E-02
34	1.41E+03	6.20E-02
35	1.81E+03	6.33E-02
36	2.32E+03	6.46E-02
37	2.98E+03	6.60E-02
38	3.83E+03	6.75E-02
39	4.92E+03	6.91E-02
40	6.32E+03	7.09E-02
41	8.11E+03	7.28E-02
42	1.04E+04	7.47E-02
43	1.34E+04	7.68E-02
44	1.72E+04	7.94E-02
45	2.20E+04	8.24E-02
46	2.83E+04	8.57E-02
47	3.63E+04	8.97E-02
48	4.67E+04	9.45E-02

*Radial thickness of polyethylene = 3.900 inches;
Density of polyethylene = 0.951 gram/cc;
Estimated accuracy is ± 10% for groups 33-100
and ± 30% for groups 1-32.

Table 13. Contd.

49	5.99E+04	1.00E-01
50	7.69E+04	1.08E-01
51	9.88E+04	1.17E-01
52	1.17E+05	1.25E-01
53	1.29E+05	1.31E-01
54	1.43E+05	1.37E-01
55	1.58E+05	1.44E-01
56	1.74E+05	1.51E-01
57	1.93E+05	1.60E-01
58	2.13E+05	1.69E-01
59	2.35E+05	1.80E-01
60	2.60E+05	1.92E-01
61	2.88E+05	2.06E-01
62	3.18E+05	2.20E-01
63	3.51E+05	2.37E-01
64	3.88E+05	2.57E-01
65	4.29E+05	2.77E-01
66	4.74E+05	3.01E-01
67	5.24E+05	3.27E-01
68	5.79E+05	3.55E-01
69	6.40E+05	3.87E-01
70	7.07E+05	4.21E-01
71	7.82E+05	4.57E-01
72	8.64E+05	4.97E-01
73	9.54E+05	5.39E-01
74	1.06E+06	5.83E-01
75	1.17E+06	6.29E-01
76	1.29E+06	6.76E-01
77	1.42E+06	7.24E-01
78	1.57E+06	7.71E-01
79	1.74E+06	8.18E-01
80	1.92E+06	8.61E-01
81	2.13E+06	8.81E-01
82	2.35E+06	9.33E-01
83	2.60E+06	9.52E-01
84	2.87E+06	9.23E-01
85	3.17E+06	9.77E-01
86	3.50E+06	9.17E-01
87	3.87E+06	9.51E-01
88	4.28E+06	1.01E-00
89	4.73E+06	1.03E-00
90	5.23E+06	1.03E-00
91	5.78E+06	1.02E-00
92	6.38E+06	9.94E-01
93	7.06E+06	9.85E-01
94	7.80E+06	9.13E-01
95	8.62E+06	9.11E-01
96	9.52E+06	8.49E-01
97	1.05E+07	7.96E-01
98	1.16E+07	7.24E-01
99	1.29E+07	6.74E-01
100	1.42E+07	6.25E-01

Table 14. Response Function for the Modified 3-in. Bonner Sphere*

Energy Group	$\bar{E}$ eV	Response Counts/ Neut/cm^2)	Energy Group	$\bar{E}$ eV	Response Counts/ Neut/cm^2)	Energy Group	$\bar{E}$ eV	Response Counts/ Neut/cm^2)
1-27	<2.449+2	negligible						
28	3.145+2	3.506-8	53	1.292+5	5.231-2	78	1.574+6	4.068-2
29	4.038+2	2.381-7	54	1.428+5	5.025-2	79	1.740+6	3.525-2
30	5.185+2	1.248-6	55	1.578+5	5.012-2	80	1.923+6	3.189-2
31	6.657+2	5.259-6	56	1.744+5	5.154-2	81	2.125+6	2.968-2
32	8.548+2	1.845-5	57	1.928+5	5.135-2	82	2.349+6	2.762-2
33	1.098+3	5.529-5	58	2.131+5	5.073-2	83	2.596+6	2.471-2
34	1.409+3	1.443-4	59	2.355+5	5.086-2	84	2.869+6	2.268-2
35	1.810+3	3.347-4	60	2.602+5	5.125-2	85	3.170+6	2.127-2
36	2.324+3	7.002-4	61	2.876+5	5.175-2	86	3.504+6	1.944-2
37	2.984+3	1.340-3	62	3.179+5	5.372-2	87	3.872+6	1.735-2
38	3.831+3	2.368-3	63	3.513+5	5.493-2	88	4.280+6	1.522-2
39	4.919+3	3.888-3	64	3.882+5	5.501-2	89	4.730+6	1.394-2
40	6.316+3	5.883-3	65	4.291+5	5.341-2	90	5.227+6	1.300-2
41	8.110+3	8.866-3	66	4.742+5	5.426-2	91	5.777+6	1.201-2
42	1.041+4	1.236-2	67	5.241+5	5.500-2	92	6.384+6	1.129-2
43	1.337+4	1.648-2	68	5.792+5	5.641-2	93	7.056+6	1.021-2
44	1.717+4	2.119-2	69	6.401+5	5.801-2	94	7.798+6	9.611-3
45	2.205+4	2.629-2	70	7.074+5	5.953-2	95	8.618+6	8.794-3
46	2.831+4	3.132-2	71	7.818+5	6.025-2	96	9.524+6	8.164-3
47	3.635+4	3.277-2	72	8.640+5	6.079-2	97	1.053+7	7.881-3
48	4.667+4	4.108-2	73	9.544+5	6.006-2	98	1.163+7	7.188-3
49	5.993+4	4.566-2	74	1.055+6	5.759-2	99	1.286+7	6.831-3
50	7.695+4	4.768-2	75	1.166+6	5.429-2	100	1.421+7	6.908-3
51	9.880+4	4.909-2	76	1.289+6	5.013-2			
52	1.169+5	5.124-2	77	1.425+6	4.604-2			

