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Sandia National Laboratories Results for the 2010 Criticality Accident Dosimetry Exercise, at the CALIBAN Reactor, CEA Valduc France.

September 2010

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Prepared by
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Abstract

This document describes the personal nuclear accident dosimeter (PNAD) used by Sandia National Laboratories (SNL) and presents PNAD dosimetry results obtained during the Nuclear Accident Dosimeter Intercomparison Study held 20 – 23 September, 2010, at CEA Valduc, France. SNL PNADs were exposed in two separate irradiations from the CALIBAN reactor. Biases for reported neutron doses ranged from -15% to +0.4% with an average bias of -7.7%. PNADs were also exposed on the back side of phantoms to assess orientation effects.

Acknowledgement

The author wishes to thank Bob Miltenberger (Sandia National Laboratories, Radiation Protection Program Manager) and David Heinricks/David Hickman (Lawrence Livermore National Laboratories) for their support and guidance regarding this work.

Acronyms and Abbreviations

Al	Aluminum
Cu	Copper
F	Fluorine
FNAD	Fixed Nuclear Accident Dosimeter
In	Indium
Na	Sodium
Ni	Nickel
PNAD	Personal Nuclear Accident Dosimeter
SNL	Sandia National Laboratories
Ti	Titanium
TLD	Thermoluminescent Dosimeter

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Introduction

Purpose

During the period of 20 – 24 September, 2010, Sandia National Laboratories (SNL) participated in a criticality accident dosimetry exercise at Commissariat A L ’énergie Atomique Et Aux Énergies Alternatives (CEA) Valduc, France. The exercise was funded by the U.S. Department of Energy Nuclear Criticality Safety Program and coordinated through Lawrence Livermore National Laboratory (LLNL). Other participating facilities included LLNL, Pacific Northwest National Laboratory (PNL), Y-12 National Security Complex, Los Alamos National Laboratory (LANL), and Oak Ridge National Laboratory (ORNL).

The goals for SNLs participation were to: (1) test and validate the procedures used to determine dose values resulting from a criticality accident; (2) test and validate the Quick-Scan procedure used to produce an initial neutron dose estimate, and (3) evaluate the use of operational field equipment for the measurement of accident dosimeter materials.

Background

The exercise was conducted using the CALIBAN reactor. CALIBAN is a metallic core cylindrical reactor. Its diameter is 19.5 cm and its height is 25 cm. It is composed of two blocks: a fixed block and a mobile one. Each block is made of five metallic plates of a molybdenum and highly enriched uranium alloy. Four cylindrical control rods, made of the same alloy, allow operation in two modes: a steady state power mode and a pulsed mode (Casoli, 2007). For this exercise, two exposures were performed consisting of an unshielded (bare) low-power pulse and a bare high-power pulse. Participants were free to select the placement of their dosimetry materials according to the radial distance from the center axis of the assembly, orientation to the assembly, and whether or not they were placed on a phantom.

The SNL Personal Nuclear Accident Dosimeter (PNAD) contains six different types of activation foils (Figure 1) and is a sealed unit (Ward et al, 1996). The dosimeter has an indefinite shelf life and remains inert until it becomes activated. SNL PNADs are serial numbered and issued to individuals. PNADs are not exchanged on an established schedule.

Per current SNL guidance, a single PNAD is worn on the upper torso along side of the SNL Whole body Thermoluminescent Dosimeter (TLD). The SNL TLD is a Thermo Electron Type 8825 dosimeter badge (See Appendix A). In an accident situation, the SNL PNAD is the primary dosimeter used to determine neutron dose ($D_{\mathbf{n}}$)[1] and elements 1 & 2 of the SNL TLD are used to estimate the deep dose due to X-rays & gammas (D_{γ}).

[1] $D_{\mathbf{n}} = D_{\mathbf{HP}} + D_{\mathbf{n}\gamma}$, See Appendix C, PNAD Data Tables

If a criticality accident should occur, an initial "rough" estimate of neutron exposures can be quickly obtained by measuring the exposure rate on the surface of the PNAD with a portable survey instrument (Figure 2). Figure 3 is the nomogram used by SNL monitoring personnel to quickly sort individuals by estimated exposure level (Ward et al, 1996; Hill 2004). This provides Health Physics and Medical personnel with a triage process. In this way, immediate medical care can be focused where it is needed the most. Medical personnel can also be provided with information that identifies individuals who may have received little or no exposure to neutron radiation. The Nomogram does not however, provide any information regarding possible exposure to X-ray/gamma radiation.

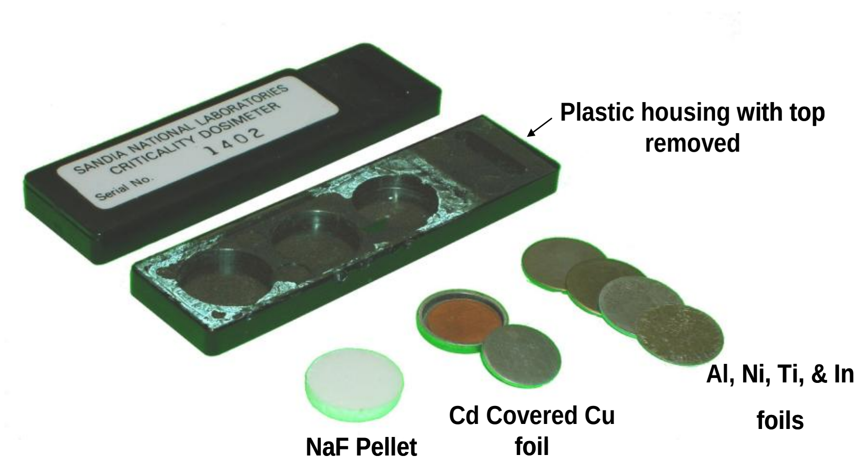

Figure 1: A PNAD measures 19 mm wide by 7 mm thick by 65 mm long. Weight is 11.3 g.

Figure 2: The SNL "PNAD Quick-Scan" process an SHP270 probe (shield in closed position) connected to an Eberline E600. The SHP270 probe is calibrated to 137Cs.

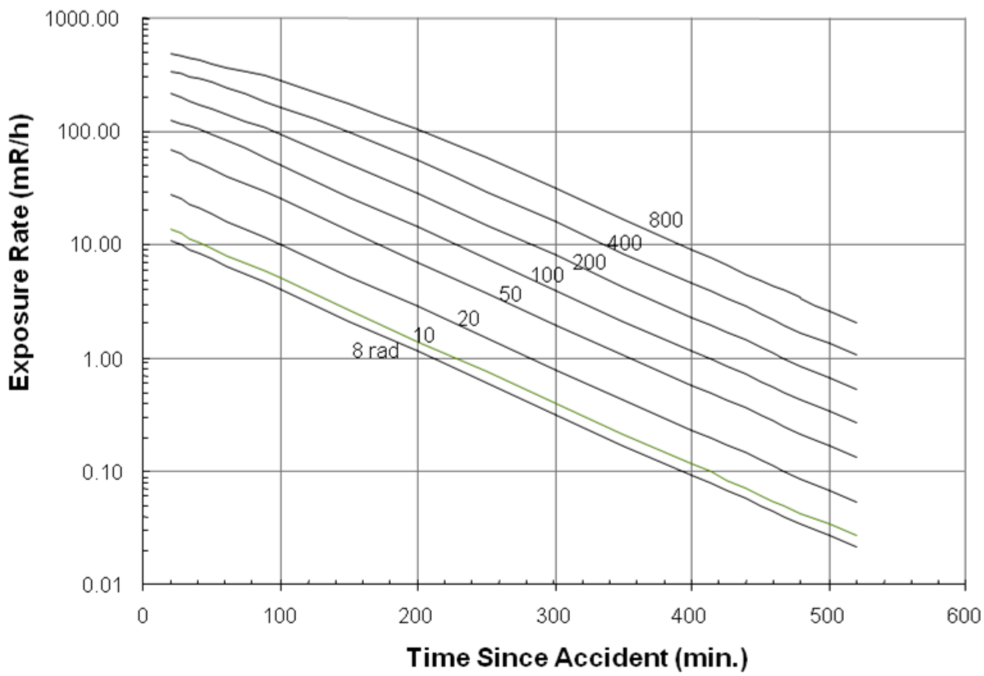

Figure 3: Nomogram for "PNAD Quick-Scan" measurements. This nomogram is applicable to a bare metal (or lightly filtered) 235U fission spectrum. Nomograms for other types of neutron spectrums can be developed (see Appendix D).

Table 1 identifies the reactions in commonly used neutron foils that are useful for dosimetry purposes (Griffin et al., 1993). The two indium reactions shown in Table 1 have different uses. The $^{115}In(n,\gamma)^{116m}In$ reaction has a very large cross section for low energy neutrons but a short (54 m) half-life. This reaction produces a relatively large foil activity that dies away quite rapidly. This activity is most useful for determining if the wearer was involved in a criticality accident. Portable health physics survey equipment is used to "Quick-Scan" the PNAD (Figure 2). Appendix B contains the Quick-Scan data obtained during this intercomparison. The Quick-Scan results are intended for medical triage purposes only.

