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IER-484 CED3b Report: AFRRI ER1 Dosimetry Characterization

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January 22, 2024

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This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.



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Auspices

This work was supported by the United States Department of Energy (DOE) Nuclear Criticality Safety Program (NCSP), funded and managed by the National Nuclear Security Administration for the DOE. This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. This work was performed with the assistance of the Armed Forces Radiobiology Research Institute at Uniformed Services University.

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Executive Summary

This report presents the preliminary work for IER 484, the characterization of the leakage radiation field from the TRIGA reactor at the Armed Forces Radiobiology Research Institute (AFRRI). The purpose of the dose characterization is to establish the reference dose needed to execute a NAD inter-comparison exercise. During the week of August 20th, a team from Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratory (SNL), and Institut de Radioprotection et de Sûreté Nucléaire (IRSN) performed various measurements in AFRRI's TRIGA ER1 (Exposure Room 1) with Passive Neutron Spectrometer (PNS) spheres and nuclear accident dosimeters (NADs) mounted on Bottle Manikin Absorption (BOMAB) phantoms (to simulate doses received by people) and additional NADs mounted on aluminum plates (to simulate doses in free air).

Without Atomic Weapons Establishment (AWE), LLNL became responsible for measuring the neutron spectrum using PNS spheres. SNL is responsible for providing photon dose data. LLNL, SNL, and IRSN each deployed their own NADs, which will be compared to the reference dose measured. Final characterization of the dose field based on analyzed data will be presented in the CED4a report.

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1 Introduction

Integral Experiment Request (IER) 484 is part of a series of dose characterization and nuclear accident dosimeter (NAD) exercises performed under the Department of Energy (DOE) Nuclear Criticality Safety Program (NCSP) [2, 3, 4, 5, 6]. The characterization plan is found in IER-484 CED2 report [1]. The objective of the dose characterization is to establish reference neutron and photon doses of the Armed Forces Radiobiology Research Institute (AFRRI) Training, Research, Isotopes, General Atomics (TRIGA) reactor. The reference doses will be used for future nuclear accident dosimeter (NAD) exercises at AFRRI. The experiment seeks to collect data to characterize dose as a function of:

1. distance from reactor core
2. angle along a radial contour
3. height above the exposure room floor
4. AFRRI ion chamber charge integral values (shown in Section 3.1)

Unfortunately, Atomic Weapons Establishment (AWE) was not able to attend the dose characterization due to unforeseen delays.

2 Method

There are multiple irradiation facilities within the AFRRI TRIGA reactor facility. Among these, Exposure Room 1 (ER1) was used for the NAD characterization. ER1 was large enough to house multiple Bottle Manakin Absorption (BOMAB) phantoms (to simulate doses received by people) and free-in-air stands to simulate doses in air. The center of the reactor was at a height of 120 cm above the exposure room floor. Figures 2.1 and 2.2 show how the dosimeters were mounted on the BOMAB phantoms and the free-in-air stands, respectively. The mounting positions for dosimeters were consistent for all irradiations. LLNL and SNL placed their dosimeters in the front of each BOMAB while IRSN placed dosimeters in the front and back of each BOMAB. Figure 2.3 provides a layout of ER1 and the irradiation locations for the dosimeters. The semi-circle portion on the right wall of ER1 is a cadmium lining (shown in Figure 2.4). There are two ion chambers mounted on the ceiling of ER1. These are denoted as MC4 and MC2. MC4 is at 0 degrees near the back of the room (~ 4 m) and MC2 is offset at about -5 degrees between 2 and 3 m distance from the Cd lining. The dose measured will be normalized to the ion chamber readings to extrapolate different dose values for different ion chamber measurements. The data from the deployed dosimeters are tabulated in Table 1 along with other equipment for this measurement. The log of irradiation and measurement is tabulated in Table 2.



Figure 2.1: BOMAB phantoms were mounted on custom aluminum exposure stands. The blue tape markers on the right indicate different heights above the floor. From top to bottom, the markers are at 145, 130, 120, 115, and 100 cm above the exposure room floor.



Figure 2.2: Three BOMAB phantoms and a free-in-air aluminum stand with dosimeters mounted on them. The dosimeters on the BOMAB phantoms were mounted at 100, 120, and 145 cm above the exposure room floor. The dosimeters on the free-in-air aluminum plate stand were mounted between 115 and 130 cm above the exposure room floor.

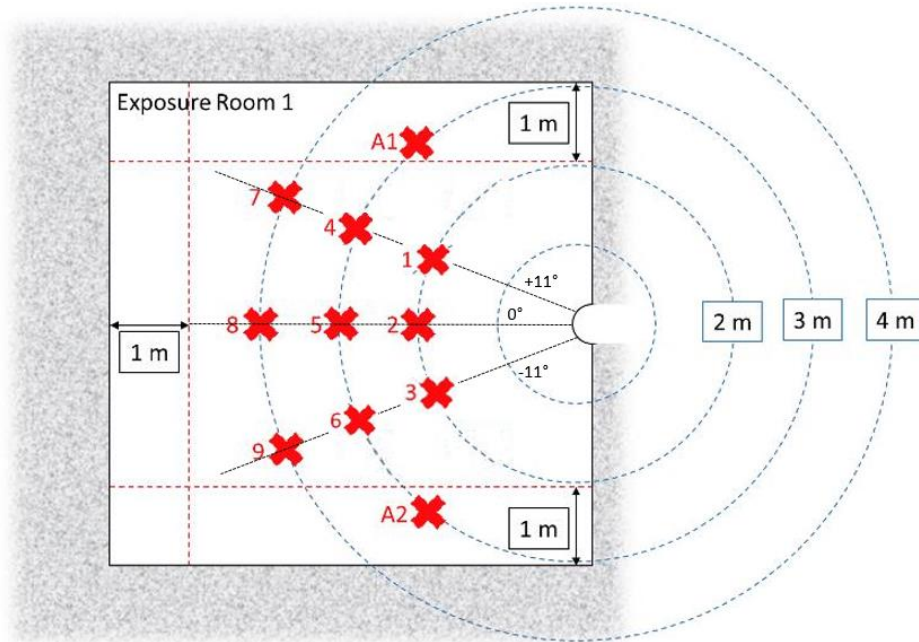


Figure 2.3: Irradiation locations in ER1. Positions were updated from the original image published in AWE Report No. 22/19 [1]. Distances shown are from the Cd lining in ER1.

Table 1: Equipment used for the dose measurements.

Lab	Equipment
	LLNL NAD
	Panasonic UD-810 TLD
	TLD PNS
LLNL	Au PNS
	Al stands
	BOMAB
	Falcon HPGe detector
	SNL NAD
SNL	CaF ₂ :Mn TLD
	Falcon HPGe detector
	IRSN NAD
	IRSN criticality belt
	RPL dosimeter
IRSN	Alanine pellets
	Si diode
	Si diode reader
	NaI detector

Table 2: Log of irradiation in ER1.

Date	Irradiation	Time (EDT)	Event	Position ¹
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		

¹Shown in Figure 2.3

2.1 LLNL PNS Sphere

The LLNL Passive Neutron Spectrometer (PNS) Sphere was used for neutron fluence measurements (see Figure 2.4). Two different versions were deployed, one loaded with Thermoluminescent Dosimeters (TLDs) and the other loaded with Au foils. These 15 cm radius spheres were fabricated from high-density polyethylene (HDPE) and have cylindrical shafts to place the TLDs or Au foils at different depths. TLDs were measured at LLNL. Au foils were measured using a Falcon 5000 HPGe detector within an hour after irradiation.