*Radial thickness of polyethylene = 0.47 inches; radial thickness of ^{10}B = 2.91 inches. Estimated accuracy is ± 10% for groups 1-100.

Table 15. Experimental Configurations

Nominal Sodium Thickness (in.)	Tank Numbers	Detector Locations (in.)* Centerline Distance Behind Slab	Detector Locations (in.)* Radial Distance From Centerline	Detector Type
30	1	24	0	Bonner Balls
		24	24	Bonner Balls
		166	0	Bonner Balls
60	3	24	0	Bonner Balls, Benjamin Spectrometer
		24	30	Bonner Balls
		359	0	Bonner Balls, Benjamin Spectrometer, NE-213 Spectrometer
		359	96	Benjamin Spectrometer, NE-213 Spectrometer
120	2+3	6→72	0	Bonner Balls
		2	0→84	Cadmium and 3-in. Bonner Balls
		2†	0→84	Cadmium and 3-in. Bonner Balls
		24	0	Benjamin Spectrometer, NE-213 Spectrometer
150	1+2+3	24	0	Bonner Balls Benjamin Spectrometer
180	1+2+3+4	6→72	0	Bonner Balls
		~24	0→84 (hor.)	3-in. and 12-in. Bonner Balls
		24	0→90 (vert.)	3-in. Bonner Ball

*Distance measured from the geometric center of the detector.

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

Table 16. Bonner Ball Counting Rates Behind 2.5 ft of Sodium (cts/min/watt)

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.
24 in. behind, on CL	58.5	840	2068	2678	2821	2163	1379	878
24 in. behind, 24 in. off CL	41.0	611	1428	1824	1801	1306	754	422
166 in. behind, on CL	4.07	55.7	129	174	187	159	113	77.5

Table 17. Bonner Ball Counting Rates Behind 5 ft of Sodium (cts/min/watt)

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod 3-in.
24 in. behind, on CL	21.4	295	590	639	551	318	149	71.8	6.94
24 in. behind, 30 in. off CL	17.2	228	435	462	389	224	102	46.6	--
359 in. behind, on CL	0.372	4.89	9.05	9.32	8.02	4.88	2.37	1.24	0.103

Table 18. Bonner Ball Counting Rates Behind 10 ft of Sodium (cts/min/watt)

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod 3-in.
6 in. behind, on CL	3.08	27.5	39.9	35.4	26.7	12.1	4.90	1.78	--
12 in. behind, on CL	2.66	23.5	34.5	30.5	22.8	10.2	4.17	1.51	--
24 in. behind, on CL	1.96	17.3	25.3	22.3	16.7	7.61	3.01	1.09	0.0308
36 in. behind, on CL	1.50	13.0	18.9	16.8	12.6	5.67	2.26	0.818	--
48 in. behind, on CL	1.14	10.1	14.7	12.8	9.52	4.31	1.71	0.616	--
60 in. behind, on CL	0.888	7.78	11.3	9.85	7.41	3.32	1.33	0.471	--
72.4 in. behind, on CL	0.707	6.07	8.82	7.74	5.78	2.61	1.03	0.368	0.0103

Table 19. Cadmium Ball Counting Rates 2 in. Behind 10 ft of Sodium (cts/min/watt)

	Air Backing the Detector	Sodium Backing the Detector†
on CL	3.55	9.88
12 in. off CL	3.36	9.54
24 in. off CL	2.95	8.57
36 in. off CL	2.39	6.97
48 in. off CL	1.69	5.12
60 in. off CL	0.909	3.13

†These measurements were made with one of the 5 ft thick sodium tanks immediately behind the detector, so that the geometry approximated an "in situ" measurement. The effects of reflection from the sodium tank are thus seen to enhance the counting rates by about a factor of three.

Table 20. 3-in. Bonner Ball Counting Rates 2 in. Behind 10 ft of Sodium (counts/min/watt)

	Air Backing the Detector	Sodium Backing† the Detector
on CL	30.6	80.2
12 in. off CL	28.8	77.3
24 in. off CL	25.3	68.8
36 in. off CL	20.3	56.2
48 in. off CL	14.0	40.1
60 in. off CL	7.34	23.9

†See note following Table 19.

