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Evaluation of LLNL's Personnel Nuclear Accident Dosimeter at the Silene Reactor, October 2009

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Introduction

The Lawrence Livermore National Laboratory uses neutron activation elements ina Panasonic TLD holder (Figure 1) as a personnel nuclear accident dosimeter (PNAD). The LLNL PNAD has periodically been tested using a Cf-252 neutron source, however it has been more than 25 years since the PNAD has been tested against a source of neutrons that arise from a reactor generatedneutron spectrum that simulates a criticality. In October 2009, LLNL participated in an intercomparison of nuclear accident dosimeters with several other Department of Energy facilities. The reactor generated neutron

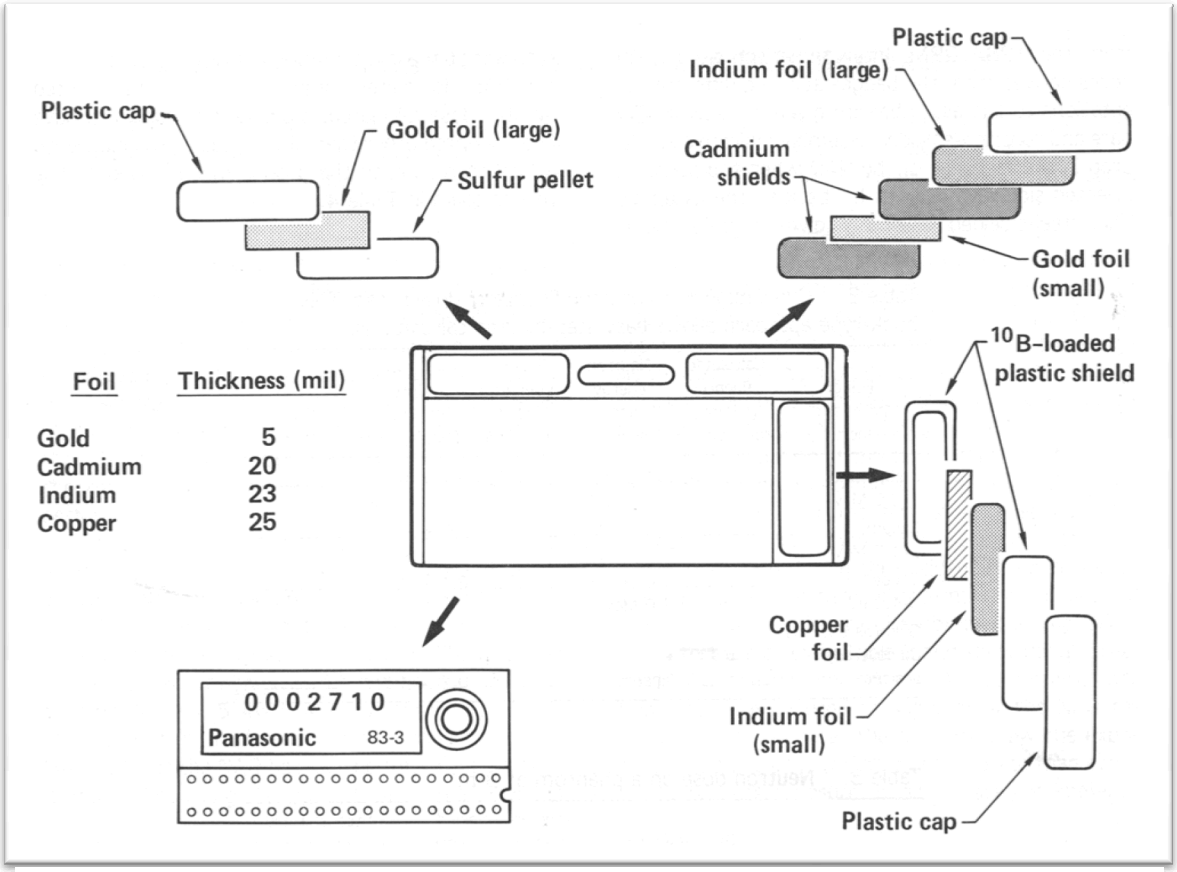

Figure 1. Lawrence Livermore National Laboratory Personnel Nuclear Accident Dosimeter design.

irradiations were performed at the *CEA* Valduc *Silene* reactor (Tournier, 1995).

The current PNAD design at LLNL was developed in the early 1980's and evaluated in 1984 using neutron leakage spectra generated by the Health Physics Research Reactor at Oak Ridge National Laboratory (Hankins 1984). Fluence and dose conversion factors developed in 1984 have been adjusted to account for changes in measurement methods; however these factors continue to be the fundamental basis for determining dose using the current PNAD system (Graham 2004).

Methods

Three pulse irradiations were performed at the Silene reactor during the week of October 12, 2009. The first pulse was performed on October 13, 2009 with the reactor core shielded by 10 cm of lead. The remaining two pulses occurred on October 14 and October 15 with no shielding (i.e., bare) around the reactor core. Dosimeters were place on water phantoms 60 cm tall, 20 cm by 30 cm truncated elliptical phantoms filled with water. Phantoms stood on aluminum stands 80.5 cm above the floor. After irradiation, the dosimeters were held by Silene personnel (typically 3 – 4 hours) to ensure that doses would be minimal to participants handling the dosimeters and foils.

In the first irradiation, three PNADs each were placed on phantoms facing the core of the reactor at 2, 4, and 6 meters from the core. The 2 meter phantom was placed at the 45° mark of a 360° radial grid around the core as marked on the floor of the reactor facility (Medoni, 2004). The dosimeters at 2 meters (#1, #2, and #3) were positioned on the surface of the phantom 98 cm above the floor. The PNADs were positioned on the left, center, and right side (respectively) of the phantom. A plumb-bob was used to assure that the dosimeters were positioned exactly at the 2 meter mark. The phantom for the 4 meter exposure was positioned at approximately the 70° radial. The PNADs (#4, #5, #6) for the 4 meter radius exposure were placed on the left, center, and right (respectively) of the phantom 119.5 cm from the floor. The phantom position 6 meters from the core was positioned at approximately the 100° radial. The NADs for the 6 meter exposure were positioned on the left, center, and right side of the phantom at 102 cm from the floor. After the first irradiation and retrieval, access to the area was restricted to Silene personnel. Silene personnel positioned dosimeters for the remaining 2 irradiations at the distances and orientations specified by LLNL personnel.

Three NADs (#11, #12, and #13) for the second irradiation were positioned on the phantom facing the reactor at 2 meters from the core. Three additional NADs (#14, #15, #16) were hung from an aluminum rod to simulate a 'free-air' exposure at 2 meters from the core. Three old pennies (total mass of 9.341 g), three new pennies (total mass of 7.47 g), and three quarters (total mass of 17.141 g) were also irradiated at 2 meters from the core.