Figure 2.4: LLNL PNS sphere sitting on an aluminum stand and mounted on top of a tri-pod in ER1. The semi-circle portion of the wall is a cadmium liner (filter). The room walls are painted with a gadolinium paint. The purpose of the liner and paint is to reduce the number of thermal neutrons in the AFFRI leakage spectrum.

2.2 SNL CaF_2 TLD

CaF_2 TLDs, supplied by SNL, were used for photon dose measurements (see Figure 2.5). After exposure, TLDs were shipped back to SNL for analysis. TLDs were exposed in sets of 5 each. Each set was placed into a brown coin envelope that could be placed at the desired exposure location (shown in Appendix A). Individual TLD results, within each set, were averaged to yield an estimated mean value for the photon dose. Reported error values represent the $\pm 2\sigma$ error for the reported mean value.



Figure 2.5: An assortment of CaF_2 TLDS used for the photon dose measurements at different distances.

3 Preliminary Results

3.1 AFRRI Ion Chamber Data

Ion chamber data was recorded for MC2 and MC4 during every irradiation. Data are shown in Figures 3.1 and 3.2. The readout for these detectors were in negative charge per 5 second time bin. Irradiations 1, 4, and 8 were free-in-air measurements where the doses 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. Reference dose for NAD exercises will be normalized to the ion chamber integral dose.

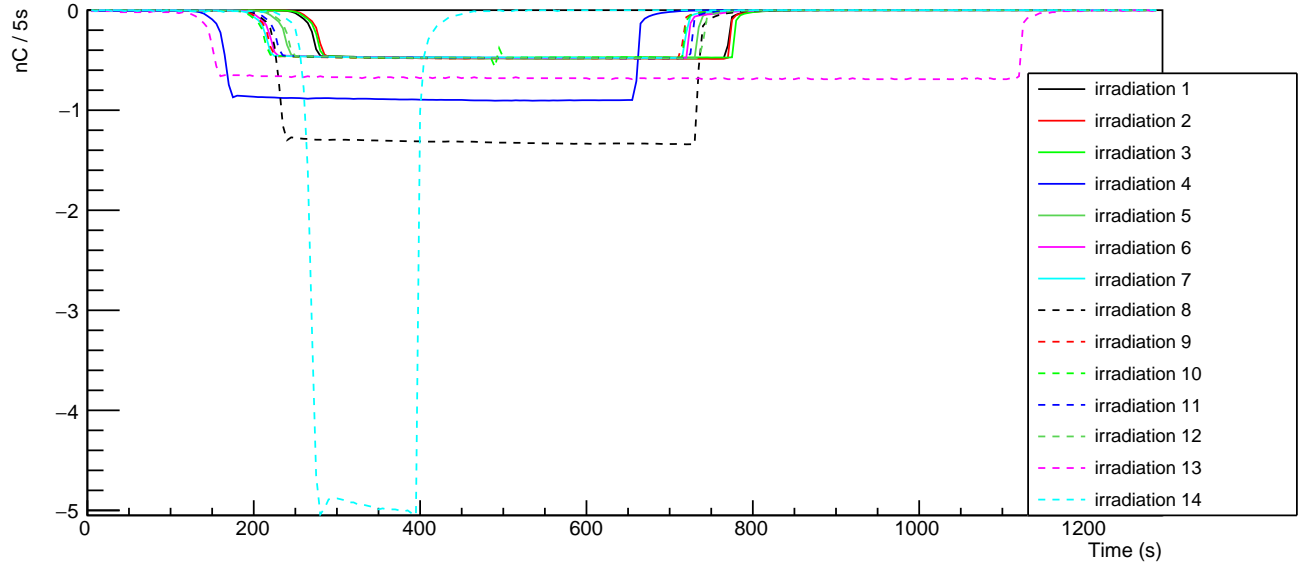


Figure 3.1: Ion chamber #2, MC2, data for each irradiation.

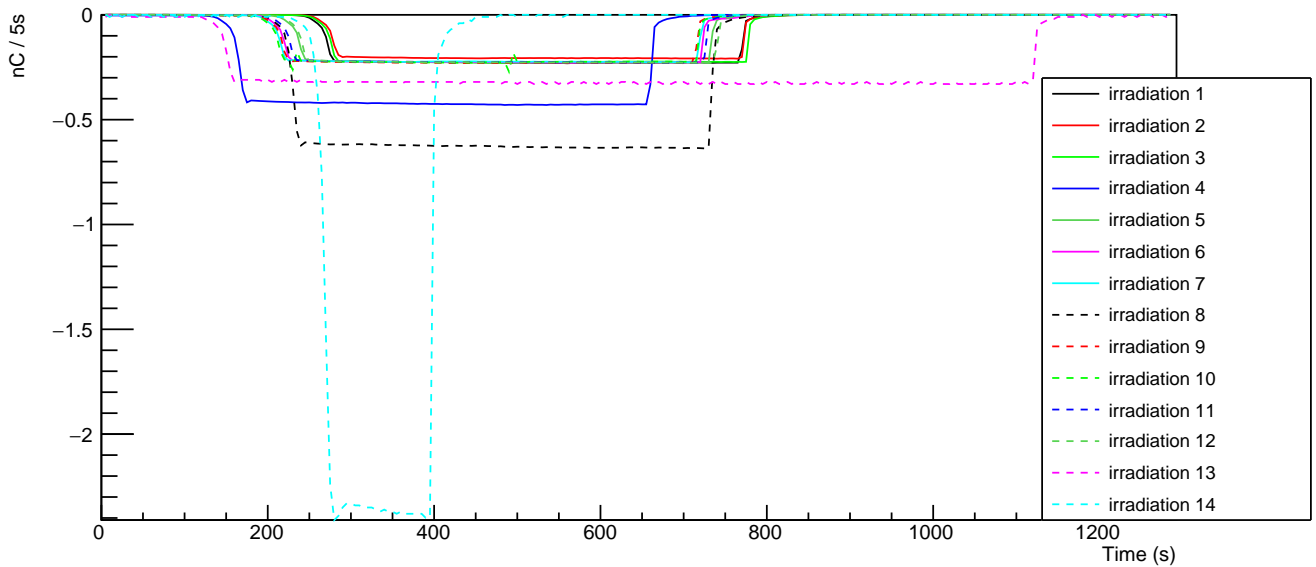


Figure 3.2: Ion chamber #4, MC4, data for each irradiation.

3.2 LLNL Au PNS Foil Activity

The LLNL Au PNS measurements consisted of 55 Au foils per irradiation. The sphere was placed on a fixed tri-pod stand where it's center was 122 cm from the floor. Each foil was measured on a Falcon HPGe detector. Specific foil activities (Bq/g) were corrected back to the time of irradiation. Tables 3 list the foil information for irradiation number 6, 10, and 12. Figures 3.3, 3.4, and 3.5 were axial profiles of the corrected Au foil specific activities. The data from the PNS measurements was used to reconstruct the neutron fluence at specific distances from the exposure room's cadmium

lining.

Table 3: Specific activity of the Au foils loaded in the LLNL Au PNS first irradiation. The position is defined as the axis and depth distance (e.g. +X1 is 1 cm deep from the positive x-axis). Data at 2, 3, and 4 meters were from irradiations number 6, 10, and 12 respectively. Uncertainties were not provided and need to be calculated for the final report.