Table 21. Bonner Ball Counting Rates Behind 12.5 ft of Sodium (cts/min/watt)

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod 3-in.
24 in. behind, on CL	0.349	2.51	3.40	2.91	2.11	0.950	0.359	0.141	0.00177

Table 22. Bonner Ball Counting Rates Behind 15 ft of Sodium (cts/min/watt)

Bonner Ball	Cd	3-in.	4-in.	5-in.	6-in.	8-in.	10-in.	12-in.	Mod 3-in.
6 in. behind, on CL	0.0920	0.585	0.773	0.626	0.453	0.199	0.0771	0.0304	--
12 in. behind, on CL	0.0765	0.507	0.661	0.543	0.392	0.174	0.0664	0.0255	---
24 in. behind, on CL	0.0570	0.394	0.496	0.405	0.289	0.127	0.0497	0.0189	0.000121*
48 in. behind, on CL	0.0330	0.220	0.287	0.232	0.166	0.0745	0.0286	0.0108	---
72 in. behind, on CL	0.0202	0.135	0.176	0.143	0.103	0.0466	0.0176	0.0070	---

*23 in. behind

Table 23. 3-in. Bonner Ball Counting Rates 24 in. Behind 15 ft of Sodium

Horizontal Traverse		Vertical Traverse			
Distance from CL (in.)	Counts/min/watt	Distance from CL (in.)	Counts/min/watt	Distance from CL (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	0.222	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 24. 12-in. Bonner Ball Counting Rates 23 in. Behind 15 ft Sodium

Horizontal Traverse	
Distance from CL (in.)	Counts/min/watt
84 South	4.04×10^{-3}
72	5.75×10^{-3}
60	8.69×10^{-3}
48	1.36×10^{-2}
36	1.69×10^{-2}
24	1.82×10^{-2}
12	2.05×10^{-2}
0	2.16×10^{-2}
12 North	2.34×10^{-2}
24	1.87×10^{-2}
36	1.57×10^{-2}
48	1.24×10^{-2}
60	8.61×10^{-3}
72	5.64×10^{-3}
84	3.87×10^{-3}

Table 25. Benjamin Counter Spectrum Behind 5 ft of Sodium

Counter	Upper Limit Energy Interval (keV)	Flux (Neuts/cm^2/MeV/Min/Watt	Standard Error %
Measurements on Centerline 24 in. Behind Slab			
10 Atmosphere	1350.0	12.3	6.7
	1186.1	11.8	7.4
	1039.5	9.9	10.2
	918.7	12.6	7.9
	806.5	9.8	11.0
	711.7	13.7	7.8
	625.4	26.9	4.1
	547.8	--	--
3 Atmosphere	700.0	16.9	9.4
	613.9	25.8	7.0
	541.4	52.9	3.4
	473.5	52.8	4.3
	419.1	59.5	3.9
	369.3	85.0	2.9
	323.9	131	2.0
	283.2	138	2.4
	251.5	116	2.7
	219.7	--	--
1 Atmosphere	300.0	148	3.6
	263.5	134	4.7
	232.5	119	5.2
	203.3	157	4.7
	179.6	181	4.2
	157.8	240	3.6
	139.5	330	2.8
	123.1	360	2.4
	106.7	355	3.0
	93.9	446	2.7
	83.0	645	2.1
	73.9	--	--

Table 25 contd.

	Measurements on Centerline 359 in. Behind Slab		
10 Atmosphere	1350.0	0.200	11.5
	1180.7	0.180	14.3
	1038.1	0.201	13.5
	913.4	0.176	16.7
	806.4	0.195	14.7
	708.4	0.200	16.1
	628.2	0.402	7.1
	548.0	--	--
3 Atmosphere	700.0	0.257	22.8
	613.0	0.278	23.6
	541.4	0.857	7.8
	473.5	0.617	13.3
	419.1	0.742	11.3
	369.3	1.21	7.2
	323.9	2.02	4.6
	283.2	1.99	6.0
	251.5	1.66	6.7
	219.7	--	--
1 Atmosphere	300.0	2.32	11.1
	263.3	2.21	14.0
	232.1	1.58	21.1
	204.6	1.88	17.5
	178.9	2.56	16.0
	158.7	3.47	10.7
	138.5	4.68	9.5
	122.0	5.36	9.0
	107.3	4.86	10.7
	94.5	5.67	10.1
	83.5	9.19	5.9
	72.5	--	--

Table 25 contd.

Measurements 96 in. off the Centerline 359 in. Behind Slab			
10 Atmosphere	1350.0	0.182	10.6
	1186.1	0.141	14.2
	1039.5	0.173	13.5
	918.7	0.175	13.0
	806.5	0.164	15.2
	711.7	0.157	15.6
	625.4	0.343	7.2
	547.8	--	--
3 Atmosphere	700.0	0.214	26.5
	413.9	0.282	22.7
	541.4	0.654	9.9
	473.5	0.528	15.2
	419.1	0.744	11.1
	369.3	1.00	8.6
	323.9	1.76	5.3
	283.2	1.72	6.9
	251.5	1.49	7.4
	219.7	--	--
1 Atmosphere	300.0	2.08	13.3
	263.5	1.58	20.6
	232.5	1.43	22.5
	203.3	2.00	19.1
	179.6	2.08	18.5
	157.8	3.77	11.9
	139.5	4.27	11.2
	123.1	4.60	9.7
	106.7	5.09	10.9
	93.9	5.86	10.5
	83.0	8.62	8.3
	73.9	--	--

