Neutron Spectrum and $^{10}\text{B}(n,\alpha)$ Measurements in ZPPR-15

Nuclear Science and Engineering Division

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ABSTRACT

Neutron spectra were measured at the core center with proton recoil spectrometers in ZPPR-15A loading 66, ZPPR-15B loading 90 and ZPPR loading 186. In addition, neutron spectra were measured in the SSNA shield configuration in ZPPR-15B loading 121 and in the BCNA shield configuration in ZPPR-15B loading 126. The ZPPR-15 neutron spectrum measurement and data processing techniques were described and analyzed. Total uncertainties were derived for all five spectrum measurements.

A back-to-back proportional counter was used to measure the $^{10}\text{B}(\text{n},\alpha)$ reaction rate at six locations in the simulated shield, radial reflector and outer core in the ZPPR-15B BCNA shield experiment. The measurements were described and analyzed. A total uncertainty was derived for the $^{10}\text{B}(\text{n},\alpha)$ reaction rate measurements.

The ZPPR-15 experimental records were used to develop detailed as-built Monte Carlo models for the five neutron spectrum measurement configurations and for the six $^{10}\text{B}(\text{n},\alpha)$ measurement configurations.

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1 Introduction

Neutron spectra were measured in matrix location 159-49 near the center of the core in ZPPR-15A loading 66, ZPPR-15B loading 90 and ZPPR-15D loading 186. In addition, neutron spectra were measured in matrix location 158-19 at the center of the simulated shield as part of the ZPPR-15B shield experiment. The shield experiment configurations with neutron spectrum measurements were ZPPR-15B loading 121 (SSNA configuration) and ZPPR-15B loading 126 (BCNA configuration). The spectrum measurements provide an experimental comparison for the accuracy of neutron flux calculations, particularly in the blanket, reflector and shield zones where significant approximations may be required to produce cross sections for deterministic calculations. The ZPPR facility is described in Ref. 1.

$^{10}\text{B}(\text{n},\alpha)$ reaction rates were measured in a back-to-back proportional counter at six locations in the shield, radial reflector, radial blanket and core in loadings 127 – 132 during the ZPPR-15B shield experiment. These reaction rate measurements provide another test of the accuracy of neutron flux and spectrum calculations in the outer core, radial blanket, radial reflector and shield zone of the ZPPR-15B shield experiment configuration.

2 Neutron Spectrum Measurements

2.1 Neutron Spectrum Measurements Technique

Two proton recoil spectrometers were used for the spectrum measurements. The spectrometers were gas-filled proportional counters. One counter consisted of a 9.53 mm diameter cylinder filled with hydrogen gas at ~10 atmospheres total pressure, and the other counter consisted of a 15.9 mm diameter cylinder filled predominantly with methane gas at ~8.2 atmospheres pressure. It is likely that a 12.7 mm lead sleeve was placed around each counter to reduce the gamma background. Figure 2.1 shows a model of the proton recoil spectrometer used in ZPPR-2. The spectrometer used in ZPPR-15 would have been very similar.

The hydrogen gas-filled counter with gamma discrimination worked well down to neutron energies around 1 keV, but the useful upper energy limit for this counter was several hundred keV. For energies above a few hundred keV, it was necessary to use a fill gas with higher stopping power such as methane. The methane-filled counter had an effective lower energy limit of ~100 keV and an effective upper energy limit in the MeV range.

Both counters were calibrated in the thermal column of the Argonne Fast Source Reactor (AFSR). A small amount of nitrogen gas was added to the hydrogen or methane in the counters. Thermal neutrons in the thermal column created monoenergetic 585 keV protons in the proportional counters via the $^{14}\text{N}(\text{n},\text{p})^{14}\text{C}$ reaction. These protons were used to establish an absolute relationship between pulse height and proton energy for the counters.

The hydrogen counter covered the energy range from 1 keV to ~110 keV, and the methane counter covered the energy range from ~90 keV to ~2000 keV. A new data acquisition system was used to record the spectrometer data, and a modified data reduction procedure was used to process the measured data. The raw data were analyzed with a code used for spectrum measurements and were corrected for detector response distortions and for gamma interactions in the counter. For practical purposes the energy range covered by the proton recoil spectrometers was 1.234 keV – 2231 keV.

Figure 2.1 Proton Recoil Spectrometer

The raw spectrum data were recorded with a very fine energy resolution. As part of the data reduction process, the measured neutron spectrum data were collapsed into the energy group structures that were used by Argonne reactor designers and analysts in the mid-1980s. Tabular spectrum data were published in these group structures. Plots of the measured spectra and of the comparisons between measured and calculated spectra were based upon the same group structures.

