Bugle-96 Validation with Morse-SGC/S Using Water and Iron Experiments from Sinbad 97

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1.0 Introduction

This document summarizes the validation of MORSE-SGC/S [1] with the BUGLE-96 cross section library [2]. SINBAD [3] Benchmark Experiment (SBE) 2.004, Winfrith Water Benchmark Experiment and SBE 6.001, Karlsruhe Iron Sphere Benchmark Experiment were utilized for this validation. The MORSE-SGC/S code with the BUGLE-96 cross-section library was used to model the experimental configurations as given in SINDBAD 97. SINDBAD is a shielding integral benchmark archive and database developed at the Oak Ridge National Laboratory (ORNL). For means of comparison, the experimental models were also executed with MORSE-SGC/S using the BUGLE-80 cross-section library. BUGLE-96 cross section will be used for shielding applications only as recommended by ORNL.

2.0 Methodology

2.1 Code System and Computer Platform

MORSE-SGC/S is the SCALE version of the MORSE-SGC code, a member of the MORSE Monte Carlo family of codes developed at Oak Ridge National Laboratory (ORNL). MORSE-SGC is unique from other versions of MORSE since it contains supergroup cross-section storage and tracking features along with an improved geometry system (MARS, Multiple ARray System) for nested rectangular array analysis. The basic theory behind all the MORSE codes is identical, however, and has been documented in Ref. 1.

The MORSE-SGC/S modular code system was received from the Radiation Shielding Information Center (RSIC) as part of the SCALE 4.3 package [4]. It was installed on the WSMS Digital Equipment Alpha Processors (DEC Alpha) UNIX Workstation cluster, where the validation calculations were executed [5].

2.2 Cross Section Library

A new multigroup cross-section library based on ENDF/B-VI data was used. This broad-group (47 neutron, 20 gamma-ray) library, designated as DLC-185/ BUGLE-96 (or simply BUGLE-96), is intended to replace the DLC-75/BUGLE-80 and DLC-76/SAILOR libraries, which are both based on ENDF/B-IV data. It also replaces DLC-175/BUGLE-93 library by correcting some deficiencies and adding several additional data sets.

The BUGLE-96 cross section library was produced and tested for light water reactor shielding and reactor pressure vessel dosimetry applications. It contains 120 nuclides, which have been processed as infinitely dilute and collapsed using an LWR concrete shield spectrum. Additionally, it contains 105 nuclides which have been energy self-shielded and collapsed using LWR-specific material composition and flux spectra.

BUGLE-96 cross section set was obtained from RSICC. The BUGLE 96 library needs to be converted from the ANISN format to an AMPX working library format before it can be used with the functional modules in SCALE like MORSE or XSDRNPM. This is different from the 27-group or the 238-group library in master library format commonly used in SCALE.

If one wants to run with the SCALE control modules like SAS1, SAS3 or SAS4, VITAMIN-B library in master library format may be used. This is the 199-group library from which BUGLE96 was collapsed.

There are two BUGLE files in the DLC-185 set. One is BUGLE-96 and the other is BUGLE-96T. In our study, BUGLE-96T is used, because it is the same cross section set as BUGLE-96 with the thermal upscattering cross sections retained.

We have used the SCALE module LAVA to convert BUGLE-96T from ANISN to AMPX format. A formatting problem was found in the original BUGLE-96T file. The problem has been corrected and the corresponding modified file is called BUGLE-96T1. The normal scale scripts (subscale, smr_scale4.3_script, batch43 (here called lava43) and scale43 (here called scale96t) have been used to run LAVA with an input deck called lava96t.in to produce an ampX formatted library called bugle96_ampx.bin.

2.3 SINBAD 97 Shielding Database

SINBAD 97/DLC-191, a shielding integral benchmark archive and database was developed at ORNL and was obtained from RSICC. SINBAD is an active and growing radiation benchmark catalogue that provides the most accurate and complete electronic data available from bulk shielding experiments. SINBAD 97 contains ten (10) fission and one (1) fusion benchmark compilations for shielding analysis. The Winfrith (ASPIS) water benchmark experiment and the Karlsruhe iron benchmark experiment were selected for MORSE- SGC/S validation with BUGLE-96 for this initial phase and more experiments will be used in the future subject to the availability of funding. The details of the experiments are outlined in Section 3.

3.0 General Experiment and Source Data

The general experimental arrangements, detector locations, and source term data for the Winfrith water experiments and the Karlsruhe iron experiments are given in Sections 3.1 and 3.2, respectively.

3.1 Winfrith Water Benchmark Experiment (SBE 2.004)

Seven sets of experiments were analyzed with different source to detector distance. Cf-252 sources were used in the experiments. The 47-group Cf-252 spontaneous fission spectrum data (identical to Bugle-96 group structure) was obtained from the University of Illinois Iron Benchmark evaluation (1975) as documented in SINBAD 97.

a) Experimental Arrangement

The general arrangement of the experiment (shown in Figure 3.1-1) consists of a light structure supporting a vertical aluminium tube in which the measurements are made. Eight neutron sources are suspended from the arms of the support structure at predetermined and accurately known distances from the axis of the measurement tube. The sources are suspended at equal distances from the arms. All measurements are made in the source plane and at distances of 15 cm and 30 cm above and below the source plane in the air-filled measurement tube. The support structure is located in a water-filled aluminium tank with a cross-section of 228 cm x 177 cm and a height of 172 cm. The nearest distance of a source to any external boundary during any measurement was approximately 38 cm. Since this is more than four times the migration length of 5 MeV neutrons in water, the whole source-detector arrangement can be safely treated as being immersed in an infinite bath of water.

Figure 3.1-1: Schematic of the benchmark experiment.

Figure 3.1-2 shows in detail the source-detector arrangement with one source at the minimum separation distance of 101.6 mm from the center of the detector. This separation distance can be increased in units of 50.8 mm and up to eight sources can be positioned symmetrically about the detector. The inner source capsule is contained by double stainless steel walls of total thickness 1.6 mm and inserted via a plug (not shown in the Figure) into an outer cylindrical stainless steel container.

The neck of the outer container contains a steel screw, which is connected by very fine steel wire to an arm of the support structure. The central region of the source capsule contains a very small amount of air and aluminium. An exact geometric model of the source is given in Figure 3.1-3.

Figure 3.1-2: Detail of the Water Benchmark Experiment

b) Source and Detector Data

The neutron source in this experiment was provided by spontaneous fission from Cf-252. Eight individual sources, calibrated at the National Physical Laboratory, were available with a total output of $1.048\text{E}+8$ neutrons/second. The composition of the source is given in Table 1.

Absolute calibration of the sources was carried out at the National Physical Laboratory, Teddington, in April 1981 using manganese bath method. The estimated standard deviation on the source strengths is 0.5% and in the measured results the appropriate (and very small) corrections for half-life have been made.

The sulfur detectors were cast into cylindrical blocks of the same nominal size but whose dimensions vary slightly. The nominal size sample is shown in Figure 3.1-2.

Figure 3.1-3: Model of the source capsule.

Table 3.1-1: Composition of the Source Capsule (see Figure 3 for region definitions).

Region	Material	Density (g/cm ³)	Composition	Proportion by weight
1	U-238*	18.9	U-238	1.0
2	Stainless Steel	7.9	Mn Cr Ni Fe	0.01587 0.1868 0.09504 0.703
3	Air Gaps		Void	-
4	Aluminium	2.7	Al	1.0
5	Water	1.0	H O	0.1119 0.8881
6	Sulfur	1.86	S	1.0

*Cf-252 actually used in the experiment is replaced by U-238 in the calculations.

c) Measurement Data

The information provided in Tables 3.1-3 to 3.1-9 was taken from Reference 3 as unfolded by RADAK [6]. The tables show the spectra determined by a 3 ml NE-213 organic liquid scintillator at seven different source-detector separations. The fractional standard deviations shown in column 5 derive from random counting statistics only; in the last column, to these was added quadratically a contribution of 5% attributable to uncertainty in the volume of the detector. This contribution is systematic throughout the measurements. The results in tables 3.1-3 to 3.1-9 are appropriate to the total source strength given in Table 3.1-2.

Reference 3 also provided the S-32(n,p)P-32 saturated reaction rates per sulfur atom per source neutron for the various source-detector separations. These are listed in Table 3.1-10. The 6% standard deviation shown for these measurements is caused by dispersion arising from the experimental method rather than from counting statistics. (The experimental values given for the off axis positions are the mean of the above and below axis measurements.) The cast sulfur samples had a density of $1.86 \pm 5\%$ g/cm³.

Table 3.1-2: Experimental Source Arrangements

Case	Source-detector Spacing (cm)	Number of Sources	Total Source Strength (n/s)
1	10.16	1	1.26E+07
2	15.24	2	2.54E+07
3	20.32	4	5.26E+07
4	25.40	8	1.05E+08
5	30.48	8	1.05E+08
6	35.56	8	1.05E+08
7	50.80	8	1.04E+08

Table 3.1-3: Neutron Spectrum at 10.16 cm

Group	Energy Boundaries (MeV)	Flux/Lethargy (cm ⁻² /s)	Flux/Lethargy per Source Neutron (cm ⁻² /s)	Std. Deviation (statistics only) (%)	Std. Deviation (total) (%)
	10.000				
19	8.825	8.50E+01	6.77E-06	13.6	14.5
18	7.788	2.07E+02	1.65E-05	9.0	10.3
17	6.873	3.45E+02	2.75E-05	6.3	8.0
16	6.065	5.80E+02	4.62E-05	4.4	6.7
15	5.353	8.36E+02	6.66E-05	3.0	5.8
14	4.724	1.15E+03	9.15E-05	2.6	5.6
13	4.169	1.33E+03	1.06E-04	2.0	5.4
12	3.679	1.70E+03	1.35E-04	1.5	5.2
11	3.247	1.82E+03	1.45E-04	1.7	5.3
10	2.865	2.25E+03	1.79E-04	1.5	5.2
9	2.528	2.61E+03	2.08E-04	1.3	5.2
8	2.231	2.68E+03	2.13E-04	1.2	5.1
7	1.969	2.64E+03	2.10E-04	2.0	5.4
6	1.738	2.48E+03	1.98E-04	1.8	5.3
5	1.534	2.49E+03	1.98E-04	2.0	5.4
4	1.353	2.54E+03	2.02E-04	2.1	5.4
3	1.194	2.26E+03	1.80E-04	3.3	6.0
2	1.054	2.34E+03	1.85E-04	3.4	6.0
1	0.930	2.02E+03	1.60E-04	2.4	5.5

Table 3.1-4: Neutron Spectrum at 15.24 cm

Group	Energy Boundaries (MeV)	Flux/Lethargy (cm ⁻² /s)	Flux/Lethargy per Source Neutron (cm ⁻² /s)	Std. Deviation (statistics only) (%)	Std. Deviation (total) (%)
	10.000				
19	8.825	6.78E+01	2.67E-06	9.2	10.5
18	7.788	1.12E+02	4.40E-06	7.1	8.7
17	6.873	2.12E+02	8.33E-06	3.7	6.2
16	6.065	3.59E+02	1.41E-04	3.0	5.8
15	5.353	4.57E+02	1.80E-05	2.9	5.8
14	4.724	5.98E+02	2.35E-05	2.0	5.4
13	4.169	7.77E+02	3.06E-05	1.4	5.2
12	3.679	7.84E+02	3.09E-05	1.8	5.3
11	3.247	8.64E+02	3.40E-05	1.7	5.3
10	2.865	1.10E+03	4.32E-05	1.2	5.1
9	2.528	1.23E+03	4.83E-05	1.2	5.1
8	2.231	1.38E+03	5.41E-05	1.5	5.2
7	1.969	1.21E+03	4.76E-05	1.9	5.3
6	1.738	1.13E+03	4.45E-05	1.5	5.2
5	1.534	1.18E+03	4.63E-05	0.8	5.1
4	1.353	1.15E+03	4.52E-05	1.2	5.1
3	1.194	9.83E+02	3.87E-05	1.7	5.3
2	1.054	1.09E+03	4.27E-05	1.3	5.2
1	0.930	8.86E+02	3.49E-05	1.2	5.1

Table 3.1-5: Neutron Spectrum at 20.32 cm

Group	Energy Boundaries (MeV)	Flux/Lethargy (cm ⁻² /s)	Flux/Lethargy per Source Neutron (cm ⁻² /s)	Std. Deviation (statistics only) (%)	Std. Deviation (total) (%)
	10.000				
19	8.825	5.49E+01	1.04E-06	7.0	8.6
18	7.788	8.53E+01	1.62E-06	6.0	7.8
17	6.873	1.56E+02	2.96E-06	3.8	6.3
16	6.065	2.49E+02	4.74E-06	2.7	5.7
15	5.353	3.19E+02	6.07E-06	2.9	5.8
14	4.724	4.39E+02	8.35E-06	2.0	5.4
13	4.169	4.81E+02	9.14E-06	1.9	5.3
12	3.679	5.05E+02	9.60E-06	1.8	5.3
11	3.247	5.11E+02	9.72E-06	1.7	5.3
10	2.865	6.80E+02	1.29E-05	1.4	5.2
9	2.528	7.54E+02	1.43E-05	1.1	5.1
8	2.231	8.56E+02	1.63E-05	0.7	5.0
7	1.969	7.45E+02	1.42E-05	0.9	5.1
6	1.738	7.08E+02	1.35E-05	1.3	5.2
5	1.534	6.70E+02	1.28E-05	1.4	5.2
4	1.353	7.03E+02	1.34E-05	1.1	5.1
3	1.194	6.03E+02	1.15E-05	1.4	5.2
2	1.054	6.85E+02	1.30E-05	1.5	5.2
1	0.93	5.65E+02	1.07E-05	1.3	5.2

Table 3.1-6: Neutron Spectrum at 25.40 cm

Group	Energy Boundaries (MeV)	Flux/Lethargy (cm ⁻² /s)	Flux/Lethargy per Source Neutron (cm ⁻² /s)	Std. Deviation (statistics only) (%)	Std. Deviation (total) (%)
	10.000				
19	8.825	3.92E+01	3.74E-07	9.0	10.3
18	7.788	7.50E+01	7.15E-07	6.0	7.8
17	6.873	1.20E+02	1.14E-06	4.2	6.5
16	6.065	1.92E+02	1.83E-06	3.2	5.9
15	5.353	2.55E+02	2.44E-06	3.3	6.0
14	4.724	3.18E+02	3.03E-06	2.7	5.7
13	4.169	3.54E+02	3.38E-06	2.0	5.4
12	3.679	3.62E+02	3.46E-06	1.8	5.3
11	3.247	3.43E+02	3.27E-06	2.0	5.4
10	2.865	4.44E+02	4.24E-06	1.7	5.3
9	2.528	5.30E+02	5.06E-06	1.5	5.2
8	2.231	5.80E+02	5.53E-06	1.4	5.2
7	1.969	5.20E+02	4.96E-06	1.4	5.2
6	1.738	4.73E+02	4.51E-06	1.6	5.2
5	1.534	4.75E+02	4.53E-06	1.3	5.2
4	1.353	4.77E+02	4.55E-06	1.6	5.2
3	1.194	4.40E+02	4.19E-06	2.7	5.7
2	1.054	5.21E+02	4.97E-06	2.3	5.5
1	0.93	4.26E+02	4.07E-06	4.0	6.4

Table 3.1-7: Neutron Spectrum at 30.48 cm

Group	Energy Boundaries (MeV)	Flux/Lethargy (cm ⁻² /s)	Flux/Lethargy per Source Neutron (cm ⁻² /s)	Std. Deviation (statistics only) (%)	Std. Deviation (total) (%)
	10.000				
19	8.825	1.85E+01	1.77E-07	7.4	8.9
18	7.788	3.19E+01	3.05E-07	4.5	6.7
17	6.873	5.71E+01	5.46E-07	2.6	5.6
16	6.065	8.41E+01	8.04E-07	2.6	5.6
15	5.353	1.02E+02	9.77E-07	2.2	5.5
14	4.724	1.29E+02	1.24E-06	1.6	5.2
13	4.169	1.42E+02	1.36E-06	1.4	5.2
12	3.679	1.32E+02	1.26E-06	1.4	5.2
11	3.247	1.26E+02	1.20E-06	1.4	5.2
10	2.865	1.65E+02	1.58E-06	1.0	5.1
9	2.528	1.89E+02	1.81E-06	0.8	5.1
8	2.231	2.13E+02	2.03E-06	0.9	5.1
7	1.969	1.83E+02	1.75E-06	1.5	5.2
6	1.738	1.69E+02	1.62E-06	1.6	5.2
5	1.534	1.64E+02	1.57E-06	1.4	5.2
4	1.353	1.66E+02	1.59E-06	1.2	5.1
3	1.194	1.52E+02	1.45E-06	1.8	5.3
2	1.054	1.82E+02	1.75E-06	1.5	5.2
1	0.93	1.69E+02	1.61E-06	0.6	5.0

