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Evaluation of LLNL's Nuclear Accident Dosimeters at the CALIBAN Reactor September 2010

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Introduction

The Lawrence Livermore National Laboratory uses neutron activation elements in a 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 until 2009, it was more than 25 years since the PNAD has been tested against a source of neutrons that arise from a reactor generated neutron spectrum that simulates a criticality. In October 2009, LLNL participated in an intercomparison of nuclear accident dosimeters at the CEA Valduc *Silene* reactor (Hickman, et.al. 2010). In September 2010, LLNL participated in a second intercomparison of nuclear accident dosimeters at CEA Valduc. The reactor generated neutron irradiations for the 2010 exercise were performed at the Caliban reactor. The Caliban results are described in this report.

The Caliban Reactor

The Caliban reactor is located at CEA Valduc outside of Dijon, France. It was built in 1971 and since has been involved in over 3000 divergences and sub-critical experiments. The reactor belongs to the unreflected HEU metal fast burst reactor family. The reactor consists of a solid core made of 10 fuel discs, shown in Figure 1, and 4 control rods of 93.5% enriched uranium metal alloyed with 10 wt% molybdenum. The combined weight is 113 kg. The reactor is highly suitable for studying the effects of a nuclear criticality accident as it can create a high yield pulse similar to that of a typical metal criticality accident. The core is housed in a 5 m x 8 m x 10 m irradiation room allowing for irradiation of dosimeters on a large scale of neutron fluence.

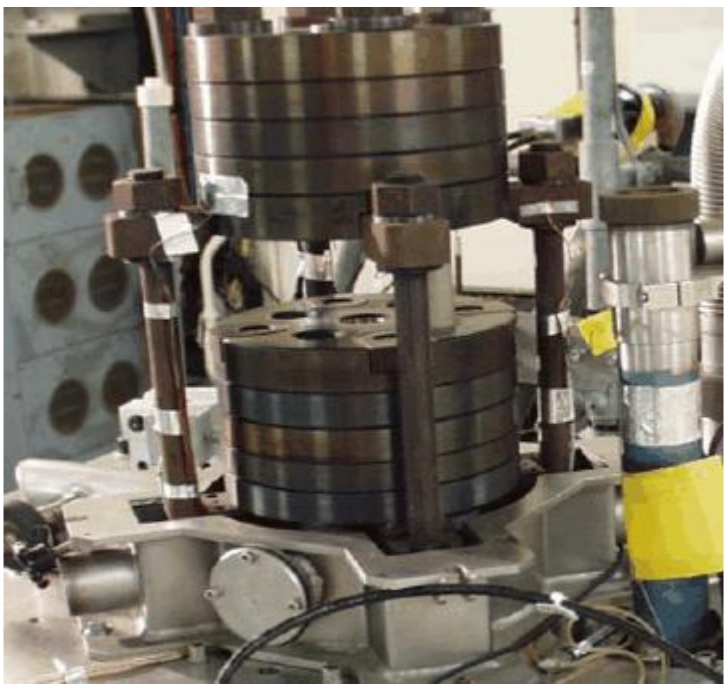


Figure 1. Photograph of the Caliban HEU Discs.[1]

To initiate a power excursion, the HEU control rods are inserted into the holes in the discs to a predetermined supercritical level. When the excursion has occurred, the material is separated ending the reaction.

The Caliban Reactor creates a high energy neutron spectrum as expected for a metal system. The spectrum was measured and calculated in a 2007 experiment and the results are shown in Figure 2.

[1] From *Valduc Laboratory Criticality Experiment Facilities*, Workshop on Future Criticality Safety Research Needs, Nuclear Energy Agency, Pocatello, ID, USA, September 21-22, 2009.

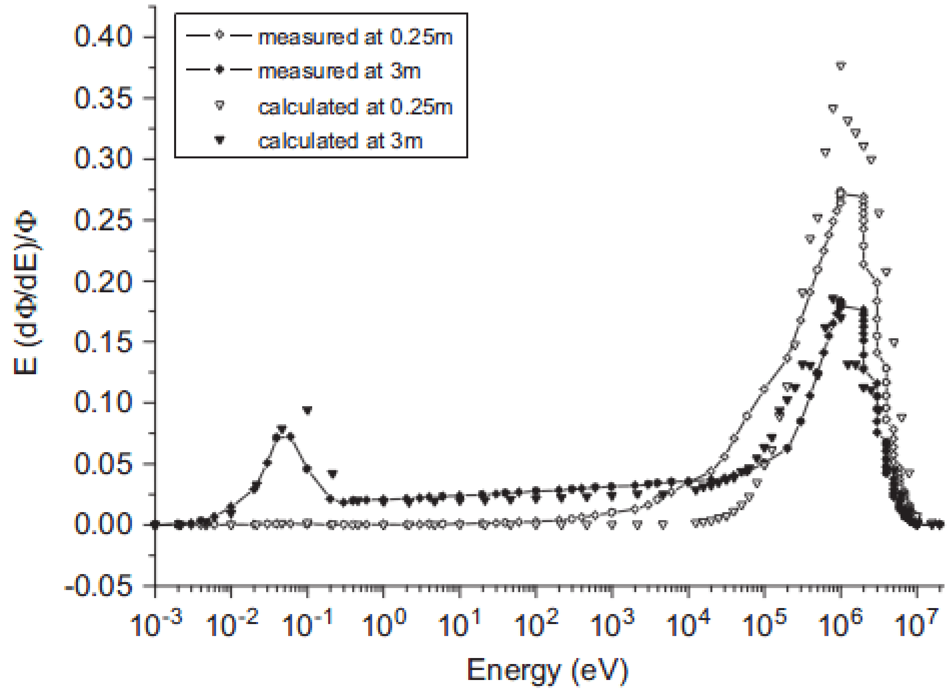


Figure 2. Comparison of calculated and measured neutron spectra in terms of lethargy unit normalized by fluence at 0.25 and 3 m distances.[2]

[2] From Trompier, F., Huet, C., Medioni, R., Robbes, I., Asselineau, B., *Dosimetry of the mixed field irradiation facility CALIBAN*, Radiation Measurements, Vol. 43, Issues 2-6, pp. 1077-1080, Elsevier Publishing, November 19, 2007.

Objectives

A previous exercise was performed at the Silene reactor in October of 2009 among six DOE laboratories. The participating laboratories at this previous test were LLNL, SRS, Oak Ridge-Y-12, PNNL, and LANL. LLNL was tasked with coordinating a second exercise at the Caliban reactor in October 2010. In addition to the previous participants, Sandia Laboratory also participated in the Caliban exercise.

The current PNAD design at LLNL was developed in the early 1980's (Figure 3) 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). The Health Physics Research Reactor at Oak Ridge National Laboratory was composed of a metal core similar to the Caliban reactor. Minor changes in material handling and analysis have been instituted over the ensuing years since the first calibration of the LLNL NADs. The exercise at Caliban allowed LLNL to reevaluate the neutron dose response of LLNL's NADs to the pulsed neutron spectrum generated by a metal core reactor.

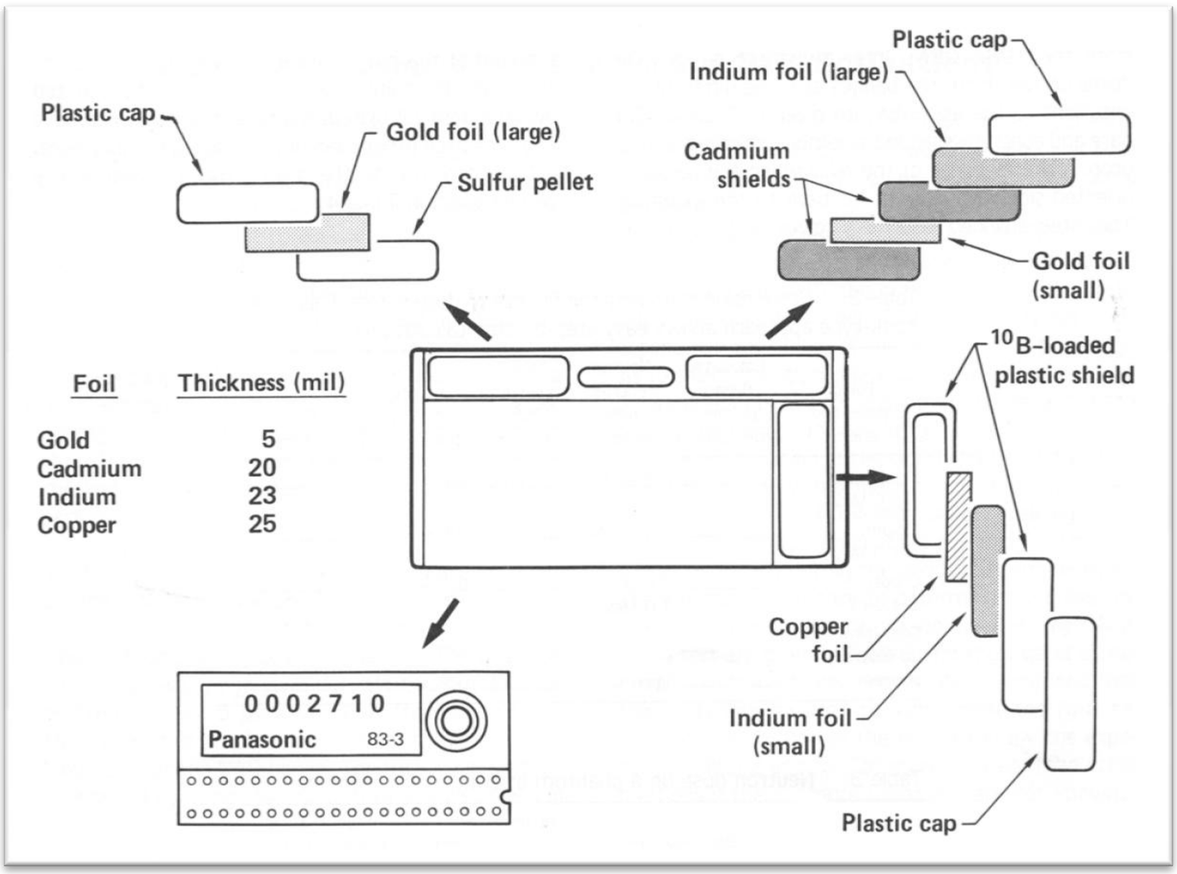
The previous exercise at the Silene reactor in 2009 noted discrepancies between reported gamma doses and dose values provided by the Silene operators. Similar discrepancies were also noted for several of the DOE participants. LLNL established additional measurements to confirm known values for gamma doses for the Caliban exercise. Since the NAD gamma response on the previous intercomparison demonstrated some discrepancy with the known gamma doses, LLNL also established a plan to evaluate gamma dose response of LLNL's NAD.

