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IER-484 CED4a Report: AFRRI ER1 Dosimetry Characterization

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IER-484 CED4a Report: AFRRI ER1 Dosimetry Characterization

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Executive Summary

This report presents an analytical function as the reference neutron and photon dose (normalized to an ion chamber integral) for future nuclear accident dosimeter (NAD) exercise at the Armed Forces Radiobiology Research Institute (AFRRI). Various dosimeters and equipment were positioned within exposure room 1 (ER1) and irradiated using a 1.1 MW Training, Research, Isotope, General Atomics (TRIGA) Mark-F nuclear reactor. An ion chamber located in ER1 was used as a normalization factor in Equation 2. This allows for a quick calculation of neutron and photon dose based on the ion chamber data. Currently, AFRRI is in preparation to host a NAD exercise this summer.

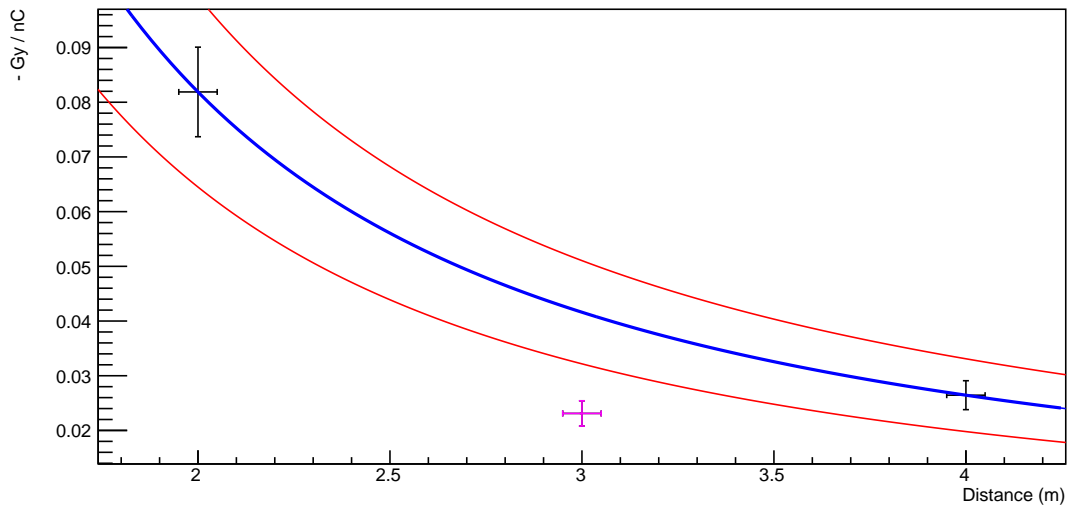


Figure 1: Measured neutron dose normalized to ER1 ion chamber integral in Equation 2. The data points are neutron dose calculated from neutron spectrum measured by LLNL's PNS spheres and converted into neutron dose in Gy. The blue line is the neutron dose as a function of distance from the Cd liner of ER1. The red lines are the fit error bounds. The magenta point at 3 meters was excluded from the fit.

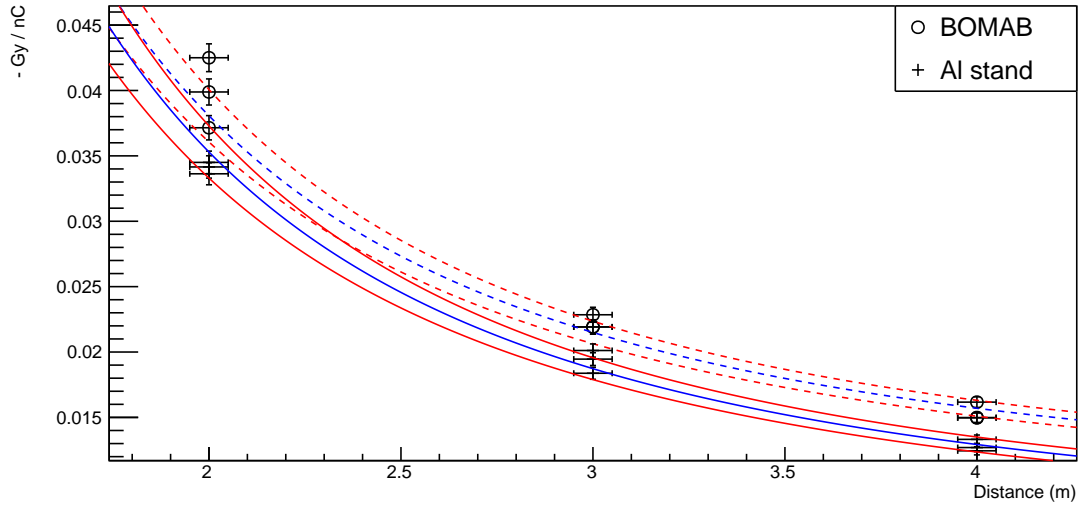


Figure 2: Measured photon dose normalized to ER1 ion chamber integral in Equation 4. The data points were measured using SNL's CaF_2 thermoluminescent dosimeters mounted on aluminum stands and BOMAB phantoms at various distances within ER1. The blue line is the photon dose as a function of distance from the Cd liner of ER1. The red lines are the fit error bounds. The solid line is the fit for photon dose on aluminum stands and the dashed line is the fit for photon dose on BOMAB phantoms.

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1 Introduction

The Armed Forces Radiobiology Research Institute (AFRRI) houses a 1.1 MW Training, Research, Isotope, General Atomics (TRIGA) Mark-F nuclear reactor. The reactor core can move up to its vessel wall towards exposure rooms ER1 and ER2. For this work, we measured and characterized the leakage dose of the TRIGA reactor in ER1 based on the plans in the IER-484 CED2 report [1]. The expected neutron spectrum in ER1 is a fast fission spectrum with down-scatter to a "cadmium cutoff" due to a cadmium liner in ER1. This is the third Nuclear Criticality Safety Program (NCSP) funded dose characterization performed. Past dose characterizations can be found in the IER-147 and IER-252 reports [3, 4].

This was a joint effort between Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratory (SNL), Naval Dosimetry Center (NDC), Atomic Weapons Establishment (AWE), Institut de Radioprotection et de Sûreté Nucléaire (IRSN), and AFRRI. This work utilized similar measurement techniques as the past dose characterization, but used the same dose-to-distance analysis method in the IER-538 CED4a report [5]. The only difference was the use of the ion chamber data in ER1 instead of a temperature probe in the Godiva-IV critical assembly. Results from this dose characterization will be the basis for the reference dose for an upcoming AFRRI nuclear accident dosimeter intercomparison exercise.