Position	Specific Activity (Bq/g)			mass (g)		
	2m	3m	4m	2m	3m	4m
+X1 (front)	61148	31443	22597	0.2035	0.2063	0.192
+X2	70949	37974	26155	0.2144	0.1702	0.1792
+X3	74851	37310	24929	0.2165	0.3028	0.2538
+X4	64979	38881	23126	0.2134	0.2492	0.2358
+X5	61817	33677	21672	0.2022	0.1736	0.2276
+X6	54596	29442	18698	0.2591	0.171	0.2243
+X7	46444	24040	16205	0.2977	0.2011	0.2692
+X9	35282	18536	11577	0.235	0.188	0.2015
+X12	20822	6989	6944	0.2334	0.2602	0.2014
+X15 (center)	13061	3370	4654	0.2048	0.2754	0.2388
-X1 (rear)	6269	5555	7600	0.2997	0.2494	0.2006
-X2	7528	5808	7646	0.202	0.2175	0.2155
-X3	7288	5876	6835	0.2397	0.195	0.2115
-X4	6282	5241	6432	0.2663	0.1566	0.2048
-X5	6411	4314	5776	0.2446	0.1466	0.2144
-X6	5979	4026	4662	0.199	0.228	0.2036
-X7	5838	3925	4190	0.249	0.2652	0.2568
-X9	6235	3474	3051	0.2093	0.2377	0.2559
-X12	7621	3533	3171	0.2133	0.2052	0.2146
+Y1 (ccw from front)	14616	9690	8063	0.204	0.1401	0.2556
+Y2	18583	12040	9820	0.2187	0.2118	0.2236
+Y3	19955	11882	9662	0.179	0.1681	0.2023
+Y4	20797	11678	9067	0.291	0.2127	0.2546
+Y5	19005	11217	8875	0.3002	0.26	0.1957
+Y6	17994	10174	8080	0.2601	0.2518	0.2258
+Y7	16307	9935	6994	0.2556	0.1832	0.2547
+Y9	15415	8126	6023	0.2256	0.2281	0.2062
+Y12	13952	6806	4778	0.23	0.2081	0.22
-Y1 (cw from front)	14701	9764	8047	0.2508	0.214	0.2711
-Y2	18791	12285	9238	0.2032	0.2121	0.234
-Y3	19350	12706	8829	0.2006	0.2266	0.2944
-Y4	18870	12276	8914	0.2093	0.2352	0.2656
-Y5	18118	12539	8180	0.2115	0.1939	0.2694
-Y6	17158	11277	6729	0.242	0.1994	0.303
-Y7	16711	10382	6540	0.2354	0.2061	0.2404
-Y9	15018	9046	5371	0.2202	0.1638	0.2154
-Y12	13808	6689	4712	0.1583	0.2445	0.206
+Z1 (top)	16778	10046	–	0.2437	0.167	0.2515

... Table 3 continued

Position	Specific Activity (Bq/g)			mass (g)		
	2m	3m	4m	2m	3m	4m
+Z2	20579	12898	8731	0.2403	0.2091	0.2349
+Z3	22014	12648	9269	0.2395	0.214	0.2096
+Z4	21611	11541	8830	0.1713	0.2414	0.2463
+Z5	21616	11470	7990	0.2245	0.1976	0.2598
+Z6	21668	9738	6776	0.1902	0.2567	0.2338
+Z7	19987	9546	6369	0.286	0.2427	0.2377
+Z9	17475	7980	5461	0.2065	0.2772	0.2255
+Z12	14209	6429	4320	0.2355	0.2478	0.2764
-Z1 (bottom)	15723	8169	–	0.2457	0.4096	0.2064
-Z2	17779	11493	–	0.2071	0.2297	0.2974
-Z3	21622	11247	9069	0.2462	0.2201	0.2092
-Z4	18287	10963	8414	0.2375	0.2265	0.2099
-Z5	17222	10403	8011	0.2397	0.202	0.282
-Z6	16902	9554	6778	0.2019	0.2347	0.2712
-Z7	16132	9386	6398	0.2674	0.2222	0.2369
-Z9	13292	6953	5491	0.2137	0.2099	0.2061
-Z12	11797	–	4496	0.2156	–	0.2117

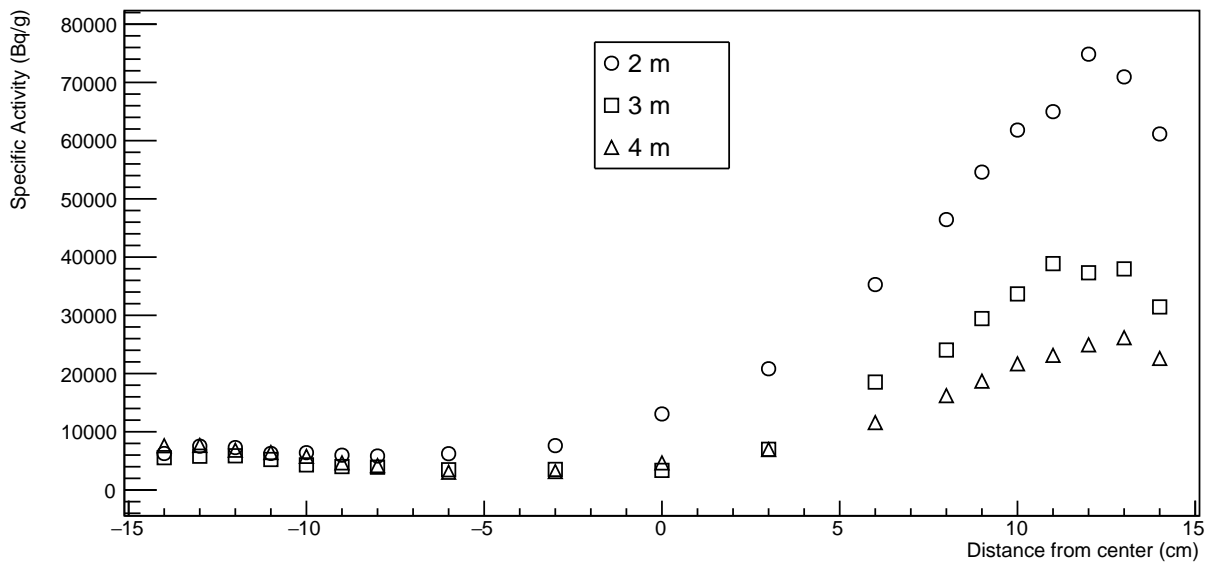


Figure 3.3: Au foil specific activity along the x-axis for a PNS sphere at various distances from the cadmium liner. The uncertainties were not shown.

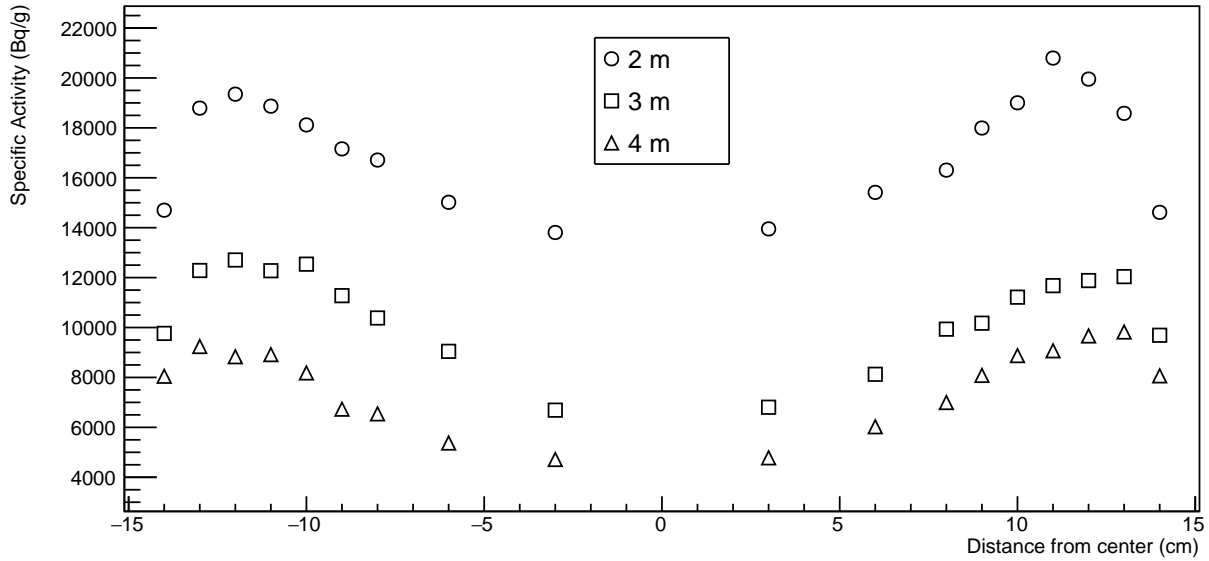


Figure 3.4: Au foil specific activity along the y-axis for a PNS sphere at various distances. The 0 cm foil is shown in Figure 3.3. The uncertainties were not shown.