When the LLNL dosimeter was developed and calibrated, an approximate dose method was developed to establish a preliminary neutron dose base on quick-sort data measurements of the NAD dosimeter. Figure 4 is the chart developed from this effort. LLNL brought portable measurement equipment to the Caliban intercomparison to confirm the validity of the quick sort curve.

LLNL maintains a correction factor for sideways orientation, however documentation does not establish whether this orientation is from the left side or the right side of the PNAD, or whether it matters if the dosimeter is left or right oriented. Sideways orientation results on the previous intercomparison (left side, based on photos provided by CEA) were inconclusive, so additional measurements on both sides of the NAD dosimeters were performed at this exercise.

Fixed Nuclear Accident Dosimeters (FNAD) are installed throughout various LLNL facilities for the post assessment of dose in the event of a nuclear criticality. The intercomparison at Caliban provided an opportunity to test the assessment capabilities of LLNL's FNADs. There are no published test results for the LLNL's FNAD s. The design of the LLNL FNAD is described by Hankins (Hankins 1988) and Figure 5 is a schematic of the original FNAD design. Minor modifications to the FNAD have occurred over the years[3]. The Caliban test will be the first published test results for the LLNL FNAD.

Figure 3. Lawrence Livermore National Laboratory Personnel Nuclear Accident Dosimeter design.



[3] For example: TLD 700 chips are no longer used. Instead, Panasonic dosimeters are co-located with the FNAD.

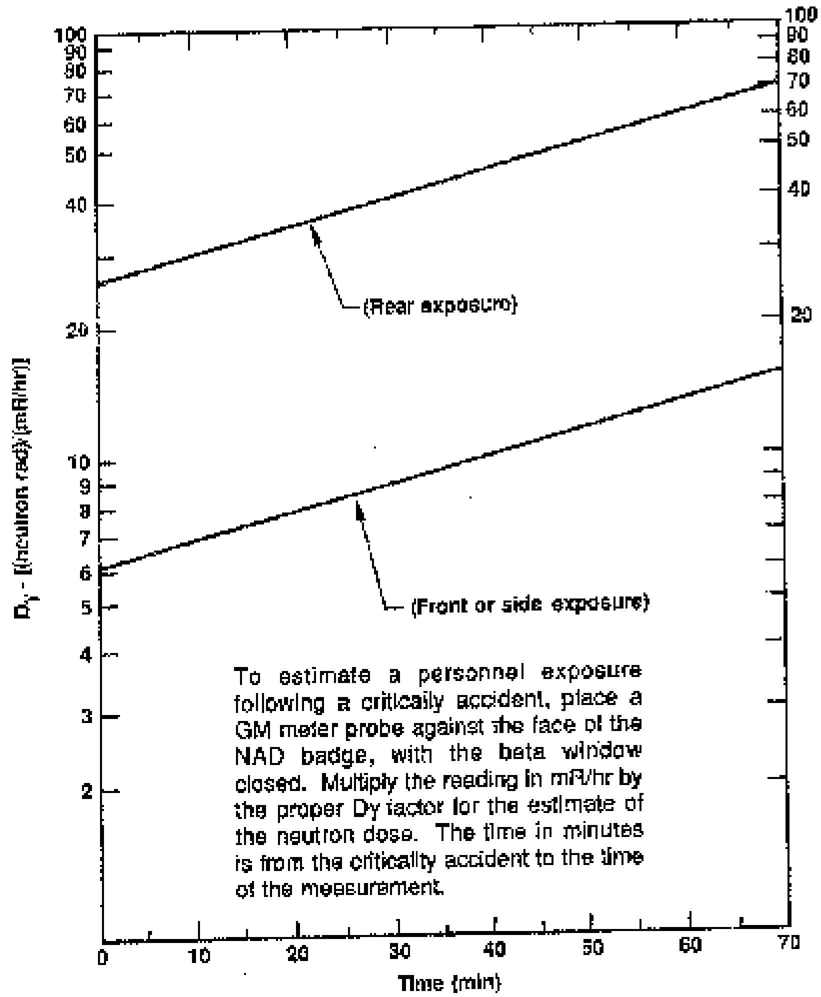


Figure 4. Quick-sort Dose Estimation for LLNL Personnel Nuclear Accident Dosimeters.

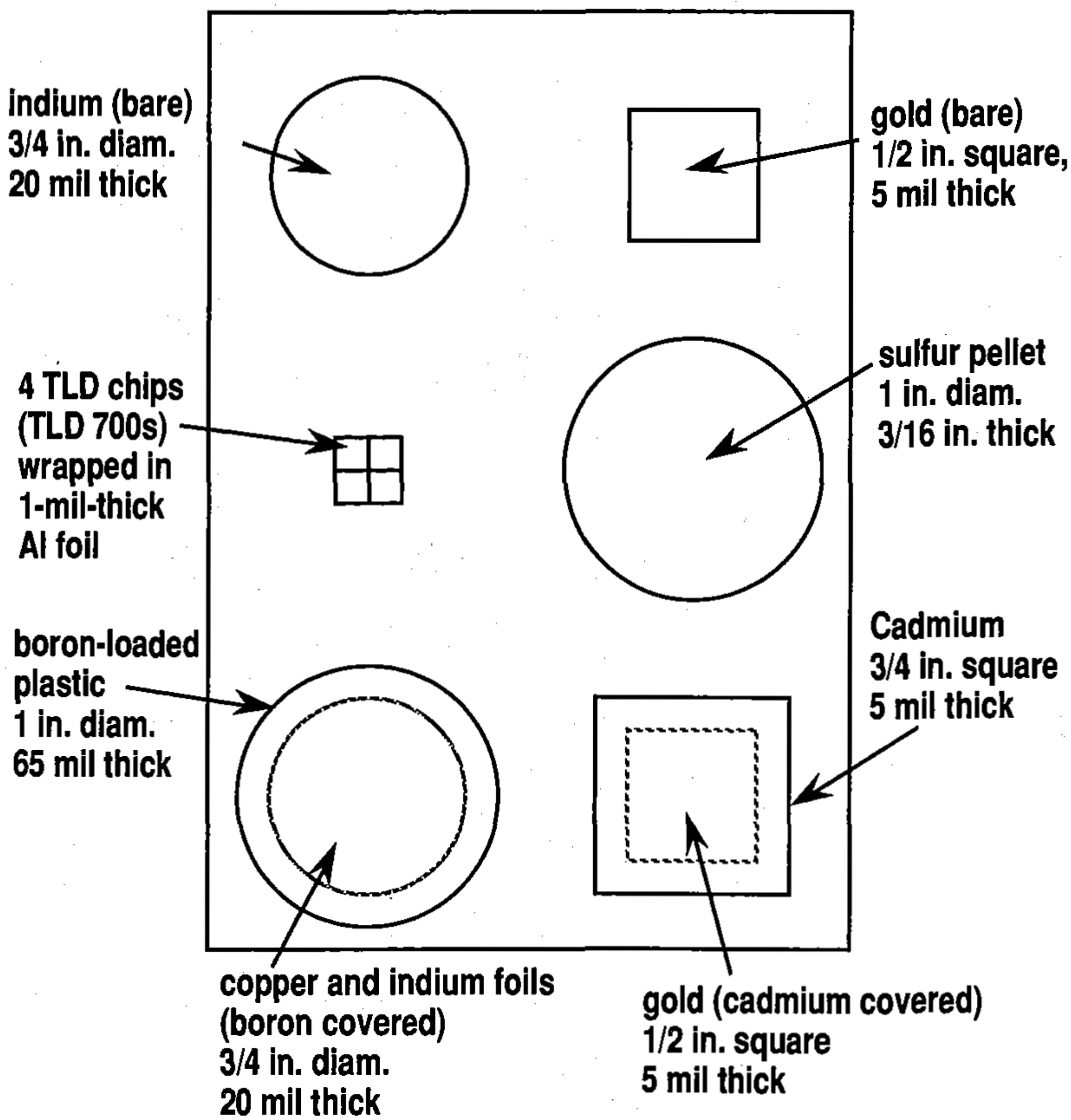


Figure 5. Original LLNL Fixed Nuclear Accident Dosimeter design.

Methods

Two pulse irradiations were performed at the Caliban reactor during the week of September 20, 2010. The first pulse was performed on September 21, 2010 at 11:11:32 with the unshielded reactor core. The second pulse occurred on September 22 at 11:13:02, also with the unshielded reactor core. Dosimeters were place in free air with aluminum backing (holding) plates to which the dosimeters were attached. The typical arrangement for dosimeters facing and dosimeters oriented sideways to the core of the reactor is shown in figure 6. After irradiation, the dosimeters were withheld by Caliban personnel (typically 3 – 4 hours) to ensure that doses while handling the dosimeters would be minimal to participants.