The second indium reaction, $^{115}In(n,n')^{115m}In$, has a longer half-life (4.36 h) and is used for dosimetry purposes. After exposure to neutron radiation, the resulting activity due to ^{116m}In is several times that of ^{115m}In. As a result (in order to minimize counting system dead time) an indium foil is not counted immediately. A cool-down period of several hours is used to allow the majority of the ^{116m}In activity to decay away.

Table 1: Dosimetry Reactions

Material	Reaction	Half-Life	E_γ (keV)	Gamma Yield (%)	Threshold (MeV)
Al	$^{27}Al(n,\alpha)^{24}Na$	15 h	1368.633	100.0	8
Ti	$^{47}Ti(n,p)^{47}Sc$	3.4 d	159.381	67.9	2
Ni	$^{58}Ni(n,p)^{58}Co$	70.9 d	810.775	99.4	3
Cu	$^{63}Cu(n,\gamma)^{64}Cu$	12.9 h	1345.77	0.47	Epithermal
In	$^{115}In(n,n')^{115m}In$	4.36 h	336.241	45.9	1
	$^{115}In(n,\gamma)^{116m}In$	54.4 m	1293.54	84.4	Thermal†
Na	$^{23}Na(n,\gamma)^{24}Na$	15 h	1368.633	100.0	Epithermal

† Not used for dosimetry purposes, but used for Quick-Scan purposes.

Methods

The CALIBAN reactor was used to provide two separate exposure pulses. Each pulse was done without any shielding external to the core. For each pulse, PNADs and TLDs were placed together. Dosimeter and PNAD locations are indicated in Table 2. For Pulse # 1, two exposure locations were used (Figure 4). The first location was on a Lucite phantom located at a distance of 4 meters from CALIBAN. The second location was a free in-air location at a distance of 2 meters from CALIBAN. The following day, Pulse # 2 was provided. The exposure location was on a torso phantom located at a distance of 2.5 meters from CALIBAN. Dosimeters were retrieved approximately 3 hours after each pulse exposure.

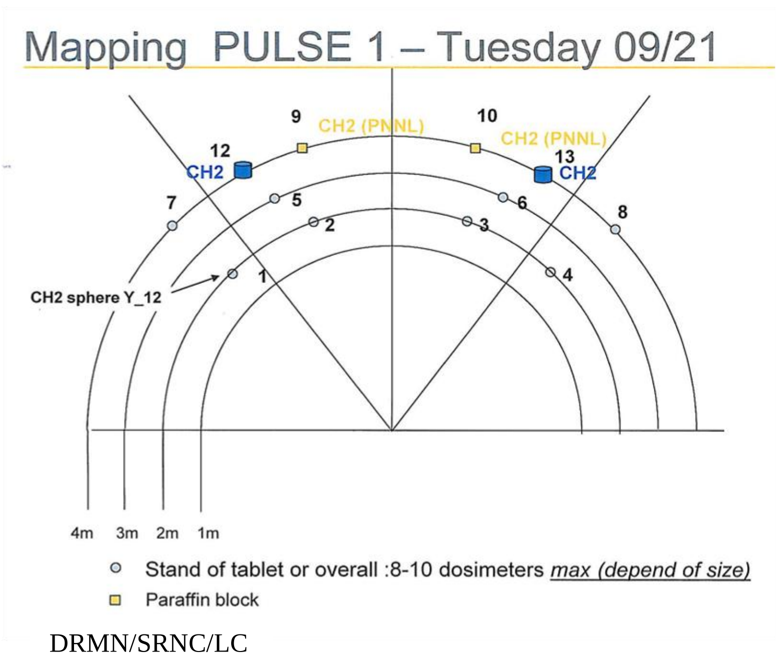

Figure 4: SNL dosimeters were located at position # 13 (Lucite phantom) and position # 2 (free in-air). (Courtesy of CEA Valduc).

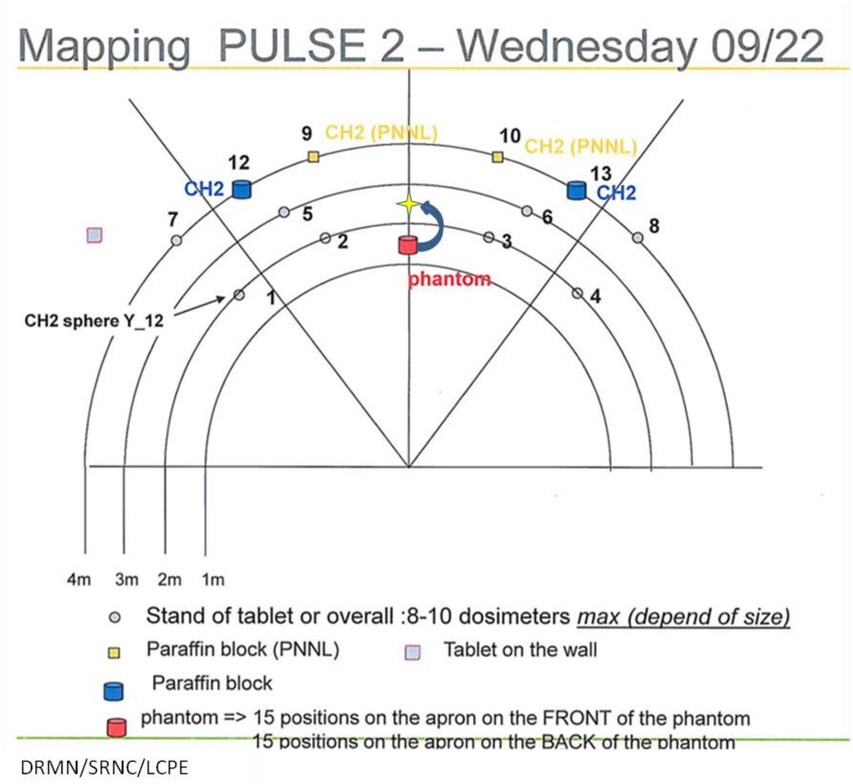

Figure 5: SNL dosimeters were located on the phantom which was located 2.5 m from CALIBAN. (Courtesy of CEA Valduc).

Upon retrieval, the PNADs and TLDs were treated differently. Surface exposure rate measurements were performed on the PNADs as shown in Figure 2. Afterwards, the PNADs were opened, their foils were visually inspected for signs of deterioration (there were no signs of deterioration) weighted, and then counted using a Falcon 5000 portable high purity germanium detector. TLD badges were opened and the cards placed into clean paper envelopes and returned to SNL for processing. TLD cards were removed from their badge holders because each holder contained thin copper and tin filters that become activated during the exposure and which were subsequently irradiating the enclosed card (See Appendix A). To ensure accuracy, the TLD cards were removed as soon as possible (approximately 3 hours post irradiation) from their holders. Foil counting data were analyzed using the methods described by Ward, et. al. (1996).

Table 2: Dosimeter Placement

Pulse #	Location	Dosimeters
1	4 meters from CALIBAN, on Lucite phantom (30 cm wide by 20 cm high by 10 cm thick)	
	Phantom Front	TLD # 54258
		TLD # 77967
		TLD # 51961
		TLD # 73154
		PNAD # 0137
		PNAD # 0085
	Phantom Side	TLD # 78166
		TLD # 67961
	Phantom Back	TLD† # 75735
		TLD† # 56354
		TLD† # 75943
		TLD† # 63126
		PNAD # 0336
		PNAD #0143
	2 meters from CALIBAN, free in-air	TLD # 52179
		TLD # 56859
		TLD # 73515
		TLD # 64788
		PNAD # 0344
		PNAD # 0364
2	2.5 meters from CALIBAN on torso phantom.	
	Phantom Front	TLD # 70074
		TLD # 75826
		TLD # 80078
		TLD # 72580
		PNAD # 0139
		PNAD # 0039
	Phantom Back	TLD† # 67195
		TLD† # 51676
		TLD† # 63698
		TLD† # 74233
		PNAD # 0372
		PNAD # 0385

† Orientation of TLD was facing away from the reactor to simulate and individuals with their backs to the source of the pulse.

Results

Overall PNAD and TLD Results

Tables 3 and 4 contain the dosimetry results. Table 5 is a summary of the relative bias between the SNL determined dose values and what was reported by CEA Valduc. ANSI N13.3 (ANSI, 1969) requires that under test conditions a criticality dosimetry system shall allow computation of neutron absorbed dose (**D_n**) to within ± 25%. Test conditions apply to dosimeters mounted on the front of the phantom (facing the source) or free in-air.

As shown in Table 5, the relative bias values (for **D_n)** for the front-mounted and free in-air dosimeters range from a low of -15% to a high of 0.4 %. All values are well within the performance limits specified in ANSI N13.3. The relative bias for gamma doses ranged for +3% to 66%.

The relative bias in SNL total dose[2] values varies from -13% to +9.6%.