Table 26. Benjamin Counter Spectrum on the Centerline 24 in. Behind 10 ft of Sodium

Counter	Upper Limit Energy Interval (keV)	Flux ($Neuts/cm^2/MeV/Min/Watt$)	Standard Error %
10 Atmosphere	1500.0	2.88×10^{-2}	13.2
	1313.1	2.77×10^{-2}	15.6
	1154.2	2.50×10^{-2}	20.0
	1023.4	3.46×10^{-2}	12.9
	892.5	2.87×10^{-2}	18.7
	789.7	3.10×10^{-2}	17.2
	696.3	5.01×10^{-2}	10.8
	612.1	9.17×10^{-2}	6.3
	537.4	--	--
3 Atmosphere	541.4	0.140	10.6
	473.5	0.143	13.1
	419.1	0.160	12.2
	369.3	0.261	8.0
	323.9	0.468	4.9
	283.2	0.436	6.9
	251.5	0.385	7.3
	219.7	--	--
1 Atmosphere	300.0	0.45	12.7
	263.1	0.490	14.4
	231.7	0.275	27.6
	204.0	0.489	17.0
	180.0	0.609	13.9
	157.8	0.921	10.8
	139.4	1.33	8.1
	122.8	1.38	8.7
	108.1	1.29	10.1
	95.1	1.86	7.9
	84.0	3.00	4.7
	72.9	--	--

Table 27. Benjamin Counter Spectrum on the Centerline 24 in. Behind 12.5 ft of Sodium

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

Table 28. NE-213 Spectrum on the Centerline 359 in. Behind 5 ft of Sodium

Energy (MeV)	Flux (Neuts/Cm^2/MeV/Min/Watt) Upper Limit	Lower Limit	Energy (MeV)	Flux (Neuts/Cm^2/MeV/Min/Watt) Upper Limit	Lower Limit
1.0	2.35×10^{-1}	1.95×10^{-1}	3.0	1.32×10^{1}	1.22×10^{1}
1.1	2.38×10^{-1}	2.05×10^{-1}	3.2	1.01×10^{-1}	9.0×10^{-2}
1.2	2.30×10^{-1}	2.08×10^{-1}	3.4	7.7×10^{-2}	6.4×10^{-2}
1.3	2.20×10^{-1}	1.95×10^{-1}	3.6	6.4×10^{-2}	5.2×10^{-2}
1.4	2.25×10^{-1}	2.00×10^{-1}	3.8	7.1×10^{-2}	5.7×10^{-2}
1.5	2.25×10^{-1}	2.05×10^{-1}	4.0	8.4×10^{-2}	7.3×10^{-2}
1.6	2.00×10^{-1}	1.78×10^{-1}	4.2	9.2×10^{-2}	8.0×10^{-2}
1.7	1.73×10^{-1}	1.53×10^{-1}	4.4	9.0×10^{-2}	7.8×10^{-2}
1.8	1.70×10^{-1}	1.40×10^{-1}	4.6	8.5×10^{-2}	7.4×10^{-2}
1.9	1.50×10^{-1}	1.35×10^{-1}	4.8	7.2×10^{-2}	6.2×10^{-2}
2.0	1.24×10^{-1}	1.10×10^{-1}	5.0	6.5×10^{-2}	5.5×10^{-2}
2.1	1.02×10^{-1}	8.7×10^{-2}	5.2	6.2×10^{-2}	5.2×10^{-2}
2.2	8.1×10^{-2}	6.5×10^{-2}	5.4	5.6×10^{-2}	4.7×10^{-2}
2.3	8.3×10^{-2}	6.8×10^{-2}	5.6	5.1×10^{-2}	4.1×10^{-2}
2.4	9.2×10^{-2}	7.8×10^{-2}	5.8	5.3×10^{-2}	4.4×10^{-2}
2.5	9.6×10^{-2}	8.4×10^{-2}	6.0	5.6×10^{-2}	4.7×10^{-2}
2.6	1.03×10^{-1}	9.1×10^{-2}	6.2	5.8×10^{-2}	4.9×10^{-2}
2.7	1.19×10^{-1}	1.06×10^{-1}	6.4	5.4×10^{-2}	4.5×10^{-2}
2.8	1.33×10^{-1}	1.20×10^{-1}	6.6	5.2×10^{-2}	4.4×10^{-2}
2.9	1.37×10^{-1}	1.27×10^{-1}	6.8	4.9×10^{-2}	4.1×10^{-2}

Table 28. Contd.