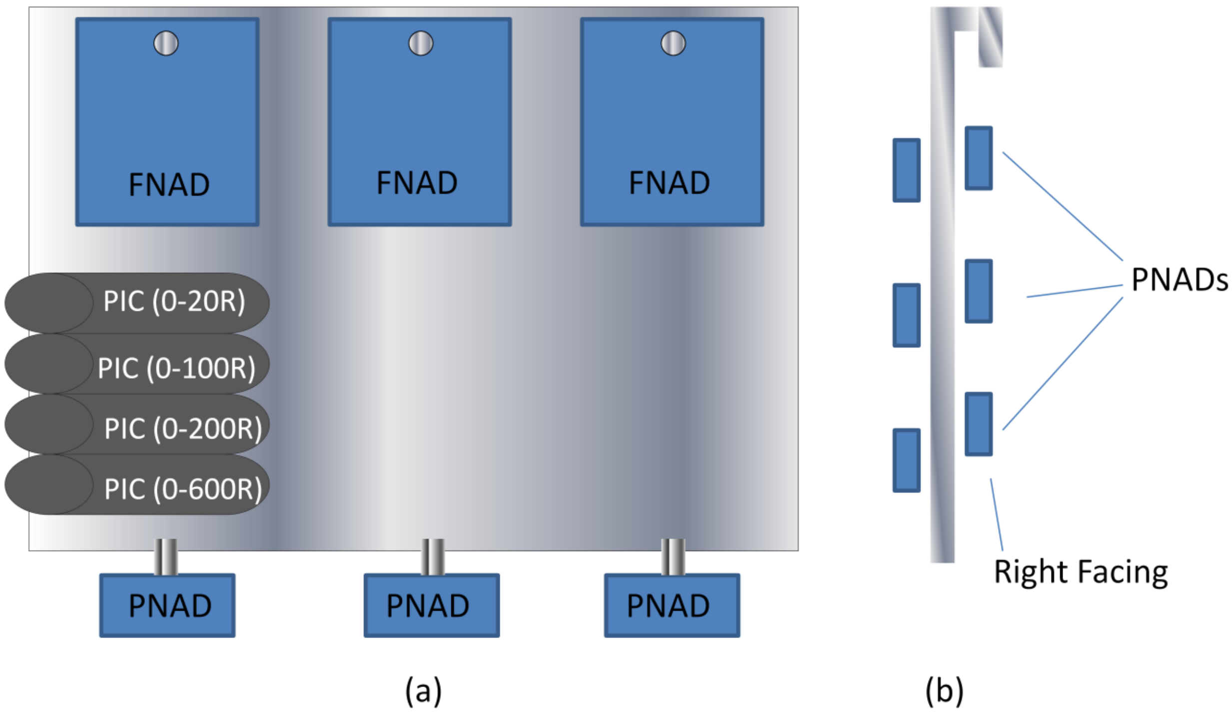


Figure 6. Typical aluminum plate mounting of dosimeters: (a) facing the reactor core; (b) sideways to the reactor core.

Irradiations facing the core of the reactor contained three LLNL Fixed Nuclear Accident Dosimeters (FNAD), Three Personnel Nuclear Accident Dosimeters (PNAD), and 4 Personnel Ion Chambers (PIC). Each PIC had a different maximum scale: 0-20R; 0-100R; 0-200R; and 0-600R. Sideways irradiations were only performed on PNAD dosimeters.

The first pulse irradiation had three core facing plates and one sideways facing plate from LLNL. Core facing plates were positioned at 2, 3, and 4 meters from the core at positions 3, 6, and 7 respectively (see Figure 7). The sideways facing plate (Figure 6b) was positioned 2 meters from the reactor core at position 4. Because of the sideways orientation the dosimeters extended 0.34 meters closer towards the reactor core, making their true distance 1.66 m from the core.

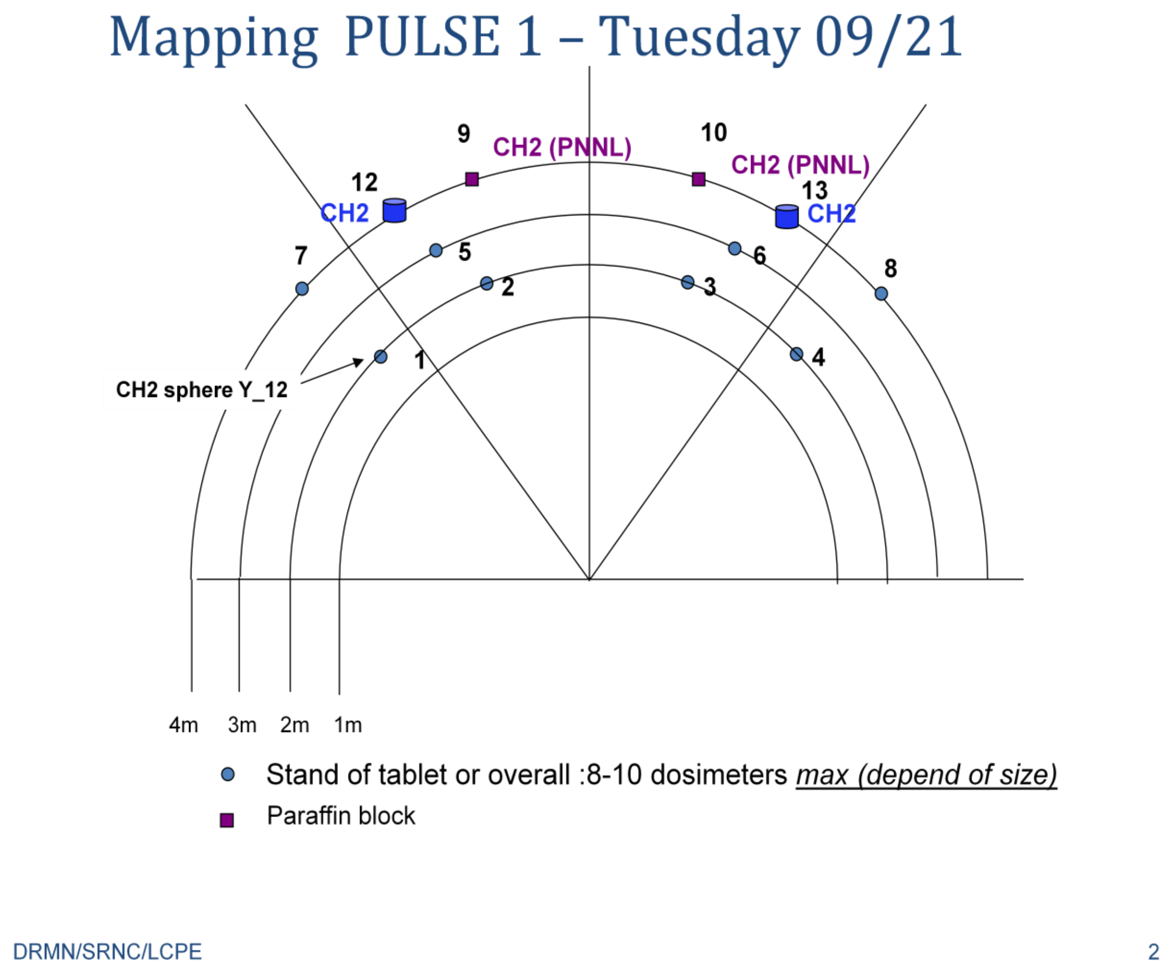


Figure 7. NAD Positions for the first NAD exposure at the Caliban Reactor (Courteously of CEA Valduc).

In the second pulse LLNL had a typical aluminum plate of dosimeters positioned on a nearby wall facing the core of the reactor at a distance of 3.63m and a height of 1.8m. At position 3 (see Figure 8) LLNL had a typical aluminum plate of dosimeters, less one FNAD, facing the reactor core at 2m from the core. At position 5, 3 m from the core, LLNL positioned an aluminum plate of 2 FNADs. Finally, 3 PNADs were positioned on a water phantom facing the reactor core at 2.5 meters from the core (noted in LLNL notes as 'position 11'). The water phantom and stand supporting the phantom (20 cm by 30 cm truncated ellipse by 60 cm tall) was filled with a sodium-water solution to simulate blood in a human body. Phantoms stood on aluminum stands 80.5 cm above the floor. A depiction of the phantom and stand with the PNADs is shown in Figure 9. The phantoms had plastic sheets with separate pockets that the dosimeters could be arranged in. In each irradiation, the location of the dosimeter relative to the body of the phantom differed slightly depending on which pocket the dosimeter was placed in.

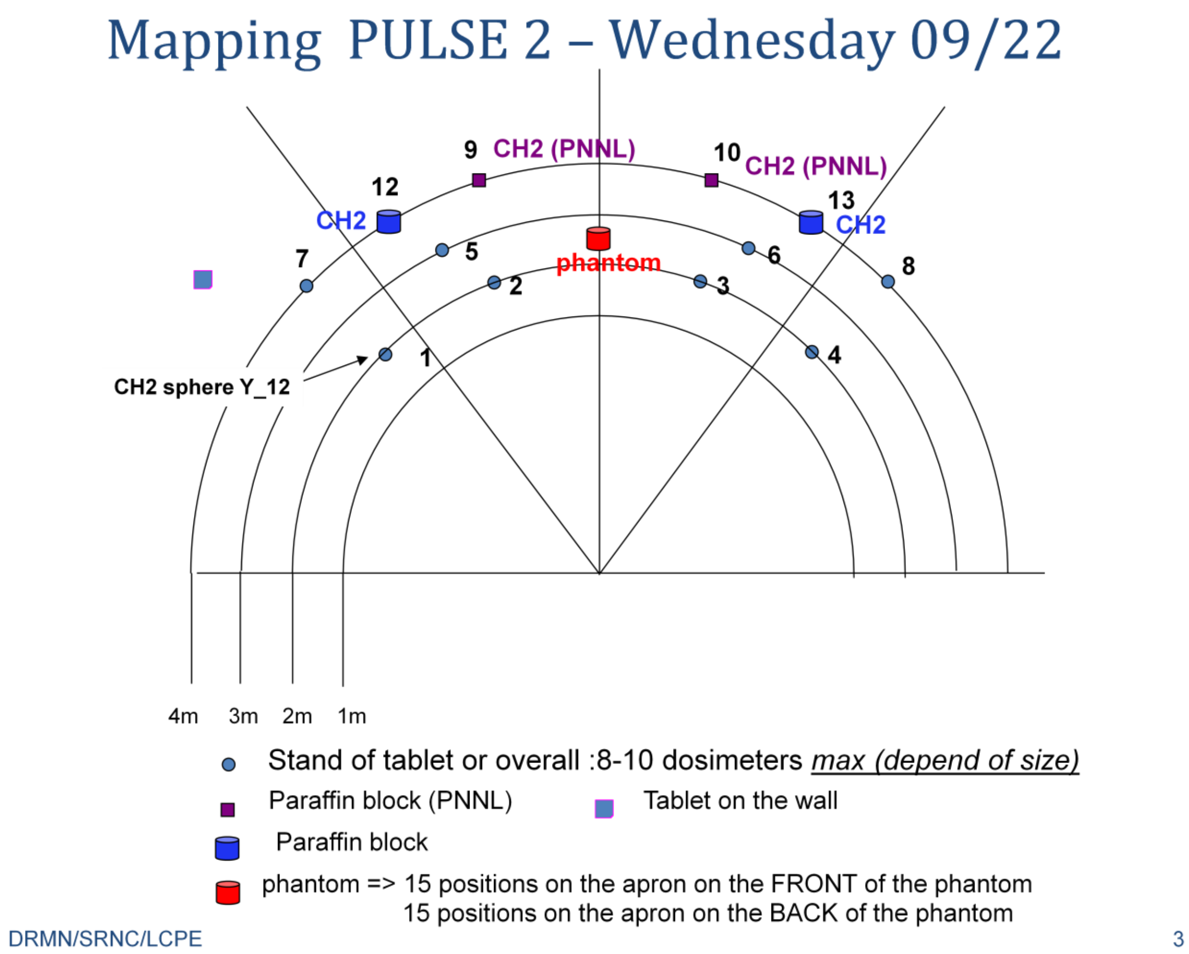


Figure 8. NAD Positions for the second NAD exposure at the Caliban Reactor (Courteously of CEA Valduc).