All NADS for the third irradiation were positioned six meters from the core on phantoms. The first set of dosimeters (#18, #19, and #20) was placed at the mid-plane on the front of the phantom. The next set of the dosimeters were placed at 6 meters on the backside of the phantom at the mid-plane position. The final set of dosimeters (#24, #25, and #26) was placed at the mid-plane of the phantom facing sideways to the core of the reactor. Pre-washed hair samples were also irradiated in the third irradiation. The hair samples were pre-weighed and placed in glassine envelopes. The hair samples were positioned 6 meters from the core at the front mid-plane of the phantom.

The metal foils in the NADs were measured using an electronically cooled high purity germanium (HPGe) detector. The calibration of the detector used average foil dimensions as given in Table 1, and the Canberra Industries ISOCS ® technology for the characterized germanium detector. Indium foils were typically counted for a period long enough to provide a minimum of 2000 counts in the 363 keV peak area. Copper foils were counted to obtain at least 500 counts in the 511 keV peak area or for fifteen minutes. If count rates low and counting times were limited, the count may have been terminated

before 500 counts were obtained in the 511 keV peak region. The set of copper foils used in the first irradiation (#1, #2, and #3) were counted with and without a non-irradiated thin copper sheet wrapped around each foil. The gold foils were counted to obtain at least 2000 counts in the 411 keV peak. Both small and large gold foils were counted.

Table 1. Average dimensions of NAD foils used for the Silene test.

Type of Foil	Avg. Weight (g)	Length (mm)	Width (mm)	Thickness (mm)
Small Indium	0.363	19.13	4.66	0.62
Large Indium	0.521	20.78	5.96	0.61
Copper	0.346	16.34	3.75	0.65
Small Gold	0.222	17.94	4.57	0.15
Large Gold	0.292	20.67	6.05	0.15

The irradiated sulfur pellets were crushed, placed into a stainless steel planchet, covered with 0.25 mil mylar and analyzed using a Ludlum Model 3030E scalar and Ludlum 43-10-1 alpha/beta probe. The average weight of the sulfur pellets was 0.855 grams. The Ludlum detector was calibrated with a 47 mm plated Sr/Y-90 source. A lead cave was made available by Valduc personnel and the detectors were placed inside the cave so that the detectors could be used in a lower background situation. Daily calibration checks were performed using a Coleman mantle containing natural beta emitting radionuclides. Sulfur pellets from two dosimeters exposed in the second irradiation (#7 & #8) were counted whole (prior to crushing) and then recounted after crushing.

Prior to gamma counting the first set of NADs, a GM measurement of the internal Panasonic 807 dosimeters was performed. It was found that these dosimeters were activated. Measurements of each set of dosimeters from the first, second, and third irradiations were performed using the gamma spectroscopy system.

Results

The average neutron dose for the irradiations where the NADs were oriented facing the core of the reactor as compared to the dose values provided for the Silene reactor are provided in Table 2. Detailed dose and neutron fluence determinations are provided in Appendix A.

Table 2 Results for NADs facing the simulated criticality event.

Irradiation	Distance (m)	Given Neutron Dose (rad)	Average Measured Neutron Dose (rad)	Percent Difference
1	2	690	791	+14
1	4	190	232	+18
1	6	110	109	-1
2	2	320	377	+18
2	2	320	344[1]	+8
3	6	150	159	+6

NR: Not Reported

The boron shielded indium foil in the LLNL dosimeter is exclusively used for measurement of dose from neutron energies above 1 MeV. The In-115m is measured to determine the fluence from neutrons with energies greater than 1 MeV. Figure 2 demonstrates that the In-115m was easily measured (336 keV peak) in the presence of In-116m (416 keV plus other peaks not shown) from thermal neutron irradiation at a time close to the irradiation (3.5 hours) when the dosimeter could be safely handled.

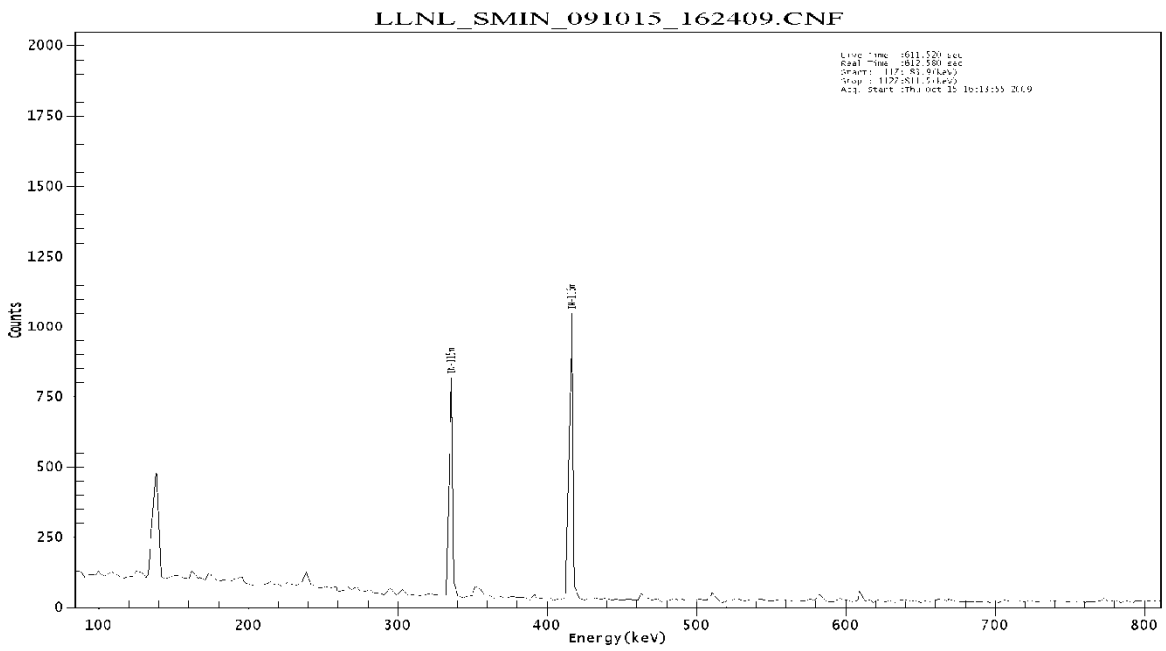

Figure 2. Gamma spectrum of the LLNL Indium foil approximately 3.5 hours after the Irradiation Pulse #3.