7.0	4.1×10^{-2}	3.3×10^{-2}	9.2	1.9×10^{-2}	1.47×10^{-2}
7.2	3.6×10^{-2}	2.9×10^{-2}	9.4	1.44×10^{-2}	1.08×10^{-2}
7.4	3.7×10^{-2}	3.0×10^{-2}	9.6	1.22×10^{-2}	9.9×10^{-3}
7.6	3.5×10^{-2}	2.9×10^{-2}	9.8	1.17×10^{-2}	9.1×10^{-3}
7.8	3.0×10^{-2}	2.4×10^{-2}	10.0	1.04×10^{-2}	8.0×10^{-3}
8.0	2.55×10^{-2}	1.95×10^{-2}	10.2	9.0×10^{-3}	5.9×10^{-3}
8.2	2.2×10^{-2}	1.65×10^{-2}	10.4	7.7×10^{-3}	4.7×10^{-3}
8.4	2.15×10^{-2}	1.65×10^{-2}	10.6	6.4×10^{-3}	3.4×10^{-3}
8.6	2.25×10^{-2}	1.8×10^{-2}	10.8	5.7×10^{-3}	2.85×10^{-3}
8.8	2.4×10^{-2}	1.95×10^{-2}	11.0	5.8×10^{-3}	2.9×10^{-3}
9.0	2.3×10^{-2}	1.9×10^{-2}	11.2	5.4×10^{-3}	2.7×10^{-3}

Table 29. NE-213 Spectrum 96 in. off the Centerline 359 in Behind 5 ft of Sodium

Energy (MeV)	Flux (Neuts/Cm^2/MeV/Min/Watt) Upper Limit	Lower Limit	Energy (MeV)	Flux (Neuts/Cm^2/MeV/Min/Watt) Upper Limit	Lower Limit
1.0	1.95×10^{-1}	1.65×10^{-1}	5.2	2.15×10^{-2}	1.85×10^{-2}
1.1	1.85×10^{-1}	1.6×10^{-1}	5.4	1.9×10^{-2}	1.5×10^{-2}
1.2	2.0×10^{-1}	1.8×10^{-1}	5.6	1.7×10^{-2}	1.4×10^{-2}
1.3	2.0×10^{-1}	1.85×10^{-1}	5.8	1.75×10^{-2}	1.4×10^{-2}
1.4	1.8×10^{-1}	1.7×10^{-1}	6.0	1.65×10^{-2}	1.4×10^{-2}
1.5	1.65×10^{1}	1.4×10^{1}	6.2	1.6×10^{-2}	1.25×10^{-2}
1.6	1.4×10^{-1}	1.25×10^{-1}	6.4	1.55×10^{-2}	1.2×10^{-2}
1.7	1.35×10^{-1}	1.2×10^{-1}	6.6	1.4×10^{-2}	1.08×10^{-2}
1.8	1.3×10^{-1}	1.15×10^{-1}	6.8	1.2×10^{-2}	9.5×10^{-3}
1.9	1.07×10^{-1}	9.9×10^{-2}	7.0	9.5×10^{-3}	7.8×10^{-3}
2.0	9.2×10^{-2}	8.4×10^{-2}	7.2	8.8×10^{-3}	6.4×10^{-3}
2.1	8.1×10^{-2}	7.4×10^{-2}	7.4	8.1×10^{-3}	5.9×10^{-3}
2.2	7.0×10^{-2}	6.3×10^{-2}	7.6	8.0×10^{-3}	5.9×10^{-3}
2.3	6.6×10^{-2}	5.9×10^{-2}	7.8	7.9×10^{-3}	5.8×10^{-3}
2.4	6.7×10^{-2}	6.0×10^{-2}	8.0	7.5×10^{-3}	5.5×10^{-3}
2.5	6.9×10^{-2}	6.2×10^{-2}	8.2	7.0×10^{-3}	5.1×10^{-3}
2.6	6.9×10^{-2}	6.3×10^{-2}	8.4	6.7×10^{-3}	4.9×10^{-3}
2.7	6.6×10^{-2}	6.0×10^{-2}	8.6	6.2×10^{-3}	4.6×10^{-3}
2.8	6.2×10^{-2}	5.7×10^{-2}	8.8	5.8×10^{-3}	4.0×10^{-3}
2.9	5.9×10^{-2}	5.4×10^{-2}	9.0	5.1×10^{-3}	3.8×10^{-3}
3.0	5.6×10^{-2}	5.2×10^{-2}	9.2	4.2×10^{-3}	2.8×10^{-3}
3.2	4.9×10^{-2}	4.4×10^{-2}	9.4	2.9×10^{-3}	1.35×10^{-3}
3.4	3.7×10^{-2}	3.2×10^{-2}	9.6	2.3×10^{-3}	6.7×10^{-4}
3.6	3.6×10^{-2}	3.1×10^{-2}	9.8	2.1×10^{-3}	8.5×10^{-4}
3.8	3.8×10^{-2}	3.2×10^{-2}	10.0	2.5×10^{-3}	1.1×10^{-3}
4.0	4.1×10^{-2}	3.6×10^{-2}	10.2	2.4×10^{-3}	1.07×10^{-3}
4.2	4.0×10^{-2}	3.5×10^{-2}	10.4	1.95×10^{-3}	7.8×10^{-4}
4.4	3.4×10^{-2}	2.9×10^{-2}	10.6	1.75×10^{-3}	7.0×10^{-4}
4.6	2.7×10^{-2}	2.3×10^{-2}	10.8	1.85×10^{-3}	9.0×10^{-4}
4.8	2.3×10^{-2}	1.95×10^{-2}	11.0	2.1×10^{-3}	1.05×10^{-3}
5.0	2.25×10^{-2}	1.9×10^{-2}	11.2	2.1×10^{-3}	1.0×10^{-3}