Table 3.1-8: Neutron Spectrum at 35.56 cm

Group	Energy Boundaries (MeV)	Flux/Lethargy (cm ⁻² /s)	Flux/Lethargy per Source Neutron (cm ⁻² /s)	Std. Deviation (statistics only) (%)	Std. Deviation (total) (%)
	10.000				
19	8.825	9.62	9.17E-08	9.0	10.3
18	7.788	1.45E+01	1.38E-07	7.4	8.9
17	6.873	2.47E+01	2.36E-07	4.8	6.9
16	6.065	3.59E+01	3.42E-07	4.5	6.7
15	5.353	4.25E+01	4.06E-07	3.9	6.3
14	4.724	5.60E+01	5.34E-07	2.5	5.6
13	4.169	5.67E+01	5.41E-07	2.2	5.5
12	3.679	5.38E+01	5.13E-07	2.4	5.5
11	3.247	4.46E+01	4.26E-07	3.8	6.3
10	2.865	6.38E+01	6.08E-07	2.7	5.7
9	2.528	6.92E+01	6.60E-07	2.6	5.6
8	2.231	7.95E+01	7.58E-07	2.4	5.5
7	1.969	6.74E+01	6.43E-07	2.1	5.4
6	1.738	6.25E+01	5.96E-07	2.0	5.4
5	1.534	6.00E+01	5.72E-07	2.3	5.5
4	1.353	5.99E+01	5.71E-07	2.1	5.4
3	1.194	5.43E+01	5.18E-07	1.3	5.2
2	1.054	6.49E+01	6.19E-07	0.7	5.0
1	0.93	5.64E+01	5.38E-07	0.5	5.0

Table 3.1-9: Neutron Spectrum at 50.80 cm

Group	Energy Boundaries (MeV)	Flux/Lethargy (cm ⁻² /s)	Flux/Lethargy per Source Neutron (cm ⁻² /s)	Std. Deviation (statistics only) (%)	Std. Deviation (total) (%)
	10.000				
19	8.825	1.43	1.36E-08	8.3	9.7
18	7.788	1.85	1.77E-08	10.2	11.4
17	6.873	2.79	2.67E-08	8.8	10.1
16	6.065	4.07	3.90E-08	6.4	8.1
15	5.353	4.82	4.61E-08	6.1	7.9
14	4.724	4.71	4.51E-08	6.4	8.1
13	4.169	5.49	5.26E-08	4.7	6.9
12	3.679	3.83	3.67E-08	5.4	7.4
11	3.247	4.21	4.03E-08	3.9	6.3
10	2.865	4.59	4.39E-08	3.1	5.9
9	2.528	5.08	4.87E-08	3.5	6.1
8	2.231	5.85	5.60E-08	4.0	6.4
7	1.969	4.58	4.39E-08	5.7	7.6
6	1.738	4.34	4.15E-08	5.8	7.7
5	1.534	4.32	4.14E-08	4.1	6.5
4	1.353	4.17	4.00E-08	2.5	5.6
3	1.194	3.94	3.77E-08	1.7	5.3
2	1.054	4.42	4.23E-08	1.2	5.1
1	0.93	4.61	4.41E-08	3.4	6.0

Table 3.1-10: S³² (n,p) P³² Measured Reaction Rates

Distance in Source Plane of Sources from Tube (cm)	Saturated Reaction Rates per S ³² Atom per Source Neutron		
	Axial Displacement (cm)		
	0	+/-15	+/-30
10.26	3.13E-29	5.37E-30	6.71E-31
15.24	7.56E-30	2.25E-30	3.22E-31
25.40	8.55E-31	4.36E-31	9.50E-32
30.48	3.43E-31	1.94E-31	5.16E-32
35.56	1.42E-31	8.92E-32	2.81E-32

3.2 Karlsruhe Iron Sphere Benchmark Experiment (SBE 6.001)

a) Experimental Arrangement

The experimental arrangement can be seen on Figure 3.2-1 (taken from Reference 3). Six different iron spheres with diameters of 15, 20, 25, 30, 35 and 40 cm were investigated. The arrangement was located in a hall, at a minimal distance of 2 m from the ground and more than 3m from the nearest walls. High purity iron (impurities: C 0.07%, Mn 0.05%, P 0.009%, S 0.007%) was used. The spheres contained a central channel 16 mm in diameter for housing the source. This channel was filled up with cylindrical pieces made of the same material as the spheres, with the exception of an empty central space (3.57 cm^3) provided for the source capsule (2.88 cm^3). The source center practically coincides with the sphere center (offset between the two is about 1 mm).

Figure 3.2-1: Arrangement of iron sphere experiment.

b) Source Data

A view of the neutron source configuration and its position in the iron sphere is given in Figure 3.2-2. The neutron source consisted of about 30 micrograms of Cf-252 (corresponding to a source strength of $7.0 \text{ E}+7 \text{ n/sec}$) deposited on a SiO_2/MgO matrix (0.14 g). This matrix was surrounded

Figure 3.2-2: Details of the neutron source.

by two capsules; an inner one (4.55 g) made of Zircaloy (Zr+1.5% Sn) and an outer one (4.87 g) made of AlMg₃ (Al+3% Mg). The number of atoms per cm³ in the source is compiled in Table 3.2-1.

Table 3.2-1: Composition of source capsules for the Karlsruhe
Iron Sphere Benchmark Experiment.

Element	Atom Density (atoms/cm ³)
Al	105.5E21
Zr	29.4E21
Mg	3.9E21
O	2.6E21
Si	0.8E21
Sn	0.4E21

The neutron source spectrum was measured with proton recoil and He-3 spectrometers. The spectra determined experimentally agree well, but they both deviate rather strongly from the normally assumed Maxwell distribution with average energy $E = 2.1$ MeV. The reason for the deviation has not been explained in the literature [3] we found.

Between 0.9 and 6 MeV, the measured source spectrum agrees to within $\pm 3\%$ with the Maxwellian distribution and therefore the calculations can be assumed to be reliable in this energy region. The numerical values of the source spectrum are given in Table 3.2-2 according to the EURLIB [3] group structure.

c) Detectors

Proton recoil (PR) proportional counters

Three types of detectors were used, the main characteristics of which are given in Table 3.2-3. Precise information about the spectral distribution could be deduced from the pulse height distribution of the cylindrical detectors only if the incident neutrons were nearly parallel to the detector axis. Therefore, the counter axis had to be directed towards the sphere center and the counter center had to be located at distances large in comparison with the sphere radius. The distances between the detectors and the center of the spheres are listed in Table 3.2-4.

Table 3.2-2: Normalized source spectrum for the Cf-252 source
in EURLIB energy group structure.

Group	Energy Range (eV)	Source Spectrum	Group	Energy Range (eV)	Source Spectrum
1	1.3499E07 - 1.4918E07	7.07E-04	29	1.2246E06 - 1.3534E06	3.60E-02
2	1.2214E07 - 1.3499E07	9.39E-04	30	1.1080E06 - 1.2246E06	3.35E-02
3	1.1052E07 - 1.2214E07	1.71E-03	31	1.0026E06 - 1.1080E06	3.08E-02
4	1.0000E07 - 1.1052E07	2.90E-03	32	9.0718E05 - 1.0026E06	2.82E-02
5	9.0484E06 - 1.0000E07	4.61E-03	33	8.2085E05 - 9.0718E05	2.57E-02
6	8.1873E06 - 9.0484E06	6.91E-03	34	7.4274E05 - 8.2085E05	2.33E-02
7	7.4082E06 - 8.1873E06	5.16E-03	35	6.7206E05 - 7.4274E05	2.10E-02
8	7.0469E06 - 7.4082E06	4.66E-03	36	6.0810E05 - 6.7206E05	1.88E-02
9	6.7032E06 - 7.0469E06	6.54E-03	37	5.5023E05 - 6.0810E05	1.68E-02
10	6.3763E06 - 6.7032E06	6.80E-03	38	4.9787E05 - 5.5023E05	1.50E-02
11	6.0653E06 - 6.3763E06	1.73E-02	39	4.5049E05 - 4.9787E05	1.33E-02
12	5.4881E06 - 6.0653E06	2.17E-02	40	4.0762E05 - 4.5049E05	1.18E-02
13	4.9659E06 - 5.4881E06	1.11E-02	41	3.6883E05 - 4.0762E05	1.04E-02
14	4.7240E06 - 4.9659E06	1.51E-02	42	3.3373E05 - 3.6883E05	9.13E-03
15	4.4933E06 - 4.7240E06	3.05E-02	43	3.0197E05 - 3.3373E05	8.02E-03
16	4.0657E06 - 4.4933E06	3.47E-02	44	2.7324E05 - 3.0197E05	7.04E-03
17	3.6788E06 - 4.0657E06	3.83E-02	45	2.4724E05 - 2.7324E05	6.16E-03
18	3.3287E06 - 3.6788E06	4.14E-02	46	2.2371E05 - 2.4724E05	5.38E-03
19	3.0112E06 - 3.3287E06	4.37E-02	47	2.0242E05 - 2.2371E05	4.70E-03
20	2.7253E06 - 3.0112E06	4.53E-02	48	1.8316E05 - 2.0242E05	4.09E-03
21	2.4660E06 - 2.7253E06	2.22E-02	49	1.6573E05 - 1.8316E05	3.56E-03
22	2.3460E06 - 2.4660E06	2.40E-02	50	1.4996E05 - 1.6573E05	3.10E-03
23	2.2313E06 - 2.3460E06	4.62E-02	51	1.3569E05 - 1.4996E05	2.69E-03
24	2.0190E06 - 2.2313E06	4.56E-02	52	1.2277E05 - 1.3569E05	2.34E-03
25	1.8268E06 - 2.0190E06	4.45E-02	53	1.1109E05 - 1.2277E05	4.57E-03
26	1.6530E06 - 1.8268E06	4.28E-02	54	8.6517E04 - 1.1109E05	3.19E-03
27	1.4957E06 - 1.6530E06	4.08E-02	55	6.7379E04 - 8.6517E04	2.22E-03
28	1.3534E06 - 1.4957E06	3.85E-02			

Table 3.2-3: Recoil proton detector characteristics.

Detector Number	Diameter (cm)	Effective Length L (cm)	Length of Dead Volume at Front (cm)	Wall Thickness (mm)	Gas Fill (atm)	Range parallel incidence (MeV)	Energy Resolution (%)
1	4.8	12.6	4	1	3 H ₂	0.06-0.8	4
2	4.8	12.6	4	1	1.5 H ₂ +1.5Kr	0.3-2.4	4
3	8.9	83.5	4	2	3 CH ₄	0.9-5.2	4

Table 3.2-4: Geometry for Leakage Measurements

Detector Number	L (cm)	D (cm)	d (cm)
1, 2	12.6	102	108
3	83.5	117	153

L is the sensitive length and D the distance between the center of the sphere and the beginning of the sensitive volume;

$$d = D * \sqrt{1 + L/D}$$

is the distance from the center of the sphere at which a point detector of the same sensitivity would record the same counting rate as the detector actually employed. It is assumed here that the neutron field at the detector position is roughly equivalent to that of a point source in the center of the sphere.

d) Measurement Data

The results of the proton recoil measurements for each of the three detectors are given in Tables 3.2-5 to 3.2-7. Since the dimensions of detectors 1 and 2 and their arrangement relative to the spheres and the source are the same. The results obtained with detectors 1 and 2 can be related to each other directly without further normalization. The results of detector 3 have been, on the other hand, normalized relative to the results obtained with the other two. This was done by fitting the integral flux value obtained by detector 3 in the range 0.88 - 1.97 MeV to that of detector 2, using the mean value of the six sphere measurements and the source spectrum. In the average, the normalization factor of the various measurements departs from the mean of all seven measurements by +3 %. The error of about 3 % in the absolute values of the flux per source neutron caused by this normalization is restricted to the energy range above 2.4 MeV.

Table 3.2-5: Detector 1 leakage spectra, proton recoil measurement for iron spheres.

Mid energy (KeV)	Detector 1 Measurements (neutrons per source neutron/lethargy unit)					
	d=15cm	d=20cm	d=25cm	d=30cm	d=35cm	d=40cm
6.325E+01	5.302E-02	4.173E-02	4.319E-02	2.163E-02	2.606E-02	4.318E-02
6.775E+01	3.479E-02	3.536E-02	5.441E-02	3.034E-02	3.217E-02	4.786E-02
7.285E+01	4.990E-02	4.797E-02	5.414E-02	3.571E-02	5.969E-02	6.884E-02
7.850E+01	5.576E-02	5.941E-02	6.054E-02	5.095E-02	5.925E-02	8.025E-02
8.415E+01	4.977E-02	5.772E-02	5.375E-02	5.154E-02	6.464E-02	9.053E-02
9.035E+01	5.211E-02	4.394E-02	5.571E-02	6.025E-02	6.217E-02	9.756E-02
9.710E+01	3.674E-02	3.965E-02	4.266E-02	5.023E-02	6.333E-02	6.874E-02
1.044E+02	4.612E-02	5.720E-02	5.754E-02	5.110E-02	6.915E-02	8.565E-02
1.123E+02	6.801E-02	6.721E-02	7.476E-02	8.565E-02	9.740E-02	1.181E-01
1.208E+02	6.462E-02	8.190E-02	9.185E-02	8.609E-02	1.298E-01	1.415E-01
1.299E+02	7.999E-02	1.060E-01	1.262E-01	1.159E-01	1.819E-01	1.792E-01
1.395E+02	9.029E-02	1.038E-01	1.448E-01	1.567E-01	1.849E-01	2.433E-01
1.496E+02	7.504E-02	7.228E-02	9.407E-02	1.382E-01	1.528E-01	2.006E-01
1.609E+02	6.241E-02	9.178E-02	9.107E-02	1.170E-01	1.674E-01	1.629E-01
1.734E+02	1.140E-01	1.300E-01	1.630E-01	1.567E-01	2.096E-01	2.342E-01
1.863E+02	1.368E-01	1.378E-01	1.657E-01	2.075E-01	2.256E-01	2.484E-01
2.004E+02	1.072E-01	1.240E-01	1.383E-01	1.829E-01	1.645E-01	1.924E-01
2.157E+02	1.268E-01	1.560E-01	1.552E-01	1.742E-01	2.067E-01	1.975E-01
2.315E+02	1.354E-01	1.339E-01	1.591E-01	1.974E-01	2.067E-01	2.546E-01
2.484E+02	1.226E-01	1.625E-01	1.670E-01	1.974E-01	2.475E-01	2.658E-01
2.677E+02	1.677E-01	2.080E-01	2.204E-01	2.613E-01	3.130E-01	3.401E-01
2.880E+02	1.876E-01	2.132E-01	2.387E-01	3.121E-01	3.465E-01	3.788E-01
3.095E+02	2.436E-01	2.743E-01	3.000E-01	3.832E-01	4.280E-01	4.715E-01
3.326E+02	2.358E-01	2.483E-01	3.039E-01	3.484E-01	3.727E-01	4.195E-01
3.575E+02	2.788E-01	3.250E-01	3.457E-01	3.788E-01	3.814E-01	4.318E-01
3.846E+02	2.462E-01	2.470E-01	2.909E-01	3.237E-01	2.591E-01	3.330E-01
4.139E+02	1.745E-01	1.976E-01	1.904E-01	1.959E-01	2.067E-01	1.985E-01
4.450E+02	1.980E-01	2.418E-01	2.439E-01	2.279E-01	2.911E-01	2.454E-01
4.783E+02	2.762E-01	2.769E-01	2.961E-01	2.845E-01	3.101E-01	3.421E-01
5.144E+02	2.462E-01	2.613E-01	2.805E-01	3.077E-01	3.130E-01	3.279E-01
5.534E+02	3.087E-01	3.445E-01	3.470E-01	3.788E-01	4.120E-01	3.992E-01
5.952E+02	4.012E-01	4.537E-01	4.840E-01	5.313E-01	6.435E-01	5.906E-01
6.398E+02	4.273E-01	4.888E-01	5.636E-01	5.995E-01	5.226E-01	6.110E-01
6.878E+02	3.817E-01	4.290E-01	4.540E-01	4.674E-01	3.930E-01	4.440E-01
7.392E+02	4.038E-01	3.757E-01	3.809E-01	3.527E-01	3.261E-01	2.820E-01
7.951E+02	3.960E-01	3.432E-01	3.561E-01	3.527E-01	3.261E-01	3.218E-01
8.550E+02	2.840E-01	3.341E-01	3.261E-01	3.121E-01	2.970E-01	2.932E-01

Table 3.2-6: Detector 2 leakage spectra, proton recoil measurements for iron spheres.