[1] Free air irradiation (no phantom)

Previous evaluations of sulfur count methods had been performed at LLNL in 2003 (Graham, 2004). These previous evaluations demonstrated significant differences in the counting efficiency when the irradiated pellet is counted whole versus as a crushed powder. When the LLNL NAD was developed, fluence conversion factors were derived based on counting of the whole sulfur pellet. After the studies counting the crushed versus whole pellet, the fluence conversion factors were updated to account for counting of crushed pellets. LLNL performed a limited experiment using the irradiations at Silene to test the current validity of the crushed versus whole pellet count ratios. Results of sulfur pellets from two dosimeters exposed in the second irradiation (#7 & #8) that were counted whole (prior to crushing) and then recounted after crushing are provided in Table 3.

Table 3. Comparison of beta counts for whole versus crushed sulfur pellets.

	Net DPM (efficiency adjusted)		
Sulfur Pellet ID	**Whole Pellet**	**Crushed Pellet**	**Ratio[2] (crushed/whole)**
7	156.9 ± 8.5	466.8 ± 14.0	2.98 ± 0.18
7 (repeat count)	149.4 ± 8.4	466.8 ± 14.0	3.12 ± 0.20
8	214.7 ± 9.3	539 ± 13.2	2.51 ± 0.12

Corrections for the orientation of the LLNL NAD relative to the source of neutrons were established in 1984 when the LLNL was tested at the Health Physics Research Reactor (HPRR) at Oak Ridge National Laboratory (Hankins, 1984). The orientation can have profound effects on the accuracy of the nuclear accident dosimeters. LLNL retested the effects of orientation at the Silene test with a limited number of dosimeters. However placement of the dosimeters on phantoms at Silene was performed by Silene personnel in order to prevent inadvertent exposure of LLNL personnel. Therefore the exact orientation of the dosimeter at Silene is somewhat unknown. The comparative results of the Silene tests and HPRR tests are provided in Table 4.

Table 4. Neutron Accident Dosimeter orientation corrections relative to a forward facing dosimeter (i.e, front of phantom).

Phantom Orientation	Silene Ratio Neutron Dose Ratio	HPRR Neutron Dose Ratio
Front	1.0	1.0
Side	0.93	0.45
Back	0.27	0.10

[2] In 1991 this ratio was determined to be 4.9. In 2002 this ratio was established to be approx. 3.8. Results for the intercomparison at Silene were determined using the original 4.9 ratio correction.

Gamma doses were measured using a specially configured Panasonic 810AS2 dosimeter. The gamma dose is specifically determined from a 7Li component within the dosimeter. The comparison of average gamma dose to the known gamma dose is presented in Table 5.

Table 5 Results of Gamma Measurement using LLNL NADs facing the simulated criticality event.

Irradiation	Distance (m)	Known Gamma Dose (rad)	Average Measured Gamma Dose (rad)	Percent Difference
1	2	50	221	+342
1	4	30	46	+53
1	6	20	28	+40
2	2	380	517	+36
2	2	380	432[3]	+14
3	6	210	172	-18

When the LLNL NAD was tested at the ORNL HPRR ratios of the neutron dose contribution for the monitored energy ranges were derived for the various shielding configurations of the reactor. These ratios are useful in establishing possible shielding and shielding effects to the dosimetry of criticality events. Comparisons of measured ratios at Silene with the HPRR were consistent for similar shielding constructs. These results are provided in Tables 6 & 7.

[3] Free air irradiation (no phantom)

Table 6. Fraction of total neutron dose contribution for pulse #1 (front of phantom measurements)[4].

	Comparative Dose Contributions:			
Energy Range	**Valduc-Silene Fraction of Dose: 10 cm LEAD Shielded Assembly[5]**	**ORNL HPRR Fraction of Dose: Bare Assembly**	**ORNL HPRR Fraction of Dose: 20 cm CONCRETE Shielded Assembly**	**ORNL HPRR Fraction of Dose: 13 cm STEEL Shielded Assembly**
>3 MeV	0.1	0.2	0.1	0.1
1 – 3 MeV	0.5	0.5	0.4	0.4
1 eV – 1 MeV	0.5	0.3	0.5	0.5
Thermal	0.01	0.01	0.03	0.01

Table 7. Fraction of total neutron dose contribution for pulses #2 & #3 (front of phantom measurements)[4].

	Comparative Dose Contributions:			
Energy Range	**Valduc-Silene Fraction of Dose: Bare Assembly[6]**	**ORNL-HPRR Fraction of Dose: Bare Assembly**	**ORNL-HPRR Fraction of Dose: 20 cm CONCRETE Shielded Assembly**	**ORNL-HPRR Fraction of Dose: 13 cm STEEL Shielded Assembly**
>3 MeV	0.3	0.2	0.1	0.1
1 – 3 MeV	0.5	0.5	0.4	0.4
1 eV – 1 MeV	0.3	0.3	0.5	0.5
Thermal	0.01	0.01	0.03	0.01

Previous intercomparisons at the Silene reactor have published gamma and neutron dose contributions for the various pulse configurations. The published contributions were used to establish estimated ratios for the exposure scenarios used in this exercise. The neutron to gamma ratios from these published values as well as the known ratio of values provided by the Silene facility at the time of the current study (CEA/VA/DRMN/SRNC DO 1076-78) are compared with neutron to gamma ratios measured with the LLNL Nuclear Accident Dosimeter in Table 7.

[4] ORNL-HPRR data based on 1984 irradiations at the ORNL-Health Physics Research Reactor
[5] Based on average of three measures of the lead shielded assembly. Rounding errors apply.
[6] Based on average of six measures of the bare assembly. Rounding errors apply.

Table 8. Average neutron to gamma dose ratios (front of phantom measurements only).

	Distance from Core (m)	Estimated Silene Neutron/ Gamma Ratio	Known Neutron/Gamma Ratio for this Test	LLNL NAD Measured Neutron/ Gamma Ratio
Pulse 1	2	12	14	4
	4	5.7	6.3	5
	6	3.2	5.5	3.9
Pulse 2	2	1.3	0.8	1.4
	2	1.3	0.8	1.3
Pulse 3	6	1.3	0.7	1.1

Discussion

The LLNL nuclear accident dosimeter (NAD) system was tested with irradiations at the Silene reactor during the week of October 12, 2009. Comparison to reported known neutron doses demonstrates that the LLNL NAD system is within 20% of the known dose. The last test of the LLNL NAD system with a reactor spectrum was performed in 1984. Other tests of the LLNL NAD system were performed between 1984 and 2004 with lower levels of dose using a high level Cf-252 neutron source. These previous tests also demonstrate the validity and accuracy of the LLNL NAD system.