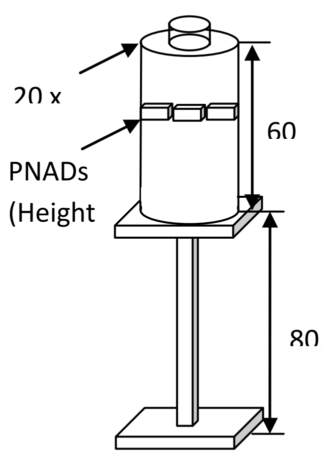


Figure 9. Diagram of phantom mounted PNADs.

Prior to gamma counting the first set of NADs, a Geiger Muller counter measurement of the internal FNAD and PNAD dosimeters was performed. Two styles of GM counters were used, a Ludlum Model 12 with a 44-38 GM probe, and an Eberline E120 with a Model 177 GM probe. The time of measurement was noted when the GM measurement was performed.

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 were low or processing times limited, the count may have been terminated before 500 counts were obtained in the 511 keV peak region. 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 Caliban test.

Type of Foil	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 counted whole, placed into a stainless steel planchet, and analyzed using a Canberra Industries iSolo alpha/beta counter. The average weight of the sulfur pellets was 5.79 ± 0.23 grams. The iSolo was calibrated with a 47 mm plated Sr/Y-90 source. Daily calibration checks were performed using a Coleman mantle containing natural beta emitting radionuclides. Because LLNL was not allowed to crush the sulfur pellets, per its normal procedure, an adjustment of 4.9 to the neutron fluence conversion factor had to be made. This factor is documented and the adjustment factor is documented in the LLNL Nuclear Accident Dosimeter Technical Basis for Fixed and Personnel NADs and Dose Analysis of NADs & Blood and Hair (Graham 2004). There have been past indications that this correction factor is not equal to 4.9 (Graham 2004, Hickman, et. al. 2010). To obtain more data regarding the appropriated correction factor for both melted and crushed sulfur, the pellets were recounted upon return to LLNL, melted and recounted, and then the melt was crushed and recounted.

The theoretical basis of LLNL's Nuclear Accident Dosimetry program is provided in Appendix A. Specifics on the design and the computational methods for LLNL's Nuclear Accident Dosimeters have been previously published (Hankins 1984, Hankins 1988, Graham 2004, Hickman, et.al. 2010).

Results

The average neutron dose for the irradiations for PNADs and FNADs compared to the known dose values provided for the Caliban reactor for the first and second pulse irradiations are provided in Tables 2 through 4. Tables 5 and 6 provide average gamma dose results. Table 7 provided the total gamma plus neutron doses for each irradiation. Detailed dose and neutron fluence determinations are provided in Appendix B.

Table 2. Neutron dose results summary for Personnel Nuclear Activation Dosimeters facing the simulated criticality.

Irradiation	Distance (m)	Given Neutron Dose (rad)	Average Measured Neutron Dose (rad)	Percent Difference
1	2	510	490	-3.9
1	3	260	290	+11
1	4	170	220	+29
2	2	720	707	-1.8
2	2.5[4]	576	580	+0.6

Table 3. Neutron dose results summary for Personnel Nuclear Activation Dosimeters sideways to the simulated criticality.

Irradiation	Distance (m)	Given Neutron Dose (rad)	Neutron Dose (rad) - Right Side Facing Core	Neutron Dose (rad) - Left Side Facing Core
1	2	510	463	643
2	2	720	627	473

Table 4. Neutron dose results summary for Fixed Nuclear Accident Dosimeters facing the simulated criticality.

Irradiation	Distance (m)	Given Neutron Dose (rad)	Average Measured Neutron Dose (rad)	Percent Difference
1	2	510	470	-7.8
1	3	260	257	-1.1
1	4	170	190	+11
2	2	720	685	-4.9
2	3	360	370	+2.7
2	3.63[5]	NA	360	

NA = not available

[4] Average of the dosimeters placed on the water phantom.
[5] On wall.

Table 5. Gamma dose results summary for Personnel Nuclear Activation Dosimeters (PNAD) and Pocket Ionization Chambers (PIC) facing the simulated criticality.

Irradiation	Distance (m)	Given Gamma Dose (rad)	Average Measured PIC Gamma Dose (rad)	Average Measured PNAD '805' Gamma Dose (rad)	Percent Difference
1	2	70	97.3	64.3	-8.1
1	3	50	53.0	18.2	-63
1	4	40	42.3	18.2	-55
2	2	100	96.7	87.0	-13
2	2.5	83[6]	107[6]	116	+40

Table 6. Gamma dose results summary for Personnel Nuclear Activation Dosimeters (PNAD) and Pocket Ionization Chambers (PIC) sideways to the simulated criticality.

Irradiation	Distance (m)	Given Gamma Dose (rad)	Gamma Dose (rad) - Right Side Facing Core	Gamma Dose (rad) - Left Side Facing Core
1	2	70	69.4	82.9
2	2	100	73.3	79.7

Table 7. Total dose results summary for Personnel Nuclear Activation Dosimeters facing the simulated criticality – Neutron plus Gamma.

Irradiation	Distance (m)	Given Total Dose (rad)	Average Measured Total Dose (rad)	Percent Difference
1	2	580	554	-4.5
1	3	300	308	+2.7
1	4	210	238	+13
2	2	820	794	-3.2
2	2.5	576[5]	687[7]	+19

Access to the irradiated PNADs was not allowed for several hours after exposure to the neutron field at Caliban. Portable meter readings were taken before dosimeters were disassembled once access to the PNADs was available. Open and closed meter readings were taken using two different styles of portable instrumentation. The results of these readings and the neutron dose conversion factor are provided in Table 8.

[6] Interpolated
[7] Average of the dosimeters placed on the water phantom.

Table 8. Measured exposure rates of PNADs facing the core.

	Ludlum Model 12 w/ 44-38 GM		Eberline E120 w/ Model 177 GM				
Minutes Post Irradiation	**Closed ($mR{\cdot}h^{-1}$)**	**Open ($mR{\cdot}h^{-1}$)**	**Closed ($mR{\cdot}h^{-1}$)**	**Open ($mR{\cdot}h^{-1}$)**	**Average ($mR{\cdot}h^{-1}$)**	**Neutron Dose (rads)**	**Factor ($rad{\cdot}h{\cdot}mR^{-1}$)**
181	5	5	6	6	5.5	170	31
184	4	4	4	4	4	170	43
187	14		18		16	720	45
189	6.5	6.5	6	6	6.25	170	27
189	12		14		13	820	63
191	14		16		15	820	55
229	2	2	2	2	2	260	130
235	6	6	6	6	6	260	43
239	6	6	6	6	6	260	43
259	4	4	4	4	4	510	128
262	3	3	3	3	3	510	170
264	3	3	3	3	3	510	170

Open and closed meter readings were also taken of the sideways oriented PNADs and the facing FNADs using the two different styles of portable instrumentation. The results of these readings and the neutron dose conversion factor are provided in Tables 9 and 10.

Table 9. Measured exposure rates of PNADs facing sideways to the core.

	Ludlum Model 12 w/ 44-38 GM		Eberline E120 w/ Model 177 GM				
Minutes Post Irradiation	**Closed ($mR{\cdot}h^{-1}$)**	**Open ($mR{\cdot}h^{-1}$)**	**Closed ($mR{\cdot}h^{-1}$)**	**Open ($mR{\cdot}h^{-1}$)**	**Average ($mR{\cdot}h^{-1}$)**	**Neutron Dose (rads)**	**Factor ($rad{\cdot}h{\cdot}mR^{-1}$)**
230	8		10		9	720	80
232	8		9		8.5	720	85
233	7		8		7.5	720	96
236	7		8		7.5	720	96
237	8		10		9	720	80
238	7		8		7.5	720	96

Table 10. Measured exposure rates of FNADs facing the core.

	Ludlum Model 12 w/ 44-38 GM		Eberline E120 w/ Model 177 GM				
Minutes Post Irradiation	Closed ($mR \cdot h^{-1}$)	Open ($mR \cdot h^{-1}$)	Closed ($mR \cdot h^{-1}$)	Open ($mR \cdot h^{-1}$)	Average ($mR \cdot h^{-1}$)	Neutron Dose (rads)	Factor ($rad \cdot h \cdot mR^{-1}$)
192	14	14	15	15	14.5	170	12
194	16	16	16	16	16	170	11
199	15	15	15	15	15	170	11
254	5	5	5	5	5	260	52
255	5	5	5	5	5	260	52
257	5	5	5	5	5	260	52
264	6	6	6	6	6	510	85
274	7	7	7	7	7	510	73
279	5	5	5	5	5	510	102
182	16		18		17	360	21
222	22		24		23	360	16
191	20		21		20.5	720	35
193	24		26		25	720	29

The ratio of the dose contributions provides information about the neutron spectrum irradiating the dosimeter. Tables 11 and 12 summarize the fraction of neutron dose contribution for the neutron energy ranges monitored by the LLNL nuclear accident dosimeters.

Table 11. Average fraction of total neutron dose contribution for PNADs at 2, 3, and 4 meters facing the core (all irradiations)[8].