2 Methods

This section has two subsections to describe the photon dose and the neutron dose characterizations. Details of the measurement is found in the IER-484 CED3b report [6], but is described here for completeness. Dosimeters and other equipments were placed in ER1 at designated locations shown in Figure 2.1. The analysis codes were written in C++/ROOT [7] and developed in the IER-538 CED4a report [5]. This is explained here for completeness as well.

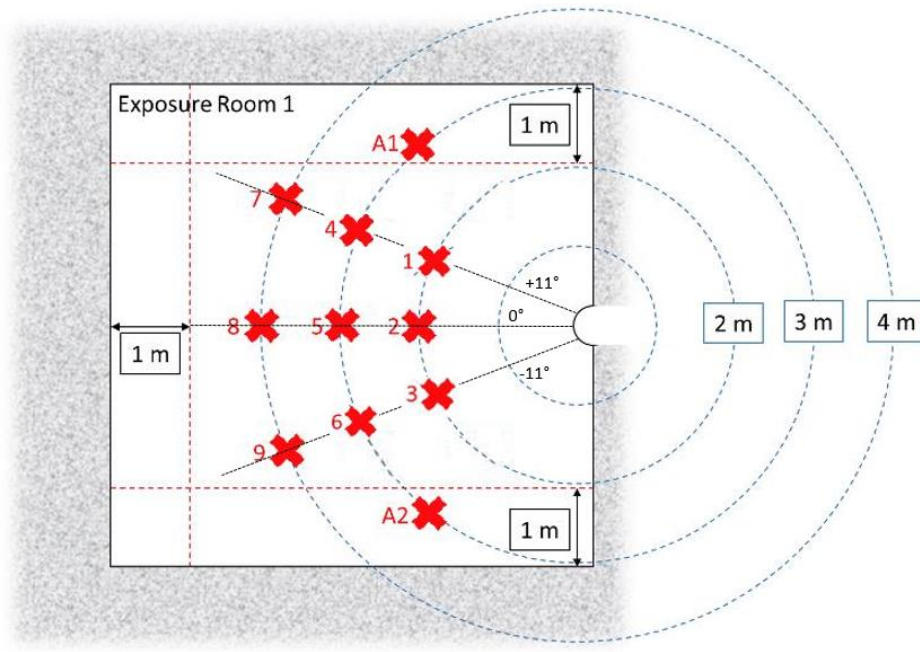


Figure 2.1: Irradiation locations in ER1. Positions were updated from the original image published in AWE Report No. 22/19 [1].

Dosimeters were mounted on bottle manakin absorption (BOMAB) phantoms and aluminum plates shown in Figure 2.2. This is important to analyze the BOMAB phantom contribution to the photon dose due to prompt gamma-rays produced during neutron irradiation.

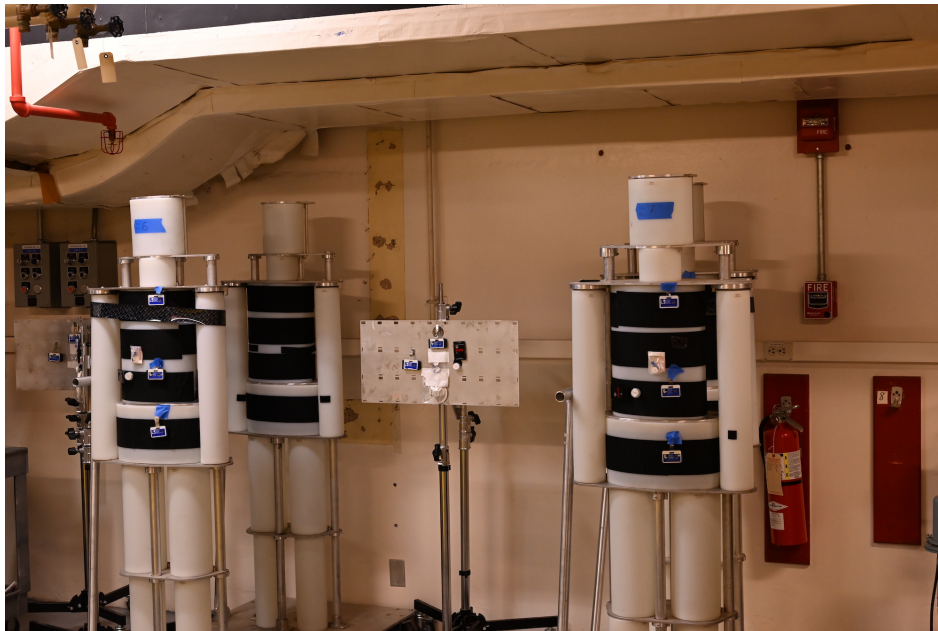


Figure 2.2: BOMABs and an aluminum stands with dosimeters mounted on them. The dosimeters on the BOMABs were mounted at 100, 120, and 145 cm from the floor. The dosimeters on the aluminum plate were mounted between 115 and 130 cm from the floor.

Ion chamber data was recorded for MC2 and MC4 during every irradiation. MC2 data is

shown in Figure 2.3. The readout for these detectors are in negative charge per 5 second time bin. Irradiation 1, 4, and 8 are free in air measurements where the dose to the NADs were targeted to be the same dose. This is why irradiation 4 and 8 have a larger integral charge compared to irradiation 1 to compensate for distance (where 8 is the largest due to being the furthest away from the reactor core). Irradiation 13 and 14 were aimed to have the same integral dose as irradiation 8 with different irradiation duration. The log of irradiation and measurement is tabulated in Table 1.