Mid energy (KeV)	Detector 2 Measurements (neutrons per source neutron/lethargy unit)					
	d=15cm	d=20cm	d=25cm	d=30cm	d=35cm	d=40cm
3.081E+02	2.275E-01	3.339E-01	3.145E-01	3.572E-01	4.349E-01	4.417E-01
3.317E+02	2.448E-01	3.051E-01	3.202E-01	3.445E-01	3.983E-01	3.784E-01
3.568E+02	2.592E-01	2.965E-01	3.490E-01	3.728E-01	4.223E-01	4.149E-01
3.833E+02	2.117E-01	2.792E-01	2.886E-01	2.693E-01	3.139E-01	3.108E-01
4.110E+02	1.786E-01	1.971E-01	2.140E-01	2.084E-01	2.181E-01	2.278E-01
4.423E+02	1.858E-01	2.432E-01	2.398E-01	2.623E-01	2.576E-01	2.799E-01
4.762E+02	2.751E-01	2.835E-01	3.231E-01	3.289E-01	3.125E-01	3.249E-01
5.130E+02	2.837E-01	2.821E-01	3.073E-01	3.019E-01	3.392E-01	3.277E-01
5.514E+02	2.895E-01	3.296E-01	3.561E-01	3.799E-01	3.800E-01	4.065E-01
5.927E+02	3.586E-01	4.145E-01	4.423E-01	5.019E-01	5.574E-01	5.851E-01
6.369E+02	4.709E-01	5.109E-01	5.874E-01	6.110E-01	6.447E-01	6.259E-01
6.840E+02	5.905E-01	4.346E-01	4.667E-01	4.225E-01	5.391E-01	4.009E-01
7.356E+02	3.082E-01	3.713E-01	3.461E-01	3.516E-01	3.519E-01	3.418E-01
7.917E+02	3.456E-01	3.353E-01	3.346E-01	3.204E-01	3.195E-01	3.094E-01
8.521E+02	4.004E-01	3.396E-01	3.418E-01	3.204E-01	3.068E-01	2.560E-01
9.155E+02	3.672E-01	3.799E-01	3.604E-01	3.558E-01	3.505E-01	3.263E-01
9.850E+02	3.629E-01	3.742E-01	3.533E-01	3.615E-01	3.181E-01	2.968E-01
1.060E+03	3.860E-01	3.627E-01	3.245E-01	2.864E-01	3.068E-01	2.349E-01
1.139E+03	4.033E-01	3.727E-01	3.691E-01	3.317E-01	3.209E-01	2.757E-01
1.225E+03	3.384E-01	3.468E-01	3.533E-01	2.991E-01	2.463E-01	2.067E-01
1.316E+03	3.730E-01	3.612E-01	3.202E-01	2.778E-01	2.322E-01	1.730E-01
1.415E+03	3.888E-01	3.382E-01	2.743E-01	2.013E-01	2.111E-01	1.547E-01
1.523E+03	3.485E-01	3.152E-01	2.484E-01	2.282E-01	1.858E-01	1.399E-01
1.638E+03	4.076E-01	3.353E-01	2.743E-01	2.041E-01	1.731E-01	1.448E-01
1.760E+03	3.269E-01	2.677E-01	2.369E-01	1.999E-01	1.618E-01	1.129E-01
1.893E+03	3.269E-01	3.137E-01	2.355E-01	1.531E-01	1.141E-01	9.790E-02
2.036E+03	2.578E-01	2.029E-01	1.795E-01	1.355E-01	9.769E-02	7.132E-02
2.189E+03	2.621E-01	1.885E-01	1.565E-01	1.273E-01	1.009E-01	6.400E-02
2.354E+03	2.318E-01	2.302E-01	1.317E-01	9.669E-02	7.348E-02	5.205E-02

Table 3.2-7: Detector 3 leakage spectra, proton recoil measurements for iron spheres.

Mid energy (KeV)	Detector 3 Measurements (neutrons per source neutron/lethargy unit)					
	d=15cm	d=20cm	d=25cm	d=30cm	d=35cm	d=40cm
9.165E+02	3.811E-01	3.643E-01	3.655E-01	3.682E-01	3.519E-01	3.247E-01
9.870E+02	3.853E-01	3.811E-01	3.674E-01	3.703E-01	3.413E-01	3.205E-01
1.063E+03	3.769E-01	3.685E-01	3.270E-01	3.114E-01	2.845E-01	2.551E-01
1.142E+03	4.001E-01	3.938E-01	3.694E-01	3.430E-01	3.055E-01	2.678E-01
1.226E+03	4.169E-01	3.938E-01	3.578E-01	3.367E-01	2.992E-01	2.572E-01
1.320E+03	3.769E-01	3.474E-01	3.001E-01	2.693E-01	2.276E-01	1.927E-01
1.419E+03	3.706E-01	3.222E-01	2.789E-01	2.399E-01	1.968E-01	1.607E-01
1.524E+03	3.453E-01	2.969E-01	2.539E-01	2.104E-01	1.713E-01	1.415E-01
1.638E+03	3.537E-01	2.990E-01	2.482E-01	1.986E-01	1.656E-01	1.282E-01
1.761E+03	3.601E-01	2.990E-01	2.501E-01	2.056E-01	1.635E-01	1.282E-01
1.896E+03	3.348E-01	2.716E-01	2.193E-01	1.742E-01	1.365E-01	1.031E-01
2.039E+03	2.906E-01	2.274E-01	1.797E-01	1.348E-01	1.051E-01	8.098E-02
2.191E+03	2.842E-01	2.253E-01	1.737E-01	1.302E-01	9.905E-02	7.255E-02
2.355E+03	2.779E-01	2.148E-01	1.622E-01	1.256E-01	8.830E-02	6.137E-02
2.533E+03	2.484E-01	1.874E-01	1.373E-01	9.890E-02	7.186E-02	5.272E-02
2.726E+03	2.337E-01	1.667E-01	1.254E-01	8.901E-02	6.385E-02	4.408E-02
2.931E+03	2.076E-01	1.480E-01	1.098E-01	8.060E-02	5.585E-02	3.901E-02
3.150E+03	1.916E-01	1.373E-01	9.755E-02	6.797E-02	4.594E-02	3.227E-02
3.387E+03	1.619E-01	1.162E-01	8.389E-02	5.871E-02	4.257E-02	2.784E-02
3.641E+03	1.453E-01	1.000E-01	7.234E-02	4.840E-02	3.161E-02	2.320E-02
3.916E+03	1.303E-01	8.108E-02	6.234E-02	3.977E-02	2.613E-02	1.696E-02
4.212E+03	1.128E-01	8.276E-02	5.445E-02	3.409E-02	2.297E-02	1.527E-02
4.527E+03	8.739E-02	5.328E-02	4.117E-02	2.862E-02	1.795E-02	1.284E-02
4.869E+03	6.970E-02	4.801E-02	3.598E-02	2.125E-02	1.385E-02	8.220E-03
5.238E+03	4.843E-02	2.864E-02	2.386E-02	1.290E-02	9.310E-03	6.810E-03

4.0 Benchmark Model Description

4.1 Winfrith Water Benchmark Model

Although the source used in the original experiment was Cf-252, it was replaced by U-238 in the material section for the calculations in this document. This approach was necessary since neither of the BUGLE cross section libraries utilized had Cf-252 as one of its nuclides. After all, the Cf-252 spectrum provided in Reference 3 was imposed to account for more accurate results.

The source-detector arrangement was modeled quite similar to that shown in Figure 3.1-2. The sulfur sample region, as well as the aluminum tube in which it is contained, were modeled as infinite cylinders. For simplicity, the arms of the support structure were not modeled in this experiment.

The outer stainless-steel source capsule was modeled as a cylinder of infinite length with a radius of 0.95 cm. The modeling of the capsule's neck was considered negligible due to the conservative radius chosen. The small amount of air and aluminum in its central region were also neglected.

The inner source capsule walls of the container holding the Cf-252 source were not represented in the model.

The whole source-detector arrangement was treated as being immersed in an infinite bath of water. This was considered a conservative assumption since the nearest distance from the source to an external boundary was more than 4 times the migration length of a 5 MeV neutron in water.

4.2 Karlsruhe Iron Sphere Benchmark Model

The model for this experiment consisted of the iron sphere containing the source and the proton recoil (PR) proportional counters positioned around it. For simplicity, the support structure and the wires that held the sphere in place were not modeled.

The source capsule inside the iron sphere was modeled much like the one depicted in Figure 3.2-2 with the following two exceptions. First, the zirconium content of the inner capsule surrounding the source was replaced by aluminium. This was a necessary approach due to the lack of zirconium as part of the BUGLE cross section libraries utilized in this experiment. Second, the capsules neck was considered negligible due to its small radius. The void to be left by the capsule neck was filled with the same material as that of the sphere.

5.0 Results

5.1 Winfrith Water Benchmark Experiment

Fast neutron spectrum measurement data made with a NE-213 organic liquid scintillator within the hollow tube at the axial midplane for each of the seven source locations along with the calculated values are shown in Tables 5.1-1 to 5.1-21. Size of water tank and the placement of sources and detectors make the essential portions of the calculational geometry two-dimensional.

Figures 5.1-1 to 5.1-7 give a graphical comparison of the ratio of the calculated (C) and experimental (E) detector readings using both BUGLE-96 and BUGLE-80 cross section libraries. The experimental values are read as 1.0 on the C/E axis.

The C/E ratios are plotted against neutron energies varying from ~1 MeV to 10 MeV. For a detector at a distance of 10.16 cm from the source, the calculated values were within 15% of the measured values from 1 MeV to about 6 MeV. From 6 MeV to about 8 MeV, the calculated flux was much higher by as much as 30%. A dip in the calculated value around 3.6 MeV was noticed, where the calculated flux was underpredicted by about 25%. The calculated C/E ratios for BUGLE-96 set were consistent and within 5% of the BUGLE-80 values. In general, the calculated values were underpredicted in the energy band except near the high energy range above 6 MeV.

The trend was similar for other detector distances. At a higher detector distances of 30.56 cm, the differences between the C/E ratios for BUGLE-96 and BUGLE-80 set were increased at energy above ~3 MeV, where the calculated flux with BUGLE-96 were generally lower and those with BUGLE-80 were generally higher than the corresponding experimental results.

In summary, the neutron flux calculated with BUGLE-96 matched well (within 15% - 20%) with the experimental value over 2 MeV to 8 MeV range. There was not much overall improvement with the BUGLE-96 cross section set over the corresponding BUGLE-80 set, and the trend for both cases was quite similar.

Table 5.1-1: BUGLE 80 results for a detector at a distance of 10.16 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	1.090E-05	6.770E-06	1.61
18	7.788	2.024E-05	1.650E-05	1.23
17	6.873	3.542E-05	2.750E-05	1.29
16	6.065	4.070E-05	4.620E-05	0.88
15	5.353	7.492E-05	6.660E-05	1.12
14	4.724	9.022E-05	9.150E-05	0.99
13	4.169	1.136E-04	1.060E-04	1.07
12	3.679	1.003E-04	1.350E-04	0.74
11	3.247	1.573E-04	1.450E-04	1.09
10	2.865	1.627E-04	1.790E-04	0.91
9	2.528	1.936E-04	2.080E-04	0.93
8	2.231	2.113E-04	2.130E-04	0.99
7	1.969	1.948E-04	2.100E-04	0.93
6	1.738	1.940E-04	1.980E-04	0.98
5	1.534	1.925E-04	1.980E-04	0.97
4	1.353	1.801E-04	2.020E-04	0.89
3	1.194	1.824E-04	1.800E-04	1.01
2	1.054	1.610E-04	1.850E-04	0.87
1	0.930	1.557E-04	1.600E-04	0.97

Table 5.1-2: BUGLE 96 results for a detector at a distance of 10.16 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	1.195E-05	6.770E-06	1.76
18	7.788	1.988E-05	1.650E-05	1.20
17	6.873	3.573E-05	2.750E-05	1.30
16	6.065	4.156E-05	4.620E-05	0.90
15	5.353	7.600E-05	6.660E-05	1.14
14	4.724	9.141E-05	9.150E-05	1.00
13	4.169	1.150E-04	1.060E-04	1.09
12	3.679	1.015E-04	1.350E-04	0.75
11	3.247	1.456E-04	1.450E-04	1.00
10	2.865	1.547E-04	1.790E-04	0.86
9	2.528	1.963E-04	2.080E-04	0.94
8	2.231	2.086E-04	2.130E-04	0.98
7	1.969	2.019E-04	2.100E-04	0.96
6	1.738	1.983E-04	1.980E-04	1.00
5	1.534	1.934E-04	1.980E-04	0.98
4	1.353	1.792E-04	2.020E-04	0.89
3	1.194	1.852E-04	1.800E-04	1.03
2	1.054	1.634E-04	1.850E-04	0.88
1	0.930	1.554E-04	1.600E-04	0.97

Table 5.1-3: BUGLE 80 and BUGLE 96 comparison. Detector at 10.16 cm from source.

Group	Energy Boundary (MeV)	Calculated/Experimental	
		BUGLE 80	BUGLE 96
20	10		
19	8.825	1.61	1.76
18	7.788	1.23	1.20
17	6.873	1.29	1.30
16	6.065	0.88	0.90
15	5.353	1.12	1.14
14	4.724	0.99	1.00
13	4.169	1.07	1.09
12	3.679	0.74	0.75
11	3.247	1.09	1.00
10	2.865	0.91	0.86
9	2.528	0.93	0.94
8	2.231	0.99	0.98
7	1.969	0.93	0.96
6	1.738	0.98	1.00
5	1.534	0.97	0.98
4	1.353	0.89	0.89
3	1.194	1.01	1.03
2	1.054	0.87	0.88
1	0.930	0.97	0.97

Figure 5.1-1: BUGLE 80 and BUGLE 96 data comparison. Detector at 10.16 cm from source.

Table 5.1-4: BUGLE 80 results for a detector at a distance of 15.24 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ² /s)	Experimental (E) (cm ² /s)	
20	10			
19	8.825	3.646E-06	2.67E-06	1.37
18	7.788	5.770E-06	4.40E-06	1.31
17	6.873	9.752E-06	8.33E-06	1.17
16	6.065	1.115E-05	1.41E-05	0.79
15	5.353	2.013E-05	1.80E-05	1.12
14	4.724	2.389E-05	2.35E-05	1.02
13	4.169	2.972E-05	3.06E-05	0.97
12	3.679	2.623E-05	3.09E-05	0.85
11	3.247	3.299E-05	3.40E-05	0.97
10	2.865	3.632E-05	4.32E-05	0.84
9	2.528	4.620E-05	4.83E-05	0.96
8	2.231	5.396E-05	5.41E-05	1.00
7	1.969	4.576E-05	4.76E-05	0.96
6	1.738	4.464E-05	4.45E-05	1.00
5	1.534	4.116E-05	4.63E-05	0.89
4	1.353	3.680E-05	4.52E-05	0.81
3	1.194	3.950E-05	3.87E-05	1.02
2	1.054	3.487E-05	4.27E-05	0.82
1	0.930	3.864E-05	3.49E-05	1.11

Table 5.1-5: BUGLE 96 results for a detector at a distance of 15.24 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	3.445E-06	2.67E-06	1.29
18	7.788	5.563E-06	4.40E-06	1.26
17	6.873	9.926E-06	8.33E-06	1.19
16	6.065	1.153E-05	1.41E-05	0.82
15	5.353	1.961E-05	1.80E-05	1.09
14	4.724	2.353E-05	2.35E-05	1.00
13	4.169	2.954E-05	3.06E-05	0.97
12	3.679	2.607E-05	3.09E-05	0.84
11	3.247	3.631E-05	3.40E-05	1.07
10	2.865	3.707E-05	4.32E-05	0.86
9	2.528	4.567E-05	4.83E-05	0.95
8	2.231	5.991E-05	5.41E-05	1.11
7	1.969	7.145E-05	4.76E-05	1.50
6	1.738	5.183E-05	4.45E-05	1.16
5	1.534	4.453E-05	4.63E-05	0.96
4	1.353	4.016E-05	4.52E-05	0.89
3	1.194	3.826E-05	3.87E-05	0.99
2	1.054	3.377E-05	4.27E-05	0.79
1	0.930	3.194E-05	3.49E-05	0.92

Table 5.1-6: BUGLE 80 and BUGLE 96 comparison. Detector at 15.24 cm from source.