	Comparative Dose Contributions:			
Energy Range	Valduc-Caliban Fraction of Dose: Bare Assembly at 2m	Valduc-Caliban Fraction of Dose: Bare Assembly at 3m	Valduc-Caliban Fraction of Dose: Bare Assembly at 4m	ORNL HPRR Fraction of Dose: Bare Assembly 3m
>3 MeV	0.2	0.2	0.1	0.2
1 – 3 MeV	0.5	0.4	0.4	0.5
1 eV – 1 MeV	0.3	0.4	0.5	0.3
Thermal	0.00	0.00	0.00	0.01

[8] ORNL-HPRR data based on 1984 irradiations at the ORNL-Health Physics Research Reactor

Table 12. Average fraction of total neutron dose contribution for FNADs at 2, 3, 3.8, and 4 meters facing the core (all irradiations).

	Comparative Dose Contributions:			
Energy Range	**Valduc-Caliban Fraction of Dose: Bare Assembly at 2m**	**Valduc-Caliban Fraction of Dose: Bare Assembly at 3m**	**Valduc-Caliban Fraction of Dose: Bare Assembly at 3.8m**	**Valduc-Caliban Fraction of Dose: Bare Assembly at 4m**
>3 MeV	0.13	0.12	0.1	0.1
1 – 3 MeV	0.62	0.54	0.5	0.5
1 eV – 1 MeV	0.25	0.34	0.4	0.4
Thermal	0.00	0.01	0.01	0.01

Table 13. Average ratio of melted and crushed sulfur measurements relative to measurement of the intact whole pellet.

Type of Pellet	Melted/Whole Pellet	Crushed/Whole Pellet
PNAD	1.99 ± 0.16	2.98 ± 0.20
FNAD	2.82 ± 0.10	2.52 ± 0.08

Discussion

The LLNL Personnel Nuclear accident Dosimeter (PNAD) and Fixed Nuclear Accident Dosimeter (FNAD) provided exceptional neutron dose results for the Caliban evaluation. PNAD neutron doses were typically measured to within 4% of the known neutron doses and FNAD neutron doses were typically measured to within 10% of the known neutron dose. The fact that the Caliban reactor is similar to the pulse reactor used to develop the LLNL dosimeter and the opportunity in October 2009 to exercise the PNAD and personnel in evaluating the LLNL PNADs most likely contributed to the improved performance observed with the Caliban exercise.

A major difference between the October 2009 and September 2010 nuclear accident dosimeter test at the CEA’s Valduc site was the processing of the activated sulfur pellets. In 2009, the sulfur pellets were measured whole, then crushed and reanalyzed. The normal mode of analysis is with crushed pellets because it is rare that pellets remain unbroken while housed in the dosimeter. As demonstrated in the 2009 testing of the sulfur pellets, crushing and analysis of the crushed sulfur pellet appears to add variability in the results. Sulfur typically provides the second highest contribution to the dose and analysis results of the whole pellet (unbroken and not crushed) during the Caliban test may have contributed to the extremely consistent results and accuracy of the LLNL PNADs and FNADS during this test. Inconsistency in the sulfur data is evident when comparing the 2009 evaluations of crushed versus uncrushed sulfur pellets with the current and previous tests. Likewise, the use of an improved beta counting system (Canberra iSolo) also contributed to the improved beta analysis.

The LLNL PNAD system still has difficulty in providing consistent and accurate gamma dose results. The gamma results for the October 2009 exercise also showed inconsistencies among all of the DOE participants. For the Caliban exercise, LLNL included gamma dose analysis of each irradiation using gamma Personal Ionization Chambers (PICs). The PICs were in excellent agreement with the reported known gamma dose values (Table 5) however; the TLD dosimetry systems incorporated into the NADs (Panasonic 810's) provided low dose readings for gamma doses and were inconsistent.

Regardless of the methodology used for the analysis of the sulfur pellets, the dose results of the LLNL nuclear accident dosimeters are well within the ANSI N13.3-1969 standard requirement of ±25% (Table 7). The measurement processes for activated metal gamma emitters remained the same from 2009 to 2010. The greatest improvement noted since the October 2009 exercise was in the consistency and accuracy of the PNAD neutron dose results. A number of factors contributed to this improvement. These include better personnel experience (due to the having participated in the October 2009 exercise), improved measurement portable equipment, and whole sulfur pellet measurement. The melting or crushing of the sulfur pellet results in higher counting efficiency, however it also propagates additional error into the measurement. The analysis of melted and crushed PNAD pellets is 1.99 and 2.98 times more efficient than analysis of the whole pellet respectively. FNAD pellets contain 6.8 times more sulfur. Melted and crushed FNAD pellets demonstrated closer ratios (2.82 and 2.52 respectively). These results indicate that there is a significant difference between whole, melted, and crushed sulfur pellet analysis, however none of the results support the use of a correction factor of 4.9 for crushed sulfur.

The Caliban exercise allowed LLNL to confirm it quick sort methods of initial neutron dose determination for PNADs facing the criticality event. By design, the LLNL PNAD and FNAD dosimeters used bare Indium foils solely to provide easily measureable gamma doses using portable field instrumentation. The exposure rate (in mR/h) is multiplied by a time dependent neutron dose factor (neutron dose in rads per mR/h gamma exposure) to obtain an initial estimate of neutron dose. The dose factor is obtained from the quick sort estimation curve (Figure 4), however since the dosimeters in the Caliban exercise were not made available to LLNL personnel during the first 70 minutes post irradiation, an extrapolation method was used to confirm the dose conversion factors of Figure 4. Dose rates were measured on the LLNL dosimeters as soon as the dosimeters were made available to LLNL personnel and prior to disassembly for activation analysis. The time of the dose rate measurements were noted (see Tables 9 and 10). Values for the dose conversion factors were taken from Figure 4 for the first 70 minutes. Measured exposure rates along with given neutron dose values were used compute the dose conversion factors observed at the time of measurement. Both measured and Figure 4 dose conversion factors, as a function of time post irradiation, are provided in Figure 10. A best fit exponential is provided for comparative purposes and use for future quick sort evaluations. Based on these results it would appear that current quick sort factors appear to provide reasonable estimates of neutron dose. Future tests should make every attempt to confirm quick sort factors for times closer to the irradiation event and expand the dataset collected during the Caliban exercise.

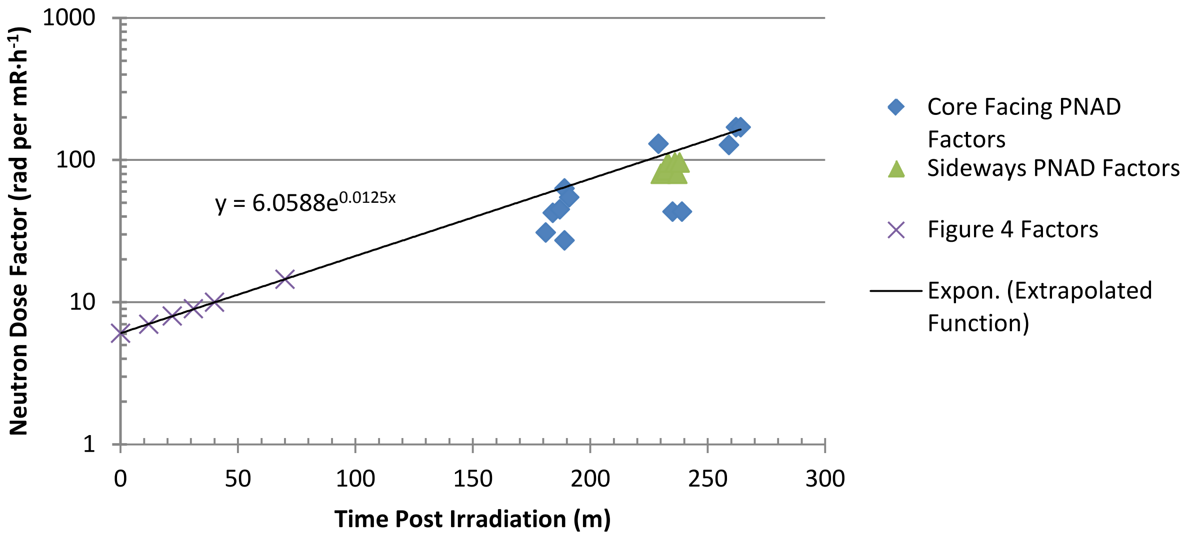


Figure 10. Extrapolated neutron dose factor function and measured neutron dose factors used for quicksorting PNADs

Irradiation of the right side and left side of the LLNL PNAD were inconclusive in verifying or deriving correction factors. Additional evaluation to confirm correction factors for backside and sideways orientation are still needed.

Conclusions & Recommendations

The procedure for measuring the nuclear accident dosimeters in the event of an accident has a solid foundation based on many experimental results and comparisons. The entire process, from receiving the activated NADs to collecting and storing them after counting was executed successfully in a field based operation. Under normal conditions at LLNL, detectors are ready and available 24/7 to perform the necessary measurement of nuclear accident components. Likewise LLNL maintains processing laboratories that are separated from the areas where measurements occur, but contained within the same facility for easy movement from processing area to measurement area. In the event of a loss of LLNL permanent facilities, the Caliban and previous Silene exercises have demonstrated that LLNL can establish field operations that will very good nuclear accident dosimetry results.

There are still several aspects of LLNL's nuclear accident dosimetry program that have not been tested or confirmed. For instance, LLNL's method for using of biological samples (blood and hair) has not been verified since the method was first developed in the 1980's. Because LLNL and the other DOE participants were limited in what they were allowed to do at the Caliban and Silene exercises and testing of various elements of the nuclear accident dosimetry programs cannot always be performed as guests at other sites, it has become evident that DOE needs its own capability to test nuclear accident dosimeters. Angular dependence determination and correction factors for NADs desperately need testing as well as more evaluation regarding the correct determination of gamma doses. It will be critical to properly design any testing facility so that the necessary experiments can be performed by DOE laboratories as well as guest laboratories. Alternate methods of dose assessment such as using various metals commonly found in pockets and clothing have yet to be evaluated.