Table 30. NE-213 Spectrum on the Centerline 24 in. Behind 10 ft of Sodium

Energy (MeV)	Flux (Neuts/Cm^2/MeV/Min/Watt) Upper Limit	Lower Limit	Energy (MeV)	Flux (Neuts/Cm^2/MeV/Min/Watt) Upper Limit	Lower Limit
1.1	4.0×10^{-2}	3.4×10^{-2}	4.8	4.3×10^{-3}	2.8×10^{-3}
1.2	4.2×10^{-2}	3.7×10^{-2}	5.0	4.7×10^{-3}	3.2×10^{-3}
1.3	4.55×10^{-2}	4.1×10^{-2}	5.2	3.65×10^{-3}	2.15×10^{-3}
1.4	4.4×10^{-2}	4.0×10^{-2}	5.4	2.15×10^{-3}	7.4×10^{-4}
1.5	3.7×10^{-2}	3.3×10^{-2}	5.6	2.35×10^{-3}	1.0×10^{-3}
1.6	3.2×10^{-2}	2.75×10^{-2}	5.8	3.4×10^{-3}	2.05×10^{-3}
1.7	2.8×10^{-2}	2.45×10^{-2}	6.0	3.3×10^{-3}	2.05×10^{-3}
1.8	2.45×10^{-2}	2.0×10^{-2}	6.2	2.0×10^{-3}	7.4×10^{-4}
1.9	2.3×10^{-2}	1.9×10^{-2}	6.4	1.0×10^{-3}	$<1.0\times10^{-4}$
2.0	2.05×10^{-2}	1.7×10^{-2}	6.6	1.65×10^{-3}	4.5×10^{-4}
2.1	1.55×10^{-2}	1.23×10^{-2}	6.8	2.5×10^{-3}	1.35×10^{-3}
2.2	1.28×10^{-2}	9.6×10^{-3}	7.0	2.5×10^{-3}	1.45×10^{-3}
2.3	1.37×10^{-2}	1.08×10^{-2}	7.2	2.3×10^{-3}	1.25×10^{-3}
2.4	1.44×10^{-2}	1.17×10^{-2}	7.4	2.3×10^{-3}	1.33×10^{-3}
2.5	1.42×10^{-2}	1.17×10^{-2}	7.6	1.87×10^{-3}	9.5×10^{-4}
2.6	1.27×10^{-2}	1.04×10^{-2}	7.8	1.04×10^{-3}	1.65×10^{-4}
2.7	1.04×10^{-2}	8.3×10^{-3}	8.0	6.25×10^{-4}	$<1.0\times10^{-4}$
2.8	9.4×10^{-3}	7.2×10^{-3}	8.2	7.2×10^{-4}	$<1.0\times10^{-4}$
2.9	1.0×10^{-2}	8.0×10^{-3}	8.4	9.8×10^{-4}	1.83×10^{-4}
3.0	1.1×10^{-2}	9.0×10^{-3}	8.6	1.25×10^{-3}	4.7×10^{-4}
3.2	9.2×10^{-3}	7.3×10^{-3}	8.8	1.31×10^{-3}	5.9×10^{-4}
3.4	7.4×10^{-3}	5.4×10^{-3}	9.0	1.22×10^{-3}	5.4×10^{-4}
3.6	6.0×10^{-3}	4.0×10^{-3}	9.2	1.13×10^{-3}	4.4×10^{-4}
3.8	7.2×10^{-3}	5.2×10^{-3}	9.4	1.07×10^{-3}	4.0×10^{-4}
4.0	7.0×10^{-3}	5.0×10^{-3}	9.6	9.6×10^{-4}	3.66×10^{-4}
4.2	4.8×10^{-3}	3.1×10^{-3}	9.8	8.25×10^{-4}	2.1×10^{-4}
4.4	4.3×10^{-3}	2.6×10^{-3}			
4.6	4.3×10^{-3}	2.75×10^{-3}			

Methods of Calculation

For sodium thicknesses of 2.5, 5, and 10 ft, the effect of multiple reflection between the sodium tanks and the materials that surround the collimator on the transmitted fluxes through the sodium below ∿1 MeV should be considered in the calculation. Thus, for these smaller thicknesses, the collimator geometry should be included in the problem, particularly the concrete surrounding the collimator (see Fig. 1). The composition of the concrete surrounding the collimator and of the borated polyethylene lining the collimator are shown in Table 31.

Table 31. Composition of the Concrete and Polyethylene Liner Surrounding the Collimator

Element	Concrete		Liner	
	Atomic Density (atoms/barn cm)	Partial Density (grams/cm^3)	Atomic Density (atoms/barn cm)	Partial Density (grams/cm^3)
Carbon	1.20×10^{-2}	0.238	3.85×10^{-2}	0.766
Hydrogen	5.80×10^{-3}	0.010	7.71×10^{-2}	0.128
Natural Boron	---	---	3.1×10^{-3}	0.056
Oxygen	4.25×10^{-2}	1.128	---	---
Calcium	1.32×10^{-2}	0.875	---	---
Silicon	1.13×10^{-3}	0.049	---	---

The approximate increase in the transmitted flux due to inclusion of this multiple reflection effect is shown in Table 32.