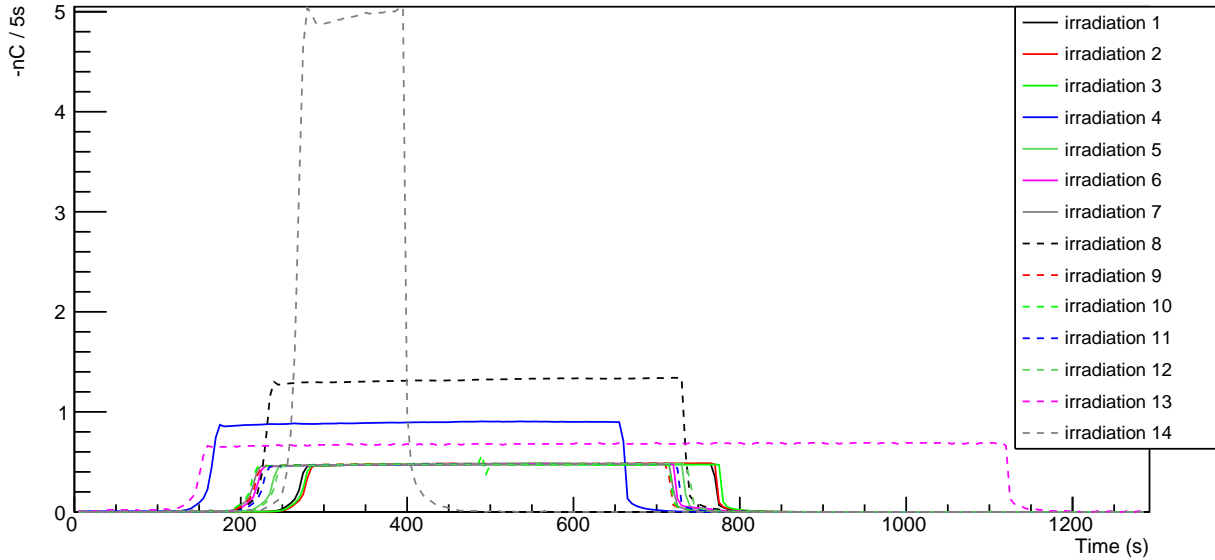


Figure 2.3: Ion chamber #2, MC2, data for each irradiation.

Table 1: Log of irradiation in ER1.

Date	Irradiation	Time (EDT)	Event	Position
August 21, 2023	1	12:31:07	Al stand irradiation at power	1, 2, 3
		12:39:16	Al stand irradiation SCRAM	
	2	13:47:19	BOMAB irradiation at power	2, 6, 7
13:55:02		BOMAB irradiation SCRAM		
	3	15:17:47	LLNL TLD PNS irradiation at power	2
		15:25:57	LLNL TLD PNS irradiation SCRAM	
August 22, 2023	4	08:51:11	Al stand irradiation at power	4, 5, 6
		08:59:12	Al stand irradiation SCRAM	
	5	10:54:51	BOMAB irradiation at power	1, 5, 9
		11:02:44	BOMAB irradiation SCRAM	
	6	13:13:38	LLNL Au PNS irradiation at power	2
		13:21:55	LLNL Au PNS irradiation SCRAM	
7	14:50:47	BOMAB irradiation at power	3, 4, 8	
	14:59:01	BOMAB irradiation SCRAM		
August 23, 2023	8	09:06:25	Al stand irradiation at power	7, 8, 9
		09:14:40	Al stand SCRAM	
	9	10:51:51	LLNL TLD PNS irradiation at power	8
		11:00:00	LLNL TLD PNS irradiation SCRAM	
10	12:28:33	LLNL Au PNS irradiation at power	5	
	12:36:48	LLNL Au PNS irradiation SCRAM		
August 24, 2023	11	09:20:43	AFRRI phantom irradiation at power	2
		09:28:58	AFRRI phantom irradiation SCRAM	
	12	10:19:46	LLNL Au PNS irradiation at power	8
		10:29:32	LLNL Au PNS irradiation SCRAM	
	13	13:39:50	Low power irradiation at power	8
13:55:56		Low power irradiation SCRAM		
14	15:06:12	High power irradiation at power	8	
		15:08:15	High power irradiation SCRAM	8

3 Results

This section describes the resulting neutron spectrum, neutron dose, and photon dose for the dose characterization measurement described in [6]. The neutron spectrum was calculated using a Python code written by Paul Maggi. The neutron dose was calculated from the neutron spectrum and neutron dose conversion factor, then analyzed using a code written in C++/ROOT. Similarly, the photon dose was analyzed using a code written in C++/ROOT.

3.1 Neutron Spectrum

There were three different irradiations of the LLNL passive neutron spectrometer (PNS) spheres at positions 2, 5, and 8. Figure 3.1 shows a PNS sphere in ER1. The gold foils were measured on a Falcon high-purity germanium detector.



Figure 3.1: PNS sphere sitting on an aluminum stand and mounted on top of a tri-pod in ER1. The walls were painted with a gadolinium paint and the semi-circle portion of the wall was a cadmium lining on top of the painted wall.

The data was processed and analyzed using a Python code written by Paul Maggi to perform a neutron spectrum unfolding algorithm. The results are shown in Figure 3.2. The right-most peak is the fission spectrum neutrons while the left-most peak resembles a “cadmium cut-off” spectrum with room return. The algorithm is still under development and results may change in the near future. The neutron spectrum is listed in Appendix A.