The current exercise provided an opportunity to make measurements on well irradiated foil samples. One improvement that would improve the processing rate of the foils would be to change the procedurally required minimal number of counts in routine procedures. For instance, Cu may be performed with fewer counts in the peak than the currently required 2000 counts. Likewise, copper sheets around the foil used to capture positron emissions and convert to 511 keV photons may not be critical and may in fact cause dose values to be artificially high. Since we do not know how the measurements of copper were performed in 1984 when the first system calibrations were first established, the use of Cu capture foils may not be appropriate since the calibration appears to be more consistent with not using the foils.

The measurement of sulfur in the NAD badge is important for the determination of >3 MeV and 1 – 3 MeV dose fractions. In 1991 LLNL changed measurement methods from measuring the whole pellets to measuring crushed pellets. For this study a ratio of 4.9 was applied to the 1984 conversion factor for sulfur to account for the change in measurement methods. Later (approximately 2004), a new study implied that the 1991 ratio of 4.9 was 30% too high, however this study was informal and not well documented. Sulfur results from the Silene irradiation used the original 1984 sulfur conversion factor divided by the 4.9 ratio (i.e., 5.19×10^{12} vs 2.9×10^{13} n/cm2/μCi/g). Further study of the effects of crushing and not crushing need to be performed as do alternative methods of processing the sulfur to get improved counting results (e.g., heating and subliming the sulfur from the plate leaving only P-32 on the plate).

The effects of orientation also need more careful consideration and evaluation. Verbal discussions with Dale Hankins, developer of the LLNL NAD system, indicate that slight changes in orientation on the curvature of water phantom can generate significant changes in the orientation ratio. Likewise, it is unknown is there is a left/right orientation difference. Speculative analysis indicates that left/right orientation may have the greatest effect on the activation of the indium foil. Monte Carlo studies may assist in evaluating these effects, however eventually a measurement using a significant exposure dose is necessary to assure adequate activity so as to reduce analytical errors associated with low count rates and derive meaningful values and limitations associated with dosimeter orientation.

Although the known doses were not provided for Pulses 2 & 3, the measured neutron to gamma ratios indicates that the relative responses of the LLNL NADs are consistent with previous evaluations of the Silene radiation field.

Gamma doses were evaluated using a specially configured Panasonic 810AS2 dosimeter. The gamma dose is measured a ^{7}Li component within the dosimeter. One element, the $CaCO_3$ element, in the Panasonic 810 is surrounded by a holding ring containing copper, as evidenced by the activation observed after neutron irradiation. The degree of influence on the gamma dose determination from this activation is uncertain. Likewise, the delay in disassembly of the nuclear accident dosimeter and removal of foils may have added to the gamma dose of the dosimeter. Additional review of these effects is needed.

LLNL has also published methods for evaluating dose using biological samples. These methods were not tested at the Silene exercise. LLNL's bioassay methods (e.g., hair, blood/body fluids, etc.) need to be re-evaluated and confirmed in future exercises.

LLNL's nuclear accident dosimeter (NAD) provides reasonable results consistent with requirements of past standards for the determination of accidental neutron exposure at life threatening doses. Gamma doses using the Panasonic dosimeter within the NAD were less accurate than desired, however since the gamma dose is usually much lower than the neutron dose in an accidental and the dosimeter over estimates the gamma dose, LLNL is assured of a conservative estimate of the total dose. Additional evaluation and study is necessary to determine the cause of gamma dose over estimates.

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Appendix A

Silene Pulse (Pulse #1 13-Oct-09 09:53 GMT)

Configuration: 10 cm of lead shielding surrounding core
Positioning: @2meters radius on the 45 degee mark - 98 cm high - center of water phantom

NAD ID	Neutron Fluence (n cm^{-2})				Neutron Dose (rad)				Total Neutron	Gamma Dose	Total Dose
#	> 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	> 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Dose (rad)	(rad)	(rad)
1	1.3E+10	1.1E+11	4.4E+11	9.7E+10	64	368	354	6.8	792	171	964
2	1.2E+10	1.1E+11	4.6E+11	1.2E+11	61	366	370	8.3	806	325	1131
3	1.2E+10	1.1E+11	4.4E+11	1.2E+11	61	349	356	8.1	775	165	940
Average:	**1.2E+10**	**1.1E+11**	**4.5E+11**	**1.1E+11**	**62**	**361**	**360**	**7.7**	**791**	**221**	**1011**

Positioning: @4m radius at approximately 70 degrees -119.5cm high on the left side of the water phantom

NAD ID	Neutron Fluence (n cm^{-2})				Neutron Dose (rad)				Total Neutron	Gamma Dose	Total Dose
#	> 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	> 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Dose (rad)	(rad)	(rad)
4	3.2E+09	2.9E+10	1.4E+11	4.5E+10	16	95	113	3.1	227	25	252
5	3.3E+09	2.8E+10	1.6E+11	4.7E+10	16	94	130	3.3	245	59	304
6	3.2E+09	2.8E+10	1.4E+11	3.9E+10	16	94	111	2.7	224	55	279
Average:	**3.2E+09**	**2.8E+10**	**1.5E+11**	**4.4E+10**	**16**	**94**	**118**	**3.1**	**232**	**46**	**278**

Positioning: @6m radius at approx. 100 degrees -102cm high, on the left side of the water phantom

NAD ID	Neutron Fluence (n cm^{-2})				Neutron Dose (rad)				Total Neutron	Gamma Dose	Total Dose
#	> 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	> 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Dose (rad)	(rad)	(rad)
7	1.5E+09	1.3E+10	6.3E+10	2.5E+10	8	45	50	1.7	104	8	112
8	1.7E+09	1.5E+10	6.3E+10	3.2E+10	9	50	51	2.2	112	41	152
9	1.6E+09	1.3E+10	7.1E+10	2.1E+10	8	44	57	1.5	111	36	146
Average:	**1.6E+09**	**1.4E+10**	**6.6E+10**	**2.6E+10**	**8**	**46**	**53**	**1.8**	**109**	**28**	**137**

Silene Pulse (Pulse #2 14-Oct-09 10:06 GMT)

Configuration: bare core of reactor
Positioning: @2meters on water phantom (placed by Silene personnel)

NAD ID #	Neutron Fluence (n cm^{-2}) > 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Neutron Dose (rad) > 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Total Neutron Dose (rad)	Gamma Dose (rad)	Total Dose (rad)
11	1.1E+10	6.0E+10	1.8E+11	3.3E+10	52	200	141	2.3	396	463	859
12	1.0E+10	6.2E+10	1.3E+11	5.6E+10	50	208	103	3.9	365	536	901
13	1.1E+10	5.7E+10	1.5E+11	5.5E+10	55	190	123	3.9	371	559	924
Average:	**1.1E+10**	**5.9E+10**	**1.5E+11**	**4.8E+10**	**52**	**200**	**122**	**3.4**	**377**	**517**	**895**