Techniques for proton recoil spectroscopy at Argonne were developed primarily by E. F. Bennett and T. J. Yule. Their report, ANL-7763, includes detailed discussions of the design of the proton recoil spectrometers used at Argonne and of corrections for systematic measurement errors that are inherent in this form of neutron spectroscopy [2].

ANL-7763 discusses five computer codes that were used in sequence to process raw data from the spectrum measurement. Collectively, these codes were referred to as the Proton Spectrum to Neutron Spectrum (PSNS) codes. The original PSNS codes performed several functions [2].

PSNS-1 performed a survey of the measured data and identified any problems in the measured data.

The first systematic error in the measured data was the nonlinear relationship between energy and ionization at low energies which introduced errors into the measurement for lower energy neutrons. The PSNS-2 code corrected the measured data for this effect.

The internal electric field lines were distorted near the ends of the counter, creating a transition region where multiplication decreased gradually relative to multiplication in the main part of the chamber. This effect introduced the second systematic error into the measured data because events near the ends of the counter did not produce the same response as events in the main part of the chamber. The PSNS-2 code applied an electric field response function to correct the spectrum for the internal electric field distortion.

The third systematic error in the measured data was a result of the finite size of the spectrometer. Some proton-recoil tracks will hit the walls of the chamber and be truncated. Other tracks will enter the end region of the chamber where there is no multiplication. In either case, collection of ionization in the sensitive region of the counter is incomplete, so the relationship of proton energy to collected ionization is biased. The PSNS-3 code corrected for the wall-and-end distortion created by the finite detector size in the methane counter. The PSNS-4 code applied the corresponding wall-and-end response correction to data obtained with the hydrogen counter.

The fourth correction related to carbon scattering in the methane counter. The ionization spectrum in the methane-filled spectrometer contained proton recoils, electrons from gamma interactions and carbon recoils from elastic scattering of neutrons by carbon. Carbon recoils produce about 25% less ionization than proton recoils for the same incident neutron energy, and the elastic scattering cross sections of carbon and hydrogen are different. Both of these factors introduce errors into the measured spectra. The PSNS-3 code included a correction for carbon recoils in the methane counter.

PSNS-5 derived the final neutron spectrum from the corrected proton recoil data produced by the first four codes in the series.

The PSNS codes, measurement equipment and data processing procedures evolved between 1971 when ANL-7763 was issued and the dates of the ZPPR-15 measurements. The original five PSNS codes were merged into a single code and simplified at ZPPR. Many of the corrections applied by the original PSNS codes were either rendered unnecessary by improvements in equipment and procedures or were shown to have little effect on improving the data. The need for electric field corrections was eliminated by changes in the proportional counter design. The correction for variations in the energy release (W) per ion pair formed as a function of energy (E) was eliminated because there were large uncertainties in the W versus E data. The uncertainties in the corrections for wall-and-end effects in the counter chamber, i.e., for the finite size of the counter chamber, have uncertainties whose magnitudes are comparable to the resulting corrections. Corrections for carbon recoils were retained in the revised code. The code that subtracts the gamma contribution was rewritten at ZPPR, and codes that produced graphic displays of the spectrum data were written.

The radial position of the counter in the drawer was fixed by stainless steel support plates. The axial position of the counter in the drawer was fixed by the preamplifier and by various support plates in the counter drawer. The internal components of the counter drawer eliminate any significant uncertainty regarding the position of the counter.

A new data acquisition system and modified data reduction procedure were used for the spectrum measurements, but the basic methodology of the proton recoil spectroscopy technique was the methodology described by Bennett and Yule [2].

Figure 2.2 shows the core matrix map for half 1 of ZPPR-15A loading 66, Figure 2.3 shows the core matrix map for half 1 of ZPPR-15B loading 90, and Figure 2.4 shows the core matrix map for half 1 of ZPPR-15D loading 186. A matrix map shows the drawer master loaded in each matrix tube in the array (see Ref. 1 for a discussion of drawer masters and matrix maps). Figure 2.5 shows the core matrix map for half 1 of ZPPR-15B loading 121, the SSNA shield configuration. Figure 2.6 shows the core matrix map for half 1 of ZPPR-15B loading 126, the BCNA shield configuration. The spectrometer was located in one of the central drawer

positions of the core in half 1 for each of the spectrum measurements in Figure 2.2, 2.3 and 2.4 and in the shielding region in half 1 for Figure 2.5 and Figure 2.6.