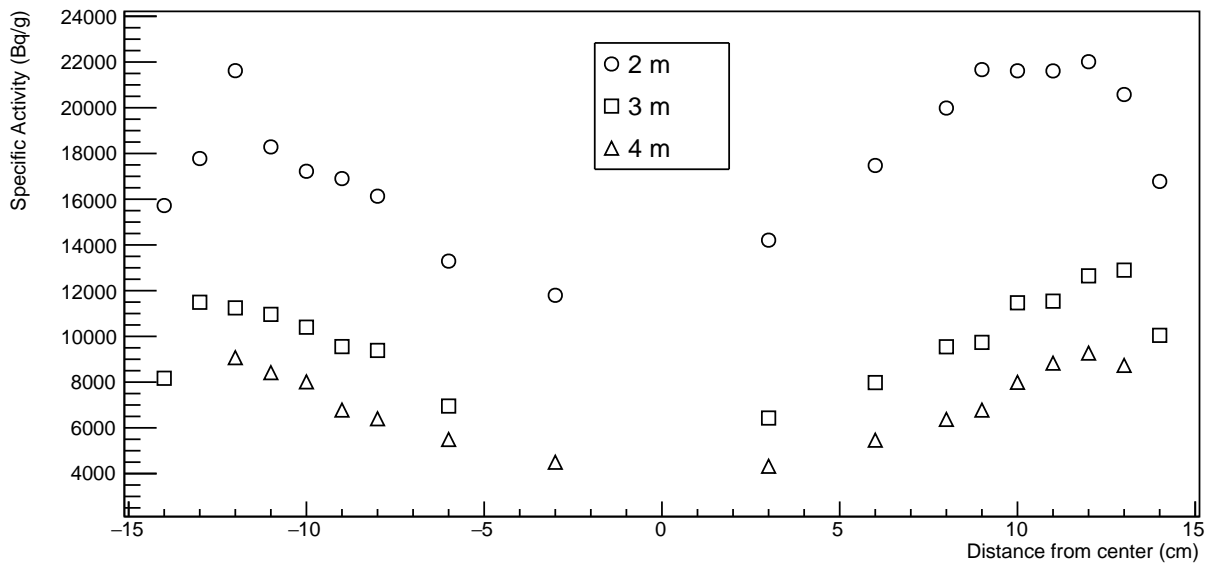


Figure 3.5: Au foil specific activity along the z-axis for a PNS sphere at various distances. The 0 cm foil is shown in Figure 3.3. The uncertainties were not shown.

3.2.1 Preliminary Neutron Spectrum

A code written in Python was used to unfold the neutron spectrum from the PNS sphere measurements (results listed in Table 4 and shown in Figure 3.6). The error of the fit was not provided and needs to be calculated for the final report.

Table 4: Calculated neutron spectrum using the PNS Au foil data.

Energy (MeV)	lethargy	Fluence at 2 m (n/cm ²)	Fluence at 3 m (n/cm ²)	Fluence at 4 m (n/cm ²)
1.00×10^{-9}	5.97×10^{-1}	9.84×10^8	2.48×10^8	8.61×10^8
1.58×10^{-9}	4.61×10^{-1}	8.23×10^8	2.90×10^8	8.79×10^8
2.51×10^{-9}	4.62×10^{-1}	9.09×10^8	4.41×10^8	8.28×10^8
3.98×10^{-9}	4.61×10^{-1}	1.10×10^9	4.91×10^8	9.79×10^8
6.31×10^{-9}	4.61×10^{-1}	8.24×10^8	3.89×10^8	8.71×10^8
1.00×10^{-8}	4.59×10^{-1}	1.20×10^9	4.84×10^8	9.45×10^8
1.58×10^{-8}	4.61×10^{-1}	1.66×10^9	1.07×10^9	8.93×10^8
2.51×10^{-8}	4.62×10^{-1}	1.78×10^9	1.28×10^9	7.26×10^8
3.98×10^{-8}	4.61×10^{-1}	1.57×10^9	1.27×10^9	8.12×10^8
6.31×10^{-8}	4.61×10^{-1}	2.99×10^9	1.15×10^9	1.25×10^9
1.00×10^{-7}	4.59×10^{-1}	2.80×10^9	1.27×10^9	1.18×10^9
1.58×10^{-7}	4.61×10^{-1}	2.46×10^9	9.65×10^8	7.77×10^8
2.51×10^{-7}	4.62×10^{-1}	1.68×10^9	6.60×10^8	6.73×10^8
3.98×10^{-7}	4.61×10^{-1}	1.37×10^9	6.91×10^8	5.09×10^8
6.31×10^{-7}	4.61×10^{-1}	9.74×10^8	5.16×10^8	2.81×10^8
1.00×10^{-6}	4.59×10^{-1}	9.34×10^8	3.26×10^8	3.60×10^8
1.58×10^{-6}	4.61×10^{-1}	8.09×10^8	2.51×10^8	2.62×10^8
2.51×10^{-6}	4.62×10^{-1}	6.89×10^8	1.90×10^8	1.97×10^8
3.98×10^{-6}	4.61×10^{-1}	7.67×10^8	1.13×10^8	1.59×10^8
6.31×10^{-6}	4.61×10^{-1}	1.87×10^8	8.23×10^7	1.53×10^8
1.00×10^{-5}	4.59×10^{-1}	1.93×10^8	6.86×10^7	1.13×10^8
1.58×10^{-5}	4.61×10^{-1}	3.26×10^8	6.68×10^7	9.26×10^7
2.51×10^{-5}	4.62×10^{-1}	2.92×10^8	6.29×10^7	8.85×10^7
3.98×10^{-5}	4.61×10^{-1}	3.08×10^8	1.09×10^7	8.65×10^7
6.31×10^{-5}	4.61×10^{-1}	1.44×10^8	9.50×10^6	1.12×10^8
1.00×10^{-4}	4.59×10^{-1}	1.01×10^8	9.02×10^6	9.14×10^7
1.58×10^{-4}	4.61×10^{-1}	9.32×10^7	6.44×10^6	9.95×10^7
2.51×10^{-4}	4.62×10^{-1}	7.28×10^7	3.74×10^6	6.89×10^7
3.98×10^{-4}	4.61×10^{-1}	5.66×10^7	8.60×10^6	5.27×10^7
6.31×10^{-4}	4.61×10^{-1}	1.07×10^8	1.14×10^7	4.60×10^7
1.00×10^{-3}	4.59×10^{-1}	1.14×10^8	8.51×10^6	4.46×10^7
1.58×10^{-3}	4.61×10^{-1}	1.56×10^8	9.03×10^6	3.84×10^7
2.51×10^{-3}	4.62×10^{-1}	2.08×10^8	2.02×10^7	4.33×10^7
3.98×10^{-3}	4.61×10^{-1}	1.83×10^8	1.99×10^7	5.27×10^7
6.31×10^{-3}	4.61×10^{-1}	1.52×10^8	6.04×10^7	5.45×10^7
1.00×10^{-2}	4.59×10^{-1}	9.10×10^7	5.35×10^7	5.74×10^7
1.58×10^{-2}	4.61×10^{-1}	1.09×10^8	6.29×10^7	6.43×10^7
2.51×10^{-2}	4.62×10^{-1}	8.43×10^7	6.76×10^7	5.95×10^7
3.98×10^{-2}	4.61×10^{-1}	1.02×10^8	5.34×10^7	5.65×10^7
6.31×10^{-2}	4.61×10^{-1}	1.72×10^8	8.01×10^7	6.31×10^7
1.00×10^{-1}	3.26×10^{-1}	2.43×10^8	2.00×10^8	7.93×10^7
1.26×10^{-1}	2.28×10^{-1}	2.46×10^8	3.82×10^8	1.41×10^8
1.58×10^{-1}	2.32×10^{-1}	3.40×10^8	3.90×10^8	1.50×10^8