Positioning: @2meters in free air (placed by Silene personnel)

NAD ID #	Neutron Fluence (n cm^{-2}) > 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Neutron Dose (rad) > 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Total Neutron Dose (rad)	Gamma Dose (rad)	Total Dose (rad)
14	1.0E+10	5.9E+10	1.0E+11	2.0E+10	48	198	83	1.4	331	444	775
15	9.6E+09	6.0E+10	1.4E+11	2.0E+10	46	201	113	1.4	362	429	790
16	1.1E+10	5.9E+10	1.1E+11	2.1E+10	54	197	87	1.5	340	423	763
Average:	**1.0E+10**	**5.9E+10**	**1.2E+11**	**2.0E+10**	**49**	**199**	**95**	**1.4**	**344**	**432**	**776**

Silene Pulse (Pulse #3 15-Oct-09 09:56 GMT)

Configuration: bare core of reactor
Positioning: @6 meters on water phantom facing the core, midplane on the phantom

NAD ID #	Neutron Fluence (n cm^{-2}) > 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Neutron Dose (rad) > 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Total Neutron Dose (rad)	Gamma Dose (rad)	Total Dose (rad)
18	3.4E+09	2.2E+10	9.8E+10	2.8E+10	17	74	78	2.0	171	173	344
19	3.8E+09	2.2E+10	7.6E+10	3.6E+10	19	74	61	2.5	155	173	329
20	3.7E+09	2.7E+10	5.2E+10	3.7E+10	18	89	42	2.6	151	168	320
Average:	**3.6E+09**	**2.4E+10**	**7.5E+10**	**3.4E+10**	**18**	**79**	**60**	**2.3**	**159**	**172**	**331**

Positioning: @6 meters at the midplane on back side of water phantom

NAD ID #	Neutron Fluence (n cm^{-2}) > 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Neutron Dose (rad) > 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Total Neutron Dose (rad)	Gamma Dose (rad)	Total Dose (rad)
21	6.9E+08	2.4E+09	2.8E+10	1.8E+10	3	8	23	1.3	35	55	91
22	4.6E+08	3.1E+09	5.3E+10	1.6E+10	2	10	42	1.1	56	64	120
23	5.9E+08	4.5E+09	2.2E+10	1.6E+10	3	15	17	1.1	37	75	112
Average:	**5.8E+08**	**3.3E+09**	**3.4E+10**	**1.7E+10**	**3**	**11**	**28**	**1.2**	**43**	**65**	**108**

Positioning: @6 meters at the midplane on front of sideways facing water phantom

NAD ID #	Neutron Fluence (n cm^{-2}) > 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Neutron Dose (rad) > 3 MeV	1 - 3 MeV	1 eV - 1 MeV	Thermal	Total Neutron Dose (rad)	Gamma Dose (rad)	Total Dose (rad)
24	3.8E+09	2.4E+10	7.1E+10	2.4E+10	19	81	57	1.7	159	147	305
25	2.4E+09	1.8E+10	8.1E+10	1.7E+10	12	61	65	1.2	139	131	270
26	3.1E+09	2.1E+10	7.2E+10	2.4E+10	15	69	57	1.6	144	122	266
Average:	**3.1E+09**	**2.1E+10**	**7.5E+10**	**2.2E+10**	**15**	**70**	**60**	**1.5**	**147**	**133**	**280**

Dimensions of LLNL NAD Foils.

	Small Indium			Large Indium			Small Gold			Large Gold			Copper		
	L	W	T	L	W	T	L	W	T	L	W	T	L	W	T
1	19.39	4.63	0.59	20.84	6.11	0.58	19.07	4.67	0.19	20.74	6.02	0.15	16.35	3.78	0.64
2	19.36	4.79	0.59	20.81	6.66	0.59	15.99	4.61	0.12	20.68	5.97	0.16	16.3	3.93	0.65
3	19.44	4.68	0.57	20.85	6.14	0.61	19.13	4.62	0.17	20.72	6.02	0.13	16.38	3.91	0.64
4	19.47	4.75	0.62	20.84	6.19	0.58	19.02	4.62	0.19	20.63	6.03	0.19	16.35	3.66	0.67
5	19.23	4.77	0.58	20.66	6	0.6	16.64	5.05	0.19	20.69	6.01	0.14	16.29	3.73	0.66
6	18.48	4.12	0.6	20.87	5.94	0.55	16.01	3.68	0.16	20.31	6.16	0.12	16.37	3.89	0.66
7	19.33	4.74	0.6	20.8	6.03	0.7	19.06	4.62	0.12	20.83	6.26	0.13	16.28	3.74	0.66
8	19.14	4.72	0.57	20.9	3.11	0.57	19.36	4.43	0.13	20.79	6.06	0.15	16.53	3.77	0.66
9	19.58	4.42	0.52	20.79	6.03	0.56	17.46	4.2	0.12	20.79	6.05	0.12	16.49	3.7	0.62
10	18.75	4.68	0.63	20.95	6.02	0.59	19.16	4.75	0.19	20.81	6.06	0.18	16.33	3.72	0.67
11	19.44	4.63	0.6	20.84	6.04	0.64	19.09	5.08	0.14	20.62	6.02	0.12	16.29	3.74	0.63
12	19.14	4.98	0.59	20.91	6.05	0.59	18.62	4.09	0.18	20.73	6.01	0.13	16.3	3.71	0.67
13	17.26	4.54	0.59	21.02	6.13	0.62	19.16	4.75	0.13	20.7	6.05	0.17	16.37	3.59	0.66
14	19.42	4.74	0.61	20.88	6.09	0.58	17.79	4.62	0.16	20.88	5.99	0.15	16.31	3.68	0.67
15	19.22	4.71	0.59	20.88	6.03	0.61	15.38	3.85	0.13	19.29	6.13	0.17	16.2	3.72	0.67
16	19.17	4.6	0.56	20.92	6.14	0.6	15.24	5.38	0.15	20.6	6.03	0.15	16.27	3.77	0.67
17	19.26	4.66	0.69	20.87	5.74	0.63	16.72	3.33	0.14	20.82	6.01	0.13	16.25	3.74	0.65
18	18.41	4.65	0.58	20.88	6.02	0.6	19	4.68	0.14	20.56	6.05	0.12	16.25	3.74	0.66
19	19.36	4.72	0.57	20.47	6.05	0.57	19.04	4.69	0.13	20.77	6	0.13	16.34	3.78	0.65
20	19.28	4.68	0.62	20.97	6.08	0.59	18.26	4.21	0.18	20.56	6.03	0.15	16.26	3.77	0.65
21	19.14	4.68	0.59	20.81	6.06	0.56	19.09	4.82	0.17	20.78	5.95	0.11	16.26	3.68	0.63
22	19.22	4.63	0.71	21.05	6	0.66	19.25	4.53	0.17	20.9	6.1	0.15	16.86	3.71	0.67
23	18.17	4.65	0.79	20.9	6.09	0.7	19.1	4.69	0.15	20.82	6.02	0.16	16.22	3.8	0.64
24	19.1	4.66	0.61	20.53	6.08	0.6	19.07	4.59	0.1	20.7	6.07	0.14	16.31	3.75	0.59
25	19.23	4.68	0.68	20.81	6.08	0.61	18.96	4.86	0.18	20.59	6.06	0.16	16.2	3.81	0.6
26	19.35	4.67	0.65	20.91	6.05	0.61	15.98	5.06	0.13	20.95	6.08	0.14	16.34	3.83	0.67
27	19.41	4.65	0.63	20.72	6.02	0.6	14.3	5.15	0.16	20.84	6.03	0.16	16.3	3.64	0.67
28	19.16	4.6	0.61	19.17	5.79	0.59	15.49	3.82	0.17	20.44	6.12	0.14	16.37	3.88	0.65
29	19.57	4.64	0.72	20.84	5.99	0.6	19.15	5.07	0.14	20.97	6.14	0.17	16.31	3.62	0.61
30	19.28	4.63	0.61	20.79	6.1	0.67	18.71	4.69	0.14	20.65	6.01	0.15	16.46	3.68	0.61
Avg	19.13	4.66	0.62	20.78	5.96	0.61	17.94	4.57	0.15	20.67	6.05	0.15	16.34	3.75	0.65
1s	0.48	0.14	0.05	0.33	0.56	0.04	1.56	0.46	0.03	0.30	0.06	0.02	0.12	0.08	0.02