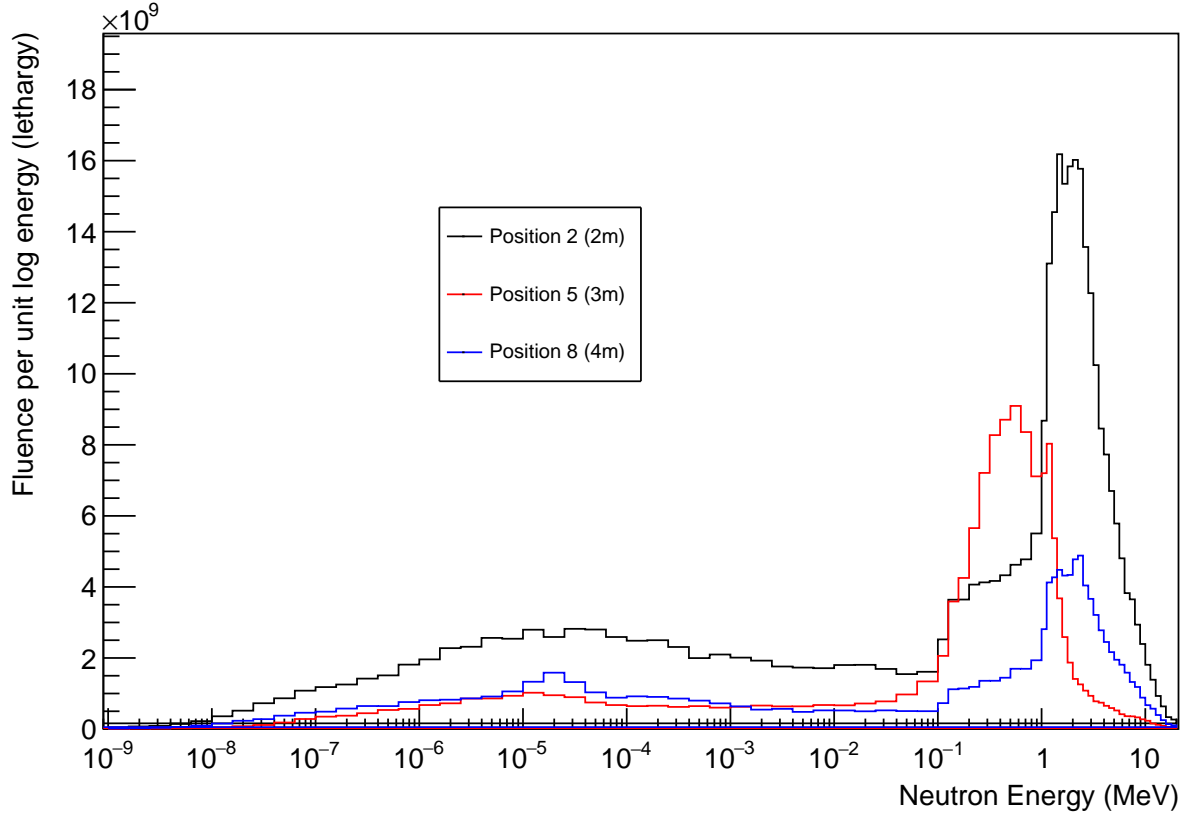


Figure 3.2: Neutron spectrum measured using LLNL’s PNS sphere and algorithm written by Paul Maggi. The algorithm produced the neutron spectra at different distances from the Cd in ER1. The 3 meter neutron spectrum is an outlier when compared to the 2 and 4 meter neutron spectra.

3.2 Neutron Dose

The neutron dose was characterized by integrating the neutron fluence multiplied by a neutron dose conversion factor. The neutron dose to a person, $Dp(10)$, is calculated by the following:

$$Dp(10) = \sum_g \Phi_g(E) \left(\frac{Dp(10)}{\Phi} \right)_g, \quad (1)$$

where $\Phi(E)$ is neutron fluence, $Dp(10)/\Phi$ is the neutron fluence-to-dose conversion factor shown in Figure 3.3, and g is neutron group energy.

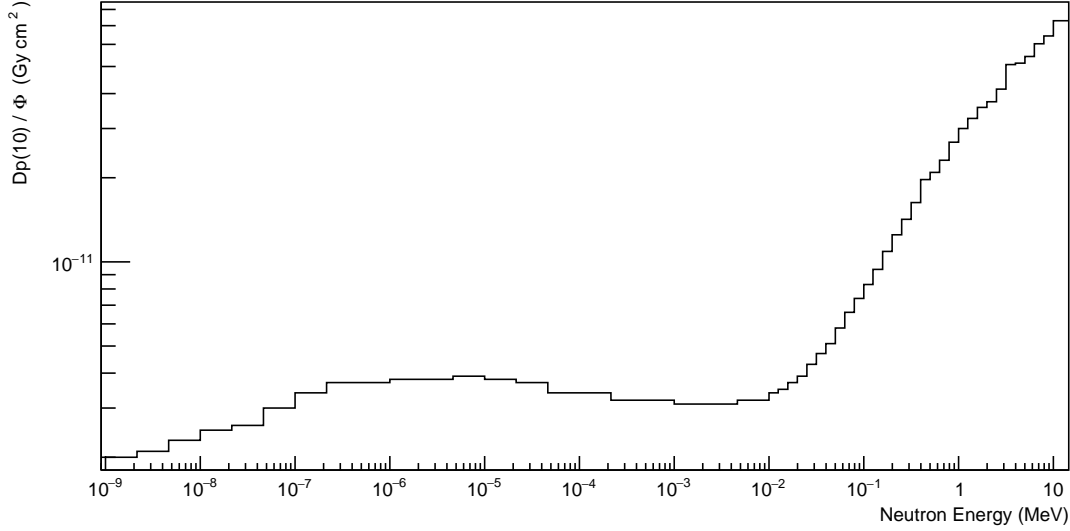


Figure 3.3: Neutron fluence to personal dose conversion factor according to ANSI/HPS N13.3-2013 (R2019)[2].

The neutron dose was normalized to ion chamber integral and fit using the following: This is due to the placement of the dosimeters on the BOMABs and plates. The BOMABs and plates do not match the curvature of a circle with the same radial distance from the Cd liner in ER1. A code written in C++ and ROOT was used to fit the data points with the following:

$$Dp(10) = n_0 e^{-n_1 r} + \frac{n_2}{r^2}, \quad (2)$$

where n_i are fit parameters and r is the radial distance from the Cd liner in ER1. The exponential term represents the attenuation of neutrons before reaching it's target and the $1/r^2$ is the point source term. The 3 meter neutron dose was excluded because it was considered to be an outlier. An initial fit was used to calculate n_1 which was fixed to solve for n_0 and n_2 . This resulted in error estimations for n_0 and n_2 , but not for n_1 as a fixed parameter. The uncertainty $\delta Dp(10)$ is calculated using error propagation:

$$\delta Dp(10) = \sqrt{(\delta n_0 e^{-n_1 r})^2 + (-\delta n_1 n_0 r e^{-n_1 r})^2 + \left(\frac{\delta n_2}{r^2}\right)^2 + \left(\delta r \left(-n_0 n_1 e^{-n_1 r} - \frac{2n_2}{r^3}\right)\right)^2} \quad (3)$$

where δn_i are error for each fit parameter n_i . Figure 3.4 shows the multiple data points at two, three, and four meters with the resulting fit and error band. The fit parameters and error are tabulated below.

Table 2: $K(r)$ fit parameters. An initial fit was used to calculate parameter n_1 which was fixed to calculate parameters n_0 and n_2 .

n_i	Value
n_0	$2(1) \times 10^{-2}$
n_1	1.8×10^{-1}
n_2	$2.7(6) \times 10^{-1}$

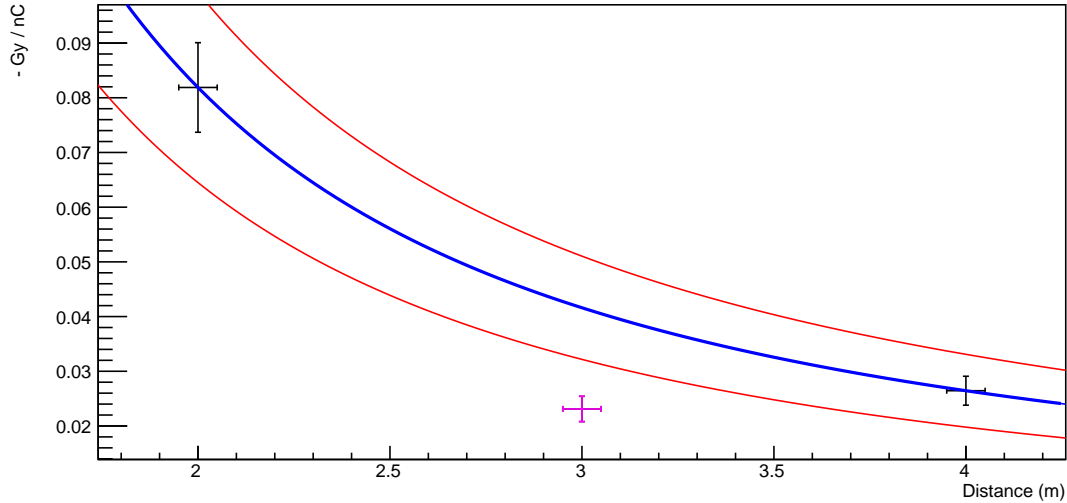


Figure 3.4: Measured neutron dose normalized to ER1 ion chamber integral in Equation 2. The data points are neutron dose calculated from neutron spectrum measured by LLNL’s PNS spheres and converted into neutron dose in Gy. The blue line is the neutron dose as a function of distance from the Cd liner of ER1. The red lines are the fit error bounds. The magenta point at 3 meters was excluded from the fit.