Group	Energy Boundary (MeV)	Calculated/Experimental	
		BUGLE 80	BUGLE 96
20	10		
19	8.825	1.37	1.29
18	7.788	1.31	1.26
17	6.873	1.17	1.19
16	6.065	0.79	0.82
15	5.353	1.12	1.09
14	4.724	1.02	1.00
13	4.169	0.97	0.97
12	3.679	0.85	0.84
11	3.247	0.97	1.07
10	2.865	0.84	0.86
9	2.528	0.96	0.95
8	2.231	1.00	1.11
7	1.969	0.96	1.50
6	1.738	1.00	1.16
5	1.534	0.89	0.96
4	1.353	0.81	0.89
3	1.194	1.02	0.99
2	1.054	0.82	0.79
1	0.930	1.11	0.92

Figure 5.1-2: BUGLE 80 and BUGLE 96 data comparison. Detector at 15.24 cm from source.

Table 5.1-7: BUGLE 80 results for a detector at a distance of 20.32 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	1.176E-06	1.04E-06	1.13
18	7.788	1.957E-06	1.62E-06	1.21
17	6.873	3.694E-06	2.96E-06	1.25
16	6.065	4.357E-06	4.74E-06	0.92
15	5.353	6.597E-06	6.07E-06	1.09
14	4.724	7.700E-06	8.35E-06	0.92
13	4.169	9.445E-06	9.14E-06	1.03
12	3.679	8.335E-06	9.60E-06	0.87
11	3.247	1.016E-05	9.20E-06	1.10
10	2.865	1.036E-05	1.29E-05	0.80
9	2.528	1.326E-05	1.43E-05	0.93
8	2.231	1.598E-05	1.63E-05	0.98
7	1.969	1.331E-05	1.42E-05	0.94
6	1.738	1.223E-05	1.35E-05	0.91
5	1.534	1.216E-05	1.28E-05	0.95
4	1.353	1.152E-05	1.34E-05	0.86
3	1.194	9.938E-06	1.15E-05	0.86
2	1.054	8.772E-06	1.30E-05	0.67
1	0.930	8.054E-06	1.07E-05	0.75

Table 5.1-8: BUGLE 96 results for a detector at a distance of 20.32 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	1.136E-06	1.04E-06	1.09
18	7.788	1.954E-06	1.62E-06	1.21
17	6.873	3.086E-06	2.96E-06	1.04
16	6.065	3.436E-06	4.74E-06	0.72
15	5.353	6.295E-06	6.07E-06	1.04
14	4.724	7.598E-06	8.35E-06	0.91
13	4.169	9.588E-06	9.14E-06	1.05
12	3.679	8.461E-06	9.60E-06	0.88
11	3.247	1.559E-05	9.20E-06	1.69
10	2.865	1.345E-05	1.29E-05	1.04
9	2.528	1.311E-05	1.43E-05	0.92
8	2.231	1.499E-05	1.63E-05	0.92
7	1.969	1.242E-05	1.42E-05	0.87
6	1.738	1.234E-05	1.35E-05	0.91
5	1.534	1.204E-05	1.28E-05	0.94
4	1.353	1.115E-05	1.34E-05	0.83
3	1.194	9.236E-06	1.15E-05	0.80
2	1.054	8.152E-06	1.30E-05	0.63
1	0.930	8.081E-06	1.07E-05	0.76

Table 5.1-9: BUGLE 80 and BUGLE 96 comparison. Detector at 20.32 cm from source.

Group	Energy Boundary (MeV)	Calculated/Experimental	
		BUGLE 80	BUGLE 96
20	10		
19	8.825	1.13	1.09
18	7.788	1.21	1.21
17	6.873	1.25	1.04
16	6.065	0.92	0.72
15	5.353	1.09	1.04
14	4.724	0.92	0.91
13	4.169	1.03	1.05
12	3.679	0.87	0.88
11	3.247	1.10	1.69
10	2.865	0.80	1.04
9	2.528	0.93	0.92
8	2.231	0.98	0.92
7	1.969	0.94	0.87
6	1.738	0.91	0.91
5	1.534	0.95	0.94
4	1.353	0.86	0.83
3	1.194	0.86	0.80
2	1.054	0.67	0.63
1	0.930	0.75	0.76

Figure 5.1-3: BUGLE 80 and BUGLE 96 data comparison. Detector at 20.32 cm from source.

Table 5.1-10: BUGLE 80 results for a detector at a distance of 25.40 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	5.260E-07	3.74E-07	1.41
18	7.788	7.106E-07	7.15E-07	0.99
17	6.873	1.514E-06	1.14E-06	1.33
16	6.065	1.855E-06	1.83E-06	1.01
15	5.353	2.677E-06	2.44E-06	1.10
14	4.724	2.851E-06	3.03E-06	0.94
13	4.169	3.206E-06	3.38E-06	0.95
12	3.679	2.829E-06	3.46E-06	0.82
11	3.247	3.486E-06	3.27E-06	1.07
10	2.865	3.643E-06	4.24E-06	0.86
9	2.528	4.699E-06	5.06E-06	0.93
8	2.231	4.835E-06	5.53E-06	0.87
7	1.969	4.002E-06	4.96E-06	0.81
6	1.738	3.661E-06	4.51E-06	0.81
5	1.534	3.400E-06	4.53E-06	0.75
4	1.353	3.088E-06	4.55E-06	0.68
3	1.194	3.178E-06	4.19E-06	0.76
2	1.054	2.805E-06	4.97E-06	0.56
1	0.930	2.607E-06	4.07E-06	0.64

Table 5.1-11: BUGLE 96 results for a detector at a distance of 25.40 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	4.772E-07	3.74E-07	1.28
18	7.788	7.444E-07	7.15E-07	1.04
17	6.873	1.642E-06	1.14E-06	1.44
16	6.065	2.020E-06	1.83E-06	1.10
15	5.353	2.517E-06	2.44E-06	1.03
14	4.724	2.712E-06	3.03E-06	0.90
13	4.169	3.087E-06	3.38E-06	0.91
12	3.679	2.724E-06	3.46E-06	0.79
11	3.247	4.223E-06	3.27E-06	1.29
10	2.865	4.136E-06	4.24E-06	0.98
9	2.528	4.220E-06	5.06E-06	0.83
8	2.231	6.185E-06	5.53E-06	1.12
7	1.969	4.115E-06	4.96E-06	0.83
6	1.738	3.891E-06	4.51E-06	0.86
5	1.534	3.899E-06	4.53E-06	0.86
4	1.353	3.695E-06	4.55E-06	0.81
3	1.194	3.477E-06	4.19E-06	0.83
2	1.054	3.477E-06	4.97E-06	0.62
1	0.930	3.477E-06	4.07E-06	0.66

Table 5.1-12: BUGLE 80 and BUGLE 96 comparison. Detector at 25.40 cm from source.

Group	Energy Boundary (MeV)	Calculated/Experimental	
		BUGLE 80	BUGLE 96
20	10		
19	8.825	1.41	1.28
18	7.788	0.99	1.04
17	6.873	1.33	1.44
16	6.065	1.01	1.10
15	5.353	1.10	1.03
14	4.724	0.94	0.90
13	4.169	0.95	0.91
12	3.679	0.82	0.79
11	3.247	1.07	1.29
10	2.865	0.86	0.98
9	2.528	0.93	0.83
8	2.231	0.87	1.12
7	1.969	0.81	0.83
6	1.738	0.81	0.86
5	1.534	0.75	0.86
4	1.353	0.68	0.81
3	1.194	0.76	0.83
2	1.054	0.56	0.62
1	0.930	0.64	0.66

Figure 5.1-4: BUGLE 80 and BUGLE 96 data comparison. Detector at 25.40 cm from source.

Table 5.1-13: BUGLE 80 results for a detector at a distance of 30.48 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	2.394E-07	1.77E-07	1.35
18	7.788	3.369E-07	3.05E-07	1.10
17	6.873	6.079E-07	5.46E-07	1.11
16	6.065	7.126E-07	8.04E-07	0.89
15	5.353	9.009E-07	9.77E-07	0.92
14	4.724	1.077E-06	1.24E-06	0.87
13	4.169	1.348E-06	1.36E-06	0.99
12	3.679	1.189E-06	1.26E-06	0.94
11	3.247	1.179E-06	1.20E-06	0.98
10	2.865	1.234E-06	1.58E-06	0.78
9	2.528	1.753E-06	1.81E-06	0.97
8	2.231	1.844E-06	2.03E-06	0.91
7	1.969	1.279E-06	1.75E-06	0.73
6	1.738	1.430E-06	1.62E-06	0.88
5	1.534	1.156E-06	1.57E-06	0.74
4	1.353	9.092E-07	1.59E-06	0.57
3	1.194	1.417E-06	1.45E-06	0.98
2	1.054	1.251E-06	1.75E-06	0.71
1	0.930	9.837E-07	1.61E-06	0.61

Table 5.1-14: BUGLE 96 results for a detector at a distance of 30.48 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	2.033E-07	1.77E-07	1.15
18	7.788	3.152E-07	3.05E-07	1.03
17	6.873	6.078E-07	5.46E-07	1.11
16	6.065	7.229E-07	8.04E-07	0.90
15	5.353	9.619E-07	9.77E-07	0.98
14	4.724	1.092E-06	1.24E-06	0.88
13	4.169	1.306E-06	1.36E-06	0.96
12	3.679	1.153E-06	1.26E-06	0.91
11	3.247	1.395E-06	1.20E-06	1.16
10	2.865	1.430E-06	1.58E-06	0.91
9	2.528	1.541E-06	1.81E-06	0.85
8	2.231	1.650E-06	2.03E-06	0.81
7	1.969	1.435E-06	1.75E-06	0.82
6	1.738	1.350E-06	1.62E-06	0.83
5	1.534	1.378E-06	1.57E-06	0.88
4	1.353	1.321E-06	1.59E-06	0.83
3	1.194	1.048E-06	1.45E-06	0.72
2	1.054	9.248E-07	1.75E-06	0.53
1	0.930	1.033E-06	1.61E-06	0.64

Table 5.1-15: BUGLE 80 and BUGLE 96 comparison. Detector at 30.48 cm from source.

Group	Energy Boundary (MeV)	Calculated/Experimental	
		BUGLE 80	BUGLE 96
20	10		
19	8.825	1.35	1.15
18	7.788	1.10	1.03
17	6.873	1.11	1.11
16	6.065	0.89	0.90
15	5.353	0.92	0.98
14	4.724	0.87	0.88
13	4.169	0.99	0.96
12	3.679	0.94	0.91
11	3.247	0.98	1.16
10	2.865	0.78	0.91
9	2.528	0.97	0.85
8	2.231	0.91	0.81
7	1.969	0.73	0.82
6	1.738	0.88	0.83
5	1.534	0.74	0.88
4	1.353	0.57	0.83
3	1.194	0.98	0.72
2	1.054	0.71	0.53
1	0.930	0.61	0.64

Figure 5.1-5: BUGLE 80 and BUGLE 96 data comparison. Detector at 30.48 cm from source.

Table 5.1-16: BUGLE 80 results for a detector at a distance of 35.56 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	9.739E-08	9.17E-08	1.06
18	7.788	1.502E-07	1.38E-07	1.09
17	6.873	3.202E-07	2.36E-07	1.36
16	6.065	3.907E-07	3.42E-07	1.14
15	5.353	4.938E-07	4.06E-07	1.22
14	4.724	5.637E-07	5.34E-07	1.06
13	4.169	6.781E-07	5.41E-07	1.25
12	3.679	5.984E-07	5.13E-07	1.17
11	3.247	5.053E-07	4.26E-07	1.19
10	2.865	4.966E-07	6.08E-07	0.82
9	2.528	5.641E-07	6.60E-07	0.85
8	2.231	6.561E-07	7.58E-07	0.87
7	1.969	8.960E-07	6.43E-07	1.39
6	1.738	5.776E-07	5.96E-07	0.97
5	1.534	4.962E-07	5.72E-07	0.87
4	1.353	4.603E-07	5.71E-07	0.81
3	1.194	4.762E-07	5.18E-07	0.92
2	1.054	4.203E-07	6.19E-07	0.68
1	0.930	3.494E-07	5.38E-07	0.65

Table 5.1-17: BUGLE 96 results for a detector at a distance of 35.56 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	1.098E-07	9.17E-08	1.20
18	7.788	1.542E-07	1.38E-07	1.12
17	6.873	2.591E-07	2.36E-07	1.10
16	6.065	2.973E-07	3.42E-07	0.87
15	5.353	4.116E-07	4.06E-07	1.01
14	4.724	4.301E-07	5.34E-07	0.81
13	4.169	4.738E-07	5.41E-07	0.88
12	3.679	4.181E-07	5.13E-07	0.82
11	3.247	5.561E-07	4.26E-07	1.31
10	2.865	4.864E-07	6.08E-07	0.80
9	2.528	5.248E-07	6.60E-07	0.80
8	2.231	1.159E-06	7.58E-07	1.53
7	1.969	4.958E-07	6.43E-07	0.77
6	1.738	6.181E-07	5.96E-07	1.04
5	1.534	5.542E-07	5.72E-07	0.97
4	1.353	4.681E-07	5.71E-07	0.82
3	1.194	3.749E-07	5.18E-07	0.72
2	1.054	3.309E-07	6.19E-07	0.53
1	0.930	3.045E-07	5.38E-07	0.57

Table 5.1-18: BUGLE 80 and BUGLE 96 comparison. Detector at 35.56 cm from source.

Group	Energy Boundary (MeV)	Calculated/Experimental	
		BUGLE 80	BUGLE 96
20	10		
19	8.825	1.06	1.20
18	7.788	1.09	1.12
17	6.873	1.36	1.10
16	6.065	1.14	0.87
15	5.353	1.22	1.01
14	4.724	1.06	0.81
13	4.169	1.25	0.88
12	3.679	1.17	0.82
11	3.247	1.19	1.31
10	2.865	0.82	0.80
9	2.528	0.85	0.80
8	2.231	0.87	1.53
7	1.969	1.39	0.77
6	1.738	0.97	1.04
5	1.534	0.87	0.97
4	1.353	0.81	0.82
3	1.194	0.92	0.72
2	1.054	0.68	0.53
1	0.930	0.65	0.57

Figure 5.1-6: BUGLE 80 and BUGLE 96 data comparison. Detector at 35.56 cm from source.

Table 5.1-19: BUGLE 80 results for a detector at a distance of 50.80 cm from source.

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	1.229E-08	1.36E-08	0.90
18	7.788	2.186E-08	1.77E-08	1.24
17	6.873	3.173E-08	2.67E-08	1.19
16	6.065	3.418E-08	3.90E-08	0.88
15	5.353	4.307E-08	4.61E-08	0.93
14	4.724	4.323E-08	4.51E-08	0.96
13	4.169	4.552E-08	5.26E-08	0.87
12	3.679	4.017E-08	3.67E-08	1.09
11	3.247	4.022E-08	4.03E-08	1.00
10	2.865	3.615E-08	4.39E-08	0.82
9	2.528	3.632E-08	4.87E-08	0.75
8	2.231	8.064E-08	5.60E-08	1.44
7	1.969	2.791E-08	4.39E-08	0.64
6	1.738	2.951E-08	4.15E-08	0.71
5	1.534	4.540E-08	4.14E-08	1.10
4	1.353	5.155E-08	4.00E-08	1.29
3	1.194	1.959E-08	3.77E-08	0.52
2	1.054	1.729E-08	4.23E-08	0.41
1	0.930	3.317E-08	4.41E-08	0.75

Table 5.1-20: BUGLE 96 results for a detector at a distance of 50.80 cm from source

Group	Energy boundary (MeV)	Flux/Lethargy per Source Neutron		C/E
		Calculated (C) (cm ⁻² /s)	Experimental (E) (cm ⁻² /s)	
20	10			
19	8.825	1.562E-08	1.36E-08	1.15
18	7.788	2.037E-08	1.77E-08	1.15
17	6.873	2.791E-08	2.67E-08	1.05
16	6.065	2.989E-08	3.90E-08	0.77
15	5.353	4.418E-08	4.61E-08	0.96
14	4.724	4.548E-08	4.51E-08	1.01
13	4.169	4.929E-08	5.26E-08	0.94
12	3.679	4.350E-08	3.67E-08	1.19
11	3.247	3.443E-08	4.03E-08	0.85
10	2.865	2.723E-08	4.39E-08	0.62
9	2.528	2.727E-08	4.87E-08	0.56
8	2.231	3.271E-08	5.60E-08	0.58
7	1.969	3.377E-08	4.39E-08	0.77
6	1.738	2.099E-08	4.15E-08	0.51
5	1.534	1.496E-08	4.14E-08	0.36
4	1.353	1.225E-08	4.00E-08	0.31
3	1.194	3.467E-08	3.77E-08	0.92
2	1.054	3.060E-08	4.23E-08	0.72
1	0.930	2.937E-08	4.41E-08	0.67

Table 5.1-21: BUGLE 80 and BUGLE 96 comparison. Detector at 50.86 cm from source.