The light blue cells in Figures 2.2 – 2.6 are the radial reflector, and the dark blue cells are the radial blanket. Empty cells outside of the radial blanket are empty matrix tubes. The numbers in the top row of each matrix map figure are the column numbers in the matrix, and the numbers in the first column of each matrix map figure are the row numbers in the matrix. The three-digit numbers in the core, radial blanket, radial reflector and shield zone cells are abbreviations for the drawer master identifiers. For example, “101” is the abbreviation for “15-0-101,” the full identifier for that particular drawer master.

White cells inside the radial blanket are core drawers containing a single column of Pu-U-Mo fuel plates (SCF). Green cells are core drawers containing two columns of Pu-U-Mo fuel plates (DCF). Brown cells are narrow drawers with an adjacent PSR control blade, and orange cells are drawers containing a detector. The salmon-colored cells in Figure 2.4 contain columns of HEU fuel plates in place of Pu-U-Mo fuel plates. The red cell near the center of the core in Figures 2.2 – 2.4 is the drawer containing the spectrometer. Likewise, the red cell near the center of the outer shield zone in Figures 2.5 and 2.6 is the drawer containing the spectrometer.

2.2 ZPPR-15 Neutron Spectrum Uncertainties

The uncertainties listed in the tables of measured neutron spectra published by the experimenters were the uncertainties due to counting statistics. The experimenters stated that additional uncertainties of 5% to 10% are applicable below 10 keV and above 1 MeV, but they do not specify the source of these additional uncertainties. The experimenters also stated that uncertainties in the energy calibration for both counters have correlated components estimated to be 1% increasing to about 15% for the range below 2 keV in the hydrogen counter. The experimenters did not provide any additional information on this issue. For the additional uncertainties below 10 keV and above 1 MeV in column 5 of Tables 2.1 – 2.5, an average value of 7.5% was assumed. For the correlated components of the calibration uncertainties, the values shown in column 6 of Tables 2.1 – 2.5 were assumed given the absence of any additional information.

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Figure 2.2 ZPPR-15A Loading 66 - Half 1 - Core Matrix Map

Neutron Spectrum and 10B(n, α) Measurements in ZPPR-15
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Figure 2.3 ZPPR-15B Loading 90 - Half 1 - Core Matrix Map

Neutron Spectrum and 10B(n, α) Measurements in ZPPR-15
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Figure 2.4 ZPPR-15D Loading 186 – Half 1 – Core Matrix Map

Neutron Spectrum and $^{10}\text{B}(n,\alpha)$ Measurements in ZPPR-15

Figure 2.5 ZPPR-15B Loading 121 – Half 1 – SSNA Shield Configuration

Figure 2.6 ZPPR-15B Loading 126 – Half 1 – BCNA Shield Configuration

2.3 ZPPR-15 Reported Neutron Spectra

The ZPPR staff reported normalized spectra for the five spectrum measurements, but they did not report the normalization factors. The measured flux and reported σ for each spectrum measurement in Tables 2.1 – 2.5 are the values reported by the ZPPR staff. The effective upper energy limit for the proton recoil spectrometers used for the ZPPR-15 neutron spectrum measurements was 2231 keV.

Table 2.2 provides the measured spectrum as reported by the experimenters for ZPPR-15B loading 90.

**Table 2.1 ZPPR-15A Loading 66 – Normalized Neutron Spectrum at the Core Center – ZPPR
Normalization**

E_{lower} , keV	Flux	σ_{reported}	σ_{reported} , relative	σ_{add} , relative	σ_{calib} , relative	σ_{total} , relative
2231.000	-----	-----	-----	-----	-----	-----
1353.000	0.4399	0.0102	0.0232	0.0750	0.0100	0.0791
820.900	0.7403	0.0098	0.0132	0.0750	0.0100	0.0768
497.900	1.2182	0.0094	0.0077	0.0000	0.0100	0.0126
302.000	1.6831	0.0114	0.0068	0.0000	0.0100	0.0121
183.200	1.8858	0.0126	0.0067	0.0000	0.0100	0.0120
111.100	2.0499	0.0130	0.0063	0.0000	0.0100	0.0118
67.380	1.6849	0.0199	0.0118	0.0000	0.0100	0.0155
40.870	1.2320	0.0134	0.0109	0.0000	0.0100	0.0148
24.790	0.8262	0.0141	0.0171	0.0000	0.0100	0.0198
15.030	0.7411	0.0098	0.0132	0.0000	0.0100	0.0166
9.119	0.5263	0.0111	0.0211	0.0750	0.0300	0.0835
5.531	0.2240	0.0063	0.0281	0.0750	0.0500	0.0944
3.355	0.1152	0.0064	0.0556	0.0750	0.0900	0.1297
2.035	0.0725	0.0037	0.0510	0.0750	0.1100	0.1426
1.234	0.0956	0.0032	0.0335	0.0750	0.1500	0.1710

Table 2.2 provides the measured spectrum as reported by the experimenters for ZPPR-15B loading 90.