3.3 Photon Dose

The SNL CaF_2 TLDs was used for photon dose measurements (see Figure 3.5). These were shipped back to SNL’s Radiation Metrology Laboratory for their analysis.



Figure 3.5: An assortment of CaF_2 TLDs used for the photon dose measurements at different distances.

Photon doses were shared and analyzed at LLNL using a code written in C++/ROOT [7]. The photon dose was characterized as dose per ion chamber integral and distance in meters by the following:

$$D_g(r) = \begin{cases} g_0 + \frac{g_1}{r^2} + g_2 & \text{BOMAB phantom} \\ g_0 + \frac{g_1}{r^2} & \text{aluminum plate} \end{cases} \quad (4)$$

where $D_g(r)$ is photon dose per ΔT in Gy per $^\circ\text{C}$, r is distance in centimeters, and g_i are fit parameters. The g_2 term is the BOMAB phantom contribution to the photon dose, which was assumed to be a constant. Data from the aluminum plate irradiations were fit using g_0 and g_1 only. Data from the BOMAB phantom irradiations had the parameters g_0 and g_1 fixed and the fit parameter was g_2 . The results of the fit is tabulated in Table 3. The uncertainty, $\delta D_g(r)$,

Table 3: $D_g(r)$ fit parameters. g_2 is the BOMAB phantom contribution term.

g_i	Value
g_0	$5.5(4) \times 10^{-3}$
g_1	$1.19(5) \times 10^{-1}$
g_2	$2.8(2) \times 10^{-3}$

is calculated by propagating the error of the fit parameters. The form of the uncertainty is the following:

$$\delta D_g(r) = \begin{cases} \sqrt{(\delta g_0)^2 + \left(\frac{\delta g_1}{r^2}\right)^2 + \left(-\frac{2g_1 \delta r}{r^3}\right)^2 + (\delta g_2)^2} & \text{BOMAB phantom} \\ \sqrt{(\delta g_0)^2 + \left(\frac{\delta g_1}{r^2}\right)^2 + \left(-\frac{2g_1 \delta r}{r^3}\right)^2} & \text{free-in-air stand} \end{cases} \quad (5)$$

where δg_i is the error associated with the parameter g_i . δg_2 is only considered for a BOMAB irradiation.

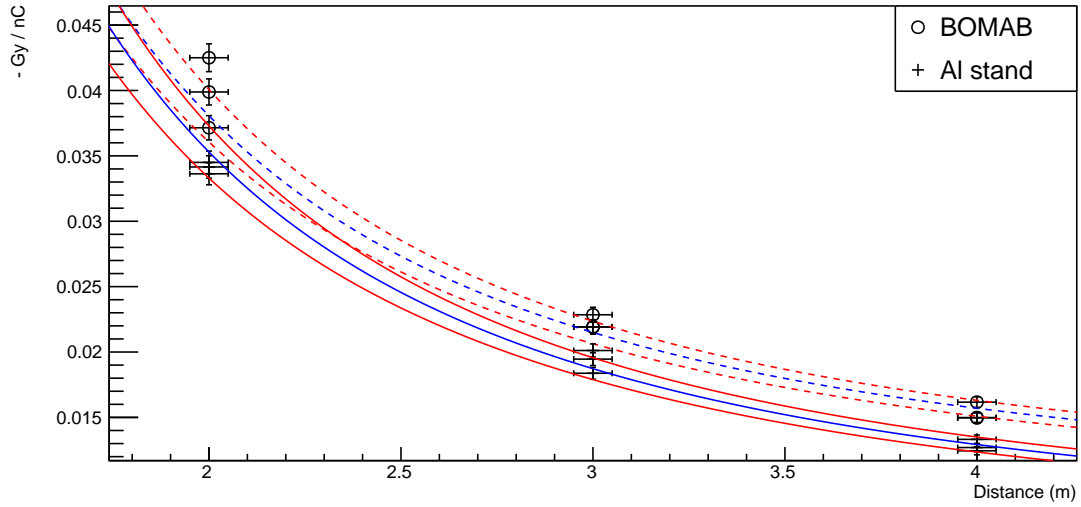


Figure 3.6: Measured photon dose normalized to ER1 ion chamber integral in Equation 4. The data points were measured using SNL's CaF_2 thermoluminescent dosimeters mounted on aluminum stands and BOMAB phantoms at various distances within ER1. The blue line is the photon dose as a function of distance from the Cd liner of ER1. The red lines are the fit error bounds. The solid line is the fit for photon dose on aluminum stands and the dashed line is the fit for photon dose on BOMAB phantoms.

4 Conclusion

The AFRRI leakage neutron and photon dose was successfully measured using a series of PNS sphere and CaF_2 TLD measurements. Using the same analysis in the IER-538 CED4a report [5], this work supports the use of an analytical solution as a quick approximation for leakage dose. By using the dose functions and ion chamber integral data, a reference dose can be calculated for a NAD intercomparison exercise.

AFRRI will be hosting a NAD exercise this summer. Currently, the main concern is the lab space required for the participants. This limits the amount of detectors, seats, and personnel in a designated room. Gamma-ray detectors will need sufficient shielding to prevent any interference between different activated foils. During the exercise, AWE will deploy their PNS sphere with a validated method to measure the neutron spectrum. Their results can improve the neutron dose characterization in this report.

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A Neutron Spectrum

Table 4: Neutron fluence at position 2 (2 meters).