Group	Energy Boundary (MeV)	Experimental/Calculated	
		BUGLE 80	BUGLE 96
20	10		
19	8.825	0.90	1.15
18	7.788	1.24	1.15
17	6.873	1.19	1.05
16	6.065	0.88	0.77
15	5.353	0.93	0.96
14	4.724	0.96	1.01
13	4.169	0.87	0.94
12	3.679	1.09	1.19
11	3.247	1.00	0.85
10	2.865	0.82	0.62
9	2.528	0.75	0.56
8	2.231	1.44	0.58
7	1.969	0.64	0.77
6	1.738	0.71	0.51
5	1.534	1.10	0.36
4	1.353	1.29	0.31
3	1.194	0.52	0.92
2	1.054	0.41	0.72
1	0.930	0.75	0.67

Figure 5.1-7: BUGLE 80 and BUGLE 96 data comparison. Detector at 50.80 cm from source.

5.2 Karlsruhe Iron Sphere Benchmark Experiment

Three types of proton recoil detectors were used to measure neutron spectra at different overlapping energy ranges for each of the six iron spheres. Detector 1 measured neutron spectrum from approximately 60 KeV to 850 KeV, the second detector measured spectrum from 300 KeV to 2300 KeV and the third measured spectrum from 900 to 5000 KeV. Results are tabulated for each of the six iron spheres. Tables 5.2-1 to 5.2-12 give the calculated and experimental values of neutron per source neutron per lethargy unit as well as the corresponding C/E ratios in each energy interval. For each sphere size, a graphical representations of the C/E ratios for the three detectors can be seen in Figures 5.2-1 to 5.2-18.

For detector 1, the calculated values lie within 20% of the experimental values from about 60 KeV to 300 KeV range. The calculated values were off by more than 20% in the 300 KeV to 500 KeV range, where a pronounced type of structure was observed. The calculated results were again in the 20% range with the measured value from 500 KeV to 700 KeV range.

For detector 2, the calculated values were within 20% of the measured value throughout most of the energy range of detector 2 except near the upper energy band of 2000 KeV. For detector 3, the calculated values were mostly higher than the measured values in the 900 KeV to 4000 KeV range and the C/E ratios lie between 1.0 to 1.1 within this range. Beyond the range of 4000 KeV, the calculated values were increasingly higher than the experimental results.

The calculated results with BUGLE-96 and BUGLE-80 were very close and differ by no more than 10%. The trend for each detector remains the same for different iron spheres (diameters vary from 15 cm to 40 cm)

Table 5.2-1: Detector Measurements for 15 cm diameter Iron Sphere using BUGLE 80 cross section library.

Detector 1				Detector 2				Detector 3			
Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E
6.775E+01	0.0219	0.0348	0.63	3.081E+02	0.2714	0.2275	1.19	9.165E+02	0.3932	0.3811	1.03
7.285E+01	0.0252	0.0499	0.51	3.317E+02	0.2633	0.2448	1.08	9.870E+02	0.3966	0.3853	1.03
7.850E+01	0.0290	0.0558	0.52	3.568E+02	0.2622	0.2592	1.01	1.063E+03	0.4129	0.3769	1.10
8.415E+01	0.0333	0.0498	0.67	3.833E+02	0.2579	0.2117	1.22	1.142E+03	0.4287	0.4001	1.07
9.035E+01	0.0381	0.0521	0.73	4.110E+02	0.2506	0.1786	1.40	1.226E+03	0.4307	0.4169	1.03
9.710E+01	0.0424	0.0367	1.15	4.423E+02	0.2469	0.1858	1.33	1.320E+03	0.4133	0.3769	1.10
1.044E+02	0.0474	0.0461	1.03	4.762E+02	0.2692	0.2751	0.98	1.419E+03	0.3884	0.3706	1.05
1.123E+02	0.0531	0.0680	0.78	5.130E+02	0.2934	0.2837	1.03	1.524E+03	0.3616	0.3453	1.05
1.208E+02	0.0596	0.0646	0.92	5.514E+02	0.3201	0.2895	1.11	1.638E+03	0.3626	0.3537	1.03
1.299E+02	0.0670	0.0800	0.84	5.927E+02	0.3711	0.3586	1.03	1.761E+03	0.3600	0.3601	1.00
1.395E+02	0.0752	0.0903	0.83	6.369E+02	0.4309	0.4709	0.92	1.896E+03	0.3411	0.3348	1.02
1.496E+02	0.0845	0.0750	1.13	6.840E+02	0.4759	0.5905	0.81	2.039E+03	0.3117	0.2906	1.07
1.609E+02	0.0706	0.0624	1.13	7.356E+02	0.3947	0.3082	1.28	2.191E+03	0.3090	0.2842	1.09
1.734E+02	0.0734	0.1140	0.64	7.917E+02	0.3123	0.3456	0.90	2.355E+03	0.3157	0.2779	1.14
1.863E+02	0.1086	0.1368	0.79	8.521E+02	0.3445	0.4004	0.86	2.533E+03	0.2572	0.2484	1.04
2.004E+02	0.1164	0.1072	1.09	9.155E+02	0.3793	0.3672	1.03	2.726E+03	0.2358	0.2337	1.01
2.157E+02	0.1221	0.1268	0.96	9.850E+02	0.3964	0.3629	1.09	2.931E+03	0.2161	0.2076	1.04
2.315E+02	0.1334	0.1354	0.99	1.060E+03	0.4128	0.3860	1.07	3.150E+03	0.1909	0.1916	1.00
2.484E+02	0.1481	0.1226	1.21	1.139E+03	0.4289	0.4033	1.06	3.387E+03	0.1623	0.1619	1.00
2.677E+02	0.1530	0.1677	0.91	1.225E+03	0.4298	0.3384	1.27	3.641E+03	0.1523	0.1453	1.05
2.880E+02	0.1652	0.1876	0.88	1.316E+03	0.4145	0.3730	1.11	3.916E+03	0.1380	0.1303	1.06
3.095E+02	0.1436	0.2436	0.59	1.415E+03	0.3899	0.3888	1.00	4.212E+03	0.1185	0.1128	1.05
3.326E+02	0.1546	0.2358	0.66	1.523E+03	0.3617	0.3485	1.04	4.527E+03	0.1048	0.0874	1.20
3.575E+02	0.1670	0.2788	0.60	1.638E+03	0.3629	0.4076	0.89	4.869E+03	0.0935	0.0697	1.34
3.846E+02	0.3162	0.2462	1.28	1.760E+03	0.3606	0.3269	1.10	5.238E+03	0.0754	0.0484	1.56
4.139E+02	0.3371	0.1745	1.93	1.893E+03	0.3425	0.3269	1.05				
4.450E+02	0.3641	0.1980	1.84	2.036E+03	0.3129	0.2578	1.21				
4.783E+02	0.3938	0.2762	1.43	2.189E+03	0.3093	0.2621	1.18				
5.144E+02	0.2973	0.2462	1.21	2.354E+03	0.3499	0.2318	1.51				
5.534E+02	0.3185	0.3087	1.03								
5.952E+02	0.3568	0.4012	0.89								
6.398E+02	0.3853	0.4273	0.90								
6.878E+02	0.4131	0.3817	1.08								
7.392E+02	0.5554	0.4038	1.38								
7.951E+02	0.5928	0.3960	1.50							BUG80/15	

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Detector 1				Detector 2				Detector 3			
Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E
6.775E+01	0.0198	0.0348	0.57	3.081E+02	0.2704	0.2275	1.19	9.165E+02	0.3736	0.3811	0.98
7.285E+01	0.0231	0.0499	0.46	3.317E+02	0.2610	0.2448	1.07	9.870E+02	0.3809	0.3853	0.99
7.850E+01	0.0269	0.0558	0.48	3.568E+02	0.2582	0.2592	1.00	1.063E+03	0.4016	0.3769	1.07
8.415E+01	0.0312	0.0498	0.63	3.833E+02	0.2518	0.2117	1.19	1.142E+03	0.4228	0.4001	1.06
9.035E+01	0.0362	0.0521	0.70	4.110E+02	0.2421	0.1786	1.36	1.226E+03	0.4278	0.4169	1.03
9.710E+01	0.0404	0.0367	1.10	4.423E+02	0.2364	0.1858	1.27	1.320E+03	0.4128	0.3769	1.10
1.044E+02	0.0455	0.0461	0.99	4.762E+02	0.2593	0.2751	0.94	1.419E+03	0.3908	0.3706	1.05
1.123E+02	0.0513	0.0680	0.75	5.130E+02	0.2846	0.2837	1.00	1.524E+03	0.3670	0.3453	1.06
1.208E+02	0.0578	0.0646	0.90	5.514E+02	0.3126	0.2895	1.08	1.638E+03	0.3664	0.3537	1.04
1.299E+02	0.0653	0.0800	0.82	5.927E+02	0.3697	0.3586	1.03	1.761E+03	0.3616	0.3601	1.00
1.395E+02	0.0737	0.0903	0.82	6.369E+02	0.4373	0.4709	0.93	1.896E+03	0.3438	0.3348	1.03
1.496E+02	0.0832	0.0750	1.11	6.840E+02	0.4889	0.5905	0.83	2.039E+03	0.3215	0.2906	1.11
1.609E+02	0.0669	0.0624	1.07	7.356E+02	0.4104	0.3082	1.33	2.191E+03	0.3123	0.2842	1.10
1.734E+02	0.0695	0.1140	0.61	7.917E+02	0.3300	0.3456	0.95	2.355E+03	0.3057	0.2779	1.10
1.863E+02	0.1068	0.1368	0.78	8.521E+02	0.3451	0.4004	0.86	2.533E+03	0.2650	0.2484	1.07
2.004E+02	0.1145	0.1072	1.07	9.155E+02	0.3606	0.3672	0.98	2.726E+03	0.2423	0.2337	1.04
2.157E+02	0.1201	0.1268	0.95	9.850E+02	0.3807	0.3629	1.05	2.931E+03	0.2220	0.2076	1.07
2.315E+02	0.1313	0.1354	0.97	1.060E+03	0.4012	0.3860	1.04	3.150E+03	0.1973	0.1916	1.03
2.484E+02	0.1456	0.1226	1.19	1.139E+03	0.4223	0.4033	1.05	3.387E+03	0.1692	0.1619	1.05
2.677E+02	0.1505	0.1677	0.90	1.225E+03	0.4271	0.3384	1.26	3.641E+03	0.1605	0.1453	1.10
2.880E+02	0.1625	0.1876	0.87	1.316E+03	0.4142	0.3730	1.11	3.916E+03	0.1475	0.1303	1.13
3.095E+02	0.1391	0.2436	0.57	1.415E+03	0.3927	0.3888	1.01	4.212E+03	0.1296	0.1128	1.15
3.326E+02	0.1497	0.2358	0.63	1.523E+03	0.3673	0.3485	1.05	4.527E+03	0.1159	0.0874	1.33
3.575E+02	0.1617	0.2788	0.58	1.638E+03	0.3664	0.4076	0.90	4.869E+03	0.1031	0.0697	1.48
3.846E+02	0.3132	0.2462	1.27	1.760E+03	0.3615	0.3269	1.11	5.238E+03	0.0828	0.0484	1.71
4.139E+02	0.3339	0.1745	1.91	1.893E+03	0.3464	0.3269	1.06				
4.450E+02	0.3606	0.1980	1.82	2.036E+03	0.3223	0.2578	1.25				
4.783E+02	0.3901	0.2762	1.41	2.189E+03	0.3121	0.2621	1.19				
5.144E+02	0.2841	0.2462	1.15	2.354E+03	0.						

Figure 5.2-1: Detector 1 Data Comparison for 15 cm Sphere

Figure 5.2-2: Detector 2 data comparison for 15 cm sphere.

Figure 5.2-3: Detector 3 Data Comparison for 15 cm Sphere

Table 5.2-3: Detector Measurements for 20cm Diameter Iron Sphere using BUGLE 80 cross section library.

Detector 1					Detector 2					Detector 3				
Mid Energy (keV)	Calc. ©	Exp. (E)	C/E		Mid Energy (keV)	Calc. ©	Exp. (E)	C/E		Mid Energy (keV)	Calc. ©	Exp. (E)	C/E	
6.775E+01	0.0283	0.0354	0.80		3.081E+02	0.3615	0.3339	1.08		9.165E+02	0.3952	0.3643	1.08	
7.285E+01	0.0327	0.0480	0.68		3.317E+02	0.3439	0.3051	1.13		9.870E+02	0.3932	0.3811	1.03	
7.850E+01	0.0379	0.0594	0.64		3.568E+02	0.3342	0.2965	1.13		1.063E+03	0.4030	0.3685	1.09	
8.415E+01	0.0437	0.0577	0.76		3.833E+02	0.3184	0.2792	1.14		1.142E+03	0.4111	0.3938	1.04	
9.035E+01	0.0504	0.0439	1.15		4.110E+02	0.2968	0.1971	1.51		1.226E+03	0.4050	0.3938	1.03	
9.710E+01	0.0557	0.0397	1.40		4.423E+02	0.2799	0.2432	1.15		1.320E+03	0.3794	0.3474	1.09	
1.044E+02	0.0621	0.0572	1.09		4.762E+02	0.3042	0.2835	1.07		1.419E+03	0.3448	0.3222	1.07	
1.123E+02	0.0694	0.0672	1.03		5.130E+02	0.3306	0.2821	1.17		1.524E+03	0.3090	0.2969	1.04	
1.208E+02	0.0777	0.0819	0.95		5.514E+02	0.3595	0.3296	1.09		1.638E+03	0.3083	0.2990	1.03	
1.299E+02	0.0870	0.1060	0.82		5.927E+02	0.4205	0.4145	1.01		1.761E+03	0.3042	0.2990	1.02	
1.395E+02	0.0974	0.1038	0.94		6.369E+02	0.4924	0.5109	0.96		1.896E+03	0.2824	0.2716	1.04	
1.496E+02	0.1091	0.0723	1.51		6.840E+02	0.5420	0.4346	1.25		2.039E+03	0.2493	0.2274	1.10	
1.609E+02	0.0931	0.0918	1.01		7.356E+02	0.4180	0.3713	1.13		2.191E+03	0.2457	0.2253	1.09	
1.734E+02	0.0968	0.1300	0.74		7.917E+02	0.2940	0.3353	0.88		2.355E+03	0.2533	0.2148	1.18	
1.863E+02	0.1404	0.1378	1.02		8.521E+02	0.3364	0.3396	0.99		2.533E+03	0.1927	0.1874	1.03	
2.004E+02	0.1504	0.1240	1.21		9.155E+02	0.3828	0.3799	1.01		2.726E+03	0.1758	0.1667	1.05	
2.157E+02	0.1578	0.1560	1.01		9.850E+02	0.3943	0.3742	1.05		2.931E+03	0.1604	0.1480	1.08	
2.315E+02	0.1725	0.1339	1.29		1.060E+03	0.4039	0.3627	1.11		3.150E+03	0.1390	0.1373	1.01	
2.484E+02	0.1914	0.1625	1.18		1.139E+03	0.4117	0.3727	1.10		3.387E+03	0.1149	0.1162	0.99	
2.677E+02	0.1977	0.2080	0.95		1.225E+03	0.4046	0.3468	1.17		3.641E+03	0.1075	0.1000	1.08	
2.880E+02	0.2135	0.2132	1.00		1.316E+03	0.3815	0.3612	1.06		3.916E+03	0.0970	0.0811	1.20	
3.095E+02	0.1608	0.2743	0.59		1.415E+03	0.3476	0.3382	1.03		4.212E+03	0.0828	0.0828	1.00	
3.326E+02	0.1731	0.2483	0.70		1.523E+03	0.3099	0.3152	0.98		4.527E+03	0.0728	0.0533	1.37	

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Figure 5.2-4: Detector 1 Data Comparison for 20 cm Sphere

Figure 5.2-5: Detector 2 data comparison for 20 cm sphere.

Figure 5.2-6: Detector 3 Data Comparison for 20 cm Sphere

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Table 5.2-5: Detector Measurements for 25cm Diameter Iron Sphere using BUGLE 80 cross section library.