Table 3: Dose Results - Pulse #1

			SNL			**CEA Valduc**		
Distance & Location	**PNAD #**	**Quick-Scan[†] Triage Est. (rad)**	**D_n From[‡] PNAD Foils (rad)**	**D_γ From TLD (rad)**	**Total (rad)**	**D_n* (rad)**	**D_γ* (rad)**	**Total* (rad)**
4 m, Phantom Front	0137	122	148±56.1	64 ± 10	218±40.8	170	40	210
	0085	120	158±55.8					
4 m, Phantom Side	n/a	n/a		58 ± 14				
	n/a	n/a						
4 m, Phantom Back	0336	92	28.8±27.5	58± 6	95±22.2			
	0143	93	44.4±32.9					
2 m, Free In-Air	0344	68	417±74	72± 14	505±55.8	510	70	580
	0364	70	450±78.6					

[†] See Appendix B for supporting data. Assumed spectrum is a bare Godiva (spectrum #12, Ward et al, [1996])

[‡] See Appendix C for supporting data. The average of the **D_n** values from the PNADs foils were used to calculate the total dose. Stated uncertainty is 2σ.

* Delivered values reported by CEA Valduc.

[2] Total dose = **$D_n + D_\gamma$**

Table 4: Dose Results - Pulse #2

			SNL			CEA Valduc		
Distance & Location	**PNAD #**	**Quick-Scan† Triage Est. (rad)**	**D_n From‡ PNAD Foils (rad)**	**D_γ From TLD (rad)**	**Total (rad)**	**D_n* (rad)**	**D_γ* (rad)**	**Total* (rad)**
2.5 m, Phantom Front	0139	207	516± 135	136± 26	638	500	82	582
	0039	207	489± 98.5					
2.5 m, Phantom Back	0372	108	74.9± 77.8	101± 10				
	0385	109	49.7± 37.8					

† See Appendix B for supporting data. Assumed spectrum is a bare Godiva (spectrum #12, Ward et al, [1996])

‡ See Appendix C for supporting data. The average of the $\mathbf{D_n}$ values from the PNAD foils was used to calculate the total dose. Calculated fluence values are available in this Appendix.

Table 5: Comparison of Measured to Delivered Doses.

		Relative Bias (%)		
Pulse #	**Location**	**D_n**	**D_γ**	**Total Dose**
1	4 m Phantom-Front	-10	60	4
	2 m Free In-Air	-15	3	-13
2	2.5 m Phantom Front	0.4	66	9.6

Dosimeters were also mounted on the back portion of the phantoms positioned at 2.5 and 4 m. The purpose of doing this was to estimate the worst case effect of wearer orientation on the dosimetry results. For the phantom mounted at 4 m, the Front-to-Back ratio for $\mathbf{D_n}$ is (153/36.6) or 4.18. For the phantom mounted at 2.5 m the ratio is (502/42.3) or 11.86. It is noted that the ratio values are very dependent upon the interplay between the incident spectrum, phantom thickness and room scatter effects. These $\mathbf{D_n}$ ratio values indicate that wearer orientation can have a large effect on calculated accident dosimetry values. In a real accident situation, extensive modeling using radiation transport codes or alternate dosimetry methods such as hair and blood analysis (Hankins, 1980), may be the only way to address this issue.

The Quick-Scan process

Multiple exposure rate measurements of intact PNADs were made to: (1) verify that dose estimates are independent of the time interval between a criticality event and when the exposure rate measurement is made, (2) to estimate the potential accuracy of the Quick-Scan dose estimate, and (3) to see if the Quick-Scan dose values produce suitable screening results. In an actual criticality event, only a single exposure rate measurement may be possible. Screening results should allow the rapid identification of personnel exposures in descending order from most-to-least severely exposed. Only a rough evaluation of doses is important at this stage (IAEA, 1982). There is no specific guidance on dose levels, but it is desirable to separate victims into those requiring immediate medical attention, (generally above 50 rad), those requiring further dose analysis and possible medical attention, (generally between 10 and 50 rad), and those who should not require further medical attention unless they develop unexpected symptoms (generally below 10 rad). This provides immediate guidance to medical services in selecting those in need of treatment and to prevent unnecessary overcrowding of medical facilities by lightly exposed individuals, reassurance to those who have received small or negligible doses and a rapid indication to management of the scope of the accident (IAEA, 1982).

Comparison of Quick-Scan versus PNAD Foil Analysis values.

Measured exposure rate values and the resulting dose estimates are contained in Appendix B. For each PNAD, measured values were plotted on the nomogram shown in Figure 3. These experimental results verify the nomogram shown in Figure 3.

The nomogram shown in Figure 3 is based upon calculated foil activation due to a specific neutron spectrum. If this selected spectrum is representative of the spectrum that the PNAD was actually exposed to, both the Quick-Scan dose value and the foil analysis value should be fairly close. If the two values are significantly different, then the analyst should suspect that the selected spectrum may not be a good match to the actual exposure spectrum. It is noted that in an actual criticality event, the neutron spectrum, at different points relative to the source, will vary due to scatter and attenuation effects.

- Performance at 4 m, phantom front: The Quick-Scan neutron dose estimate was 121 ± 5 rad and the average of the PNAD foil values was 153 ± 40 rad. These values are not significantly different and they suggest that the Bare Godiva[3] spectrum chosen for this analysis was appropriate. The Quick-Scan value would produce the correct screening result which would be in the > 50 rad category, i.e., immediate medical attention. The foil estimate of 153 rad was in good agreement with the 170 rad value provided by CEA Valduc.
- Performance at 4 m, phantom back: The Quick-Scan neutron dose estimate was 92 ± 5 rad and the PNAD foil value was 36.6 ± 21 rad. These values are significantly different and

[3] Bare Godiva means no significant shielding between the core and the instrumentation used to make spectral measurements.

suggest that the actual exposure spectrum was of lower average energy and fluence than the Bare Godiva spectrum assumed in the calculations. Use of the Quick-Scan dose value for screening purposes would have produced the correct screening result which would be in the > 50 rad category, i.e., immediate medical attention. The significant difference between the two values strongly suggests to the analyst that further evaluation is needed, and that neither estimated dose value is accurate.

- Performance at 2 m, free in-air: The Quick-Scan neutron dose estimate was 69 ± 5 rad and the PNAD foil estimate was 433 ± 54 rad. These values are significantly different. The neutron spectrum that the PNAD sees in a phantom mounted situation with significant absorption and reflection is different than what the free in-air PNAD sees. The Quick-Scan dose rate is determined by the magnitude of the $^{115}In(n,\gamma)^{116m}In$ reaction which has a thermal threshold and is affected mostly by the low energy component of the spectrum. Since the foil dose estimate is greater than the Quick-Scan estimate, the free in-air spectrum had a smaller proportion of low energy neutrons than the assumed Bare Godiva spectrum. This strongly suggests that use of a different (and harder spectrum) may provide better agreement between the free in-air Quick-Scan and foil estimates. It is noted that free in-air exposure is typical of a fixed criticality dosimeter. Since the majority of tissue dose comes from the spectral component above 0.1 Mev, and the $^{115}In(n,n')^{115m}In$ reaction used for dosimetry responds primarily to neutrons of 1 Mev and above, the foil dose estimate of 433 rad cannot be discounted. It is noted that the foil dose estimate is 15% below the value given by CEA Valduc. When analyzing PNAD and FNAD dosimeters, different neutron spectrums may have to be used. The degree of difference between the Quick-Scan and foil estimates for a dosimeter should be minimized when the most appropriate spectrum is used.

PNAD Foil Activation

Although the In foils in each PNAD showed measureable levels of activation, none of the Cu, Al, Ti and Ni foils showed any detectable activity based upon the dosimetry reactions shown in Table 1. A review of the neutron fluence levels and foil cross section[4] values indicated the following:

- The expected activation of the In foils is above the MDA of the counting system and activity should be detectable.
- The cross section values for the $^{47}Ti(n,p)^{47}Sc$ and $^{27}Al(n,\alpha)^{24}Na$ reactions are (respectively) one and three orders of magnitude smaller than for In and the anticipated amount of activation is below the MDA of the counting system.
- The expected amount of activation in the Ni foils was just below the MDA of the counting system.

[4] Spectrum # 12, Godiva Bare.

- The current measurement process for the Cu foils relies upon the detection of a 1345.77 keV gamma. This gamma has a yield of only 0.47%. The result is that any expected levels of activity during this intercomparison would be below the MDA of the counting system. It was noted that other attendees were using a different protocol for their Cu foils. The activation product, ^{64}Cu, is also a positron emitter and the yield for the 511 keV annihilation radiation photons is several orders of magnitude larger. Use of this protocol would have resulted in the detection of measureable levels of activity in the Cu foils.

Operational Field Equipment

Two types of field equipment were used during this intercomparison. Both functioned very well and were found appropriate for their assigned tasks.

- Eberline E600 with SHP270 Probe. Measurements could be performed in any (indoor/outdoor) low background area. Each intact PNAD was placed next to the SHP270 probe (Figure 2) for about 30 seconds. An average reading value was recorded.
- Falcon 5000® Portable HPGe-Based Radionuclide Identifier: This unit needs to be used in a clean, indoor, low background area that has either 120 V or 220 V electrical power available. The factory supplied tungsten shield was used to reduce background levels. Several other participants also had Falcon 5000 units. Due to operational limitations (# of samples to count and available time), counting times of only a few minutes were possible. Even with only a few minutes of counting time, the MDA values for Indium were adequate. It was determined that a minimum spacing of 8 – 10 feet between counting units was needed to minimize "sample crosstalk" effects. Sample materials also needed to be stored using the same minimum spacing to avoid high background levels.

Neutron and Gamma Dose Measurements Using the SNL TLDs

Glow curves for all TLD elements were reviewed, per current processing protocol.