Mass (g) of NAD materials in each dosimeter.

ID	Sulfur	Small In	Large In	Small Au	Large Au	Cu
1	0.834	0.366	0.52	0.222	0.281	0.348
2	0.874	0.37	0.541	0.181	0.288	0.367
3	0.837	0.368	0.531	0.205	0.283	0.362
4	0.853	0.362	0.521	0.207	0.291	0.346
5	0.869	0.367	0.521	0.211	0.287	0.35
6	0.863	0.322	0.509	0.15	0.294	0.365
7	0.867	0.368	0.523	0.217	0.323	0.349
8	0.875	0.337	0.527	0.215	0.287	0.358
9	0.855	0.37	0.52	0.175	0.3	0.347
10	0.843	0.359	0.521	0.214	0.303	0.352
11	0.814	0.37	0.523	0.203	0.291	0.344
12	0.852	0.37	0.525	0.167	0.285	0.348
13	0.847	0.316	0.522	0.213	0.288	0.344
14	0.857	0.366	0.538	0.21	0.285	0.347
15	0.881	0.378	0.521	0.144	0.281	0.353
16	0.804	0.363	0.527	0.207	0.29	0.355
17	0.876	0.376	0.524	0.144	0.297	0.355
18	0.85	0.352	0.524	0.208	0.291	0.356
19	0.841	0.369	0.507	0.206	0.279	0.345
20	0.856	0.37	0.517	0.173	0.289	0.349
21	0.84	0.363	0.515	0.205	0.291	0.344
22	0.873	0.373	0.524	0.205	0.286	0.343
23	0.901	0.349	0.532	0.209	0.299	0.355
24	0.863	0.367	0.513	0.2	0.283	0.352
25	0.844	0.367	0.513	0.2	0.29	0.341
26	0.81	0.364	0.518	0.179	0.291	0.365
27	0.846	0.37	0.519	0.159	0.282	0.341
28	0.876	0.373	0.488	0.14	0.321	0.374
29	0.865	0.374	0.519	0.205	0.317	0.339
30	0.87	0.364	0.525	0.222	0.292	0.346
Avg	0.855	0.363	0.521	0.193	0.292	0.351

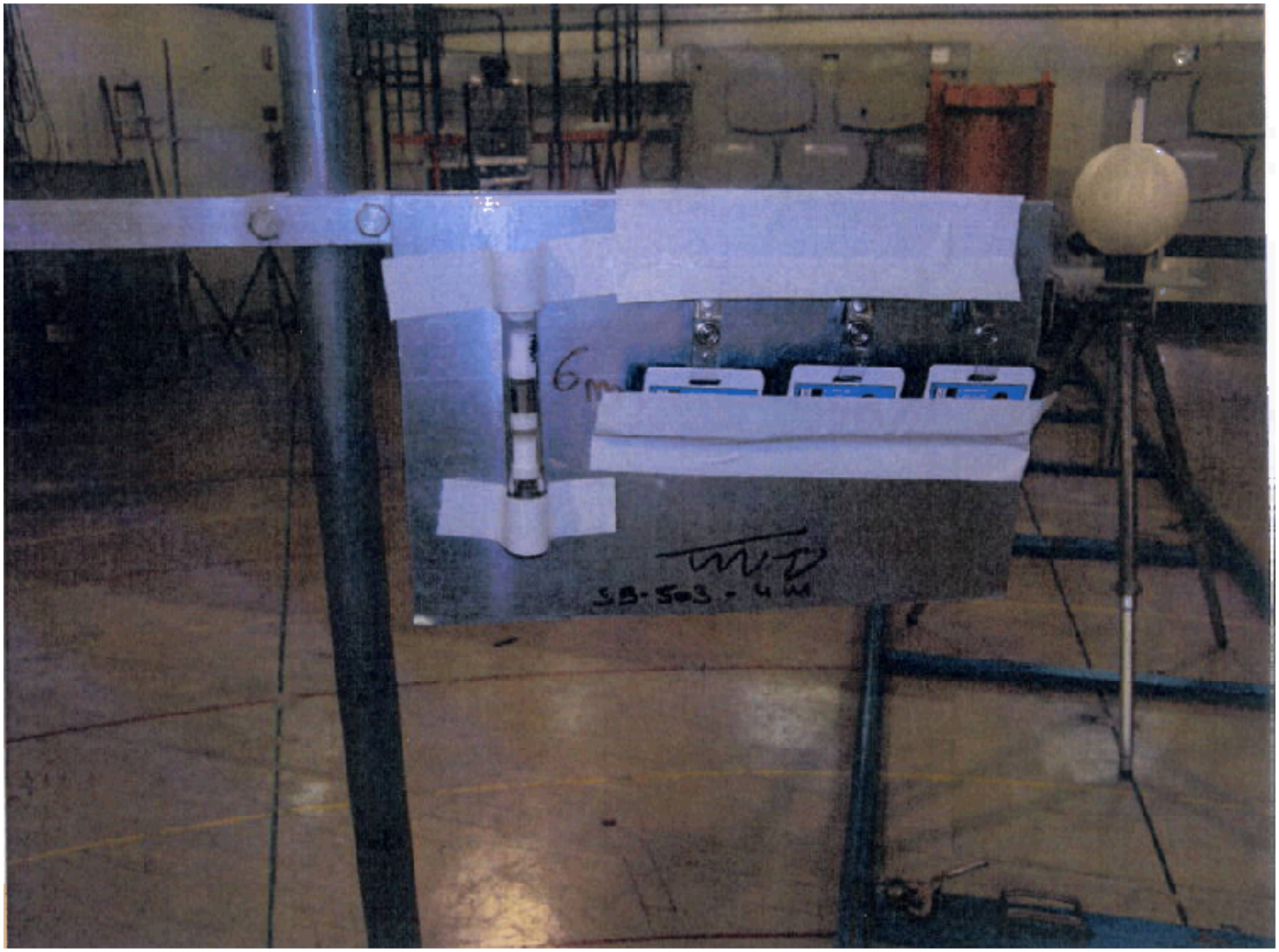
Measured LLNL Foil Activities for Silene Irradiations (μCi/g)[7]