... Table 4 continued

Energy (MeV)	lethargy	Fluence at 2 m (n/cm ²)	Fluence at 3 m (n/cm ²)	Fluence at 4 m (n/cm ²)
2.00×10^{-1}	2.31×10^{-1}	5.17×10^8	4.84×10^8	2.20×10^8
2.51×10^{-1}	2.29×10^{-1}	6.80×10^8	8.87×10^8	4.39×10^8
3.16×10^{-1}	2.31×10^{-1}	1.61×10^9	1.44×10^9	8.29×10^8
3.98×10^{-1}	2.30×10^{-1}	3.25×10^9	2.73×10^9	2.34×10^9
5.01×10^{-1}	2.30×10^{-1}	5.68×10^9	6.71×10^9	2.58×10^9
6.31×10^{-1}	2.30×10^{-1}	6.95×10^9	5.30×10^9	2.79×10^9
7.94×10^{-1}	2.30×10^{-1}	6.97×10^9	7.44×10^9	3.03×10^9
1.00	1.67×10^{-1}	7.72×10^9	3.31×10^9	1.85×10^9
1.12	1.16×10^{-1}	7.35×10^9	1.34×10^9	2.02×10^9
1.26	1.15×10^{-1}	3.48×10^9	9.31×10^8	1.75×10^9
1.41	1.13×10^{-1}	2.04×10^9	5.82×10^8	9.99×10^8
1.58	1.17×10^{-1}	1.36×10^9	2.63×10^8	4.70×10^8
1.78	1.18×10^{-1}	1.29×10^9	1.53×10^8	2.46×10^8
2.00	1.15×10^{-1}	1.24×10^9	5.42×10^7	1.75×10^8
2.24	1.14×10^{-1}	3.80×10^8	4.89×10^7	1.47×10^8
2.51	1.15×10^{-1}	2.24×10^8	4.34×10^7	1.63×10^8
2.82	1.15×10^{-1}	1.61×10^8	4.52×10^7	1.40×10^8
3.16	1.15×10^{-1}	1.36×10^8	4.35×10^7	1.22×10^8
3.55	1.15×10^{-1}	1.00×10^8	2.93×10^7	8.78×10^7
3.98	1.15×10^{-1}	8.76×10^7	2.53×10^7	9.80×10^7
4.47	1.15×10^{-1}	1.03×10^8	1.81×10^7	6.62×10^7
5.01	1.14×10^{-1}	1.02×10^8	1.88×10^7	6.37×10^7
5.62	1.15×10^{-1}	8.03×10^7	1.37×10^7	6.21×10^7
6.31	1.15×10^{-1}	5.73×10^7	7.35×10^6	2.46×10^7
7.08	1.15×10^{-1}	5.58×10^7	5.06×10^6	2.79×10^7
7.94	1.15×10^{-1}	4.59×10^7	4.47×10^6	3.18×10^7
8.91	1.15×10^{-1}	2.95×10^7	6.02×10^6	3.45×10^7
1.00×10^1	1.14×10^{-1}	5.51×10^7	7.52×10^6	2.80×10^7
1.12×10^1	1.16×10^{-1}	5.62×10^7	7.54×10^6	2.71×10^7
1.26×10^1	1.15×10^{-1}	5.53×10^7	5.74×10^6	2.05×10^7
1.41×10^1	1.13×10^{-1}	4.10×10^7	6.13×10^6	1.05×10^7
1.58×10^1	1.17×10^{-1}	3.06×10^7	9.37×10^6	1.06×10^7
1.78×10^1	1.18×10^{-1}	3.11×10^7	1.20×10^7	9.38×10^6

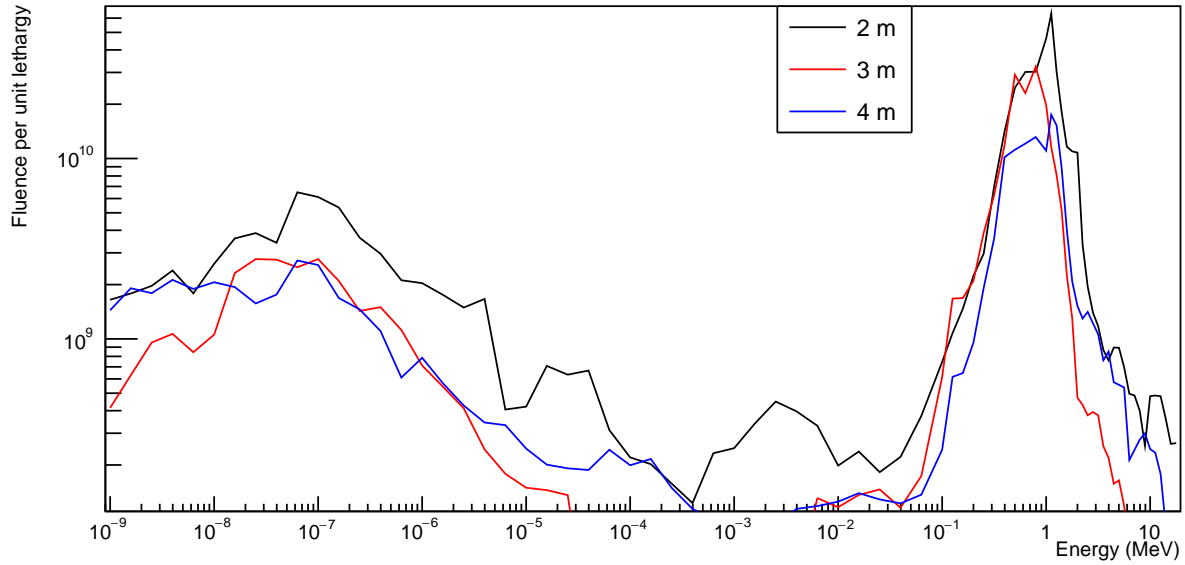


Figure 3.6: Preliminary neutron spectrum calculated using the PNS Au foil data.

3.3 LLNL NADs

The LLNL NADs were mounted on both the free-in-air aluminum stands and BOMAB phantoms. Table 5 lists the neutron dose for each position and location. The stand irradiation were targeted to be the same doses at their respective location (increased operating power for stands further away), but variation in measured dose may be caused by small variations in the timing of the exposure pulse widths and/or associated power levels. The BOMAB irradiation were all targeted to be the same dose overall, but different doses at similar positions suggests the same reason stated for the stands. Further analysis must be performed to produce final dose numbers.