E_i	E_{i+1}	Fluence	Δ lethargy	Fluence per unit lethargy
1.00E-09	1.58E-09	2.30E+07	4.57E-01	5.03E+07
1.58E-09	2.51E-09	3.35E+07	4.63E-01	7.23E+07
2.51E-09	3.98E-09	4.03E+07	4.61E-01	8.74E+07
3.98E-09	6.31E-09	6.84E+07	4.61E-01	1.48E+08
6.31E-09	1.00E-08	1.02E+08	4.60E-01	2.22E+08
1.00E-08	1.58E-08	1.64E+08	4.57E-01	3.59E+08
1.58E-08	2.51E-08	2.39E+08	4.63E-01	5.17E+08
2.51E-08	3.98E-08	3.35E+08	4.61E-01	7.26E+08
3.98E-08	6.31E-08	3.99E+08	4.61E-01	8.65E+08
6.31E-08	1.00E-07	4.97E+08	4.60E-01	1.08E+09
1.00E-07	1.58E-07	5.40E+08	4.57E-01	1.18E+09
1.58E-07	2.51E-07	5.80E+08	4.63E-01	1.25E+09
2.51E-07	3.98E-07	6.54E+08	4.61E-01	1.42E+09
3.98E-07	6.31E-07	6.96E+08	4.61E-01	1.51E+09
6.31E-07	1.00E-06	8.35E+08	4.60E-01	1.81E+09
1.00E-06	1.58E-06	8.97E+08	4.57E-01	1.96E+09
1.58E-06	2.51E-06	1.05E+09	4.63E-01	2.28E+09
2.51E-06	3.98E-06	1.07E+09	4.61E-01	2.32E+09
3.98E-06	6.31E-06	1.18E+09	4.61E-01	2.57E+09
6.31E-06	1.00E-05	1.17E+09	4.60E-01	2.54E+09
1.00E-05	1.58E-05	1.28E+09	4.57E-01	2.80E+09
1.58E-05	2.51E-05	1.20E+09	4.63E-01	2.59E+09
2.51E-05	3.98E-05	1.30E+09	4.61E-01	2.82E+09
3.98E-05	6.31E-05	1.29E+09	4.61E-01	2.80E+09
6.31E-05	1.00E-04	1.19E+09	4.60E-01	2.59E+09
1.00E-04	1.58E-04	1.14E+09	4.57E-01	2.49E+09
1.58E-04	2.51E-04	1.16E+09	4.63E-01	2.50E+09
2.51E-04	3.98E-04	1.06E+09	4.61E-01	2.31E+09
3.98E-04	6.31E-04	9.20E+08	4.61E-01	2.00E+09
6.31E-04	1.00E-03	9.66E+08	4.60E-01	2.10E+09
1.00E-03	1.58E-03	9.20E+08	4.57E-01	2.01E+09
1.58E-03	2.51E-03	8.91E+08	4.63E-01	1.93E+09
2.51E-03	3.98E-03	8.11E+08	4.61E-01	1.76E+09
3.98E-03	6.31E-03	7.97E+08	4.61E-01	1.73E+09
6.31E-03	1.00E-02	7.89E+08	4.60E-01	1.71E+09
1.00E-02	1.58E-02	8.24E+08	4.57E-01	1.80E+09
1.58E-02	2.51E-02	8.36E+08	4.63E-01	1.81E+09
2.51E-02	3.98E-02	7.80E+08	4.61E-01	1.69E+09
3.98E-02	6.31E-02	7.13E+08	4.61E-01	1.55E+09
6.31E-02	1.00E-01	7.42E+08	4.60E-01	1.61E+09
1.00E-01	1.26E-01	5.83E+08	2.31E-01	2.52E+09
1.26E-01	1.58E-01	8.24E+08	2.26E-01	3.64E+09

1.58E-01	2.00E-01	8.59E+08	2.36E-01	3.65E+09
2.00E-01	2.51E-01	9.24E+08	2.27E-01	4.07E+09
2.51E-01	3.16E-01	9.51E+08	2.30E-01	4.13E+09
3.16E-01	3.98E-01	9.62E+08	2.31E-01	4.17E+09
3.98E-01	5.01E-01	9.96E+08	2.30E-01	4.33E+09
5.01E-01	6.31E-01	1.07E+09	2.31E-01	4.62E+09
6.31E-01	7.94E-01	1.10E+09	2.30E-01	4.78E+09
7.94E-01	1.00E+00	1.27E+09	2.31E-01	5.51E+09
1.00E+00	1.12E+00	9.84E+08	1.13E-01	8.68E+09
1.12E+00	1.26E+00	1.54E+09	1.18E-01	1.31E+10
1.26E+00	1.41E+00	1.64E+09	1.12E-01	1.46E+10
1.41E+00	1.58E+00	1.84E+09	1.14E-01	1.62E+10
1.58E+00	1.78E+00	1.83E+09	1.19E-01	1.53E+10
1.78E+00	2.00E+00	1.85E+09	1.17E-01	1.58E+10
2.00E+00	2.24E+00	1.82E+09	1.13E-01	1.60E+10
2.24E+00	2.51E+00	1.79E+09	1.14E-01	1.58E+10
2.51E+00	2.82E+00	1.58E+09	1.16E-01	1.36E+10
2.82E+00	3.16E+00	1.40E+09	1.14E-01	1.23E+10
3.16E+00	3.55E+00	1.19E+09	1.16E-01	1.02E+10
3.55E+00	3.98E+00	9.67E+08	1.14E-01	8.46E+09
3.98E+00	4.47E+00	8.97E+08	1.16E-01	7.73E+09
4.47E+00	5.01E+00	7.64E+08	1.14E-01	6.70E+09
5.01E+00	5.62E+00	6.65E+08	1.15E-01	5.79E+09
5.62E+00	6.31E+00	5.56E+08	1.16E-01	4.81E+09
6.31E+00	7.08E+00	4.41E+08	1.15E-01	3.83E+09
7.08E+00	7.94E+00	4.18E+08	1.15E-01	3.65E+09
7.94E+00	8.91E+00	3.39E+08	1.15E-01	2.94E+09
8.91E+00	1.00E+01	2.76E+08	1.15E-01	2.39E+09
1.00E+01	1.12E+01	2.05E+08	1.13E-01	1.81E+09
1.12E+01	1.26E+01	1.63E+08	1.18E-01	1.39E+09
1.26E+01	1.41E+01	1.05E+08	1.12E-01	9.31E+08
1.41E+01	1.58E+01	7.25E+07	1.14E-01	6.37E+08
1.58E+01	1.78E+01	3.99E+07	1.19E-01	3.35E+08
1.78E+01	2.00E+01	3.11E+07	1.17E-01	2.67E+08

Table 5: Neutron fluence at position 5 (3 meters).