Detector 1				Detector 2				Detector 3			
Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E
6.775E+01	0.0368	0.0544	0.68	3.081E+02	0.4547	0.3145	1.45	9.165E+02	0.3804	0.3655	1.04
7.285E+01	0.0427	0.0541	0.79	3.317E+02	0.4263	0.3202	1.33	9.870E+02	0.3730	0.3674	1.02
7.850E+01	0.0496	0.0605	0.82	3.568E+02	0.4062	0.3490	1.16	1.063E+03	0.3755	0.3270	1.15
8.415E+01	0.0573	0.0538	1.07	3.833E+02	0.3771	0.2886	1.31	1.142E+03	0.3752	0.3694	1.02
9.035E+01	0.0663	0.0557	1.19	4.110E+02	0.3390	0.2140	1.58	1.226E+03	0.3624	0.3578	1.01
9.710E+01	0.0725	0.0427	1.70	4.423E+02	0.3071	0.2398	1.28	1.320E+03	0.3329	0.3001	1.11
1.044E+02	0.0801	0.0575	1.39	4.762E+02	0.3326	0.3231	1.03	1.419E+03	0.2940	0.2789	1.05
1.123E+02	0.0887	0.0748	1.19	5.130E+02	0.3601	0.3073	1.17	1.524E+03	0.2545	0.2539	1.00
1.208E+02	0.0983	0.0919	1.07	5.514E+02	0.3900	0.3561	1.10	1.638E+03	0.2531	0.2482	1.02
1.299E+02	0.1090	0.1262	0.86	5.927E+02	0.4569	0.4423	1.03	1.761E+03	0.2485	0.2501	0.99
1.395E+02	0.1209	0.1448	0.83	6.369E+02	0.5359	0.5874	0.91	1.896E+03	0.2259	0.2193	1.03
1.496E+02	0.1342	0.0941	1.43	6.840E+02	0.5865	0.4667	1.26	2.039E+03	0.1922	0.1797	1.07
1.609E+02	0.1225	0.0911	1.35	7.356E+02	0.4271	0.3461	1.23	2.191E+03	0.1904	0.1737	1.10
1.734E+02	0.1273	0.1630	0.78	7.917E+02	0.2679	0.3346	0.80	2.355E+03	0.2016	0.1622	1.24
1.863E+02	0.1731	0.1657	1.04	8.521E+02	0.3153	0.3418	0.92	2.533E+03	0.1420	0.1373	1.03
2.004E+02	0.1855	0.1383	1.34	9.155E+02	0.3673	0.3604	1.02	2.726E+03	0.1285	0.1254	1.03
2.157E+02	0.1945	0.1552	1.25	9.850E+02	0.3733	0.3533	1.06	2.931E+03	0.1161	0.1098	1.06
2.315E+02	0.2127	0.1591	1.34	1.060E+03	0.3762	0.3245	1.16	3.150E+03	0.0991	0.0976	1.02
2.484E+02	0.2359	0.1670	1.41	1.139E+03	0.3762	0.3691	1.02	3.387E+03	0.0800	0.0839	0.95
2.677E+02	0.2438	0.2204	1.11	1.225E+03	0.3629	0.3533	1.03	3.641E+03	0.0744	0.0723	1.03
2.880E+02	0.2632	0.2387	1.10	1.316E+03	0.3357	0.3202	1.05	3.916E+03	0.0666	0.0623	1.07
3.095E+02	0.1751	0.3000	0.58	1.415E+03	0.2973	0.2743	1.08	4.212E+03	0.0559	0.0545	1.03
3.326E+02	0.1884	0.3039	0.62	1.523E+03	0.2554	0.2484	1.03	4.527E+03	0.0487	0.0412	1.18
3.575E+02	0.2036	0.3457	0.59	1.638E+03	0.2537	0.2743	0.92	4.869E+03	0.0432	0.0360	1.20
3.846E+02	0.5109	0.2909	1.76	1.760E+03	0.2489	0.2369	1.05	5.238E+03	0.0345	0.0239	1.45
4.139E+02	0.5446	0.1904	2.86	1.893E+03	0.2266	0.2355	0.96				
4.450E+02	0.5882	0.2439	2.41	2.036E+03	0.1929	0.1795	1.07				
4.783E+02	0.6363	0.2961	2.15	2.189E+03	0.1905	0.1565	1.22				
5.144E+02	0.3704	0.2805	1.32	2.354E+03	0.2265	0.1317	1.72				
5.534E+02	0.3968	0.3470	1.14								
5.952E+02	0.4346	0.4840	0.90								
6.398E+02	0.4693	0.5636	0.83								
6.878E+02	0.5032	0.4540	1.11								
7.392E+02	0.6958	0.3809	1.83								
7.951E+02	0.7428	0.3561	2.09							BUG80/25	

Detector 1					Detector 2					Detector 3				
Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E		Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E		Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	
6.775E+01	0.0325	0.0544	0.60		3.081E+02	0.4668	0.3145	1.48		9.163E+02	0.3531	0.3655	0.97	
7.285E+01	0.0384	0.0541	0.71		3.317E+02	0.4336	0.3202	1.35		9.870E+02	0.3523	0.3674	0.96	
7.850E+01	0.0453	0.0605	0.75		3.568E+02	0.4082	0.3490	1.17		1.063E+03	0.3624	0.3270	1.11	
8.415E+01	0.0532	0.0538	0.99		3.833E+02	0.3725	0.2886	1.29		1.142E+03	0.3711	0.3694	1.00	
9.035E+01	0.0623	0.0557	1.12		4.110E+02	0.3264	0.2140	1.53		1.226E+03	0.3641	0.3578	1.02	
9.710E+01	0.0686	0.0427	1.61		4.423E+02	0.2885	0.2398	1.20		1.320E+03	0.3371	0.3001	1.12	
1.044E+02	0.0765	0.0575	1.33		4.762E+02	0.3169	0.3231	0.98		1.419E+03	0.3012	0.2789	1.08	
1.123E+02	0.0855	0.0748	1.14		5.130E+02	0.3482	0.3073	1.13		1.524E+03	0.2636	0.2539	1.04	
1.208E+02	0.0956	0.0919	1.04		5.514E+02	0.3829	0.3561	1.08		1.638E+03	0.2599	0.2482	1.05	
1.299E+02	0.1070	0.1262	0.85		5.927E+02	0.4618	0.4423	1.04		1.761E+03	0.2524	0.2501	1.01	
1.395E+02	0.1197	0.1448	0.83		6.369E+02	0.5562	0.5874	0.95		1.896E+03	0.2340	0.2193	1.07	
1.496E+02	0.1341	0.0941	1.43		6.840E+02	0.6217	0.4667	1.33		2.039E+03	0.2070	0.1797	1.15	
1.609E+02	0.1148	0.0911	1.26		7.356E+02	0.4590	0.3461	1.33		2.191E+03	0.1976	0.1737	1.14	
1.734E+02	0.1193	0.1630	0.73		7.917E+02	0.2924	0.3346	0.87		2.355E+03	0.1937	0.1622	1.19	
1.863E+02	0.1725	0.1657	1.04		8.521E+02	0.3156	0.3418	0.92		2.533E+03	0.1515	0.1373	1.10	
2.004E+02	0.1849	0.1383	1.34		9.155E+02	0.3401	0.3604	0.94		2.726E+03	0.1343	0.1254	1.07	
2.157E+02	0.1939	0.1552	1.25		9.850E+02	0.3516	0.3533	1.00		2.931E+03	0.1206	0.1098	1.10	
2.315E+02	0.2120	0.1591	1.33		1.060E+03	0.3616	0.3245	1.11		3.150E+03	0.1046	0.0976	1.07	
2.484E+02	0.2352	0.1670	1.41		1.139E+03	0.3704	0.3691	1.00		3.387E+03	0.0868	0.0839	1.03	
2.677E+02	0.2430	0.2204	1.10		1.225E+03	0.3631	0.3533	1.03		3.641E+03	0.0821	0.0723	1.13	
2.880E+02	0.2624	0.2387	1.10		1.316E+03	0.3384	0.3202	1.06		3.916E+03	0.0751	0.0623	1.20	
3.095E+02	0.1712	0.3000	0.57		1.415E+03	0.3030	0.2743	1.10		4.212E+03	0.0655	0.0545	1.20	
3.326E+02	0.1843	0.3039	0.61		1.523E+03	0.2639	0.2484	1.06		4.527E+03	0.0583	0.0412	1.41	
3.575E+02	0.1991	0.3457	0.58		1.638E+03	0.2606	0.2743	0.95		4.869E+03	0.0517	0.0360	1.44	
3.846E+02	0.5196	0.2909	1.79		1.760E+03	0.2538	0.2369	1.07		5.238E+03	0.0413	0.0239	1.73	
4.139E+02	0.5539	0.1904	2.91		1.893E+03	0.2353	0.235							

Figure 5.2-7: Detector 1 Data Comparison for 25 cm Sphere

Figure 5.2-8: Detector 2 data comparison for 25 cm sphere.

Figure 5.2-9: Detector 3 Data Comparison for 25 cm Sphere

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Table 5.2-8: Detector Measurements for 30cm Diameter Iron Sphere using BUGLE 96 cross section library.

Detector 1					Detector 2					Detector 3				
Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E		Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E		Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	
6.775E+01	0.0413	0.0303	1.36		3.081E+02	0.5688	0.3572	1.59		9.165E+02	0.2657	0.3682	0.72	
7.285E+01	0.0490	0.0357	1.37		3.317E+02	0.5220	0.3445	1.52		9.870E+02	0.3193	0.3703	0.86	
7.850E+01	0.0581	0.0510	1.14		3.568E+02	0.4832	0.3728	1.30		1.063E+03	0.3249	0.3114	1.04	
8.415E+01	0.0684	0.0515	1.33		3.833E+02	0.4303	0.2693	1.60		1.142E+03	0.3286	0.3430	0.96	
9.035E+01	0.0804	0.0603	1.33		4.110E+02	0.3630	0.2084	1.74		1.226E+03	0.3184	0.3367	0.95	
9.710E+01	0.0876	0.0502	1.74		4.423E+02	0.3052	0.2623	1.16		1.320E+03	0.2900	0.2693	1.08	
1.044E+02	0.0967	0.0511	1.89		4.762E+02	0.3350	0.3289	1.02		1.419E+03	0.2528	0.2399	1.05	
1.123E+02	0.1069	0.0857	1.25		5.130E+02	0.3678	0.3019	1.22		1.524E+03	0.2146	0.2104	1.02	
1.208E+02	0.1183	0.0861	1.37		5.514E+02	0.4042	0.3799	1.06		1.638E+03	0.2101	0.1986	1.06	
1.299E+02	0.1310	0.1159	1.13		5.927E+02	0.4869	0.5019	0.97		1.761E+03	0.2023	0.2056	0.98	
1.395E+02	0.1451	0.1567	0.93		6.369E+02	0.5857	0.6110	0.96		1.896E+03	0.1844	0.1742	1.06	
1.496E+02	0.1609	0.1382	1.16		6.840E+02	0.6509	0.4225	1.54		2.039E+03	0.1595	0.1348	1.18	
1.609E+02	0.1482	0.1170	1.27		7.356E+02	0.4577	0.3516	1.30		2.191E+03	0.1512	0.1302	1.16	
1.734E+02	0.1540	0.1567	0.98		7.917E+02	0.2599	0.3204	0.81		2.355E+03	0.1477	0.1256	1.18	
1.863E+02	0.2075	0.2075	1.00		8.521E+02	0.2851	0.3204	0.89		2.533E+03	0.1113	0.0989	1.13	
2.004E+02	0.2224	0.1829	1.22		9.155E+02	0.3121	0.3558	0.88		2.726E+03	0.0988	0.0890	1.11	
2.157E+02	0.2333	0.1742	1.34		9.850E+02	0.3197	0.3615	0.88		2.931E+03	0.0875	0.0806	1.09	
2.315E+02	0.2550	0.1974	1.29		1.060E+03	0.3253	0.2864	1.14		3.150E+03	0.0747	0.0680	1.10	
2.484E+02	0.2830	0.1974	1.43		1.139E+03	0.3291	0.3317	0.99		3.387E+03	0.0605	0.0587	1.03	
2.677E+02	0.2923	0.2613	1.12		1.225E+03	0.3183	0.2991	1.06		3.641E+03	0.0571	0.0484	1.18	
2.880E+02	0.3156	0.3121	1.01		1.316E+03	0.2920	0.2778	1.05		3.916E+03	0.0522	0.0398	1.31	
3.095E+02	0.1851	0.3832	0.48		1.415E+03	0.2550	0.2013	1.27		4.212E+03	0.0454	0.0341	1.33	
3.326E+02	0.1992	0.3484	0.57		1.523E+03	0.2146	0.2282	0.94		4.527E+03	0.0404	0.0286	1.41	

Figure 5.2-10: Detector 1 Data Comparison for 30 cm Sphere

Figure 5.2-11: Detector 2 data comparison for 30 cm sphere.

Figure 5.2-12: Detector 3 Data Comparison for 30 cm Sphere

Detector 1				Detector 2				Detector 3			
Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E
6.775E+01	0.0368	0.0322	1.14	3.081E+02	0.6259	0.4349	1.44	9.165E+02	0.3202	0.3519	0.91
7.285E+01	0.0427	0.0597	0.71	3.317E+02	0.5743	0.3983	1.44	9.870E+02	0.3058	0.3413	0.90
7.850E+01	0.0496	0.0593	0.84	3.568E+02	0.5316	0.4223	1.26	1.063E+03	0.2980	0.2845	1.05
8.415E+01	0.0573	0.0646	0.89	3.833E+02	0.4733	0.3139	1.51	1.142E+03	0.2859	0.3055	0.94
9.035E+01	0.0663	0.0622	1.07	4.110E+02	0.3992	0.2181	1.83	1.226E+03	0.2667	0.2992	0.89
9.710E+01	0.1106	0.0633	1.75	4.423E+02	0.3337	0.2576	1.30	1.320E+03	0.2364	0.2276	1.04
1.044E+02	0.1201	0.0692	1.74	4.762E+02	0.3583	0.3125	1.15	1.419E+03	0.1974	0.1968	1.00
1.123E+02	0.1306	0.0974	1.34	5.130E+02	0.3843	0.3392	1.13	1.524E+03	0.1583	0.1713	0.92
1.208E+02	0.1420	0.1298	1.09	5.514E+02	0.4122	0.3800	1.08	1.638E+03	0.1571	0.1656	0.95
1.299E+02	0.1545	0.1819	0.85	5.927E+02	0.4785	0.5574	0.86	1.761E+03	0.1538	0.1635	0.94
1.395E+02	0.1679	0.1849	0.91	6.369E+02	0.5568	0.6447	0.86	1.896E+03	0.1352	0.1365	0.99
1.496E+02	0.1828	0.1528	1.20	6.840E+02	0.6012	0.5391	1.12	2.039E+03	0.1078	0.1051	1.03
1.609E+02	0.1907	0.1674	1.14	7.356E+02	0.4055	0.3519	1.15	2.191E+03	0.1063	0.0991	1.07
1.734E+02	0.1982	0.2096	0.95	7.917E+02	0.2093	0.3195	0.66	2.355E+03	0.1155	0.0883	1.31
1.863E+02	0.2369	0.2256	1.05	8.521E+02	0.2571	0.3068	0.84	2.533E+03	0.0735	0.0719	1.02
2.004E+02	0.2538	0.1645	1.54	9.155E+02	0.3096	0.3505	0.88	2.726E+03	0.0648	0.0639	1.02
2.157E+02	0.2662	0.2067	1.29	9.850E+02	0.3066	0.3181	0.96	2.931E+03	0.0574	0.0559	1.03
2.315E+02	0.2911	0.2067	1.41	1.060E+03	0.2991	0.3068	0.98	3.150E+03	0.0483	0.0459	1.05
2.484E+02	0.3229	0.2475	1.30	1.139E+03	0.2872	0.3209	0.90	3.387E+03	0.0381	0.0426	0.90
2.677E+02	0.3336	0.3130	1.07	1.225E+03	0.2670	0.2463	1.08	3.641E+03	0.0352	0.0316	1.11
2.880E+02	0.3602	0.3465	1.04	1.316E+03	0.2387	0.2322	1.03	3.916E+03	0.0310	0.0261	1.19
3.095E+02	0.1986	0.4280	0.46	1.415E+03	0.2000	0.2111	0.95	4.212E+03	0.0255	0.0230	1.11
3.326E+02	0.2138	0.3727	0.57	1.523E+03	0.1588	0.1858	0.85	4.527E+03	0.0219	0.0180	1.22
3.575E+02	0.2309	0.3814	0.61	1.638E+03	0.1574	0.1731	0.91	4.869E+03	0.0195	0.0139	1.41
3.846E+02	0.6874	0.2591	2.65	1.760E+03	0.1541	0.1618	0.95	5.238E+03	0.0155	0.0093	1.67
4.139E+02	0.7328	0.2067	3.55	1.893E+03	0.1362	0.1141	1.19				
4.450E+02	0.7914	0.2911	2.72	2.036E+03	0.1088	0.0977	1.11				
4.783E+02	0.8561	0.3101	2.76	2.189E+03	0.1054	0.1009	1.04				
5.144E+02	0.4034	0.									

Table 5.2-10: Detector Measurements for 35cm Diameter Iron Sphere using BUGLE 96 cross section library.