Table 5: LLNL neutron dose measured using NADs mounted on BOMABs and stands. These were grouped by irradiation. The uncertainties listed were $\pm 2\sigma$.

irradiation	mount	position	height (cm)	offset	dose (Gy)	unc. (Gy)		
1	Stand	1	–	center	2.41	0.18		
			–	left	2.71	0.19		
		2	–	center	2.64	0.18		
			–	left	2.73	0.15		
		3	–	center	2.90	0.19		
			–	left	3.03	0.22		
4	Stand	4	–	center	1.06	0.08		
			–	left	1.20	0.09		
		5	–	center	1.09	0.08		
			–	left	1.15	0.07		
		6	–	center	1.24	0.08		
			–	left	1.07	0.07		
8	Stand	7	–	center	1.08	0.07		
			–	left	1.30	0.08		
		8	–	center	1.41	0.08		
			–	left	1.41	0.08		
		9	–	center	1.15	0.08		
			–	left	1.30	0.08		
2	BOMAB	2	145	–	2.64	0.18		
			120	–	2.80	0.20		
			100	–	2.79	0.21		
		6	145	–	1.49	0.12		
			120	–	1.45	0.10		
			100	–	1.38	0.09		
		7	145	–	1.22	0.12		
			120	–	1.06	0.09		
			100	–	0.90	0.07		
		5	BOMAB	1	145	–	1.45	0.11
					120	–	1.18	0.06
					100	–	1.25	0.08
5	145			–	0.76	0.05		
	120			–	0.70	0.04		
	100			–	0.68	0.04		
9	145			–	0.43	0.03		
	120			–	0.48	0.03		
	100			–	0.44	0.03		
7	BOMAB			3	145	–	1.35	0.09
					120	–	1.51	0.12
					100	–	1.12	0.05
		4	145	–	0.65	0.05		
			120	–	0.72	0.05		
			100	–	0.84	0.06		
		8	145	–	0.48	0.04		
			120	–	0.51	0.04		
			100	–	0.45	0.04		

3.4 IRSN NADs

The IRSN NADs were mounted alongside the LLNL NADs. Table 6 lists the neutron and photon dose for each position and location. Because the Si diodes are only sensitive to fast neutrons, further analysis of other NAD components is necessary to provide neutron dose in other energy regimes. The photon doses were measured using RPL (radio-photoluminescence) dosimeters, specifically RPL GD 351 dosimeters. Similar photon doses for the free-in-air stand irradiations are consistent with the same target doses.

Table 6: IRSN neutron and photon dose measured using Si diodes for fast neutrons and RPL for photons.

IRSN coding	irradiation	position	mount	distance (m)	height (cm)	Si-1 diodes $D_p(10)$ (Gy)	Si-2 diodes $D_p(10)$ (Gy)	RPL GD 351 $D_p(10)$ (Gy)
1	1	1	Stand	2	120	2.29	2.34	4.07
2	1	2	Stand	2	120	2.31	2.45	4.23
3	1	3	Stand	2	120	2.33	2.22	4.23
4	2	7	BOMAB front	4	120	0.67	0.77	2.13
5	2	2	BOMAB front	2	120	2.26	2.33	4.32
6	2	2	BOMAB back	2+BOMAB thickness	120	0.25	0.28	1.61
7	2	2	BOMAB front	2	145	2.20	2.39	4.27
8	2	2	BOMAB front	2	100	2.20	2.32	4.45
9	2	6	BOMAB front	3	120	1.07	1.21	2.56
10	3	4	Stand	3	120	2.22	2.32	4.24
11	3	5	Stand	3	120	2.19	2.36	4.16
12	3	6	Stand	3	120	2.34	2.25	4.23
13	4	1	BOMAB front	2	120	2.19	2.39	4.48
14	4	5	BOMAB front	3	120	1.07	1.24	2.52
15	4	5	BOMAB front	3	100	1.05	1.20	2.46
16	4	5	BOMAB front	3	145	1.04	1.26	2.58
17	4	5	BOMAB back	3+BOMAB thickness	120	0.15	0.16	1.26
18	4	9	BOMAB front	4	120	0.60	0.84	1.63
19	5	4	BOMAB front	3	120	1.68	2.36	4.47
20	5	8	BOMAB front	4	120	0.60	0.79	1.65
21	5	8	BOMAB back	4+BOMAB thickness	120	0.11	0.15	0.89
22	5	8	BOMAB front	4	145	0.61	0.58	1.64
23	5	8	BOMAB front	4	100	0.61	0.79	1.60
24	5	3	BOMAB front	2	120	1.04	1.24	2.47
25	6	4	Stand	4	120	2.13	2.17	4.04
26	6	5	Stand	4	120	2.25	2.22	4.10
27	6	6	Stand	4	120	2.13	2.25	4.13
28	7	2	Plastinaut front	2	123	2.41	2.54	4.40
29	7	2	Plastinaut back	2	123	0.26	0.32	2.17
30	8	8	Stand	4	120	2.06	–	4.14
31	9	8	Stand	4	120	2.21	–	4.03

3.5 SNL CaF₂ TLDs

The SNL dosimeters were mounted alongside the LLNL and IRSN NADs. Table 7 and 8 lists the photon dose for each position and location.

Table 7: SNL photon dose measured using CaF₂ TLDs mounted on the free-in-air stands. TLDs were placed at 90 and 120 cm from the floor. Dose to soft tissue estimated 2 σ error was 5%.

distance (m)	position	dose at 120 cm (Gy)	dose at 90 cm (Gy)
2	1	3.86	3.71
2	2	3.92	3.86
2	3	3.96	3.88
3	4	3.91	3.78
3	5	4.14	4.05
3	6	4.28	4.11
4	7	4.26	4.06
4	8	3.98	4.15
4	9	4.06	4.24

Table 8: SNL photon dose measured using CaF₂ TLDs mounted on BOMABs. TLDs were placed at different positions on the BOMABs. Dose to soft tissue estimated 2 σ error was 5%.

distance (m)	position	Front dose at 120 cm (Gy)	Front dose at 90 cm (Gy)	Back dose at 120 cm (Gy)	Right dose at 120 cm (Gy)
2	1	4.22	4.35	2.19	3.68
2	2	4.39	4.43	2.22	3.69
2	3	4.55	4.37	2.14	3.63
3	4	2.50	2.54	1.26	2.13
3	5	2.49	2.41	1.26	2.07
3	6	2.36	2.54	1.28	2.09
4	7	1.67	1.59	0.96	1.39
4	8	1.71	1.78	0.83	1.44
4	9	1.70	1.78	0.99	1.39

3.6 NDC dose measurements

In addition to LLNL, IRSN, and SNL dosimeter irradiation, NDC deployed a couple of dosimeters. Monday was the first irradiation where the NDC dosimeter was placed in front of a BOMAB at 2 meters. Gamma dose was 3.60 Gy and neutron dose was 2.42 Gy. A second set of NDC dosimeters were irradiated on Wednesday during an Al stand irradiation. Gamma dose was 3.29 Gy and neutron dose was 1.89 Gy. The Al stand irradiation were targeted for an equivalent dose to a BOMAB at 2 meters. The difference in doses needs to be further analyzed and may be correlated to reactor operating conditions.

4 Conclusion

The dose characterization measurements were successfully executed. Ion chamber data collected will normalize the dose, so that future exercises will be related to the ion chamber reading. The LLNL PNS sphere data is being analyzed to calculate the neutron fluence at various distances and calculate the neutron dose. The dosimeters from IRSN and SNL is being analyzed at their respective facilities. These results and will be shared in the CED4a report.