Table 32. Approximate Increase in the Total Fluxes Above Thermal Transmitted Thru the Sodium Due to Multiple Reflection Between the Collimator Materials and Sodium Tanks

Sodium Thickness (ft)	Flux with Mult. Refl/Flux without
2.5	1.20
5	1.15
10	1.10
12.5	1.05
15	1.03

The importance of the concrete collar surrounding the sodium tanks can be gauged by noting that for the most critical case (i.e., behind 15 ft of sodium) only about 1/4 of the calculated neutrons that leak the rear face of the sodium and remain above thermal energies have suffered a collision in the collar. Thus, most of the non-thermalized neutrons that succeed in leaking 15 ft of sodium are those that do not migrate more than 5.5 ft from the centerline. However, for accurate calculations, the two-dimensional cylindrical geometry depicted in Fig. 1, including 18 in. of concrete collar, the aluminum, and at least a rudimentary collimator geometry, is recommended.

This experiment has been calculated by ORNL in two separate ways - by discrete ordinates and by Monte Carlo. Either way is recommended, but there are problem areas in each method which should be mentioned.

In using Monte Carlo, biasing is necessary for sodium penetrations of 10 ft and greater. The ORNL calculations employed path length stretching and source energy biasing with the biasing parameters being obtained from adjoint ANISN calculations. The biasing parameters are in general functions of the sodium thickness to be penetrated and energy region of the transmitted spectrum to be calculated. The concrete collar can be replaced by a reflecting medium having the more important differential albedo properties of concrete, in order to save computing time. Since the effect of the concrete collar on the sodium transmitted fluxes in the vicinity of the centerline is relatively small, one is permitted to treat the collar in a somewhat cavalier fashion. If fluxes immediately behind the concrete collar are to be calculated, however, these calculations must use the cross-section data of the concrete as well. For Monte Carlo calculations, the source on the exit plane described in Table 3 multiplied by 1200 cm^2 may be used, spatially sampled over the open end of the collimator by first choosing an incident direction randomly over the interval, $1 \geq \cos\theta \geq 0.99188$, $0 \leq \phi \leq 2\pi$ from the virtual point source and then calculating the intersection of this ray with the exit plane of the collimator. Uncollided contributions to detectors located along the centerline should be calculated analytically where they are important (i.e., for sodium thickness of 2.5 and 5 ft) using the entries directly from Table 3 as the ϕ_0 (E_g) and calculating

$$\phi_{unc}(Z,E_g) = \phi_0(E_g) \times \left(\frac{59.5}{59.5+Z}\right)^2 \times \exp\left(-\int_0^T \Sigma_T(E_g,Z')dZ'\right) ,$$

where the detector is located a distance of Z inches from the exit plane of the collimator, T is the thickness of the sodium tank in inches, and $\Sigma_T(Z')$ is expressed in in.$^{-1}$. Calculated fluxes in the NE-213 region (0.5-12 MeV) should be smoothed with the resolution function appearing in Table 4 before comparing with experiment. Calculated fluxes in the Benjamin counter region (50 keV-1.5 MeV) should be smoothed with a constant 10% FWHM resolution before comparing with experiment. Calculated spectral fluxes at the center of detection of each Bonner ball (see Table 5) must be integrated over the response functions (Tables 6-14) before comparing with experiment. Calculations of the Bonner ball counting rates involve evaluation of the following expression:

$$\text{Counts/min/watt}(r) = \sum_g \phi(E_g, r-\Delta)R(E_g),$$

where r is the distance of the geometric center of the ball from the center of the exit face of the tanks,

Δ is the center of detection correction given in Table 5,

$r-\Delta$ is the location of the detector for the calculated fluxes,

and $R(E_g)$ is the response function of the Bonner ball for group E_g.

Note that the numbering of the groups in the response function tabulations in Tables 6-14 has been reversed, so that $R(E_g)$ in the above equation appears as $R(E_{101-g})$ in the tables. Errors of the order of 1-10% are incurred if calculated fluxes at the geometric center of the Bonner ball are used and are such that the Bonner ball counting rates are under-estimated. The errors increase with increasing size of the Bonner ball and decreasing distance between the ball and the rear face of the tanks.

For discrete ordinate calculations, a two-dimensional code such as DOT-III is recommended. Use of a first-collision source routine in the code is necessary when the uncollided contribution is important (2.5 and 5 ft of sodium), otherwise, a spurious and unknown uncollided contribution is calculated in the mockup of the point anisotropic source which is strongly dependent on the order of angular quadrature used. The source used by ORNL for the collimated source beam was represented 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 $\tan^{-1} \frac{15.25}{2x59.5} = 7.30°$, measured from the centerline, of total intensity $4\pi(59.5x2.54)^2\ (2.702x10^5) = 7.76x10^{10}$ 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 3 multipled by the factor $4\pi\ (59.5x2.54)^2 = 2.87x10^5$. The uncollided contribution was analytically calculated in a manner identical to that employed in the Monte Carlo calculation previously described. Since the detectors all lie beyond the sodium, an additional calculation was necessary to translate the discrete ordinate angular fluxes calculated in the sodium tank to total group fluxes at the detector locations by integrating over the collisions in the sodium tank with a last flight calculation to the detector. This calculation involved use of the routine FALSTF, and is simpler and more accurate than incorporating air around the sodium tanks and using the detector as a space point directly in the discrete ordinates calculation.