Table 2.2 ZPPR-15B Loading 90 – Normalized Neutron Spectrum at the Core Center – ZPPR Normalization

E_{lower} , keV	Flux	σ_{reported}	σ_{reported} , relative	σ_{add} , relative	σ_{calib} , relative	σ_{total} , relative
2231.000	-----	-----	-----	-----	-----	-----
1353.000	0.4531	0.0104	0.0230	0.0750	0.0100	0.0791
820.900	0.7496	0.0099	0.0132	0.0750	0.0100	0.0768
497.900	1.2258	0.0096	0.0078	0.0000	0.0100	0.0127
302.000	1.6965	0.0116	0.0068	0.0000	0.0100	0.0121
183.200	1.8646	0.0128	0.0069	0.0000	0.0100	0.0121
111.100	1.9578	0.0131	0.0067	0.0000	0.0100	0.0120
67.380	1.6896	0.0204	0.0121	0.0000	0.0100	0.0157
40.870	1.2643	0.0138	0.0109	0.0000	0.0100	0.0148
24.790	0.8075	0.0146	0.0181	0.0000	0.0100	0.0207
15.030	0.7819	0.0102	0.0130	0.0000	0.0100	0.0164
9.119	0.5470	0.0117	0.0214	0.0750	0.0300	0.0836
5.531	0.2409	0.0068	0.0282	0.0750	0.0500	0.0945
3.355	0.1206	0.0069	0.0572	0.0750	0.0900	0.1304
2.035	0.0534	0.0040	0.0749	0.0750	0.1100	0.1528
1.234	0.1306	0.0035	0.0268	0.0750	0.1500	0.1698

Table 2.3 provides the measured spectrum as reported by the experimenters for ZPPR-15D loading 186.

Table 2.3 ZPPR-15D Loading 186 – Normalized Neutron Spectrum at the Core Center – ZPPR Normalization

E_{lower} , keV	Flux	σ_{reported}	$\sigma_{\text{reported, relative}}$	$\sigma_{\text{add, relative}}$	$\sigma_{\text{calib, relative}}$	$\sigma_{\text{total, relative}}$
2231.000	-----	-----	-----	-----	-----	-----
1353.000	0.4357	0.0110	0.0252	0.0750	0.0100	0.0798
820.900	0.7330	0.0105	0.0143	0.0750	0.0100	0.0770
497.900	1.2093	0.0102	0.0084	0.0000	0.0100	0.0131
302.000	1.6758	0.0124	0.0074	0.0000	0.0100	0.0124
183.200	1.8606	0.0137	0.0074	0.0000	0.0100	0.0124
111.100	1.9801	0.0149	0.0075	0.0000	0.0100	0.0125
67.380	1.7124	0.0326	0.0190	0.0000	0.0100	0.0215
40.870	1.2893	0.0222	0.0172	0.0000	0.0100	0.0199
24.790	0.7854	0.0237	0.0302	0.0000	0.0100	0.0318
15.030	0.8052	0.0165	0.0205	0.0000	0.0100	0.0228
9.119	0.5375	0.0192	0.0357	0.0750	0.0300	0.0883
5.531	0.2556	0.0113	0.0442	0.0750	0.0500	0.1004
3.355	0.1089	0.0116	0.1065	0.0750	0.0900	0.1583
2.035	0.0462	0.0068	0.1472	0.0750	0.1100	0.1985
1.234	0.1020	0.0058	0.0569	0.0750	0.1500	0.1771

Table 2.4 provides the measured spectrum as reported by the experimenters for ZPPR-15B loading 121, the SSNA shield configuration.

Table 2.4 ZPPR-15B Loading 121 – Normalized Neutron Spectrum in the SSNA Shield Zone – ZPPR Normalization