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A Pictorial Compendium

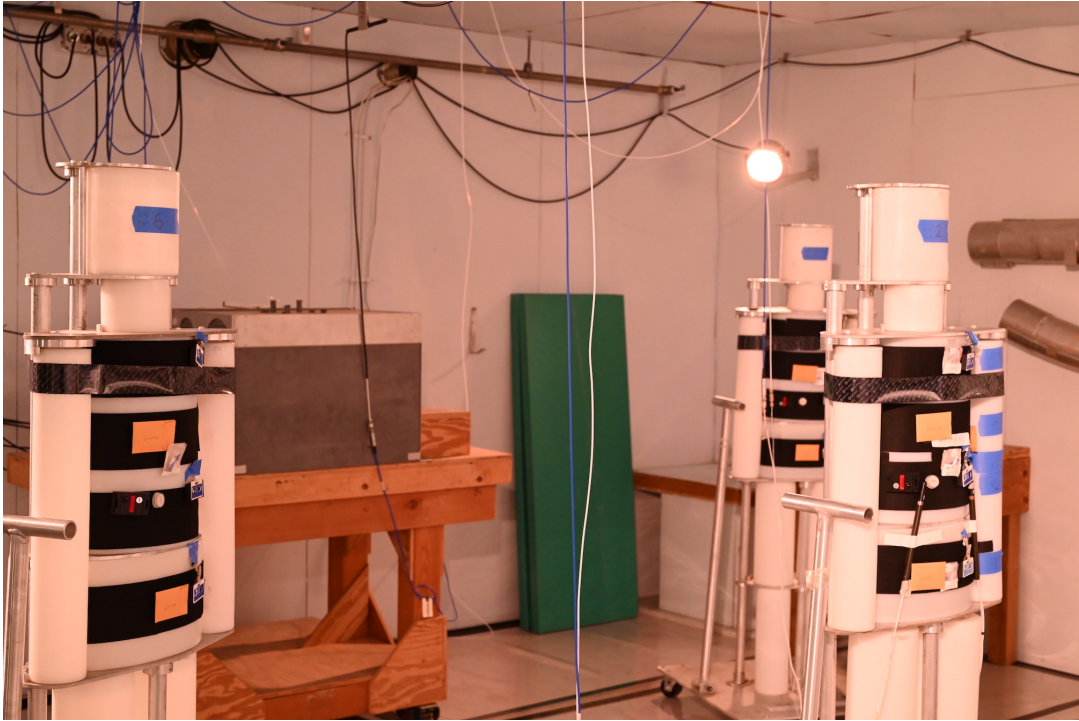


Figure A.1: BOMABs placed at position 2, 6, and 7 in ER1.

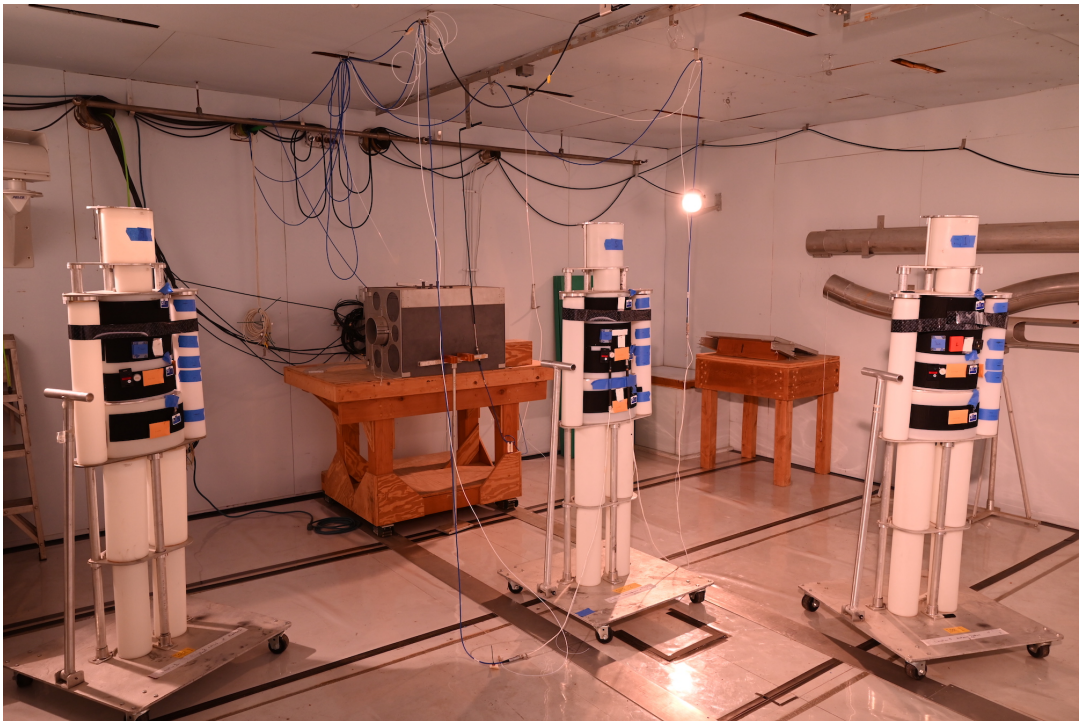


Figure A.2: BOMABs placed at position 1, 5, and 9 in ER1.



Figure A.3: BOMABs placed at position 3, 4, and 8 in ER1.

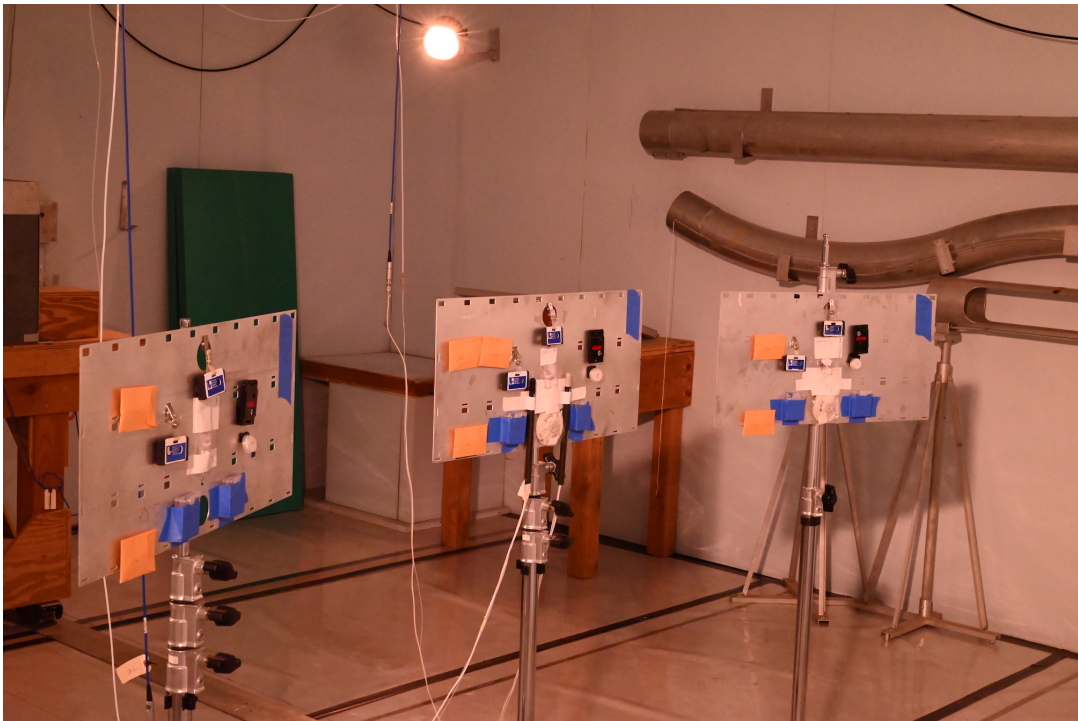


Figure A.4: Aluminum plates placed at 2 meters from core in ER1.