- The SNL protocol is to obtain photon doses (D_γ) from the individual's TLD. Glow curves for elements 1, 2 and 3, for all TLDs, were found to be acceptable. Results are shown in column 5 of Tables 3 and 4.
- The SNL protocol for criticality dosimetry does not currently utilize information from the neutron sensitive element on the individual's TLD. This information could be useful to dosimetry personnel if neutron spectral information was made available.
- A review of glow curves for the neutron sensitive element of each TLD (element #4) showed that measurement equipment had saturated due to large signals. It was determined that the SNL TLD readers are not equipped with neutral density optical filters needed to process dosimeters with high (> rad) neutron exposures.
- An indication of potential high gamma or neutron doses on an individual's TLD can be obtained by examining the Quick-Scan exposure rate values for the associated PNAD. If

there is any measureable exposure rate from the PNAD, then the associated TLD should be processed as if it has received a high gamma/neutron exposure.

- When exposed to a large neutron fluence, the tin and copper filters, in the badge holder, will become activated. The X-ray and gamma emissions from the activated filters will subsequently contribute to the exposure of the TLD elements in the badge. As a good practice, dosimetry personnel should remove the TLD cards from their holders as soon as possible to minimize this effect.
- Upon retrieval, irradiated PNADs and TLD badges were not stored together. After retrieval from CALIBAN, TLD cards were removed from their holders to minimize irradiation effects due to activated filter elements (appendix A, Figure A-2.)

Conclusions

The SNL Personal Nuclear Accident Dosimeter (PNAD) meets the ANSI N13.3 performance standard for determination of absorbed dose to within ± 25%.

There is a need to review the current protocol for counting the Cu foils. The current measurement process for the Cu foils relies upon the detection of a 1345.77 keV gamma from ^{64}Cu which is produced by the following reaction: ^{63}Cu(n,γ)^{64}Cu. Unfortunately, the yield for this gamma is only 0.47%, which makes use of the Cu foils impractical at neutron doses less that several hundreds of rad. It was noted that other attendees were using a different protocol for their Cu foils. The activation product, ^{64}Cu, is also a positron emitter and the yield for the 511 keV annihilation radiation photons is several orders of magnitude larger. Use of this different protocol will allow better utilization of information from the Cu foils.

There is a need to equip the SNL TLD readers with neutral density optical filters to allow the processing of dosimeters with high (> rad) neutron exposures.

References

American National Standards Institute (ANSI) Standard N13.3-1969 (R1981), Dosimetry For Criticality Accidents, American National Standards Institute, New York, New York.

Casoli, P.; Authier, N., Reactivity Worth Measurements with Caliban and Silene Experimental Reactors, International Conference on Nuclear Data for Science and Technology 2007.

Hankins, D. E., Dosimetry of Criticality Accidents Using Activation of The Blood and Hair, Health Physics 38, No. 4, pp. 529-541, April, 1980.

Hill, Carolyn D., 2004, Verification and Documentation of the Sandia PNAD Quick-Scan Procedure, SAND2004-5828P, Sandia National Laboratories, Albuquerque, NM.

International Atomic Energy Agency (IAEA). Compendium of Neutron Spectra in Criticality Accident Dosimetry. Technical Report Series No. 180. IAEA. 1978

International Atomic Energy Agency (IAEA). 1982. Dosimetry for Criticality Accidents, A Manual, IAEA Technical Reports Series No. 211, Vienna, Austria: IAEA.

P. J. Griffin, J. G. Kelly, T. F. Luera, J. VanDenburg, 1993. SNL RML Recommended Dosimetry Cross Section Compendium, SAND92-0094. Sandia National Laboratories, Albuquerque NM.

Ward, D. C.; Mohagheghi, A., and Burrows, R. Personal Nuclear Accident Dosimetry at Sandia National Laboratories, Sand Report SAND96-2204, September 1996.

APPENDIX A: Description of the Thermo Electron Type 8823 TLD

The Thermo Electron[5] Type 8825 whole-body dosimeter (Figure A-1) consists of a four-element aluminum TLD card holder containing three TLD-700 (7LiF:Mg,Ti) chips and one TLD-600 chip, surrounded by a polyethylene case containing filtration for each of the four chips. The TLD-700 chips in positions one and two are 0.38 mm (0.015 in.) thick, while the position three chip is 0.15 mm (0.006 in.) thick. The TLD-600 chip in position four is 0.38 mm (0.015 in.) thick. All chips measure 3mm × 3mm (1/8 × 1/8) in. in area. The 8825 holder filtration for element 1 consists of a 91 mg/cm2 copper filter and 242 mg/cm2 ABS plastic. Element 2 is filtered by 1000 mg/cm2 PTFE and ABS plastic. Element 3 is filtered by 8 mg/cm2 Teflon and 9 mg/cm2 Mylar. Element 4 filtration consists of 240 mg/cm^2 ABS plastic and 463 mg/cm^2 tin.

Each chip/filter combination performs a specific function as follows:

- The TLD-700 chip in Element 1 with its ABS and copper filter is used for low energy photon discrimination and dose to the lens of the eye measurement.
- The TLD-700 chip in Element 2 with its PTFE/ABS filtration measures deep dose.
- The thin TLD-700 chip in Element 3 with its aluminized Mylar filter is used for shallow dose determination.
- The TLD-600 chip with its ABS and tin filters is located in Element 4 and is used for neutron dose measurement and medium energy photon discrimination.

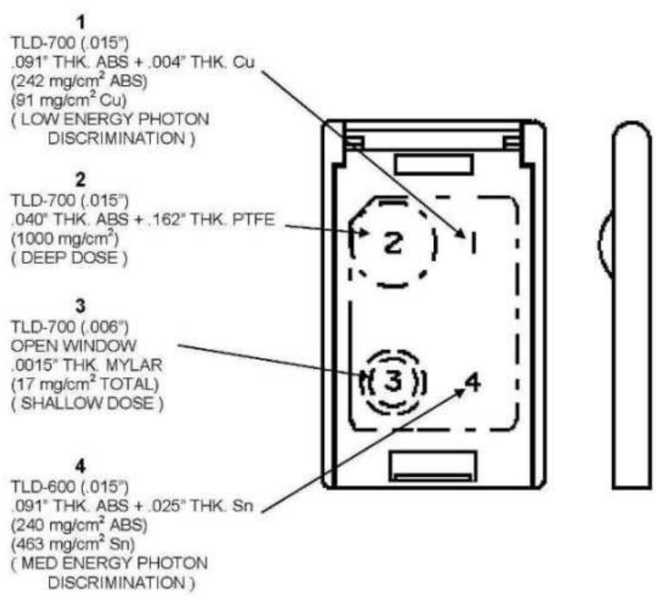

Figure A- 1: The four type 8823 dosimeter card elements and associated filters.

[5] Thermo Electron Corporation (formerly Solon Technologies, Inc. and the Englehard Corporation). Prior to that, the company's name was the Harshaw/Filtrol Partnership. For brevity, this report will reference the company name as "Thermo."

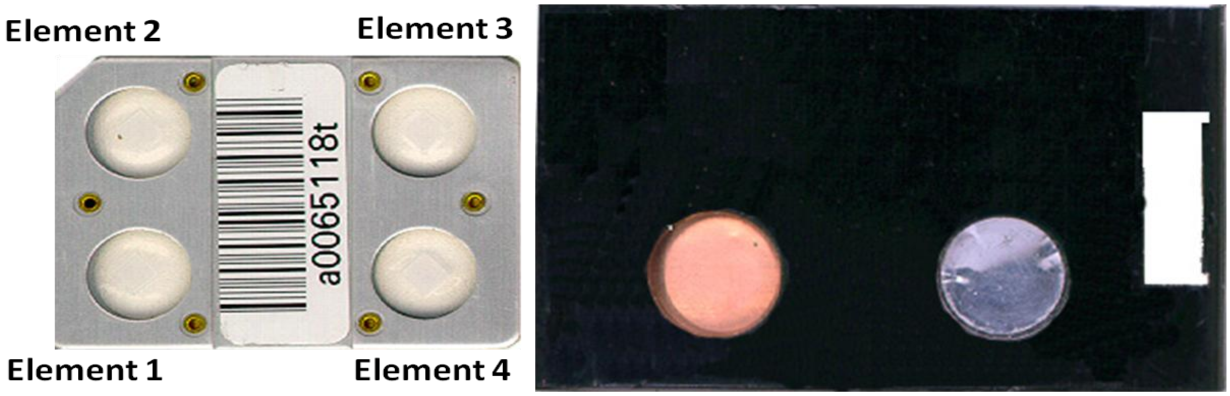

Figure A-2: Picture of the Thermo Electron four-element aluminum TLD card and polyethylene case front with Cu and Sn filters.