E_i	E_{i+1}	Fluence	Δ lethargy	Fluence per unit lethargy
1.00E-09	1.58E-09	3.13E+06	4.57E-01	6.84E+06
1.58E-09	2.51E-09	5.35E+06	4.63E-01	1.16E+07
2.51E-09	3.98E-09	6.09E+06	4.61E-01	1.32E+07
3.98E-09	6.31E-09	1.02E+07	4.61E-01	2.22E+07
6.31E-09	1.00E-08	1.68E+07	4.60E-01	3.65E+07
1.00E-08	1.58E-08	2.31E+07	4.57E-01	5.05E+07
1.58E-08	2.51E-08	3.67E+07	4.63E-01	7.92E+07
2.51E-08	3.98E-08	5.24E+07	4.61E-01	1.14E+08
3.98E-08	6.31E-08	8.44E+07	4.61E-01	1.83E+08
6.31E-08	1.00E-07	1.30E+08	4.60E-01	2.82E+08
1.00E-07	1.58E-07	1.59E+08	4.57E-01	3.49E+08
1.58E-07	2.51E-07	1.74E+08	4.63E-01	3.75E+08
2.51E-07	3.98E-07	2.05E+08	4.61E-01	4.45E+08
3.98E-07	6.31E-07	2.47E+08	4.61E-01	5.36E+08
6.31E-07	1.00E-06	2.61E+08	4.60E-01	5.66E+08
1.00E-06	1.58E-06	3.09E+08	4.57E-01	6.75E+08
1.58E-06	2.51E-06	3.35E+08	4.63E-01	7.24E+08
2.51E-06	3.98E-06	3.95E+08	4.61E-01	8.57E+08
3.98E-06	6.31E-06	3.96E+08	4.61E-01	8.60E+08
6.31E-06	1.00E-05	4.31E+08	4.60E-01	9.36E+08
1.00E-05	1.58E-05	4.67E+08	4.57E-01	1.02E+09
1.58E-05	2.51E-05	4.40E+08	4.63E-01	9.51E+08
2.51E-05	3.98E-05	4.13E+08	4.61E-01	8.96E+08
3.98E-05	6.31E-05	3.44E+08	4.61E-01	7.47E+08
6.31E-05	1.00E-04	3.11E+08	4.60E-01	6.75E+08
1.00E-04	1.58E-04	2.95E+08	4.57E-01	6.45E+08
1.58E-04	2.51E-04	3.03E+08	4.63E-01	6.56E+08
2.51E-04	3.98E-04	2.87E+08	4.61E-01	6.22E+08
3.98E-04	6.31E-04	2.97E+08	4.61E-01	6.45E+08
6.31E-04	1.00E-03	2.77E+08	4.60E-01	6.02E+08
1.00E-03	1.58E-03	2.86E+08	4.57E-01	6.26E+08
1.58E-03	2.51E-03	3.06E+08	4.63E-01	6.61E+08
2.51E-03	3.98E-03	2.94E+08	4.61E-01	6.38E+08
3.98E-03	6.31E-03	2.94E+08	4.61E-01	6.39E+08
6.31E-03	1.00E-02	3.11E+08	4.60E-01	6.76E+08
1.00E-02	1.58E-02	3.05E+08	4.57E-01	6.67E+08
1.58E-02	2.51E-02	3.33E+08	4.63E-01	7.19E+08
2.51E-02	3.98E-02	3.59E+08	4.61E-01	7.78E+08
3.98E-02	6.31E-02	4.48E+08	4.61E-01	9.73E+08
6.31E-02	1.00E-01	6.17E+08	4.60E-01	1.34E+09
1.00E-01	1.26E-01	4.76E+08	2.31E-01	2.06E+09
1.26E-01	1.58E-01	8.12E+08	2.26E-01	3.59E+09
1.58E-01	2.00E-01	1.00E+09	2.36E-01	4.25E+09
2.00E-01	2.51E-01	1.28E+09	2.27E-01	5.66E+09

2.51E-01	3.16E-01	1.66E+09	2.30E-01	7.21E+09
3.16E-01	3.98E-01	1.91E+09	2.31E-01	8.27E+09
3.98E-01	5.01E-01	2.00E+09	2.30E-01	8.71E+09
5.01E-01	6.31E-01	2.10E+09	2.31E-01	9.10E+09
6.31E-01	7.94E-01	1.92E+09	2.30E-01	8.36E+09
7.94E-01	1.00E+00	1.64E+09	2.31E-01	7.11E+09
1.00E+00	1.12E+00	8.16E+08	1.13E-01	7.20E+09
1.12E+00	1.26E+00	9.46E+08	1.18E-01	8.03E+09
1.26E+00	1.41E+00	6.04E+08	1.12E-01	5.37E+09
1.41E+00	1.58E+00	4.19E+08	1.14E-01	3.68E+09
1.58E+00	1.78E+00	3.09E+08	1.19E-01	2.59E+09
1.78E+00	2.00E+00	2.18E+08	1.17E-01	1.87E+09
2.00E+00	2.24E+00	1.60E+08	1.13E-01	1.41E+09
2.24E+00	2.51E+00	1.43E+08	1.14E-01	1.26E+09
2.51E+00	2.82E+00	1.26E+08	1.16E-01	1.08E+09
2.82E+00	3.16E+00	1.06E+08	1.14E-01	9.35E+08
3.16E+00	3.55E+00	9.07E+07	1.16E-01	7.79E+08
3.55E+00	3.98E+00	8.48E+07	1.14E-01	7.42E+08
3.98E+00	4.47E+00	7.58E+07	1.16E-01	6.53E+08
4.47E+00	5.01E+00	6.74E+07	1.14E-01	5.91E+08
5.01E+00	5.62E+00	6.00E+07	1.15E-01	5.22E+08
5.62E+00	6.31E+00	4.82E+07	1.16E-01	4.17E+08
6.31E+00	7.08E+00	4.16E+07	1.15E-01	3.61E+08
7.08E+00	7.94E+00	4.09E+07	1.15E-01	3.56E+08
7.94E+00	8.91E+00	3.79E+07	1.15E-01	3.28E+08
8.91E+00	1.00E+01	3.16E+07	1.15E-01	2.74E+08
1.00E+01	1.12E+01	2.64E+07	1.13E-01	2.33E+08
1.12E+01	1.26E+01	1.82E+07	1.18E-01	1.55E+08
1.26E+01	1.41E+01	1.33E+07	1.12E-01	1.19E+08
1.41E+01	1.58E+01	1.01E+07	1.14E-01	8.85E+07
1.58E+01	1.78E+01	7.12E+06	1.19E-01	5.97E+07
1.78E+01	2.00E+01	5.43E+06	1.17E-01	4.66E+07

Table 6: Neutron fluence at position 8 (4 meters).