E_{lower} , keV	Flux	σ_{reported}	$\sigma_{\text{reported, relative}}$	$\sigma_{\text{add, relative}}$	$\sigma_{\text{calib, relative}}$	$\sigma_{\text{total, relative}}$
2231.000	-----	-----	-----	-----	-----	-----
1353.000	0.0036	0.0007	0.1944	0.0750	0.0100	0.2086
820.900	0.0324	0.0012	0.0370	0.0750	0.0100	0.0842
497.900	0.1481	0.0020	0.0135	0.0000	0.0100	0.0168
302.000	0.3912	0.0036	0.0092	0.0000	0.0100	0.0136
183.200	0.8817	0.0054	0.0061	0.0000	0.0100	0.0117
111.100	1.4423	0.0077	0.0053	0.0000	0.0100	0.0113
67.380	1.8062	0.0218	0.0121	0.0000	0.0100	0.0157
40.870	1.6497	0.0169	0.0102	0.0000	0.0100	0.0143
24.790	1.2899	0.0200	0.0155	0.0000	0.0100	0.0185
15.030	1.7357	0.0155	0.0089	0.0000	0.0100	0.0134
9.119	1.3423	0.0198	0.0148	0.0750	0.0300	0.0821
5.531	0.8213	0.0126	0.0153	0.0750	0.0500	0.0914
3.355	0.4152	0.0135	0.0325	0.0750	0.0900	0.1216
2.035	0.0755	0.0078	0.1033	0.0750	0.1100	0.1685
1.234	0.6040	0.0069	0.0114	0.0750	0.1500	0.1681

Table 2.5 provides the measured spectrum as reported by the experimenters for ZPPR-15B loading 126, the BCNA shield configuration.

Table 2.5 ZPPR-15B Loading 126 – Normalized Neutron Spectrum in the BCNA Shield Zone – ZPPR Normalization

E _{lower} , keV	Flux	σ_{reported}	$\sigma_{\text{reported, relative}}$	$\sigma_{\text{add, relative}}$	$\sigma_{\text{calib, relative}}$	$\sigma_{\text{total, relative}}$
2231.000	-----	-----	-----	-----	-----	-----
1353.000	0.0522	0.0037	0.0709	0.0750	0.0100	0.1037
820.900	0.1696	0.0043	0.0254	0.0750	0.0100	0.0798
497.900	0.3904	0.0054	0.0138	0.0000	0.0100	0.0171
302.000	0.6054	0.0074	0.0122	0.0000	0.0100	0.0158
183.200	0.8578	0.0086	0.0100	0.0000	0.0100	0.0142
111.100	1.3054	0.0108	0.0083	0.0000	0.0100	0.0130
67.380	1.6140	0.0273	0.0169	0.0000	0.0100	0.0196
40.870	1.5973	0.0211	0.0132	0.0000	0.0100	0.0166
24.790	1.4019	0.0258	0.0184	0.0000	0.0100	0.0209
15.030	1.5536	0.0199	0.0128	0.0000	0.0100	0.0163
9.119	1.3331	0.0252	0.0189	0.0750	0.0300	0.0830
5.531	0.8381	0.0160	0.0191	0.0750	0.0500	0.0921
3.355	0.4215	0.0173	0.0410	0.0750	0.0900	0.1241
2.035	0.0809	0.0099	0.1224	0.0750	0.1100	0.1808
1.234	0.4397	0.0087	0.0198	0.0750	0.1500	0.1689

2.4 Renormalized ZPPR-15 Neutron Spectra

The fluxes listed in Tables 2.1 – 2.5 are the normalized fluxes as reported by the experimenters. The factors used to produce the normalized values in Tables 2.1 – 2.5 were not reported by the ZPPR staff. The measured fluxes in Tables 2.1 – 2.5 were renormalized to a maximum value of 1.0 for each measurement configuration to provide a more convenient value for comparison with calculations.

Table 2.6 provides the renormalized measured flux and total uncertainty for ZPPR-15A loading 66.

Table 2.6 ZPPR-15A Loading 66 – Renormalized Neutron Spectrum at the Core Center

E_{lower} , keV	Normalized Flux	σ_{total} , %
2231.000	-----	-----
1353.000	0.2146	8.00
820.900	0.3611	7.77
497.900	0.5943	1.73
302.000	0.8211	1.69
183.200	0.9199	1.69
111.100	1.0000	1.67
67.380	0.8219	1.95
40.870	0.6010	1.89
24.790	0.4030	2.31
15.030	0.3615	2.04
9.119	0.2567	8.43
5.531	0.1093	9.52
3.355	0.0562	13.02
2.035	0.0354	14.31
1.234	0.0466	17.14

Table 2.7 provides the renormalized measured flux and total uncertainty for ZPPR-15B loading 90.

Table 2.7 ZPPR-15B Loading 90 – Renormalized Neutron Spectrum at the Core Center

E_{lower} , keV	Normalized Flux	σ_{total} , %
2231.000	-----	-----
1353.000	0.2314	8.00
820.900	0.3829	7.77
497.900	0.6261	1.75
302.000	0.8665	1.71
183.200	0.9524	1.71
111.100	1.0000	1.70
67.380	0.8630	1.98
40.870	0.6458	1.91
24.790	0.4125	2.39
15.030	0.3994	2.04
9.119	0.2794	8.44
5.531	0.1230	9.52
3.355	0.0616	13.09
2.035	0.0273	15.32
1.234	0.0667	17.03

Table 2.8 provides the renormalized measured flux and total uncertainty for ZPPR-15D loading 186.