Detector 1				Detector 2				Detector 3			
Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E
6.775E+01	0.0515	0.0322	1.60	3.081E+02	0.6565	0.4349	1.51	9.165E+02	0.2887	0.3519	0.82
7.285E+01	0.0609	0.0597	1.02	3.317E+02	0.5969	0.3983	1.50	9.870E+02	0.2826	0.3413	0.83
7.850E+01	0.0721	0.0593	1.22	3.568E+02	0.5453	0.4223	1.29	1.063E+03	0.2841	0.2845	1.00
8.415E+01	0.0847	0.0646	1.31	3.833E+02	0.4761	0.3139	1.52	1.142E+03	0.2832	0.3055	0.93
9.035E+01	0.0993	0.0622	1.60	4.110E+02	0.3888	0.2181	1.78	1.226E+03	0.2706	0.2992	0.90
9.710E+01	0.1071	0.0633	1.69	4.423E+02	0.3123	0.2576	1.21	1.320E+03	0.2429	0.2276	1.07
1.044E+02	0.1171	0.0692	1.69	4.762E+02	0.3417	0.3125	1.09	1.419E+03	0.2071	0.1968	1.05
1.123E+02	0.1283	0.0974	1.32	5.130E+02	0.3739	0.3392	1.10	1.524E+03	0.1706	0.1713	1.00
1.208E+02	0.1407	0.1298	1.08	5.514E+02	0.4094	0.3800	1.08	1.638E+03	0.1654	0.1656	1.00
1.299E+02	0.1543	0.1819	0.85	5.927E+02	0.4918	0.5574	0.88	1.761E+03	0.1572	0.1635	0.96
1.395E+02	0.1691	0.1849	0.91	6.369E+02	0.5904	0.6447	0.92	1.896E+03	0.1414	0.1365	1.04
1.496E+02	0.1857	0.1528	1.22	6.840E+02	0.6522	0.5391	1.21	2.039E+03	0.1198	0.1051	1.14
1.609E+02	0.1831	0.1674	1.09	7.356E+02	0.4417	0.3519	1.26	2.191E+03	0.1136	0.0991	1.15
1.734E+02	0.1903	0.2096	0.91	7.917E+02	0.2272	0.3195	0.71	2.355E+03	0.1127	0.0883	1.28
1.863E+02	0.2401	0.2256	1.06	8.521E+02	0.2521	0.3068	0.82	2.533E+03	0.0802	0.0719	1.12
2.004E+02	0.2574	0.1645	1.56	9.155E+02	0.2787	0.3505	0.80	2.726E+03	0.0700	0.0639	1.10
2.157E+02	0.2699	0.2067	1.31	9.850E+02	0.2829	0.3181	0.89	2.931E+03	0.0622	0.0559	1.11
2.315E+02	0.2951	0.2067	1.43	1.060E+03	0.2846	0.3068	0.93	3.150E+03	0.0526	0.0459	1.14
2.484E+02	0.3274	0.2475	1.32	1.139E+03	0.2840	0.3209	0.88	3.387E+03	0.0420	0.0426	0.99
2.677E+02	0.3382	0.3130	1.08	1.225E+03	0.2712	0.2463	1.10	3.641E+03	0.0395	0.0316	1.25
2.880E+02	0.3652	0.3465	1.05	1.316E+03	0.2454	0.2322	1.06	3.916E+03	0.0360	0.0261	1.38
3.095E+02	0.1961	0.4280	0.46	1.415E+03	0.2098	0.2111	0.99	4.212E+03	0.0311	0.0230	1.35
3.326E+02	0.2111	0.3727	0.57	1.523E+03	0.1710	0.1858	0.92	4.527E+03	0.0275	0.0180	1.53
3.575E+02	0.2280	0.3814	0.60	1.638E+03	0.1657	0.1731	0.96	4.869E+03	0.0244	0.0139	1.76
3.846E+02	0.7138	0.2591	2.75	1.760E+03	0.1574	0.1618	0.97	5.238E+03	0.0195	0.0093	2.10
4.139E+02	0.7609	0.2067	3.68	1.893E+03	0.1420	0.1141	1.24				
4.450E+02	0.8218	0.2911	2.82	2.036E+03	0.1204	0.0977	1.23				
4.783E+02	0.8889	0.3101	2.87	2.189E+03	0.1133	0.1009	1.12				
5.144E+02	0.3756	0.3130	1.20	2.354E+03	0.1330	0.0735	1.81				
5.534E+02	0.4024	0.4120	0.98								
5.952E+02	0.4564	0.6435	0.71								
6.398E+02	0.4928	0.5226	0.94								
6.878E+02	0.5284	0.3930	1.34								
7.392E+02	0.7802	0.3261	2.39								
7.951E+02	0.8328	0.3261	2.55							BUG96/35	

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Figure 5.2-13: Detector 1 Data Comparison for 35 cm Sphere

Figure 5.2-14: Detector 2 data comparison for 35 cm sphere.

Figure 5.2-15: Detector 3 Data Comparison for 35 cm Sphere

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Table 5.2-12: Detector Measurements for 40cm Diameter Iron Sphere using BUGLE 96 cross section library.

Detector 1				Detector 2				Detector 3			
Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E	Mid Energy (keV)	Calc. (C)	Exp. (E)	C/E
6.775E+01	0.0629	0.0479	1.31	3.081E+02	0.7309	0.4417	1.65	9.165E+02	0.2515	0.3247	0.77
7.285E+01	0.0744	0.0688	1.08	3.317E+02	0.6592	0.3784	1.74	9.870E+02	0.2436	0.3205	0.76
7.850E+01	0.0880	0.0803	1.10	3.568E+02	0.5952	0.4149	1.43	1.063E+03	0.2416	0.2551	0.95
8.415E+01	0.1034	0.0905	1.14	3.833E+02	0.5103	0.3108	1.64	1.142E+03	0.2369	0.2678	0.88
9.035E+01	0.1212	0.0976	1.24	4.110E+02	0.4038	0.2278	1.77	1.226E+03	0.2238	0.2572	0.87
9.710E+01	0.1294	0.0687	1.88	4.423E+02	0.3100	0.2799	1.11	1.320E+03	0.1986	0.1927	1.03
1.044E+02	0.1402	0.0857	1.64	4.762E+02	0.3391	0.3249	1.04	1.419E+03	0.1661	0.1607	1.03
1.123E+02	0.1521	0.1181	1.29	5.130E+02	0.3710	0.3277	1.13	1.524E+03	0.1328	0.1415	0.94
1.208E+02	0.1651	0.1415	1.17	5.514E+02	0.4062	0.4065	1.00	1.638E+03	0.1285	0.1282	1.00
1.299E+02	0.1792	0.1792	1.00	5.927E+02	0.4838	0.5851	0.83	1.761E+03	0.1218	0.1282	0.95
1.395E+02	0.1943	0.2433	0.80	6.369E+02	0.5761	0.6259	0.92	1.896E+03	0.1086	0.1031	1.05
1.496E+02	0.2111	0.2006	1.05	6.840E+02	0.6313	0.4009	1.57	2.039E+03	0.0905	0.0810	1.12
1.609E+02	0.2234	0.1629	1.37	7.356E+02	0.4153	0.3418	1.22	2.191E+03	0.0847	0.0726	1.17
1.734E+02	0.2323	0.2342	0.99	7.917E+02	0.1945	0.3094	0.63	2.355E+03	0.0829	0.0614	1.35
1.863E+02	0.2736	0.2484	1.10	8.521E+02	0.2178	0.2560	0.85	2.533E+03	0.0580	0.0527	1.10
2.004E+02	0.2932	0.1924	1.52	9.155E+02	0.2429	0.3263	0.74	2.726E+03	0.0502	0.0441	1.14
2.157E+02	0.3075	0.1975	1.56	9.850E+02	0.2439	0.2968	0.82	2.931E+03	0.0441	0.0390	1.13
2.315E+02	0.3362	0.2546	1.32	1.060E+03	0.2423	0.2349	1.03	3.150E+03	0.0370	0.0323	1.15
2.484E+02	0.3730	0.2658	1.40	1.139E+03	0.2381	0.2757	0.86	3.387E+03	0.0292	0.0278	1.05
2.677E+02	0.3854	0.3401	1.13	1.225E+03	0.2243	0.2067	1.09	3.641E+03	0.0275	0.0232	1.18
2.880E+02	0.4161	0.3788	1.10	1.316E+03	0.2006	0.1730	1.16	3.916E+03	0.0250	0.0170	1.47
3.095E+02	0.2058	0.4715	0.44	1.415E+03	0.1682	0.1547	1.09	4.212E+03	0.0216	0.0153	1.41
3.326E+02	0.2215	0.4195	0.53	1.523E+03	0.1332	0.1399	0.95	4.527E+03	0.0190	0.0128	1.48
3.575E+02	0.2393	0.4318	0.55	1.638E+03	0.1286	0.1448	0.89	4.869E+03	0.0168	0.0082	2.05
3.846E+02	0.7882	0.3330	2.37	1.760E+03	0.1217	0.1129	1.08	5.238E+03	0.0134	0.0068	1.97
4.139E+02	0.8402	0.1985	4.23	1.893E+03	0.1087	0.0979	1.11				
4.450E+02	0.9075	0.2454	3.70	2.036E+03	0.0907	0.0713	1.27				
4.783E+02	0.9816	0.3421	2.87	2.189E+03	0.0850	0.0640	1.33				
5.144E+02	0.3728	0.3279	1.14	2.354E+03	0.0970	0.0521	1.86				
5.534E+02	0.3994	0.3992	1.00								
5.952E+02	0.4528	0.5906	0.77								
6.398E+02	0.4889	0.6110	0.80								
6.878E+02	0.5242	0.4440	1.18								
7.392E+02	0.7567	0.2820	2.68								
7.951E+02	0.8078	0.3218	2.51							BUG96/40	

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Figure 5.2-16: Detector 1 Data Comparison for 40 cm Sphere

Figure 5.2-18: Detector 3 Data Comparison for 40 cm Sphere

6.0 Conclusion

MORSE-SGC/S code was validated with the BUGLE-96 cross section set for the parameters described in Table 6.1. Two sets of benchmark measurement data were obtained from the SINBAD 97 database. The neutron spectrum measurement data in water was obtained from the Winfrith Water Benchmark Experiment and the leakage spectrum data in iron was obtained from the Karlsruhe Iron Sphere Benchmark Experiment. In both cases, the Cf-252 source was used and a standard Cf-252 source data (neutron spectrum) was taken from the University of Illinois Iron Sphere Benchmark evaluation in SINBAD 97 database, since it was given in 47 group BUGLE-96 format. All calculations with the BUGLE-96 cross section set were repeated with the BUGLE-80 set to determine the improvement (if any) in predicting the neutron spectrum due to the fact that BUGLE-96 was derived from the latest ENDF/B-VI evaluation.

The experimental spectra for neutron both in water and in iron were well predicted by MORSE-SGC/S with the BUGLE-96 cross section set. The differences between the calculated and measured values lie within a 20% range for most of the energy band in each case. The BUGLE-96 generated spectra were close to those generated using the BUGLE-80 cross section set, and a distinct advantage of the BUGLE-96 set over the earlier cross section set was not determined from this limited validation study. This validation study should be continued with several other benchmark experiments available from the SINBAD 97 database to complete the validation of MORSE-SCG/S with the BUGLE-96 cross section set.

Table 6.1: MORSE-SGC/S Validation with BUGLE-96 cross sections

Parameters	Water	Iron
Material Thickness	Infinite	7.5 cm to 20 cm
Energy Range	0.9 to 8.8 MeV	60 KeV to 2 MeV*, 1.0-4.MeV**
Detector to Source Distance (cm)	10.16 to 50.80	102 to 117

*Based on detectors at a distance of 102 cm from source.

** Based on detector at a distance of 117 cm from source.

7.0 References

1. J. T. West et. al, MORSE-SCG/S for the SCALE system, NUREG/CR-0200, Rev.5.
2. DLC-185/ BUGLE-96, Coupled 47 Neutrons, 20 Gamma-Ray Group Cross Section Library
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3. SINBAD 97/DLC-191, Shielding Integral Benchmark Archive and Database, Oak Ridge
National Laboratory, September 1997.
4. RSICC ,CCC-545, SCALE 4.3 Modular Code System for Performing Standardized
Computer Analysis for Licensing Evaluation, Oak Ridge National Laboratory, March 1997.
5. WSMS-CTG-98-0009, "Software Configuration and Control Guidance for SCALE 4.3 (U)",
G. Kessler, February, 1998.
6. M. J. Grimstone, The RADAK User's Manual, AEEW-M1455 (1976)

APPENDIX A: Input Listings for Winfrith Water Benchmark Experiment

```
=morse
SINDBAD SBE 2.004 Winfrith(ASPIS) Water Benchmark Experiment at 10.16 (BUGLE 80)
4f861e50
1$$ 0 3000 5000 1000 1011 100000e
2$$ 5 9 0 1 0 e
3$$ 470 0000004247000000078003e
4$$ -1 4700e
5$$ 147 470013444r012r011f0e
t
SBE 2.004 flux estimate at detector, at 10.16
0010
rcc 1 0 0 84.6 0 0 87.4 1.400
rcc 2 0 0 0 0 0 172.0 3.351
rcc 3 0 0 0 0 0 172.0 3.755
rcc 4 10.16 0 85.8 10.16 0 86.26 0.240
rcc 5 10.16 0 84.9 10.16 0 87.25 0.950
rpp 6 -114 114 -88.5 88.5 0 172
sph 7 0 0 0 1e4
end
sul +1
air +2 -1
al +3 -2
u8 +4
ss +5 -4
h2o +6 -3 -5
voi +7 -6
end
1 1 1 1 1 1 1
7r0
1 1000 2 3 4 5 0
0
6** 300. 0. 1. 0. 9.92 10.40 -0.24 0.24 85.8 86.26
8** 47r100.0 20r1e-10 26r1.0 1e34 20r0.5 26r1e-6 1e-30 e
12$$ 1 2 3 4 4 4 4 5 5
13$$ 16032
13027
92238
25055 24000 28000 26000
1001 8016
14** 3.5022e-2
6.0261e-2
4.7812e-2
1.3743e-3 1.7091e-2 7.7039e-3 5.9886e-2
6.6855e-2 3.3428e-2
17**
1.77863E-04 4.97090E-04 2.24463E-03 4.33019E-03 8.47886E-03
2.12840E-02 3.66444E-02 8.78090E-02 7.79489E-02 4.31208E-02
4.49049E-02 1.90710E-02 3.82283E-03 2.30500E-02 6.92225E-02
6.76384E-02 8.46895E-02 1.10074E-01 6.04808E-02 2.63742E-02
4.54912E-02 3.67124E-02 4.13280E-02 2.15884E-02 3.10648E-02
1.64009E-02 8.06957E-03 3.90728E-03 1.10794E-03 6.34475E-04
1.93375E-04 2.26691E-04 6.04447E-04 5.43329E-04 1.77137E-04
5.76214E-05 2.34756E-05 2.87325E-06 9.32885E-07 3.48420E-07
8.47274E-08 1.03648E-08 3.87084E-09 7.50834E-10 2.43763E-10
1.03267E-10 1.39116E-11
t
dose rate at specified location
dose rate , mrem/hr
flunce
19**
0 0 86.0
20**
fl.0
21$$ 45il 47
t
end
```