APPENDIX B: Quick-Scan Data

Quick-Scan results for Pulse #1, on Phantom

For this exposure, the PNADs were mounted on a 30 cm wide X 20 cm high X 10 cm thick Lucite phantom, at a distance of 4 meters from CALIBAN. PNAD locations are indicated in Table B-1. The Quick-scan procedure uses a nomogram based upon a bare Godiva spectrum (spectrum #12, Ward et al, [1996]). This spectrum was considered to be the most representative for work at Sandia. In this particular intercomparison, a bare Godiva spectrum is also considered to be representative of the CALIBAN spectrum. Quick-scan results will therefore be the most accurate for the two PNADs placed on the front of the phantom. The results for the two PNADs on the backside of the phantom will be slightly different due to moderation and attenuation of the neutron spectrum as it passes through the phantom material. The intent of a front-to-back comparison is to estimate the error associated with applying the current Quick-scan process without regard to the orientation of the wearer.

Table B-1 contains measured exposure rate data for both the front and back mounted PNADs. The time between exposure and retrieval from CALIBAN was about three hours. Even after 3 to 4 hours post-exposure time, each PNAD had an easily measureable exposure rate. This exposure rate is due mainly to the short lived isotope of ^{116}In.   In an accident situation, only a single Quick-scan measurement of exposure rate is needed. After the Quick-scan measurement is completed, a further delay of several hours will be needed to allow for additional decay of the ^{116}In activity in the Indium foil. This delay is suggested in order to minimize the dead time of the counting system. During this cool-down time, the other PNAD foils can be counted.

Table B-1: Quick-Scan Data for Pulse # 1; On Phantom

Time Since "Accident" (min)	Exposure Rate (mR/h)			
	Front		Backside	
	# 0137	# 0085	# 0336	# 0143
196	17.6	17.4		
204			12.2	11.8
209	15.1	14.7		
218	13.5	13.4		10.0
220		13.4		
228			9.1	9.1
237	11.1	10.4		
283		6.2		
286				4.5
318			3.0	2.9
341			2.40	

Figures B-1 through B-4 show results from individual PNADs. The series of measurements for each PNAD was plotted and a best-fit line was added. The estimated neutron dose (D_n) was determined based upon the value of the best-fit line. Using this process, the two front mounted PNADs suggested neutron doses of 122 ± 2 and 120 ± 2 rad, and the two back mounted PNADs suggested doses of 92 ± 2 and 93 ± 2 rad.

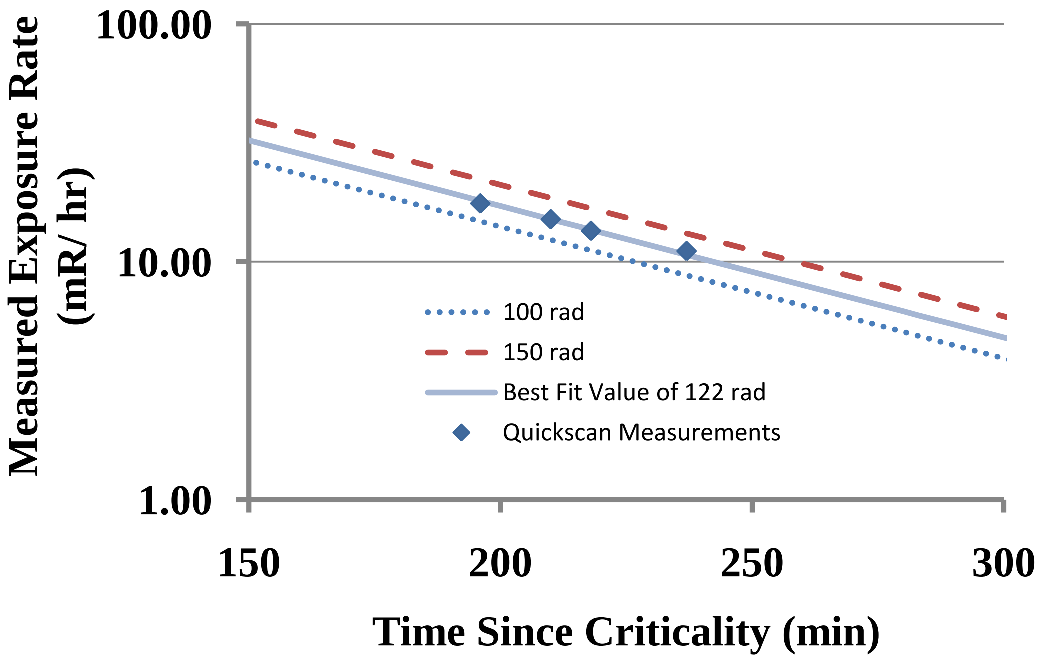

Figure B- 1: Quick-Scan data from PNAD # 0137. This PNAD was front mounted on the phantom.

Both the front and back sets of readings suggest an excellent reproducibility of just a few percent (± 2%) between individual PNAD s. The average of the two front readings was 121 rad and the average of the two back readings was 92 rad. Both average values are sufficient for medical triage purposes. This suggests that the Quick-scan process does not need to be modified to account for wearer orientation with respect to the neutron source.

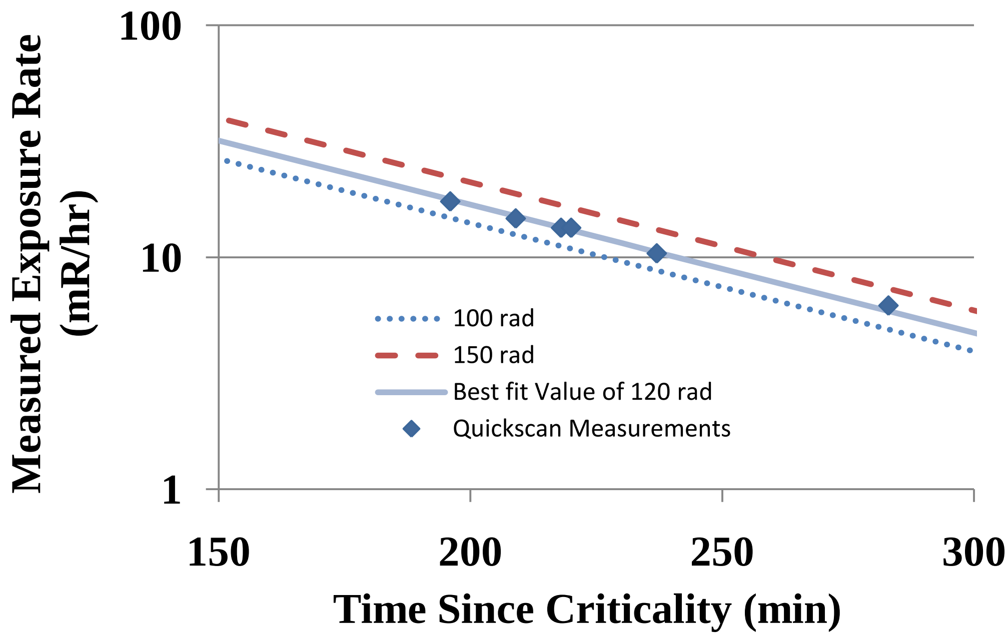

Figure B-2: Quick-Scan data from PNAD # 0085. This PNAD was front mounted on the Phantom.

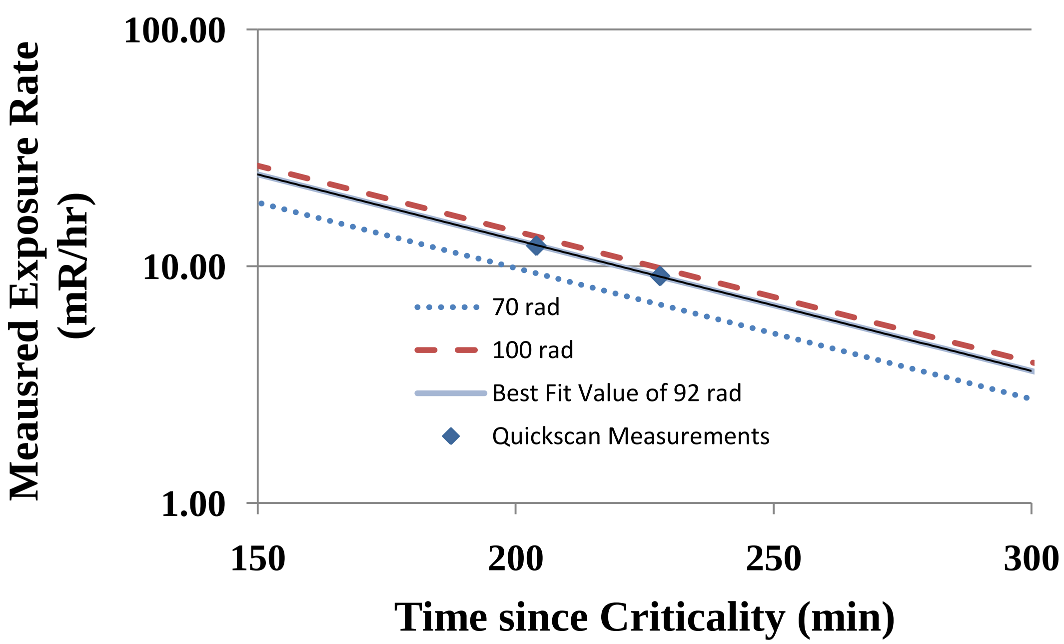

Figure B-3: Quick-Scan data from PNAD # 0336. The PNAD was back mounted on the phantom.