Table 2.8 ZPPR-15D Loading 186 – Renormalized Neutron Spectrum at the Core Center

E_{lower} , keV	Normalized Flux	σ_{total} , %
2231.000	-----	-----
1353.000	0.2200	8.07
820.900	0.3702	7.80
497.900	0.6107	1.81
302.000	0.8463	1.76
183.200	0.9396	1.76
111.100	1.0000	1.77
67.380	0.8648	2.49
40.870	0.6511	2.35
24.790	0.3966	3.42
15.030	0.4066	2.60
9.119	0.2715	8.92
5.531	0.1291	10.12
3.355	0.0550	15.88
2.035	0.0233	19.89
1.234	0.0515	17.75

Table 2.9 provides the renormalized measured flux and total uncertainty for ZPPR-15B loading 121, the SSNA shield configuration.

Table 2.9 ZPPR-15B Loading 121 – Renormalized Neutron Spectrum in the SSNA Shield Zone

E_{lower} , keV	Normalized Flux	σ_{total} , %
2231.000		
1353.000	0.0020	20.92
820.900	0.0179	8.57
497.900	0.0820	2.30
302.000	0.2166	2.07
183.200	0.4882	1.96
111.100	0.7985	1.93
67.380	1.0000	2.22
40.870	0.9134	2.12
24.790	0.7142	2.42
15.030	0.9610	2.06
9.119	0.7432	8.36
5.531	0.4547	9.28
3.355	0.2299	12.26
2.035	0.0418	16.92
1.234	0.3344	16.88

Table 2.10 provides the renormalized measured flux and total uncertainty for ZPPR-15B loading 126, the BCNA shield configuration.

Table 2.10 ZPPR-15B Loading 126 – Renormalized Neutron Spectrum in the BCNA Shield Zone

E_{lower} , keV	Normalized Flux	σ_{total} , %
2231.000	-----	-----
1353.000	0.0323	10.55
820.900	0.1051	8.22
497.900	0.2419	2.60
302.000	0.3751	2.52
183.200	0.5315	2.42
111.100	0.8088	2.35
67.380	1.0000	2.78
40.870	0.9897	2.57
24.790	0.8686	2.87
15.030	0.9626	2.55
9.119	0.8260	8.53
5.531	0.5193	9.42
3.355	0.2612	12.57
2.035	0.0501	18.19
1.234	0.2724	17.00

2.5 ZPPR-15 Spectrum Measurement Models

An as-built MCNP model was created for each of the ZPPR-15 flux spectrum measurements. The models are;

- m15066v7 – ZPPR-15A loading 66,
- m15090v7 – ZPPR-15B loading 90,
- m15186v7 – ZPPR-15D loading 186,
- m15121v7 – ZPPR-15B loading 121 – SSNA shield configuration, and
- m15126v7 – ZPPR-15B loading 126 – BCNA shield configuration.

For loadings 66, 90 and 186, the flux spectrum can be calculated by Monte Carlo with a standard flux tally. In principle, the flux spectrum could be computed by Monte Carlo for loadings 121 and 126 as well. Without using variance reduction techniques, approximately 100 times as many histories are required to obtain meaningful results by Monte Carlo for loadings 121 and 126 as are required for loadings 66, 90 and 186. The spectrometer was placed in the center of the core where the flux peaks for the spectrum measurements in loadings 66, 90 and 186. For the spectrum measurements in loadings 121 and 126, the spectrometer was placed in the middle of the shield. The neutron flux falls by several orders of magnitude between the middle of the core and the middle of the shield, so Monte Carlo calculations of the measured spectrum in

loadings 121 and 126 require far more histories than Monte Carlo calculations for loadings 66, 90, and 186 to obtain comparable statistical uncertainty. Note that this is not an issue for deterministic models but generation of multi-group cross section data in the outer shield regions is a considerable problem.

3 $^{10}\text{B}(\text{n},\alpha)$ Reaction Rate Measurements in ZPPR-15

3.1 $^{10}\text{B}(\text{n},\alpha)$ Reaction Rate Measurement Technique

The $^{10}\text{B}(\text{n},\alpha)$ reaction rate was measured as part of the ZPPR-15B shield experiment. The measurements were performed by placing a flowing gas proportional counter into a drawer at six locations in the shield, radial reflector, radial blanket and core of ZPPR-15B.