ID	P-32 (Sulfur)	In-115m	Cu-64	Au-198	Au-198[8]
1	2.05E-3	1.82E-1	9.82E-2	4.97	1.73
2	1.98E-3	1.80E-1	9.24E-2	5.93	1.97
3	1.98E-3	1.73E-1	8.89E-2	5.67	1.83
4	5.18E-4	4.70E-3	2.82E-2	2.28	7.92E-1
5	5.30E-3	4.67E-3	3.26E-2	2.33	7.49E-1
6	5.26E-3	4.62E-3	2.78E-2	1.99	6.83E-1
7	2.45E-4	2.20E-2	1.25E-2	1.25	4.31E-1
8	2.80E-4	2.48E-2	1.27E-2	1.40	3.53E-1
9	2.53E-4	2.19E-2	1.43E-2	1.20	5.07E-1
11	1.66E-3	1.04E-1	3.54E-2	2.03	9.38E-1
12	1.60E-3	1.07E-1	2.58E-2	2.81	9.36E-1
13	1.76E-3	1.00E-1	3.06E-2	2.49	6.51E-1
14	1.55E-3	1.02E-1	2.08E-2	1.10	4.30E-1
15	1.47E-3	1.03E-1	2.83E-2	1.11	4.50E-1
16	1.75E-3	1.03E-1	2.18E-2	1.12	4.31E-1
18	5.51E-4	3.76E-2	1.95E-2	1.41	4.66E-1
19	6.08E-4	3.81E-2	1.51E-2	1.64	4.48E-1
20	5.92E-4	4.46E-2	1.04E-2	1.66	4.38E-1
21	1.11E-4	4.51E-3	5.66E-3	0.779	1.68E-1
22	7.45E-5	5.21E-3	1.06E-2	0.703	1.59E-1
23	9.55E-5	7.48E-3	4.37E-3	0.714	1.83E-1
24	6.12E-4	4.14E-2	1.42E-2	1.10	3.07E-1
25	3.86E-4	3.05E-2	1.63E-2	0.810	2.35E-1
26	4.96E-4	3.53E-2	1.44E-2	1.10	3.19E-1

[7] Activity is corrected time of irradiation
[8] Smaller foil - Cd Shielded

Measured Panasonic 810 Dosimeter Results for Silene Irradiations (Rem)

NAD ID	Panasonic ID	Deep Dose	Shallow Dose	Beta Dose	Neutron Dose
1	0013073	171	162	0	2852
2	0007722	325	306	0	3095
3	0012860	165	113	0	2833
4	0013139	24.9	15.5	0	2028
5	0009806	59.2	23.8	0	2295
6	0011418	55.0	29.0	0	1963
7	0007690	8.3	0	0	1379
8	0003900	40.5	14.0	0	1640
9	0002049	35.6	10.4	0	1386
11	0011719	463	460	0	2053
12	0095933	536	486	0	2796
13	0011665	553	501	0	2278
14	0030307	444	455	0	1124
15	0009880	429	437	0	1225
16	0007535	423	442	0	1165
18	0010301	173	159	0	1901
19	0008371	173	151	0	1864
20	0007571	168	132	0	1998
21	0012650	55.3	64.3	0	883
22	0008726	64.2	51.7	0	797
23	0012607	75.3	66.4	0	871
24	0007906	147	137	0	1520
25	0007274	131	117	0	976
26	0011732	122	107	0	1356



FigureA1. Second irradiation @2meters in free air simulation (photo from CEA/VA/DRMN/SRNC DO 1078).