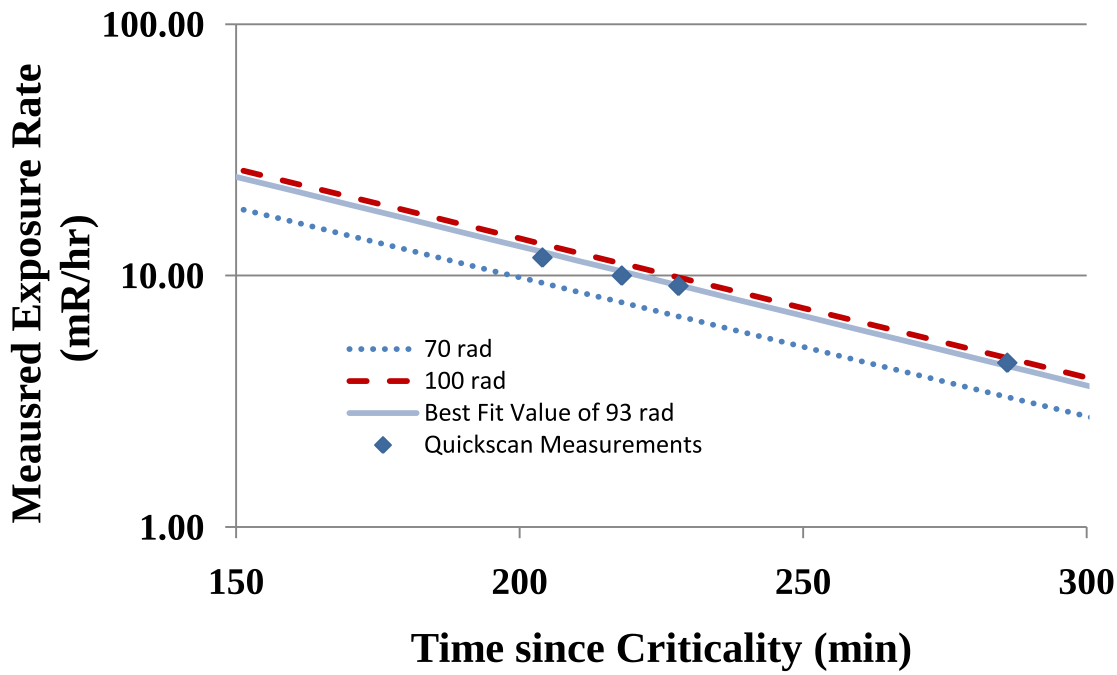

Figure B-4: Quick-Scan data from PNAD # 0143. This PNAD was back mounted on the phantom.

Quick-Scan results for Pulse #1, Free In-Air

The Quick-Scan procedure was performed on two PNADs mounted free in-air. The PNADs were located at a distance of 2 meters from CALIBAN. Results are shown in Figures B-5 and B-6.

Table B-2: Quick-Scan Data For Pulse # 1; Free In-Air

Time Since "Accident" (min)	PNAD # 0344	PNAD # 0364
215	7.8	8.3
227	7.1	6.8
284	3.2	
285		3.2
318	2.2	2.4
341	1.60	1.60
360	1.42	1.41
380	1.22	

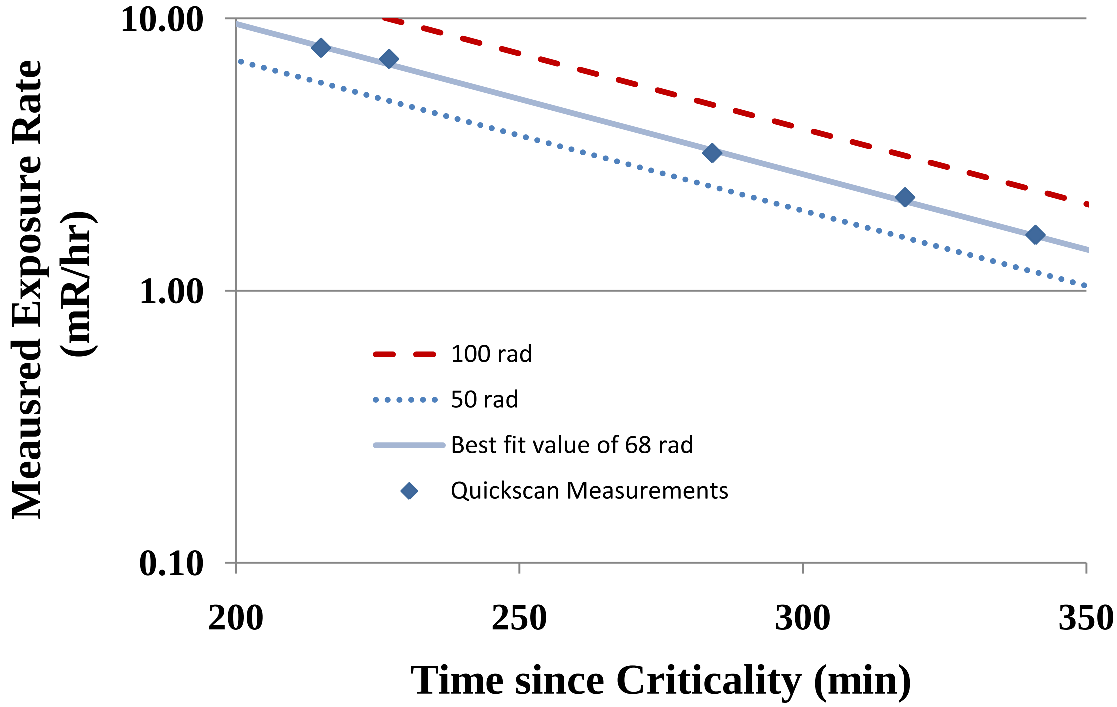

Figure B-5: Quick-Scan data from PNAD # 0344. This PNAD was free in-air.

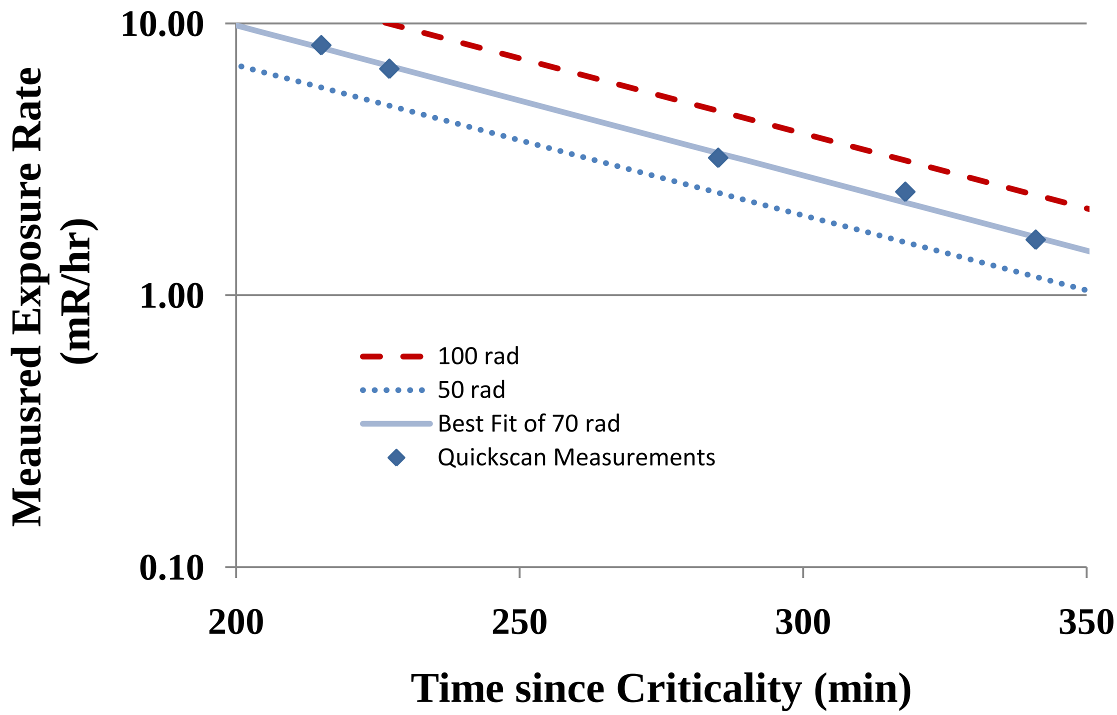

Figure B-6: Quick-Scan data from PNAD # 0364. This PNAD was free in-air.