The counter was a cylindrical back-to-back (BTB) counter. A metal plate along the axis of the cylinder divided the counter into two chambers. One chamber contained a 55.19 mm x 9.52 mm rectangular deposit of enriched boron on a stainless steel backing. The boron deposit contained 96.5% ^{10}B . The boron deposit was sufficiently thin that the boron could be regarded as infinitely dilute for analysis purposes. The other chamber was empty. It was necessary to remove the central 12.7 mm column of plates along the entire length of the experimental drawer to accommodate the BTB counter, its gas flow tubes and cables.

Counts were recorded in both chambers of the BTB counter. Counts in the empty chamber were induced by gammas. The counts in the empty chamber were subtracted from the total number of counts in the boron chamber to correct for gamma-induced counts in the boron chamber. The reactor was slightly subcritical for these measurements to avoid saturating the electronics and avoid the need for dead time corrections. The ZPPR ex-core detectors were used to normalize the counts from the BTB chambers to a constant reactor power.

There was only one ^{10}B BTB proportional counter. The $^{10}\text{B}(\text{n},\alpha)$ reaction rate was measured in the ZPPR-15B shield experiment by moving this counter from one matrix location to another in six successive loadings. Table 3.1 shows the core loading numbers and corresponding counter positions in the ZPPR matrix for these measurements.

Table 3.1 Matrix Locations for the $^{10}\text{B}(\text{n},\alpha)$ Reaction Rate Measurements

Core Loading	Matrix Position
127	158-19
128	158-22
129	158-24
130	158-25
131	158-27
132	158-35

The ^{10}B proportional counter was located in half 1 for these measurements. Figures 3.1 – 3.6 show the matrix maps for half 1 for the ^{10}B reaction rate measurements. The color code for the cells in Figures 3.1 – 3.6 is identical to the color code in Section 2.1 for Figures 2.2 – 2.6. The position of the ^{10}B proportional counter in loadings 127 – 132 for the ^{10}B reaction rate measurements is the red-colored drawer position. The matrix loading in half 2 was not changed

during these measurements, so Figure 3.7 shows the matrix map for half 2 of loadings 127 – 132.

Table 3.2 shows the reported $^{10}\text{B}(n,\alpha)$ reaction rate measured in loadings 127 – 132. The exact boron mass in the deposit in the BTB counter and the efficiency of the counter were not known, so it was not possible to determine absolute reaction rates. Consequently, the reaction rates in Table 3.2 were normalized to 10.0 in matrix location 158-35 by the experimenters.

Figure 3.1 ZPPR-15B Loading 127 - Half 1 - Core Matrix Map

Neutron Spectrum and 10B(n, α) Measurements in ZPPR-15
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Figure 3.2 ZPPR-15B Loading 128 – Half 1 – Core Matrix Map

Neutron Spectrum and 10B(n, α) Measurements in ZPPR-15
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Figure 3.3 ZPPR-15B Loading 129 – Half 1 – Core Matrix Map

Neutron Spectrum and 10B(n, α) Measurements in ZPPR-15
April 30, 2020

Figure 3.4 ZPPR-15B Loading 130 - Half 1 - Core Matrix Map.

Neutron Spectrum and 10B(n, α) Measurements in ZPPR-15
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Figure 3.5 ZPPR-15B Loading 131 - Half 1 - Core Matrix Map

Neutron Spectrum and 10B(n,α) Measurements in ZPPR-15
April 30, 2020

Figure 3.6 ZPPR-15B Loading 132 – Half 1 – Core Matrix Map

Table 3.2 Relative ^{10}B Capture Rates in the BCNA Configuration of the ZPPR-15B Shield Experiment

Loading	Region ^a	Location		$^{10}\text{B}(\text{n},\alpha)^b$	$\sigma_{\text{relative}},$ %
		Row	Column		
127	SP	158	19	0.0311	0.0225
128	SH(BCNA)	158	22	0.0603	0.0133
129	SH(BCNA)	158	24	0.2730	0.0070
130	SH(BCNA)	158	25	0.6660	0.0041
131	RR(SSNA)	158	27	6.3820	0.0020
132	OC	158	35	10.0000	0.0100

- Regions were: SP – sodium pool, RR – radial reflector, SH – shield, OC – outer core, SSNA – stainless steel/sodium configuration, BCNA – boron carbide/sodium configuration.
- The $^{10}\text{B}(\text{n},\alpha)$ reaction rates were normalized to 10.0 in matrix location 158-35 by the experimenters.
- The σ_{relative} is the relative uncertainty, i.e., the measured uncertainty reported by the experimenters divided by the measured reaction rate.