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```
=morse
SINDBAD SBE 2.004 Winfrith(ASPIS) Water Benchmark Experiment at 10.16 (BUGLE 96)
4f861e50
1$$$ 0 3000 5000 1000 1011 1000000 e
2$$$ 5 9 0 1 0 e
3$$$ 470 000004 247000000 77003 e
4$$$ -14700 e
5$$$ 147 470013444r012r011f0 e
t
SBE 2.004 flux estimate at detector, at 10.16
0010
rcc 1 0 0 84.6 0 0 87.4 1.400
rcc 2 0 0 0 0 0 172.0 3.351
rcc 3 0 0 0 0 0 172.0 3.755
rcc 4 10.16 0 85.8 10.16 0 86.26 0.240
rcc 5 10.16 0 84.9 10.16 0 87.25 0.950
rpp 6 -114 114 -88.5 88.5 0 172
sph 7 0 0 0 1e4
end
sul +1
air +2 -1
al +3 -2
u8 +4
ss +5 -4
h2o +6 -3 -5
voi +7 -6
end
1 1 1 1 1 1 1
7r0
1 1000 2 3 4 5 0
0
6** 300. 0. 1. 0. 9.92 10.40 -0.24 0.24 85.8 86.26
8** 47r100.0 20r1e-10 26r1.0 1e34 20r0.5 26r1e-6 1e-30 e
12$$$ 1 2 3 4 4 4 4 5 5
13$$$ 16032
13027
92238
25055 24052 28058 26056
1001 8016
14** 3.5022e-2
6.0261e-2
4.7812e-2
1.3743e-3 1.7091e-2 7.7039e-3 5.9886e-2
6.6855e-2 3.3428e-2
17**
1.77863E-04 4.97090E-04 2.24463E-03 4.33019E-03 8.47886E-03
2.12840E-02 3.66444E-02 8.78090E-02 7.79489E-02 4.31208E-02
4.49049E-02 1.90710E-02 3.82283E-03 2.30500E-02 6.92225E-02
6.76384E-02 8.46895E-02 1.10074E-01 6.04808E-02 2.63742E-02
4.54912E-02 3.67124E-02 4.13280E-02 2.15884E-02 3.10648E-02
1.64009E-02 8.06957E-03 3.90728E-03 1.10794E-03 6.34475E-04
1.93375E-04 2.26691E-04 6.04447E-04 5.43329E-04 1.77137E-04
5.76214E-05 2.34756E-05 2.87325E-06 9.32885E-07 3.48420E-07
8.47274E-08 1.03648E-08 3.87084E-09 7.50834E-10 2.43763E-10
1.03267E-10 1.39116E-11
t
dose rate at specified location
dose rate , mrem/hr
flunce
19**
0 0 86.0
20**
fl.0
21$$$ 4511 47
t
end
```

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```
=morse
SINDBAD SBE 2.004 Winfrith(ASPIS) Water Benchmark Experiment at 30.48cm (BUGLE 80)
  4f861e50
1$$$ 0 3000 5000 1000 1011 1000000e
2$$$ 5 9 0 1 0 e
3$$$ 47 0 00000424700000078003e
4$$$ -1 47 0 0 e
5$$$ 1 47 47 0 0 1 34 4 4 r0 1 2 r0 1 1 r0 e
t
SBE 2.004 flux estimate at detector, at 30.48cm
0 0 1 0
rcc 1 0 0 84.6 0 0 87.4 1.400
rcc 2 0 0 0 0 0 172.0 3.351
rcc 3 0 0 0 0 0 172.0 3.755
rcc 4 30.48 0 85.8 30.48 0 86.26 0.240
rcc 5 30.48 0 84.9 30.48 0 87.25 0.950
rpp 6 -114 114 -88.5 88.5 0 172
sph 7 0 0 0 1e4
end
sul +1
air +2 -1
al +3 -2
u8 +4
ss +5 -4
h2o +6 -3 -5
voi +7 -6
end
1 1 1 1 1 1 1
7r0
1 1000 2 3 4 5 0
0
6** 300. 0. 1. 0. 30.24 30.72 -0.24 0.24 85.8 86.26
8** 47r100.0 20r1e-10 26r1.0 1e34 20r0.5 26r1e-6 1e-30 e
12$$$ 1 2 3 4 4 4 4 5 5
13$$$ 16032
13027
92238
25055 24000 28000 26000
1001 8016
14** 3.5022e-2
6.0261e-2
4.7812e-2
1.3743e-3 1.7091e-2 7.7039e-3 5.9886e-2
6.6855e-2 3.3428e-2
17**
1.77863E-04 4.97090E-04 2.24463E-03 4.33019E-03 8.47886E-03
2.12840E-02 3.66444E-02 8.78090E-02 7.79489E-02 4.31208E-02
4.49049E-02 1.90710E-02 3.82283E-03 2.30500E-02 6.92225E-02
6.76384E-02 8.46895E-02 1.10074E-01 6.04808E-02 2.63742E-02
4.54912E-02 3.67124E-02 4.13280E-02 2.15884E-02 3.10648E-02
1.64009E-02 8.06957E-03 3.90728E-03 1.10794E-03 6.34475E-04
1.93375E-04 2.26691E-04 6.04447E-04 5.43329E-04 1.77137E-04
5.76214E-05 2.34756E-05 2.87325E-06 9.32885E-07 3.48420E-07
8.47274E-08 1.03648E-08 3.87084E-09 7.50834E-10 2.43763E-10
1.03267E-10 1.39116E-11
t
dose rate at specified location
dose rate , mrem/hr
flunce
19**
0 0 86.0
20**
fl.0
21$$$ 4511 47
t
end
```

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```
=morse
SINDBAD SBE 2.004 Winfrith(ASPIS) Water Benchmark Experiment at 30.48cm (BUGLE 96)
4f861e50
1$$$ 0 3000 5000 1000 1 0 1 1 1 0 0 0 0 0 e
2$$$ 5 9 0 1 0 e
3$$$ 47 0 0 0 0 0 4 2 47 0 0 0 0 0 0 77 0 0 3 e
4$$$ -1 47 0 0 e
5$$$ 1 47 47 0 0 1 34 4 4r0 1 2r0 1 1 f0 e
t
SBE 2.004 flux estimate at detector, at 30.48cm
0 0 1 0
rcc 1 0 0 84.6 0 0 87.4 1.400
rcc 2 0 0 0 0 0 172.0 3.351
rcc 3 0 0 0 0 0 172.0 3.755
rcc 4 30.48 0 85.8 30.48 0 86.26 0.240
rcc 5 30.48 0 84.9 30.48 0 87.25 0.950
rpp 6 -114 114 -88.5 88.5 0 172
sph 7 0 0 0 1e4
end
sul +1
air +2 -1
al +3 -2
u8 +4
ss +5 -4
h2o +6 -3 -5
voi +7 -6
end
1 1 1 1 1 1 1
7r0
1 1000 2 3 4 5 0
0
6** 300. 0. 1. 0. 30.24 30.72 -0.24 0.24 85.8 86.26
8** 47r100.0 20r1e-10 26r1.0 1e34 20r0.5 26r1e-6 1e-30 e
12$$$ 1 2 3 4 4 4 4 5 5
13$$$ 16032
13027
92238
25055 24052 28058 26056
1001 8016
14** 3.5022e-2
6.0261e-2
4.7812e-2
1.3743e-3 1.7091e-2 7.7039e-3 5.9886e-2
6.6855e-2 3.3428e-2
17**
1.77863E-04 4.97090E-04 2.24463E-03 4.33019E-03 8.47886E-03
2.12840E-02 3.66444E-02 8.78090E-02 7.79489E-02 4.31208E-02
4.49049E-02 1.90710E-02 3.82283E-03 2.30500E-02 6.92225E-02
6.76384E-02 8.46895E-02 1.10074E-01 6.04808E-02 2.63742E-02
4.54912E-02 3.67124E-02 4.13280E-02 2.15884E-02 3.10648E-02
1.64009E-02 8.06957E-03 3.90728E-03 1.10794E-03 6.34475E-04
1.93375E-04 2.26691E-04 6.04447E-04 5.43329E-04 1.77137E-04
5.76214E-05 2.34756E-05 2.87325E-06 9.32885E-07 3.48420E-07
8.47274E-08 1.03648E-08 3.87084E-09 7.50834E-10 2.43763E-10
1.03267E-10 1.39116E-11
t
dose rate at specified location
dose rate , mrem/hr
flunce
19**
0 0 86.0
20**
fl.0
21$$$ 45il 47
t
end
```

APPENDIX B: Input Listings for Karlsruhe Iron Sphere Benchmark Experiment

```
=morse
SINDBAD SBE 6.001 Karlsruhe Iron Sphere Benchmark Experiment (BUGLE 80)
4f861e50
1$$ 0 3000 5000 1000 1010 000000e
2$$ 2 10 0 10 e
3$$ 470 00000424700000078001e
4$$ -14700e
5$$ 247 470013444r012r011f0e
t
SBE 6.001 20cm diameter iron sphere
0010
rcc 1 -0.75 0 0 1.50 0 0 0.75
sph 2 0 0 0 10
rpp 3 -300 300 -300 300 -200 200
sph 4 0 0 0 1e4
end
sou +1
iron +2 -1
air +3 -2
voi +4 -3
end
1 1 1 1
4r0
1 2 1000 0
0
6** 300. 0. 1. 0. -0.75 0.75 -0.75 0.75 -0.75 0.75
12$$ 1 1 1 1 1 2 2 2 2 2
13$$ 13027 12000 8016 14000 50000
26000 6012 25055 15031 16032
14** 1.349e-1 3.90e-3 2.60e-3 8.00e-4 4.00e-4
8.475e-2 2.7621e-4 4.3133e-5 1.3771e-5 1.0346e-5
17**
1.77863E-04 4.97090E-04 2.24463E-03 4.33019E-03 8.47886E-03
2.12840E-02 3.66444E-02 8.78090E-02 7.79489E-02 4.31208E-02
4.49049E-02 1.90710E-02 3.82283E-03 2.30500E-02 6.92225E-02
6.76384E-02 8.46895E-02 1.10074E-01 6.04808E-02 2.63742E-02
4.54912E-02 3.67124E-02 4.13280E-02 2.15884E-02 3.10648E-02
1.64009E-02 8.06957E-03 3.90728E-03 1.10794E-03 6.34475E-04
1.93375E-04 2.26691E-04 6.04447E-04 5.43329E-04 1.77137E-04
5.76214E-05 2.34756E-05 2.87325E-06 9.32885E-07 3.48420E-07
8.47274E-08 1.03648E-08 3.87084E-09 7.50834E-10 2.43763E-10
1.03267E-10 1.39116E-11
t
dose rate at specified location
dose rate , mrem/hr
flunce
19**
108 0 0
153 0 0
20**
fl.0
21$$ 4511 47
t
end
```


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```
=morse
SINDBAD SBE 6.001 Karlsruhe Iron Sphere Benchmark Experiment (BUGLE 96)
4f861e50
1$$$ 0 3000 5000 1000 1 0 1 0 0 0 0 0 0 e
2$$$ 2 10 0 1 0 e
3$$$ 47 0 0 0 0 0 4 2 47 0 0 0 0 0 77 0 0 1 e
4$$$ -1 47 0 0 e
5$$$ 2 47 47 0 0 1 34 4 4r0 1 2r0 1 1 f0 e
t
SBE 6.001 20cm diameter iron sphere
0 0 1 0
rcc 1 -0.75 0 0 1.50 0 0 0.75
sph 2 0 0 0 10
rpp 3 -300 300 -300 300 -200 200
sph 4 0 0 0 1e4
end
sou +1
iron +2 -1
air +3 -2
voi +4 -3
end
1 1 1 1
4r0
1 2 1000 0
0
6** 300. 0. 1. 0. -0.75 0.75 -0.75 0.75 -0.75 0.75
12$$$ 1 1 1 1 1 2 2 2 2 2
13$$$ 13027 12000 8016 14000 50000
26056 6012 25055 15031 16032
14** 1.349e-1 3.90e-3 2.60e-3 8.00e-4 4.00e-4
8.475e-2 2.7621e-4 4.3133e-5 1.3771e-5 1.0346e-5
17**
1.77863E-04 4.97090E-04 2.24463E-03 4.33019E-03 8.47886E-03
2.12840E-02 3.66444E-02 8.78090E-02 7.79489E-02 4.31208E-02
4.49049E-02 1.90710E-02 3.82283E-03 2.30500E-02 6.92225E-02
6.76384E-02 8.46895E-02 1.10074E-01 6.04808E-02 2.63742E-02
4.54912E-02 3.67124E-02 4.13280E-02 2.15884E-02 3.10648E-02
1.64009E-02 8.06957E-03 3.90728E-03 1.10794E-03 6.34475E-04
1.93375E-04 2.26691E-04 6.04447E-04 5.43329E-04 1.77137E-04
5.76214E-05 2.34756E-05 2.87325E-06 9.32885E-07 3.48420E-07
8.47274E-08 1.03648E-08 3.87084E-09 7.50834E-10 2.43763E-10
1.03267E-10 1.39116E-11
t
dose rate at specified location
dose rate , mrem/hr
flunce
19**
108 0 0
153 0 0
20**
fl.0
21$$$ 4511 47
t
end
```

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AND IRON EXPERIMENTAL DATA FROM SINDBAD 97

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```
=morse
SINDBAD SBE 6.001 Karlsruhe Iron Sphere Benchmark Experiment (BUGLE 80)
4f861e50
1SS 0 3000 5000 1000 10 10 000000e
2SS 2 10 0 10 e
3SS 470 00000424700000078001e
4SS -14700e
5SS 247 470013444r012r011f0e
t
SBE 6.001 35cm diameter iron sphere
0010
rcc 1 -0.75 0 0 1.50 0 0 0.75
sph 2 0 0 0 17.5
rpp 3 -300 300 -300 300 -200 200
sph 4 0 0 0 1e4
end
sou +1
iron +2 -1
air +3 -2
voi +4 -3
end
1111
4r0
1210000
0
6** 300. 0. 1. 0. -0.75 0.75 -0.75 0.75 -0.75 0.75
12SS 111112222
13SS 13027 12000 8016 14000 50000
26000 6012 25055 15031 16032
14** 1.349e-1 3.90e-3 2.60e-3 8.00e-4 4.00e-4
8.475e-2 2.7621e-4 4.3133e-5 1.3771e-5 1.0346e-5
17**
1.77863E-04 4.97090E-04 2.24463E-03 4.33019E-03 8.47886E-03
2.12840E-02 3.66444E-02 8.78090E-02 7.79489E-02 4.31208E-02
4.49049E-02 1.90710E-02 3.82283E-03 2.30500E-02 6.92225E-02
6.76384E-02 8.46895E-02 1.10074E-01 6.04808E-02 2.63742E-02
4.54912E-02 3.67124E-02 4.13280E-02 2.15884E-02 3.10648E-02
1.64009E-02 8.06957E-03 3.90728E-03 1.10794E-03 6.34475E-04
1.93375E-04 2.26691E-04 6.04447E-04 5.43329E-04 1.77137E-04
5.76214E-05 2.34756E-05 2.87325E-06 9.32885E-07 3.48420E-07
8.47274E-08 1.03648E-08 3.87084E-09 7.50834E-10 2.43763E-10
1.03267E-10 1.39116E-11
t
dose rate at specified location
dose rate , mrem/hr
flunce
19**
108 0 0
153 0 0
20**
fl.0
21SS 45il 47
t
end
```

BUGLE 96 VALIDATION WITH MORSE USING WATER
AND IRON EXPERIMENTAL DATA FROM SINDBAD 97

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```
=morse
SINDBAD SBE 6.001 Karlsruhe Iron Sphere Benchmark Experiment (BUGLE 96)
4f861e50
1$$$ 0 3000 5000 1000 10 10 0 0 0 0 0 0 e
2$$$ 2 10 0 1 0 e
3$$$ 47 0 0 0 0 0 4 2 47 0 0 0 0 0 0 77 0 0 1 e
4$$$ -1 47 0 0 e
5$$$ 2 47 47 0 0 1 34 4 4r0 1 2r0 1 1 r0 e
t
SBE 6.001 35cm diameter iron sphere
0 0 1 0
rcc 1 -0.75 0 0 1.50 0 0 0.75
sph 2 0 0 0 17.5
rpp 3 -300 300 -300 300 -200 200
sph 4 0 0 0 1e4
end
sou +1
iron +2 -1
air +3 -2
voi +4 -3
end
1 1 1 1
4r0
1 2 1000 0
0
6** 300. 0. 1. 0. -0.75 0.75 -0.75 0.75 -0.75 0.75
12$$$ 1 1 1 1 1 2 2 2 2 2
13$$$ 13027 12000 8016 14000 50000
26056 6012 25055 15031 16032
14** 1.349e-1 3.90e-3 2.60e-3 8.00e-4 4.00e-4
8.475e-2 2.7621e-4 4.3133e-5 1.3771e-5 1.0346e-5
17**
1.77863E-04 4.97090E-04 2.24463E-03 4.33019E-03 8.47886E-03
2.12840E-02 3.66444E-02 8.78090E-02 7.79489E-02 4.31208E-02
4.49049E-02 1.90710E-02 3.82283E-03 2.30500E-02 6.92225E-02
6.76384E-02 8.46895E-02 1.10074E-01 6.04808E-02 2.63742E-02
4.54912E-02 3.67124E-02 4.13280E-02 2.15884E-02 3.10648E-02
1.64009E-02 8.06957E-03 3.90728E-03 1.10794E-03 6.34475E-04
1.93375E-04 2.26691E-04 6.04447E-04 5.43329E-04 1.77137E-04
5.76214E-05 2.34756E-05 2.87325E-06 9.32885E-07 3.48420E-07
8.47274E-08 1.03648E-08 3.87084E-09 7.50834E-10 2.43763E-10
1.03267E-10 1.39116E-11
t
dose rate at specified location
dose rate , mrem/hr
flunce
19**
108 0 0
153 0 0
20**
fl.0
21$$$ 4511 47
t
end
```