Quick-scan Results for Pulse # 2 – Torso Phantom

Table B-3: Quick-Scan Data For Pulse # 2; On Torso Phantom

Time Since "Accident" (min)	Exposure Rate (mR/h)			
	Front		Backside	
	# 0139	# 0039	# 0372	# 0385
181			19.8	19.8
191	31.9	32.0		
196				16.2
216			12.1	
217	22.9			
218		23.4		
236	18.6		9.8	
247	16.2		8.3	
279	10.7			

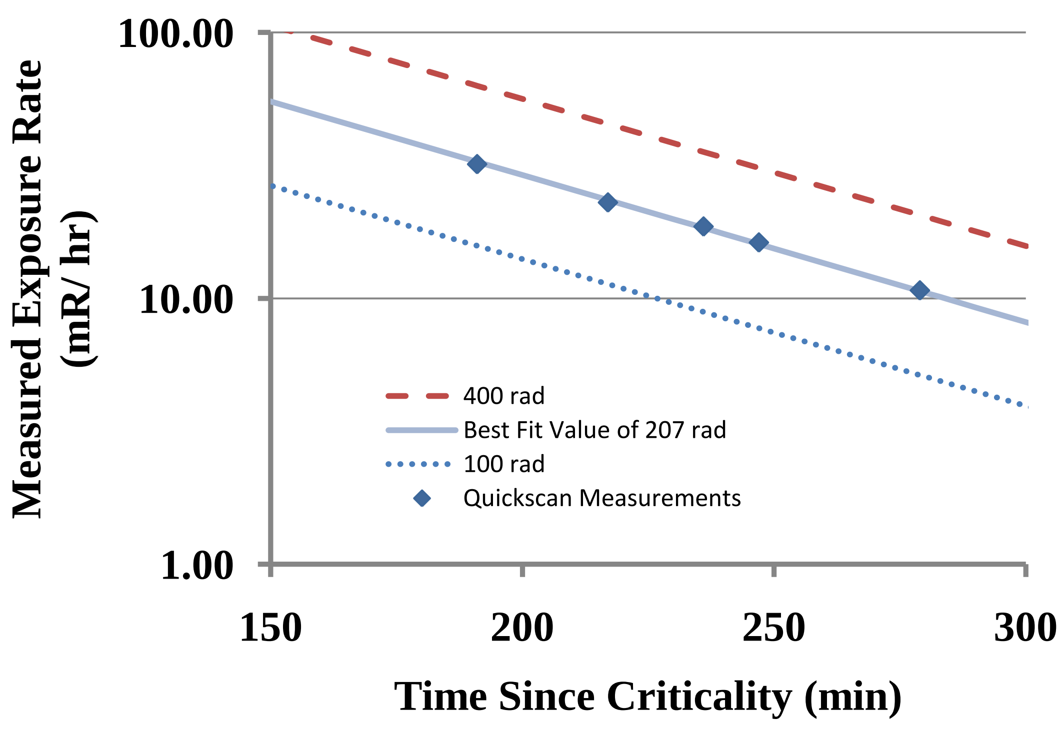

Figure B-7: Quick-Scan data from PNAD # 0139. This PNAD was front mounted on a human torso phantom. The phantom was located at a distance of 2.5 m from CALIBAN.

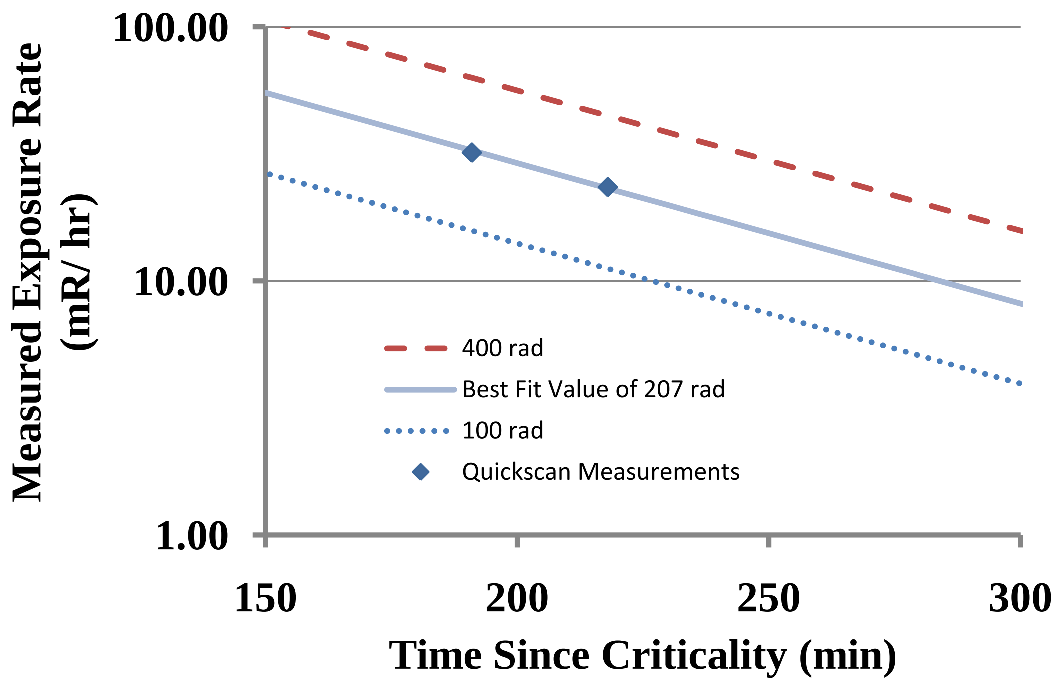

Figure B-8: Quick-Scan data from PNAD # 0039. This PNAD was front mounted on a human torso phantom. The front side of the phantom was located at a distance of 2.5 m from CALIBAN.

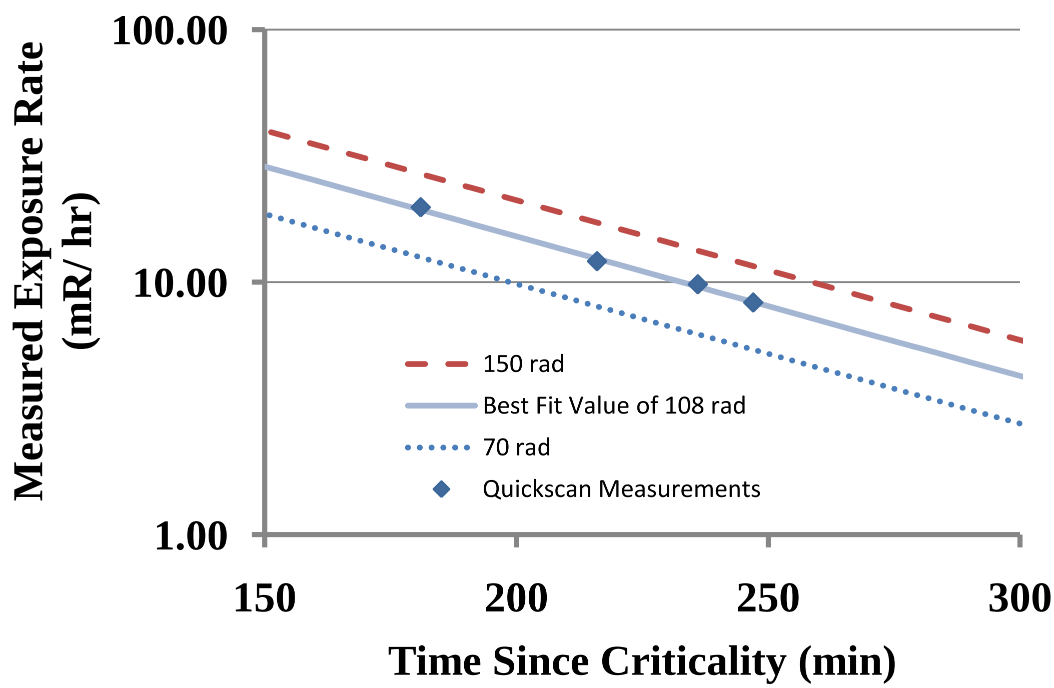

Figure B-9: Quick-Scan data from PNAD # 0372. This PNAD was back mounted on a human torso phantom. The front side of the phantom was located at a distance of 2.5 m from CALIBAN.

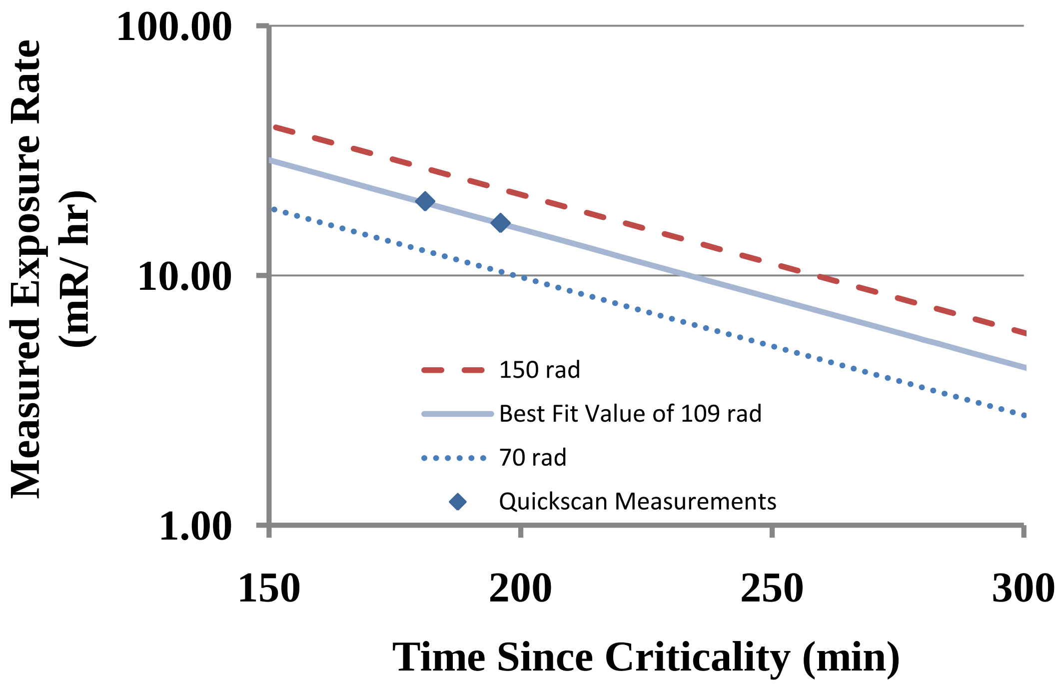

Figure B-10: Quick-Scan data from PNAD # 0385. This PNAD was back mounted on a human torso phantom. The phantom was located at a distance of 2.5 m from CALIBAN.