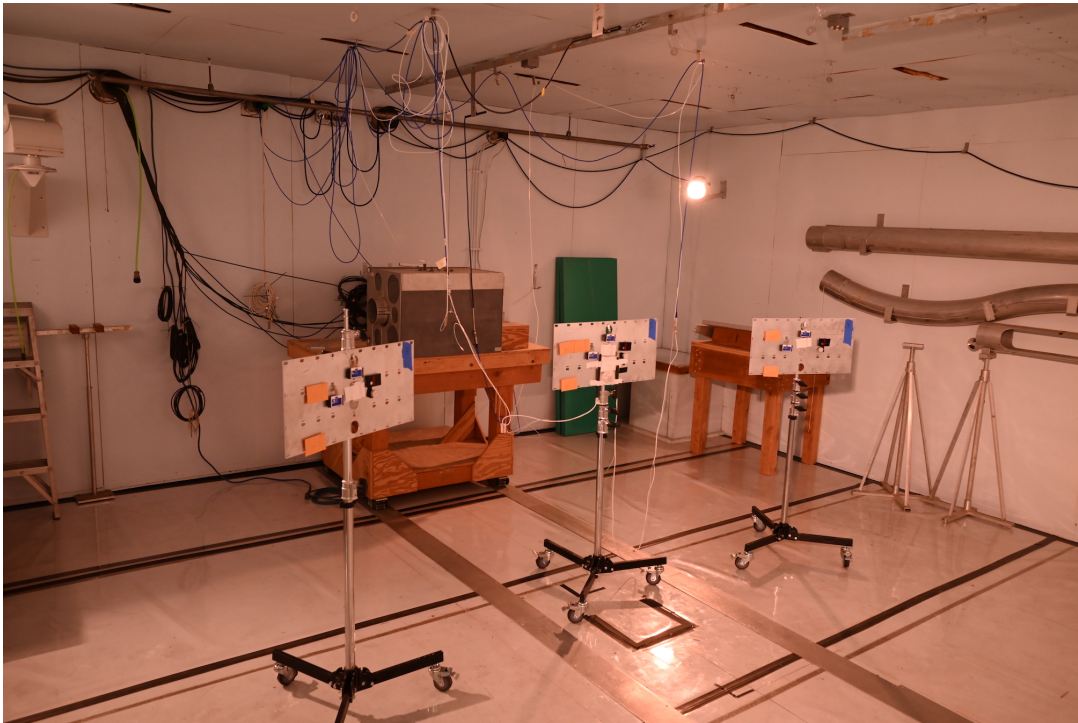


Figure A.5: Aluminum plates placed at 3 meters from core in ER1.

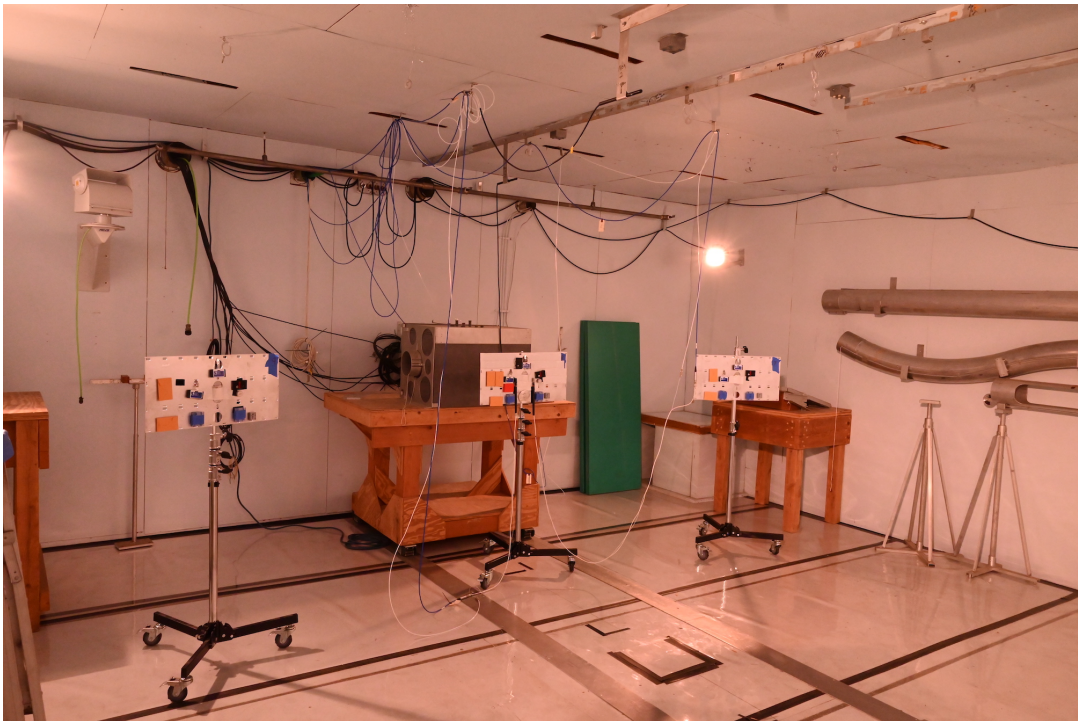


Figure A.6: Aluminum plates placed at 4 meters from core in ER1.

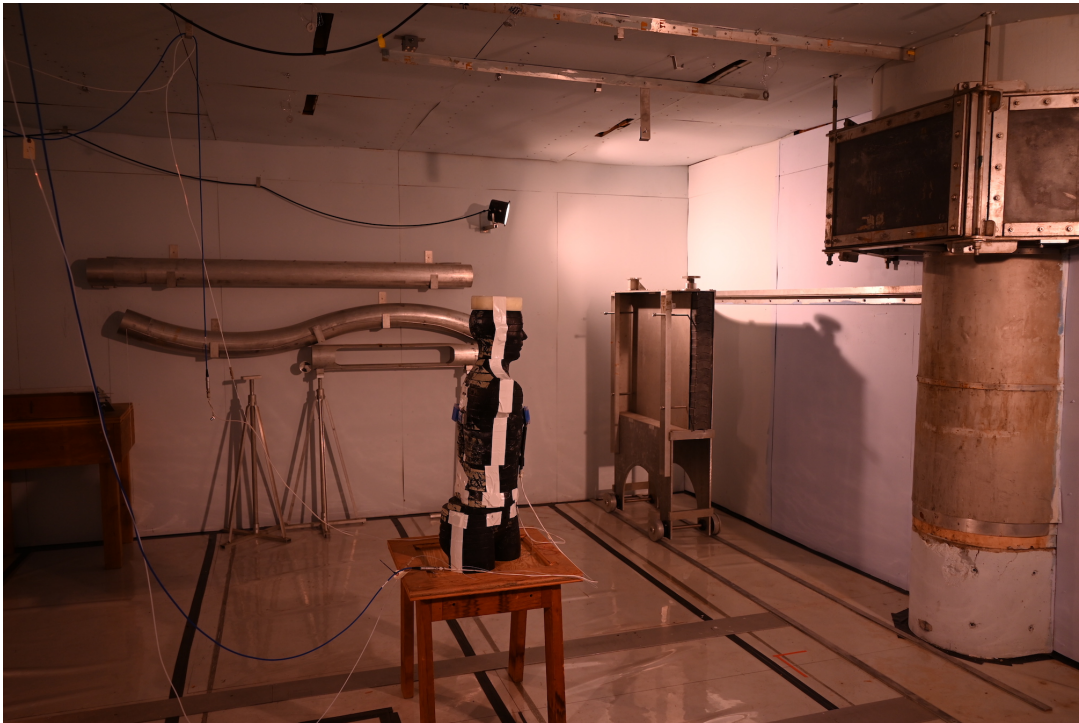


Figure A.7: AFRRI phantom in ER1.