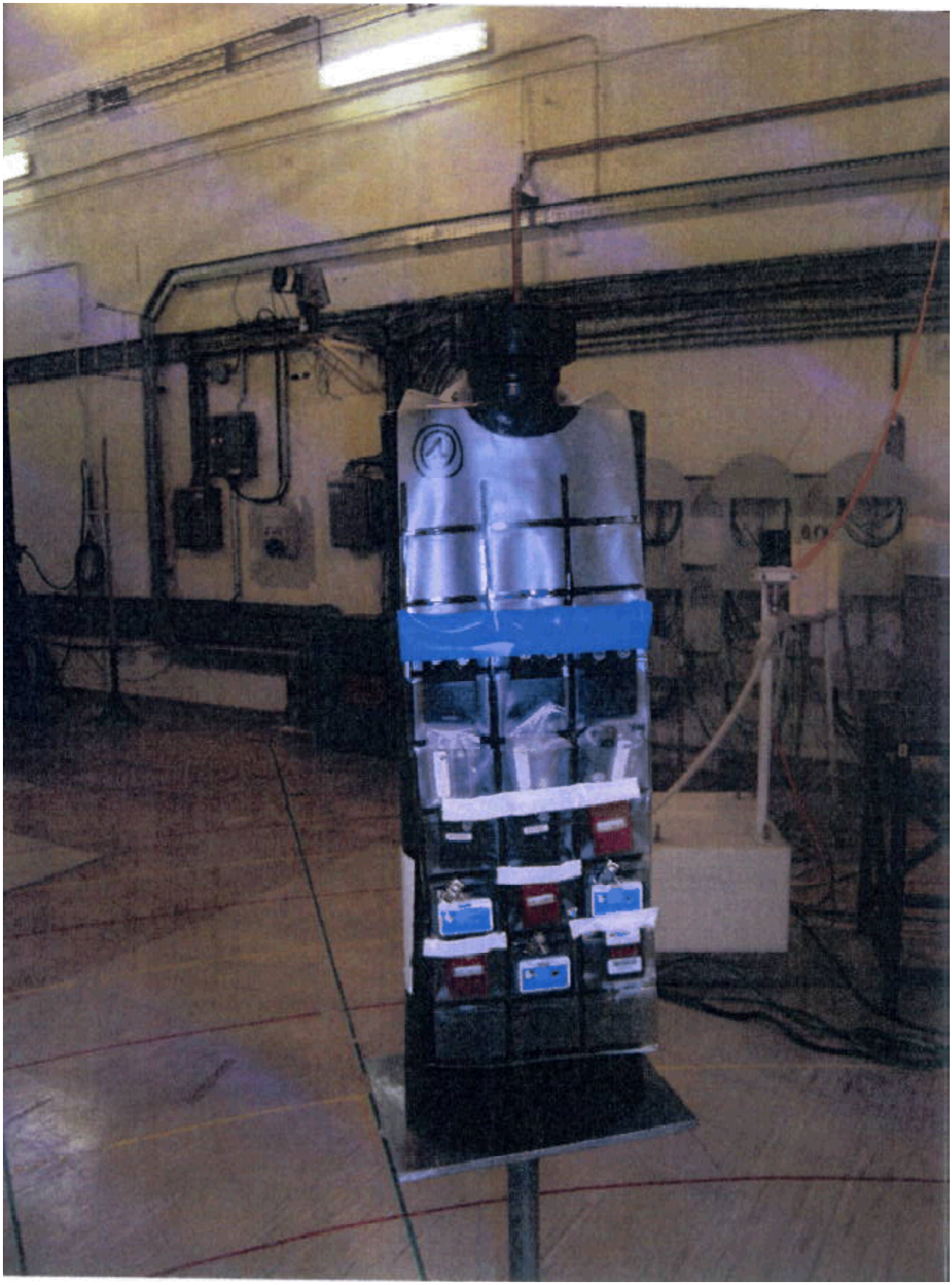


Figure A2. Second irradiation @ 2 meters (photo from CEA/VA/DRMN/SRNC DO 1078).

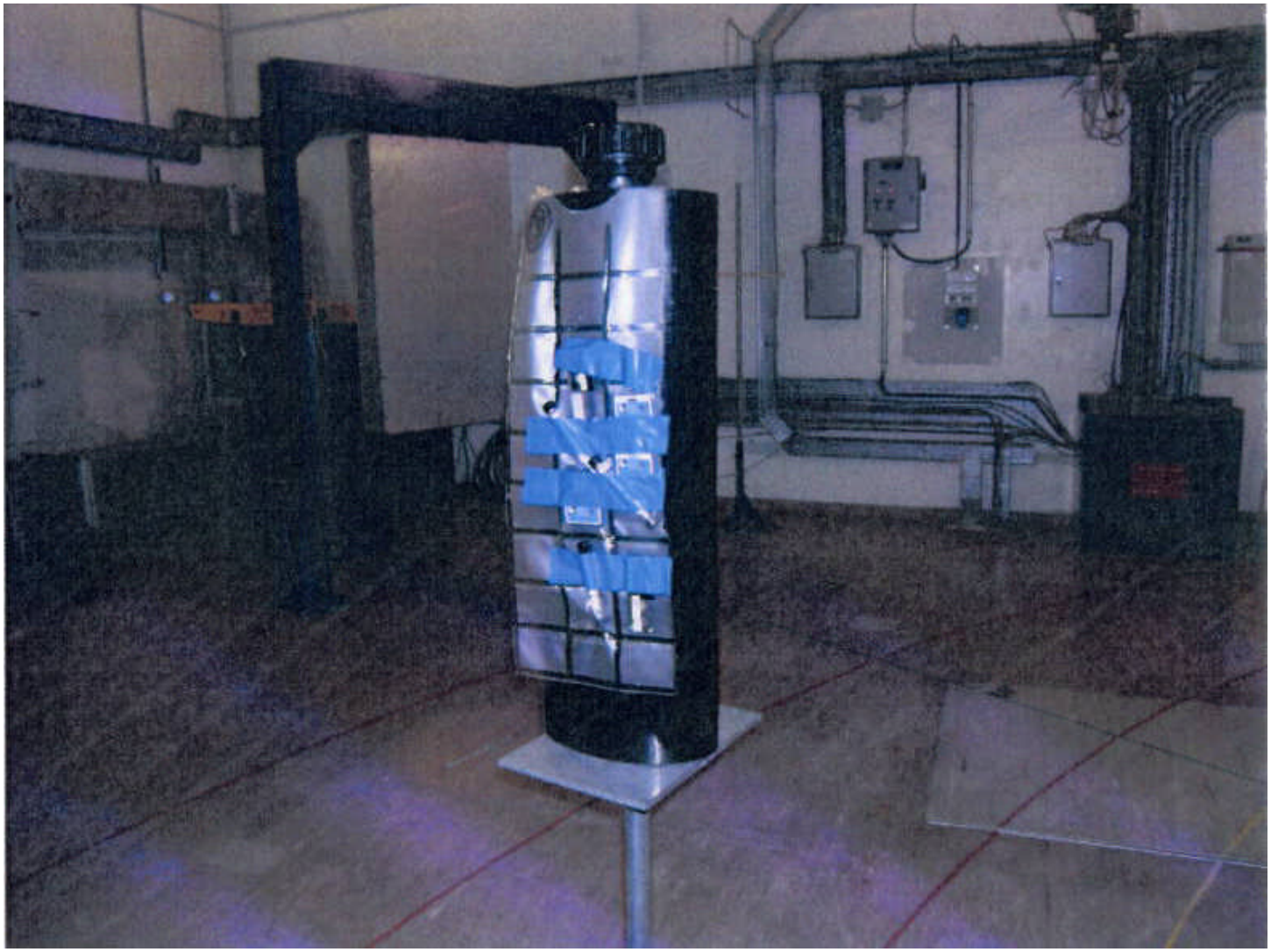


Figure A3. Third irradiation @6 meters on front of sideways facing water phantom (the core and irradiation occurs from the left side of the phantom (photo from CEA/VA/DRMN/SRNC DO 1076).

Figure A4. Third irradiation @6 meters on water phantoms facing towards, away from, and sideways to the core, midplane on the phantom (photo from CEA/VA/DRMN/SRNC DO 1076).