For either method of calculation, thermal group calculations may be omitted since the measurements reported herein involve zero sensitivity to thermal neutrons.

The recommended choice for either method of calculation for the group structure is 100 groups (GAM-II) expanded through P_3 in the angular distribution of scatter. Table 33 shows a comparison of ANISN calculations using various combinations of group structure and P_n expansion of the neutrons leaking a 5-meter radius sphere of sodium from a point fission source at the center.

Table 33. Comparisons of Surface Leakages Calculated by ANISN (neutrons/source neutron)

Group 100	Group 50	ΔE		50-Group P_1	50-Group P_3	100-Group P_1	100-Group P_3
1,2	1	12.2-14.9	MeV	1.14-11	4.27-11	1.17-11	4.44-11
3,4	2	10.0-12.2		4.31-11	1.27-10	4.39-11	1.30-10
5,6	3	8.19-10.0		1.37-10	3.69-10	1.36-10	3.67-10
7,8	4	6.70-8.10		4.22-10	1.11-9	4.08-10	1.08-9
9,10	5	5.49-6.70		4.89-10	1.20-9	5.05-10	1.14-9
11,12	6	4.49-5.49		8.77-10	1.93-9	8.46-10	1.88-9
13,14	7	3.68-4.49		8.88-10	1.74-9	9.34-10	1.84-9
15,16	8	3.01-3.68		1.70-9	3.11-9	1.66-9	3.11-9
17,18	9	2.47-3.01		1.95-9	3.40-9	1.98-9	3.47-9
19,20	10	2.02-2.47		1.97-9	3.32-9	2.05-9	3.49-9
21,22	11	1.65-2.02		4.16-9	6.64-9	4.23-9	6.84-9
23,24	12	1.35-1.65		6.31-9	9.63-9	6.01-9	9.34-9
25,26	13	1.11-1.35		5.15-9	7.73-9	5.26-9	7.97-9
27,28	14	0.907-1.11		3.98-9	5.91-9	3.91-9	5.88-9
29,30	15	0.743-0.907		3.77-9	5.56-9	3.86-9	5.75-9
31,32	16	0.608-0.743		2.62-9	3.85-9	2.64-9	3.92-9
33,34	17	0.497-0.608		7.59-9	1.09-8	8.02-9	1.16-8
35,36	18	0.408-0.497		9.48-9	1.33-8	9.44-9	1.34-8
37,38	19	0.334-0.408		1.14-8	1.57-8	1.15-8	1.61-8
39,40	20	0.273-0.334		2.03-8	2.73-8	2.00-8	2.73-8
41,42	21	0.224-0.273		1.31-8	1.75-8	1.35-8	1.81-8
43,44	22	0.183-0.224		1.59-8	2.10-8	1.66-8	2.22-8
45,46	23	0.150-0.183		2.84-8	3.68-8	2.81-8	3.67-8
47,48	24	0.123-0.150		3.25-8	4.15-8	3.20-8	4.13-8
49,50	25	0.0865-0.123		8.08-8	1.00-7	7.52-8	9.44-8

Table 33. Contd.

51,52	26	52.5-86.5	keV	7.51-8	9.18-8	8.19-8	1.01-7
53	27	40.9-52.5		6.45-8	7.79-8	6.59-8	8.01-8
54	28	31.8-40.9		8.97-8	1.07-7	9.12-8	1.09-7
55	29	24.8-31.8		1.04-7	1.22-7	1.06-7	1.25-7
56	30	19.3-24.8		1.17-7	1.37-7	1.20-7	1.40-7
57	31	15.0-19.3		1.26-7	1.45-7	1.29-7	1.49-7
58-60	32	7.10-15.0		3.77-7	4.27-7	3.43-7	3.94-7
61-62	33	4.31-7.10		8.75-8	9.90-8	8.86-8	1.01-7
63	34	3.35-4.31		5.12-9	5.81-9	4.83-9	5.52-9
64	35	2.61-3.35		1.26-9	1.68-9	1.30-9	1.61-9
65	36	2.03 -2.61		7.95-9	9.33-9	7.69-9	8.91-9
66	37	1.58-2.03		6.17-8	6.95-8	6.03-8	6.85-8
67	38	1.23-1.58		1.76-7	1.97-7	1.73-7	1.95-7
68	39	0.961-1.23		3.15-7	3.48-7	3.12-7	3.47-7
69-71	40	454-961	eV	3.57-6	3.78-6	2.16-6	2.35-6
72-74	41	214-454		1.03-5	1.06-5	5.46-6	5.74-6
75-77	42	101-214		2.39-5	2.43-5	1.24-5	1.28-5
78-80	43	47.9-101		4.69-5	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	4.75-5
84-86	45	10.7-22.6		1.27-4	1.28-4	7.89-5	7.96-5
8							
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		2.26-4	2.26-4	1.62-4	1.63-4
93-95	48	1.13-2.38		2.56-4	2.56-4	1.97-4	1.98-4
96-99	49	0.414-1.113		3.47-4	3.48-4	2.78-4	2.78-4

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