E_i	E_{i+1}	Fluence	Δ lethargy	Fluence per unit lethargy
1.00E-09	1.58E-09	7.62E+06	4.57E-01	1.67E+07
1.58E-09	2.51E-09	1.11E+07	4.63E-01	2.41E+07
2.51E-09	3.98E-09	1.56E+07	4.61E-01	3.38E+07
3.98E-09	6.31E-09	2.46E+07	4.61E-01	5.34E+07
6.31E-09	1.00E-08	4.50E+07	4.60E-01	9.76E+07
1.00E-08	1.58E-08	7.06E+07	4.57E-01	1.54E+08
1.58E-08	2.51E-08	1.08E+08	4.63E-01	2.32E+08
2.51E-08	3.98E-08	1.28E+08	4.61E-01	2.78E+08
3.98E-08	6.31E-08	1.73E+08	4.61E-01	3.76E+08
6.31E-08	1.00E-07	2.11E+08	4.60E-01	4.59E+08
1.00E-07	1.58E-07	2.24E+08	4.57E-01	4.89E+08
1.58E-07	2.51E-07	2.67E+08	4.63E-01	5.76E+08
2.51E-07	3.98E-07	2.98E+08	4.61E-01	6.47E+08
3.98E-07	6.31E-07	2.98E+08	4.61E-01	6.46E+08
6.31E-07	1.00E-06	3.49E+08	4.60E-01	7.59E+08
1.00E-06	1.58E-06	3.71E+08	4.57E-01	8.11E+08
1.58E-06	2.51E-06	3.82E+08	4.63E-01	8.26E+08
2.51E-06	3.98E-06	3.98E+08	4.61E-01	8.63E+08
3.98E-06	6.31E-06	4.22E+08	4.61E-01	9.15E+08
6.31E-06	1.00E-05	4.87E+08	4.60E-01	1.06E+09
1.00E-05	1.58E-05	6.09E+08	4.57E-01	1.33E+09
1.58E-05	2.51E-05	7.34E+08	4.63E-01	1.59E+09
2.51E-05	3.98E-05	6.09E+08	4.61E-01	1.32E+09
3.98E-05	6.31E-05	4.76E+08	4.61E-01	1.03E+09
6.31E-05	1.00E-04	4.06E+08	4.60E-01	8.83E+08
1.00E-04	1.58E-04	4.21E+08	4.57E-01	9.20E+08
1.58E-04	2.51E-04	4.18E+08	4.63E-01	9.04E+08
2.51E-04	3.98E-04	3.95E+08	4.61E-01	8.58E+08
3.98E-04	6.31E-04	3.69E+08	4.61E-01	8.00E+08
6.31E-04	1.00E-03	3.33E+08	4.60E-01	7.22E+08
1.00E-03	1.58E-03	2.92E+08	4.57E-01	6.38E+08
1.58E-03	2.51E-03	2.53E+08	4.63E-01	5.46E+08
2.51E-03	3.98E-03	2.62E+08	4.61E-01	5.68E+08
3.98E-03	6.31E-03	2.22E+08	4.61E-01	4.83E+08
6.31E-03	1.00E-02	2.42E+08	4.60E-01	5.25E+08
1.00E-02	1.58E-02	2.39E+08	4.57E-01	5.23E+08
1.58E-02	2.51E-02	2.31E+08	4.63E-01	4.99E+08
2.51E-02	3.98E-02	2.42E+08	4.61E-01	5.25E+08
3.98E-02	6.31E-02	2.33E+08	4.61E-01	5.05E+08
6.31E-02	1.00E-01	2.31E+08	4.60E-01	5.02E+08
1.00E-01	1.26E-01	1.68E+08	2.31E-01	7.29E+08
1.26E-01	1.58E-01	2.53E+08	2.26E-01	1.12E+09
1.58E-01	2.00E-01	2.69E+08	2.36E-01	1.14E+09
2.00E-01	2.51E-01	2.69E+08	2.27E-01	1.19E+09

2.51E-01	3.16E-01	3.13E+08	2.30E-01	1.36E+09
3.16E-01	3.98E-01	3.13E+08	2.31E-01	1.36E+09
3.98E-01	5.01E-01	3.32E+08	2.30E-01	1.44E+09
5.01E-01	6.31E-01	3.91E+08	2.31E-01	1.70E+09
6.31E-01	7.94E-01	3.90E+08	2.30E-01	1.70E+09
7.94E-01	1.00E+00	4.46E+08	2.31E-01	1.93E+09
1.00E+00	1.12E+00	3.19E+08	1.13E-01	2.81E+09
1.12E+00	1.26E+00	4.86E+08	1.18E-01	4.13E+09
1.26E+00	1.41E+00	4.80E+08	1.12E-01	4.27E+09
1.41E+00	1.58E+00	5.10E+08	1.14E-01	4.48E+09
1.58E+00	1.78E+00	5.15E+08	1.19E-01	4.32E+09
1.78E+00	2.00E+00	5.05E+08	1.17E-01	4.34E+09
2.00E+00	2.24E+00	5.41E+08	1.13E-01	4.78E+09
2.24E+00	2.51E+00	5.56E+08	1.14E-01	4.88E+09
2.51E+00	2.82E+00	4.71E+08	1.16E-01	4.04E+09
2.82E+00	3.16E+00	4.17E+08	1.14E-01	3.66E+09
3.16E+00	3.55E+00	3.74E+08	1.16E-01	3.21E+09
3.55E+00	3.98E+00	3.18E+08	1.14E-01	2.78E+09
3.98E+00	4.47E+00	2.84E+08	1.16E-01	2.45E+09
4.47E+00	5.01E+00	2.47E+08	1.14E-01	2.16E+09
5.01E+00	5.62E+00	2.24E+08	1.15E-01	1.95E+09
5.62E+00	6.31E+00	2.10E+08	1.16E-01	1.81E+09
6.31E+00	7.08E+00	1.83E+08	1.15E-01	1.59E+09
7.08E+00	7.94E+00	1.52E+08	1.15E-01	1.32E+09
7.94E+00	8.91E+00	1.36E+08	1.15E-01	1.18E+09
8.91E+00	1.00E+01	1.02E+08	1.15E-01	8.84E+08
1.00E+01	1.12E+01	7.61E+07	1.13E-01	6.71E+08
1.12E+01	1.26E+01	6.74E+07	1.18E-01	5.73E+08
1.26E+01	1.41E+01	4.43E+07	1.12E-01	3.94E+08
1.41E+01	1.58E+01	2.85E+07	1.14E-01	2.50E+08
1.58E+01	1.78E+01	1.65E+07	1.19E-01	1.39E+08
1.78E+01	2.00E+01	1.21E+07	1.17E-01	1.04E+08