The DOE is planning to utilize the Godiva or Flattop reactor for testing nuclear accident dosimeters. LLNL has been assigned the primary operational authority for such testing. Proper testing of nuclear accident dosimeters will require highly specific characterization of the pulse fields. Just as important as the characterization of the pulsed fields will be the design of facilities used to process the NADs. Appropriate facilities will be needed to allow for early access to dosimeters to test and develop quick sorting techniques. These facilities will need appropriate laboratory preparation space and an area for measurements. Finally, such a facility will allow greater numbers of LLNL and DOE laboratory personnel to train on the processing and interpretation of nuclear accident dosimeters and results. Until this facility is fully operational for test purposes, DOE laboratories may need to continue periodic testing as guests of other reactor facilities such as Silene and Caliban.

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Appendix A. Theoretical Basis for LLNL's Nuclear Accident Dosimetry

Neutron activation analysis (NAA) is a method used to determine the fluence of a neutron spectrum within the confines of a nuclear accident dosimetry program. The activity measured in the irradiated sample is directly proportional to the neutron fluence that it was exposed to. Most stable nuclides have relatively high cross sections for neutron capture. Because of this when neutron fluence passes through a material foil these stable nuclides become radioactive. Since the major decay processes of the unstable isotopes created in the foil materials used in the nuclear accident dosimeters (NADs) are known, by measuring the gamma or beta radiation being released by the material, the amount of activated isotopes can be determined.

In the NAA used for nuclear accident dosimetry a thin foil of known physical and nuclear properties undergoes irradiation. After the irradiation, the foil is transferred to a detector where the activity of the foil is measured. The reaction rate for the neutrons interacting with nuclei in the foil in a small thickness *dx* and at the position *x*, which is relative to the foil face, is given by:

$$dR(x) = \phi(x) n_t \sigma_t dx$$

Where: n_t is the nuclei density [nuclei/cm^3]
σ_t is the total microscopic neutron cross section [cm^2]
$\phi(x)$ is the neutron flux [n*cm^{-2}*s^{-1}]
$R(x)$ is the number of interactions in the neutron beam [reactions*cm^{-2}*s^{-1}] up to position *x*

The microscopic cross section, σ_t, is a measure of the probability of occurrence per target nucleus of any nuclear reaction occurring in the medium, not just a reaction with a product that will be measured by the detectors. Complicating the issue is the fact that the flux is not constant through the foil, but is equal to the incident flux minus the reaction rate defined above at which neutrons are removed from the beam. The interactions consist of either absorption or neutron scatter into a different direction. The result is the reduction of the flux described by:

$$\phi(x) = \phi_0 - R(x)$$

Where: $\phi(x)$ is the incident neutron flux [n*cm^{-2}*s^{-1}]
$R(x)$ is the number of interactions in neutron beam

Through substitution of the reaction rate equation and the application of initial conditions at *x*=0 that *R*=0, the following equation for reaction rate is defined:

$$R(x) = \phi_0(1 - e^{-n_t \sigma_t x}) \text{ [reactions/cm}^2\text{]}$$

When the above equation is multiplied by foil area perpendicular to the neutron beam, the total rate at which neutrons interact with nuclei in the foil is calculated. This total interaction rate includes scattering events and many types of absorption reactions. The assumption is made that the scattered neutrons do not react further in the foil which is true if the foils are sufficiently thin. The activity that will be measured in the foil for neutron accident dosimetry is produced by a particular reaction, "z", depending on the material type. Thus, it is the rate at which the particular reaction is occurring, not the total rate of reactions that needs to be related to activity in the foil.

The particular reaction rate is determined using the total reaction rate discussed above and multiplying by the relative probability that the particular reaction of interest will happen. The relative probability is determined by the ratio of the macroscopic cross section Σ_z for the particular reaction to the total macroscopic cross section Σ_t. The rate at which the nuclei of interest are activated is calculated using the following equation:

$$R_z(x) * Area = \phi_0 * Area * (1 - e^{-n_t \sigma_t x}) \frac{\Sigma_z}{\Sigma_t}$$

During activation, the rate of change of the number *N* of the activated species is equal to the rate of species creation given above minus the decay rate as shown below:

$$\frac{dN}{dt} = R_z(x) * Area - \lambda N$$

After the irradiation, the rate of change of activated species is given by just the decay term:

$$\frac{dN}{dt} = -\lambda N$$

This decay results in the number of activated species at a given time *t* of:

$$N(t) = N_0 e^{-\lambda t}$$

It will take a time t_1 to transport the sample to the counting laboratory and a time $\Delta t = t_2 - t_1$ to count the sample. The number of atoms which decay in time Δt *is* ΔN given by:

$$\Delta N = N_0 e^{-\lambda t_1} - N_0 e^{-\lambda(t_1 + t_2)}$$

The activity at $t = t_0$ is A_0, which is equal to λN_0 and thus the calculation for activity is:

$$A_0 = \frac{\Delta N}{\Delta t} e^{\lambda t_1} \frac{\lambda \Delta t}{(1 - e^{-\lambda \Delta t})}$$

Once the initial activity has been determined using NAA, calculations with known physical constants and the effective absorption cross section may be used to determine the neutron fluence that passed through the material during irradiation. This calculation has been previously published (Hankins, 1984, Hickman, et. al. 2009).

Appendix B. Lawrence Livermore National Laboratory Nuclear Accident Dosimeter Data

Table B1. Individual Dosimeter Fluence and Dose Results for Irradiation #1.

NADs Located on Metal Stand – Front Facing Core											
2 m	Neutron Fluence (n cm^{-2})				Neutron Dose (Rad)				Total Neutron Dose (rad)	Gamma Dose (rad)	Total Dose (rad)
NAD ID #	**> 3 MeV**	**1 MeV – 3 MeV**	**1 eV – 1 MeV**	**Thermal**	**> 3 MeV**	**1 MeV- 3 MeV**	**1 eV – 1 MeV**	**Thermal**			
1464	2.1E+10	6.7E+10	2.0E+11	2.2E+10	110	220	160	1.5	490	87.8	578
2478	2.0E+10	7.1E+10	1.8E+11	1.8E+10	110	230	150	1.3	490	64.5	554
12716	2.0E+10	7.3E+10	1.7E+11	2.2E+10	110	240	140	1.6	490	40.5	531
FNAD 1	1.2E+10	8.8E+10	1.4E+11	1.5E+10	64	290	120	1	480	-	-
FNAD 2	1.2E+10	8.6E+10	1.5E+11	2.1E+10	63	280	120	1.5	460	-	-
FNAD 3	1.1E+10	8.7E+10	1.5E+11	2.1E+10	60	290	120	1.5	470	-	-
AVG	**1.6E+10**	**7.9E+10**	**1.7E+11**	**2.0E+10**	**86**	**258**	**135**	**1.4**	**480 ± 13**	**64.3**	**544**
NADs Located on Metal Stand - Left Side Facing Core											
2 m	Neutron Fluence (n cm^{-2})				Neutron Dose (Rad)				Total Neutron Dose (Rad)	Gamma Dose (rad)	Total Dose (rad)
NAD ID #	**> 3 MeV**	**1 MeV – 3 MeV**	**1 eV – 1 MeV**			**1 MeV- 3 MeV**	**1 eV – 1 MeV**	**Thermal**			
5160	1.9E+10	1.1E+11	2.2E+11	2.1E+10	100	360	180	1.5	640	79.7	720
6201	2.0E+10	1.1E+11	2.2E+11	2.1E+10	110	350	180	1.5	640	86.7	727
7290	2.1E+10	1.1E+11	2.4E+11	1.9E+10	110	350	190	1.3	650	82.4	732
AVG	**2.0E+10**	**1.1E+11**	**2.3E+11**	**2.0E+10**	**107**	**353**	**183**	**1.4**	**643 ± 6**	**82.9**	**746**
NADs Located on Metal Stand - Right Side Facing Core											
2 m	Neutron Fluence (n cm^{-2})				Neutron Dose (Rad)				Total Neutron Dose (Rad)	Gamma Dose (rad)	Total Dose (rad)
NAD ID #	**> 3 MeV**	**1 MeV – 3 MeV**	**1 eV – 1 MeV**			**1 MeV- 3 MeV**	**1 eV – 1 MeV**	**Thermal**			
3241	2.8E+10	5.1E+10	1.7E+11	2.1E+10	150	170	140	1.5	460	91.4	551
10389	2.7E+10	6.4E+10	1.5E+11	1.8E+10	140	210	120	1.3	470	68.8	539
12781	3.0E+10	4.5E+10	1.8E+11	1.8E+10	160	150	150	1.3	460	47.9	508
AVG	**2.8E+10**	**5.3E+10**	**1.7E+11**	**1.9E+10**	**150**	**177**	**137**	**1.4**	**463 ± 6**	**69.4**	**532**

Table B1. Individual Dosimeter Fluence and Dose Results for Irradiation #1 (continued).

NADs Located on Metal Stand – Front Facing Core

3 m	Neutron Fluence (n cm^{-2})				Neutron Dose (Rad)				Total Neutron Dose (RAD)	Gamma Dose (rad)	Total Dose (rad)
NAD ID #	**> 3 MeV**	**1 MeV – 3 MeV**	**1 eV – 1 MeV**			**1 MeV- 3 MeV**	**1 eV – 1 MeV**	**Thermal**			
9067	9.6E+09	3.8E+10	1.5E+11	1.9E+10	51	130	120	1.4	300	18.0	318
11810	9.7E+09	3.0E+10	1.4E+11	2.0E+10	52	99	120	1.4	270	17.0	287
13225	9.4E+09	3.5E+10	1.6E+11	2.0E+10	50	120	130	1.4	300	19.6	320
FNAD11	6.3E+09	4.3E+10	1.1E+11	2.2E+10	33	140	88	1.5	260	-	-
FNAD12	5.7E+09	4.3E+10	1.1E+11	2.0E+10	30	140	91	1.4	260	-	-
FNAD14	5.5E+09	4.0E+10	1.1E+11	2.0E+10	29	130	87	1.4	250	-	-
AVG	**7.7E+09**	**3.8E+10**	**1.3E+11**	**2.0E+10**	**41**	**127**	**106**	**1.4**	**273 ± 22**	**18.2**	**295**

NADs Located on Metal Stand – Front Facing Core

4 m	Neutron Fluence (n cm^{-2})				Neutron Dose (Rad)				Total Neutron Dose (Rad)	Gamma Dose (rad)	Total Dose (rad)
NAD ID #	**> 3 MeV**	**1 MeV – 3 MeV**	**1 eV – 1 MeV**			**1 MeV- 3 MeV**	**1 eV – 1 MeV**	**Thermal**			
858	5.9E+09	2.5E+10	1.5E+11	1.9E+10	31	81	120	1.4	230	28.6	259
5081	5.7E+09	2.4E+10	1.2E+11	1.9E+10	30	80	99	1.4	210	20.6	231
12697	5.3E+09	2.3E+10	1.5E+11	1.9E+10	28	75	120	1.3	220	5.4	225
FNAD 5	3.3E+09	2.9E+10	1.1E+11	2.1E+10	17	97	86	1.4	200	-	-
FNAD 6	3.3E+09	2.7E+10	9.6E+10	2.0E+10	17	88	78	1.4	180	-	-
FNAD 7	3.2E+09	2.8E+10	1.0E+11	2.0E+10	17	91	82	1.4	190	-	-
AVG	**4.5E+09**	**2.6E+10**	**1.2E+11**	**2.0E+10**	**23**	**85**	**98**	**1.4**	**205 ± 19**	**18.2**	**223**

Table B2. Individual Dosimeter Fluence and Dose Results for Irradiation #2.