3.2 $^{10}\text{B}(\text{n},\alpha)$ Reaction Rate Measurement Uncertainties

Because the actual mass of the boron deposit and the efficiency of the counter were not known, calibration for absolute count rates was not performed. The experimenters normalized the reaction rates shown in Table 3.2 to the measured value at matrix location 158-35, so any calibration uncertainties would cancel out in any case.

For the relative $^{10}\text{B}(\text{n},\alpha)$ reaction rates shown in Table 3.2, there are two relevant uncertainty components. The first component is the statistical uncertainty in the total count rate in the boron chamber of the BTB counter. The second component of the uncertainty for these measurements is the uncertainty due to the correction for gamma-induced counts. Gamma rays induce counts in both chambers of the BTB counter. Subtracting the gamma-induced count rate in the empty chamber from the total count rate in the boron chamber yields the $^{10}\text{B}(\text{n},\alpha)$ reaction rate in the boron chamber. The experimenters assumed the uncertainty in the gamma ray correction was 5% of the gamma-induced count rate. The importance of this correction was greatest in the core location, 158-35, and diminished as the BTB counter location moved outward in the reflector and shield because the gamma spectrum softens and gamma flux levels decrease in the radial reflector and shield. The uncertainties shown in Table 3.2 include the statistical uncertainty in the total count rate in the boron chamber and the 5% uncertainty from the gamma ray correction.

In principle, there could be a small uncertainty contribution related to the statistical uncertainty in the count rate for the ex-core detectors used for power normalization between the different reactor runs. However, this contribution would be small compared to the contributions from the statistical uncertainty in the total count rate in the boron chamber and the uncertainty in the gamma ray correction, so any uncertainty contribution from the statistical uncertainty in the count rate of the ex-core detectors is assumed to be negligible. The uncertainties shown in Table 3.2 are the total uncertainties for the $^{10}\text{B}(\text{n},\alpha)$ reaction rate measurements.

3.3 $^{10}\text{B}(\text{n},\alpha)$ Reaction Rate MCNP Models

An MCNP as-built model was created for each loading in the $^{10}\text{B}(\text{n},\alpha)$ reaction rate measurement series. The models are:

- m15127v7 – ZPPR-15B loading 127,
- m15128v7 – ZPPR-15B loading 128,
- m15129v7 – ZPPR-15B loading 129,
- m15130v7 – ZPPR-15B loading 130,
- m15131v7 – ZPPR-15B loading 131, and
- m15132v7 – ZPPR-15B loading 132.

Each of these cases can be computed by Monte Carlo with a tally for the $^{10}\text{B}(\text{n},\alpha)$ reaction rate in the BTB chamber or with a deterministic model.

4 Summary

The neutron spectrum measurements performed in ZPPR-15A loading 66, ZPPR-15B loading 90, ZPPR-15B loading 121, ZPPR-15B loading 126 and ZPPR-15D loading 186 were described and analyzed. Total uncertainties were derived for the five neutron spectrum measurements. As-built MCNP models were created for all of the neutron spectrum measurement configurations. It is feasible to compute the neutron spectra for ZPPR-15A loading 66, ZPPR-15B loading 90 and ZPPR-15D loading 186 by Monte Carlo methods. The spectrum measurements for loadings 66, 90 and 186 were performed at the center of the core. The spectrum measurements for loadings 121 and 126 were performed in the center of the simulated shield zone where the flux is several orders of magnitude lower than the flux at the core center. Consequently, far more histories are required for loadings 121 and 126 to achieve Monte Carlo statistics comparable to the statistics obtained for Monte Carlo calculation of the neutron spectrum in loadings 66, 90 and 186. The neutron spectra can be calculated with deterministic models for all five measurements.

The $^{10}\text{B}(\text{n},\alpha)$ reaction rate in a back-to-back proportional counter was measured at six locations in loadings 127 – 132 during the ZPPR-15B shield experiment. These measurements were described and analyzed. As-built MCNP models were created for the $^{10}\text{B}(\text{n},\alpha)$ measurement configurations in loadings 127 – 132, and total uncertainties were derived for the $^{10}\text{B}(\text{n},\alpha)$ measurements. The measured $^{10}\text{B}(\text{n},\alpha)$ reaction rates can be calculated by Monte Carlo methods or with a deterministic model.

5 REFERENCES

1. R. M. Lell, M. A. Smith and Z. Zhong, “ZPPR-15 Criticality Measurements,” Argonne National Laboratory, ANL-VTR-51, April 2020.
2. E. F. Bennett and T. J. Yule, “Techniques and Analyses of Fast-Reactor Neutron Spectroscopy with Proton-Recoil Proportional Counters,” Argonne National Laboratory, ANL-7763, August 1971.

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