NADs Located on Metal Stand – Front Facing Core											
2 m	Neutron Fluence (n cm^{-2})				Neutron Dose (Rad)				Total Neutron Dose (Rad)	Gamma Dose (rad)	Total Dose (rad)
NAD ID #	> 3 MeV	1 MeV – 3 MeV	1 eV – 1 MeV			1 MeV- 3 MeV	1 eV – 1 MeV	Thermal			
2137	3.1E+10	1.0E+11	2.7E+11	3.0E+10	160	340	220	2.1	720	100	820
3533	3.1E+10	1.0E+11	2.4E+11	3.0E+10	160	330	190	2.1	680	103	783
95991	2.9E+10	9.9E+10	2.8E+11	2.7E+10	160	330	230	1.9	720	57.6	778
FNAD16	1.7E+10	1.3E+11	2.0E+11	3.0E+10	89	440	160	2.1	690	-	
FNAD17	1.6E+10	1.3E+11	2.1E+11	2.9E+10	86	420	170	2	680	-	
AVG	**2.5E+10**	**1.1E+11**	**2.4E+11**	**2.9E+10**	**131**	**372**	**194**	**2.0**	**698 ± 20**	**87.0**	**793**
NADs Located on Metal Stand - Left Side Facing Core											
2 m	Neutron Fluence (n cm^{-2})				Neutron Dose (Rad)				Total Neutron Dose (Rad)	Gamma Dose (rad)	Total Dose (rad)
NAD ID #	> 3 MeV	1 MeV – 3 MeV	1 eV – 1 MeV			1 MeV- 3 MeV	1 eV – 1 MeV	Thermal			
6665	2.4E+10	6.0E+10	1.5E+11	2.6E+10	130	200	130	1.8	460	84.5	544
12737	2.5E+10	6.3E+10	2.0E+11	2.9E+10	130	210	160	2	500	88.7	589
8100	2.3E+10	1.1E+11	2.3E+11	2.7E+10	120	350	190	1.9	660	65.9	726
AVG	**2.4E+10**	**7.7E+10**	**2.0E+11**	**2.7E+10**	**127**	**253**	**160**	**1.9**	**540 ± 106**	**79.7**	**620**
NADs Located on Metal Stand - Right Side Facing Core											
2 m	Neutron Fluence (n cm^{-2})				Neutron Dose (Rad)				Total Neutron Dose (Rad)	Gamma Dose (rad)	Total Dose (rad)
NAD ID #	> 3 MeV	1 MeV – 3 MeV	1 eV – 1 MeV			1 MeV- 3 MeV	1 eV – 1 MeV	Thermal			
8100	2.3E+10	1.1E+11	2.3E+11	2.7E+10	120	350	190	1.9	660	85.6	746
13055	1.4E+10	1.1E+11	2.2E+11	3.1E+10	74	350	180	2.1	610	64.9	675
34187	1.8E+10	1.0E+11	2.2E+11	3.0E+10	95	330	180	2.1	610	69.6	680
AVG	**1.8E+10**	**1.0E+11**	**2.3E+11**	**2.9E+10**	**96**	**343**	**183**	**2.0**	**627 ± 29**	**73.3**	**700**

Table B2. Individual Dosimeter Fluence and Dose Results for Irradiation #2 (continued).

NADs Located on Phantom											
2.5 m	**Neutron Fluence (n cm^{-2})**				**Neutron Dose (Rad)**				**Total Neutron Dose (Rad)**	**Gamma Dose (rad)**	**Total Dose (rad)**
NAD ID #	**> 3 MeV**	**1 MeV – 3 MeV**	**1 eV – 1 MeV**			**1 MeV- 3 MeV**	**1 eV – 1 MeV**	**Thermal**			
5275	2.1E+10	7.8E+10	2.8E+11	6.7E+10	110	260	230	4.7	600	135	735
7232	2.4E+10	7.6E+10	2.3E+11	6.6E+10	130	250	190	4.6	570	106	676
96038	2.1E+10	7.5E+10	2.6E+11	5.3E+10	110	250	210	3.7	570	108	678
AVG	**2.2E+10**	**7.6E+10**	**2.6E+11**	**6.2E+10**	**117**	**253**	**210**	**4.3**	**580 ± 17**	**116**	**696**
NADs Located on Metal Stand – Front Facing Core											
3 m	**Neutron Fluence (n cm^{-2})**				**Neutron Dose (Rad)**				**Total Neutron Dose (RAD)**	**Gamma Dose (rad)**	**Total Dose (rad)**
NAD ID #	**> 3 MeV**	**1 MeV – 3 MeV**	**1 eV – 1 MeV**			**1 MeV- 3 MeV**	**1 eV – 1 MeV**	**Thermal**			
FNAD15	7.8E+09	5.9E+10	1.5E+11	2.9E+10	41	200	120	2	360	-	-
FNAD18	8.2E+09	6.2E+10	1.6E+11	3.0E+10	43	200	130	2.1	380	-	-
AVG	**8.0E+09**	**6.0E+10**	**1.6E+11**	**2.9E+10**	**42**	**200**	**125**	**2.1**	**370 ± 14**	**-**	**-**
NADs Located on Reactor Cell Wall											
3.63 m	**Neutron Fluence (n cm^{-2})**				**Neutron Dose (Rad)**				**Total Neutron Dose (Rad)**	**Gamma Dose (rad)**	**Total Dose (rad)**
NAD ID #	**> 3 MeV**	**1 MeV – 3 MeV**	**1 eV – 1 MeV**			**1 MeV- 3 MeV**	**1 eV – 1 MeV**	**Thermal**			
FNAD10	6.3E+09	5.0E+10	1.6E+11	3.2E+10	34	160	130	2.3	330	-	-
FNAD 8	6.1E+09	5.2E+10	2.2E+11	3.2E+10	32	170	180	2.3	380	-	-
FNAD 9	6.0E+09	5.3E+10	1.9E+11	3.3E+10	32	180	160	2.3	370	-	-
AVG	**6.1E+09**	**5.2E+10**	**1.9E+11**	**3.2E+10**	**33**	**170**	**157**	**2.3**	**360 ± 26**	**-**	**-**

Table B3. Individual PIC Measurement Results for 1st and 2nd Irradiations.

Caliban 1st Irradiation	2 Meters	3 Meters	4 Meters
JG215044			
JG215045			
JG215046			
JG215048	92000		
JG215055	99000		
JG215061	101000		
JG215049		60000	
JG215057		60000	
JG215058		39000	
JG215052			41000
JG215054			41000
JG215062			45000

Caliban 2nd Irradiation	2 Meters	3 Meters	4 Meters	Wall
JG215043				
JG215047				
JG215050	92000			
JG215053	98000			
JG215059	100000			
JG215051				50000
JG215056				53000
JG215060				58000

Table B4. Caliban Lookup Values for Dose Computations.

Element	$T_{1/2}$	units	lambda	CF	Fluence Conversion Value (n g/cm uCi)	Dose Factor (rads cm^2 / n)	Approximate Energy Range
1_In	4.5	h	0.1540	2244	6.81E+11	3.3E-09	1 - 3 MeV
2_S	14.26	d	0.0020	31000	2.90E+13	5.3E-09	> 3 MeV
3_Cu	12.8	h	0.0542	4000	5.01E+12	8.1E-10	1 eV - 1 MeV
4_Bare Au	64.8	h	0.0107	2.1	3.00E+10	7.0E-11	Thermal
5_Shielded Au	64.8	h	0.0107	2.1	3.00E+10	----	----

Sulfur Fluence Conversion Factor is based on counting a solid pellet.

Sulfur Counting Efficiency Calibration based on a 47 mm distributed Sr/Y-90 source.

Table B5. PNAD irradiation, position and mass (in g) data for Caliban exercise.

Dosimeter_ID	Irradiation_No	Position	Distance	Type	B Covered In	In Mass Bare In	S Sulfur Mass	Cu Copper	Bare Au	Shielded Au Cd Covered Au
858	Caliban 1	#7	4 Meters	PNAD	0.381	0.521	0.858	0.349	0.301	0.176
1464	Caliban 1	#3	2 Meters	PNAD	0.369	0.523	0.791	0.340	0.291	0.159
1822	Control			PNAD	0.372	0.525	0.843	0.344	0.290	0.141
2137	Caliban 2	#2	2 Meters	PNAD	0.362	0.492	0.852	0.341	0.287	0.149
2249	Control			PNAD	0.371	0.505	0.866	0.342	0.286	0.131
2478	Caliban 1	#3	2 Meters	PNAD	0.374	0.526	0.867	0.343	0.285	0.153
2922	Control			PNAD	0.371	0.492	0.850	0.346	0.263	0.214
3241	Caliban 1	#4	2 Meters (RS)	PNAD	0.367	0.489	0.867	0.343	0.274	0.170
3533	Caliban 2	#2	2 Meters	PNAD	0.367	0.501	0.841	0.342	0.294	0.169
5081	Caliban 1	#7	4 Meters	PNAD	0.370	0.504	0.874	0.342	0.287	0.125
5160	Caliban 1	#4	2 Meters (LS)	PNAD	0.361	0.478	0.864	0.341	0.280	0.180
5275	Caliban 2	#11	Phantom (C)	PNAD	0.372	0.494	0.854	0.345	0.277	0.130
6201	Caliban 1	#4	2 Meters (LS)	PNAD	0.383	0.515	0.892	0.342	0.290	0.175
6665	Caliban 2	#4	2 Meters (LS)	PNAD	0.363	0.514	0.861	0.344	0.270	0.147
6849	Caliban 2	#4	2 Meters (LS)	PNAD	0.341	0.520	0.850	0.368	0.287	0.142
7232	Caliban 2	#11	Phantom (L)	PNAD	0.374	0.498	0.863	0.343	0.292	0.154
7290	Caliban 1	#4	2 Meters (LS)	PNAD	0.377	0.502	0.861	0.342	0.334	0.150
8100	Caliban 2	#4	2 Meters (RS)	PNAD	0.364	0.517	0.864	0.344	0.278	0.180
8591	Control			PNAD	0.371	0.503	0.845	0.342	0.288	0.128
9607	Caliban 1	#6	3 Meters	PNAD	0.366	0.514	0.843	0.342	0.294	0.187
10389	Caliban 1	#4	2 Meters (RS)	PNAD	0.371	0.497	0.873	0.342	0.286	0.208
11225	Control			PNAD	0.374	0.519	0.870	0.353	0.300	0.201
11810	Caliban 1	#6	3 Meters	PNAD	0.348	0.527	0.830	0.343	0.207	0.135
12625	Control			PNAD	0.367	0.513	0.858	0.342	0.251	0.167
12645	Caliban 2		Wall	PNAD	0.365	0.492	0.877	0.341	0.290	0.178
12697	Caliban 1	#7	4 Meters	PNAD	0.373	0.503	0.862	0.342	0.279	0.154
12716	Caliban 1	#3	2 Meters	PNAD	0.372	0.513	0.869	0.342	0.275	0.143
12725	Caliban 2		Wall	PNAD	0.374	0.504	0.883	0.343	0.257	0.186
12737	Caliban 2	#4	2 Meters (LS)	PNAD	0.365	0.462	0.849	0.341	0.293	0.154
12781	Caliban 1	#4	2 Meters (RS)	PNAD	0.374	0.512	0.836	0.342	0.259	0.173
13055	Caliban 2	#4	2 Meters (RS)	PNAD	0.340	0.454	0.850	0.346	0.274	0.164
13127	Caliban 2		Wall	PNAD	0.379	0.516	0.875	0.342	0.268	0.172
13225	Caliban 1	#6	3 Meters	PNAD	0.361	0.493	0.892	0.342	0.291	0.170
34187	Caliban 2	#4	2 Meters (RS)	PNAD	0.372	0.507	0.882	0.342	0.280	0.164
95991	Caliban 2	#2	2 Meters	PNAD	0.366	0.528	0.845	0.344	0.291	0.182
96038	Caliban 2	#11	Phantom (R)	PNAD	0.340	0.502	0.865	0.342	0.265	0.142

Table B6. FNAD irradiation, position and physical data for Caliban exercise.

Dosimeter_ID	Irradiation_No	Position	Distance	Type	In B Covered In (g) (SmIn Section 3)	Bare In (g) (not used)	S Sulfur Mass (g) (Section 1)	Cu Copper (g) (Section 3)	Bare Au Bare Au (g) (Section 1)	Shielded Au Cd Covered Au (g) (Section 2)
				Wall 1					Caliban 1	#3
Wall 2	Caliban 1	#3	2 Meters	FNAD	1.255	1.437	5.778	1.653	0.344	0.386
Wall 3	Caliban 1	#3	2 Meters	FNAD	1.421	1.409	5.828	1.658	0.357	0.398
Wall 4	Control			FNAD	1.312	1.376	5.923	1.655	0.382	0.346
Wall 5	Caliban 1	#7	4 Meters	FNAD	1.051	1.330	5.707	1.650	0.385	0.403
Wall 6	Caliban 1	#7	4 Meters	FNAD	1.186	1.385	5.952	1.652	0.397	0.379
Wall 7	Caliban 1	#7	4 Meters	FNAD	1.320	1.369	5.996	1.651	0.384	0.374
Wall 8	Caliban 2		Wall	FNAD	1.324	1.313	5.816	1.659	0.376	0.381
Wall 9	Caliban 2		Wall	FNAD	1.230	1.400	5.932	1.663	0.405	0.396
Wall 10	Caliban 2		Wall	FNAD	1.302	1.363	5.632	1.651	0.371	0.396
Wall 11	Caliban 1	#6	3 Meters	FNAD	1.208	1.418	5.055	1.655	0.354	0.388
Wall 12	Caliban 1	#6	3 Meters	FNAD	1.094	1.343	5.797	1.654	0.362	0.344
Wall 13	Control			FNAD	1.011	1.364	5.665	1.652	0.392	0.353
Wall 14	Caliban 1	#6	3 Meters	FNAD	1.230	1.384	5.698	1.649	0.354	0.399
Wall 15	Caliban 2	#5	3 Meters	FNAD	1.207	1.387	5.825	1.658	0.384	0.377
Wall 16	Caliban 2	#2	2 Meters	FNAD	1.062	1.427	6.078	1.652	0.368	0.381
Wall 17	Caliban 2	#2	2 Meters	FNAD	1.131	1.297	6.060	1.658	0.338	0.350
Wall 18	Caliban 2	#5	3 Meters	FNAD	1.101	1.407	5.791	1.653	0.375	0.399

Table B7. Sulfur pellet count results for counts performed at LLNL post exercise.

		Whole Pellet	Melted		Crushed	
NAD ID	**Pellet Weight**	**Decay Corrected Activity (µCi)**	**Decay Corrected Activity (µCi)**	**Melted /Pellet**	**Decay Corrected Activity (µCi)**	**Crushed /Pellet**
858	0.858	1.312E-04	3.015E-04	2.30	3.945E-04	3.01
1464	0.791	4.601E-04	8.711E-04	1.89	1.365E-03	2.97
2137	0.852	6.937E-04	1.313E-03	1.89	1.850E-03	2.67
2478	0.867	4.891E-04	9.259E-04	1.89	1.413E-03	2.89
3241	0.867	6.011E-04	1.231E-03	2.05	1.630E-03	2.71
3533	0.841	6.660E-04	1.282E-03	1.93	1.956E-03	2.94
5081	0.874	1.101E-04	2.535E-04	2.30	3.981E-04	3.62
5160	0.864	4.460E-04	8.855E-04	1.99	1.337E-03	3.00
5275	0.854	4.794E-04	9.624E-04	2.01	1.428E-03	2.98
6201	0.892	4.341E-04	8.880E-04	2.05	1.321E-03	3.04
6665	0.861	5.866E-04	1.211E-03	2.06	1.725E-03	2.94
6849	0.85	5.244E-04	1.053E-03	2.01	1.580E-03	3.01
7232	0.863	5.157E-04	9.002E-04	1.75	1.542E-03	2.99
7290	0.861	5.164E-04	9.884E-04	1.91	1.454E-03	2.82
8100	0.864	5.169E-04	1.078E-03	2.09	1.478E-03	2.86
9607	0.843	2.109E-04	4.285E-04	2.03	6.070E-04	2.88
10389	0.873	6.236E-04	1.254E-03	2.01	1.842E-03	2.95
11810	0.83	2.056E-04	4.022E-04	1.96	5.745E-04	2.79
12697	0.862	1.212E-04	2.779E-04	2.29	3.805E-04	3.14
12716	0.869	4.738E-04	9.136E-04	1.93	1.393E-03	2.94
12737	0.849	5.715E-04	1.095E-03	1.92	1.697E-03	2.97
12781	0.836	6.706E-04	1.054E-03	1.57	1.873E-03	2.79
13055	0.85	3.125E-04	6.170E-04	1.97	8.857E-04	2.83
13225	0.892	2.278E-04	4.818E-04	2.12	7.070E-04	3.10
34187	0.882	3.948E-04	8.283E-04	2.10	1.280E-03	3.24
95991	0.845	6.726E-04	1.264E-03	1.88	2.009E-03	2.99
96038	0.865	4.818E-04	9.508E-04	1.97	1.631E-03	3.38
Wall 1	5.706	1.836E-03	5.132E-03	2.80		
Wall 10	5.632	8.904E-04	2.584E-03	2.90		
Wall 11	5.055	8.515E-04	2.387E-03	2.80		
Wall 12	5.797	8.521E-04	2.373E-03	2.79	2.118E-03	2.49
Wall 14	5.665	8.542E-04	2.363E-03	2.77		
Wall 15	5.698	1.149E-03	3.337E-03	2.91		
Wall 16	6.078	2.637E-03	7.104E-03	2.69		
Wall 17	6.06	2.484E-03	7.001E-03	2.82		
Wall 18	5.791	1.214E-03	3.280E-03	2.70	3.037E-03	2.50
Wall 2	5.778	1.880E-03	4.989E-03	2.65	4.686E-03	2.49
Wall 3	5.828	1.818E-03	5.371E-03	2.95	4.374E-03	2.41
Wall 3	5.923				4.613E-03	2.54
Wall 5	5.707	5.221E-04	1.426E-03	2.73	1.395E-03	2.67
Wall 6	5.952	5.032E-04	1.416E-03	2.81	1.285E-03	2.55
Wall 7	5.996	5.086E-04	1.504E-03	2.96		
Wall 8	5.816	8.924E-04	2.644E-03	2.96		
Wall 9	5.932	9.148E-04	2.617E-03	2.86		

Table B8. SRS and LLNL results intercomparison of gamma counts for foils measured during the Caliban exercise.

Nad Foil Owner	Foil Type	SRS Results	LLNL Results	% Difference
LLNL	Small Gold	.0878	.0897	2.1
SRS	Large Indium[9]	.00616[10]/4.037	0.110/3.825	NA/5.2
LLNL	FNAD Indium[9]	0.053/0.143	0.056/0.161	5.6/12.6
PNNL	FNAD Gold	0.2714	0.2952	8.0
PNNL	Indium[9]	0.00000/3.477	.002846/3.462	NA/0.4

[9] In115m/In116m

[10] Low level of identification confidence (i.e., peak not highly prominent)