APPENDIX C: PNAD Data Tables

PNAD # 0137	SET UP: Pulse # 1, On Phantom, Front / Spectrum Type†: # 12 Godiva Bare	Materials				
		In	**Cu**	**Ti**	**Ni**	**Al**
	Foil Wt (g)	0.2300	0.6095	0.524	0.8371	0.271
	MDA (u`Ci)	5.42E-03	N/A	N/A	N/A	N/A
	Foil Activity (uCi)	8.87E-03	NDA	NDA	NDA	NDA
	Uncertainty in Foil Activity (2σ)	3.81E-03	N/A	N/A	N/A	N/A
	A=Specific Foil Activity (uCi/g)	3.86E-02	N/A	N/A	N/A	N/A
	$\overline{D}$ (nrad n^{-1} cm^2)†	2.07	2.07	2.07	2.07	2.07
	Effective Cross Section‡	0.101	0.101	0.0103	0.0607	0.000693
	$\overline{Dn\gamma}$ (nrad n^{-1} cm^2) ††	0.255	0.255	0.255	0.255	0.255
	Φ = Fluence (n/cm^2)	6.38E+10	N/A	N/A	N/A	N/A
	D_{HP} = Absorbed Dose (rad)	1.32E+02	N/A	N/A	N/A	N/A
	$D_{n\gamma}$ = Capture Gamma Dose (rad)	1.63E+1	N/A	N/A	N/A	N/A
	D_n = Total Neutron Dose*	1.48E+02	N/A	N/A	N/A	N/A
	Uncertainty In Absorbed Dose	5.67E+01	N/A	N/A	N/A	N/A

† Heavy particle dose conversion factor. $D_{HP} = \Phi * \overline{D}$.
‡Values selected from Ward et al., 1996, Appendix A
†† Conversion factor for dose from gamma rays produced by $^1H(n,\gamma)^2H$ reaction. $D_{n\gamma} = \overline{Dn\gamma} * \Phi$
* $D_n = D_{HP} + D_{n\gamma}$

PNAD # 0085	SET UP: Pulse # 1, On Phantom, Front / Spectrum Type†: # 12 Godiva Bare	Materials				
		In	**Cu**	**Ti**	**Ni**	**Al**
	Foil Wt (g)	0.2270	0.6075	0.5207	0.8312	0.2709
	MDA (uCi)	5.13E-03	N/A	N/A	N/A	N/A
	Foil Activity (uCi)	9.36E-03	NDA	NDA	NDA	NDA
	Uncertainty in Foil Activity (2σ)	3.70E-03	N/A	N/A	N/A	N/A
	A=Specific Foil Activity (uCi/g)	4.12E-02	N/A	N/A	N/A	N/A
	$\overline{D}$† (nrad n^{-1} cm^2)	2.07	2.07	2.07	2.07	2.07
	Effective Cross Section‡	0.101	0.101	0.0103	0.0607	0.000693
	$\overline{Dn\gamma}$ (nrad n^{-1} cm^2) ††	0.255	0.255	0.255	0.255	0.255
	Φ = Fluence (n/cm^2)	6.82E+10	N/A	N/A	N/A	N/A
	D_{HP} = Absorbed Dose (rad)	1.41E+02	N/A	N/A	N/A	N/A
	$D_{n\gamma}$ = Capture Gamma Dose (rad)	1.74E+1	N/A	N/A	N/A	N/A
	D_n = Total Neutron Dose* (rad)	1.58E+02	N/A	N/A	N/A	N/A
	Uncertainty In Absorbed Dose	5.58E+01	N/A	N/A	N/A	N/A

† Heavy particle dose conversion factor. $D_{HP} = \Phi * \overline{D}$.
‡Values selected from Ward et al., 1996, Appendix A
†† Conversion factor for dose from gamma rays produced by $^1H(n,\gamma)^2H$ reaction. $D_{n\gamma} = \overline{Dn\gamma} * \Phi$
* $D_n = D_{HP} + D_{n\gamma}$

PNAD # 0336	SET UP: Pulse # 1, On Phantom, Back / Spectrum Type†: # 13 Godiva with 12 cm Lucite	**Materials**				
		In	**Cu**	**Ti**	**Ni**	**Al**
	Foil Wt (g)	0.2177	0.603	0.5222	0.8327	0.2737
	MDA (uCi)	2.97E-03	N/A	N/A	N/A	N/A
	Foil Activity (uCi)	1.68E-03	NDA	NDA	NDA	NDA
	Uncertainty in Foil Activity (2σ)	1.86E-03	N/A	N/A	N/A	N/A
	A=Specific Foil Activity (uCi/g)	7.72E-03	N/A	N/A	N/A	N/A
	$\overline{D}$† (nrad n^{-1} cm^2)	1.4	2.07	2.07	2.07	2.07
	Effective Cross Section‡	0.0728	0.143	0.0064	0.0364	0.000257
	$\overline{Dn\gamma}$ (nrad n^{-1} cm^2) ††	0.228	0.228	0.228	0.228	0.228
	Φ = Fluence (n/cm^2)	1.77E+10	N/A	N/A	N/A	N/A
	D_{HP} = Absorbed Dose (rad)	2.48E+01	N/A	N/A	N/A	N/A
	$D_{n\gamma}$ = Capture Gamma Dose (rad)	4.04E+00	N/A	N/A	N/A	N/A
	D_n = Total Neutron Dose* (rad)	2.88E+01	N/A	N/A	N/A	N/A
	Uncertainty In Absorbed Dose	2.75E+01	N/A	N/A	N/A	N/A

† Heavy particle dose conversion factor. $D_{HP} = \Phi * \overline{D}$.

‡ Values selected from Ward et al., 1996, Appendix A

†† Conversion factor for dose from gamma rays produced by $^1H(n,\gamma)^2H$ reaction. $D_{n\gamma} = \overline{Dn\gamma} * \Phi$

* $D_n = D_{HP} + D_{n\gamma}$

PNAD # 0143	SET UP: Pulse # 1, On Phantom, Back / Spectrum Type†: # 13 Godiva with 12 cm Lucite	**Materials**				
		In	**Cu**	**Ti**	**Ni**	**Al**
	Foil Wt (g)	0.2253	0.6127	0.5237	0.8356	0.2731
	MDA (uCi)	3.62E-03	9.09E-02	1.96E-04	3.04E-04	3.67E-04
	Foil Activity (uCi)	2.68E-03	NDA	NDA	NDA	NDA
	Uncertainty in Foil Activity (2σ)	2.31E-03	N/A	N/A	N/A	N/A
	A=Specific Foil Activity (uCi/g)	1.19E-02	N/A	N/A	N/A	N/A
	$\overline{D}$† (nrad n^{-1} cm^2)	1.4	1.4	1.4	1.4	1.4
	Effective Cross Section‡	0.0728	0.143	0.0064	0.0364	0.000257
	$\overline{Dn\gamma}$ (nrad n^{-1} cm^2) ††	0.228	0.228	0.228	0.228	0.228
	Φ = Fluence (n/cm^2)	2.73E+10	N/A	N/A	N/A	N/A
	D_{HP} = Absorbed Dose (rad)	3.82E+01	N/A	N/A	N/A	N/A
	$D_{n\gamma}$ = Capture Gamma Dose (rad)	6.22E+00	N/A	N/A	N/A	N/A
	D_n = Total Neutron Dose* (rad)	4.44E+01	N/A	N/A	N/A	N/A
	Uncertainty In Absorbed Dose	3.29E+01	N/A	N/A	N/A	N/A

† Heavy particle dose conversion factor. $D_{HP} = \Phi * \overline{D}$.
‡Values selected from Ward et al., 1996, Appendix A
†† Conversion factor for dose from gamma rays produced by $^1H(n,\gamma)^2H$ reaction. $D_{n\gamma} = \overline{Dn\gamma} * \Phi$
* $D_n = D_{HP} + D_{n\gamma}$

PNAD # 0344	SET UP: Pulse # 1, Free In-Air, 2 m from CALIBAN / Spectrum Type†: # 12 Godiva Bare	Materials				
		In	**Cu**	**Ti**	**Ni**	**Al**
	Foil Wt (g)	0.2318	0.6127	0.5333	0.8355	0.2707
	MDA (uCi)	2.48E-03	N/A	N/A	N/A	N/A
	Foil Activity (uCi)	2.51E-02	NDA	NDA	NDA	NDA
	Uncertainty in Foil Activity (2σ)	5.01E-03	N/A	N/A	N/A	N/A
	A=Specific Foil Activity (uCi/g)	1.08E-01	N/A	N/A	N/A	N/A
	$\overline{D}$† (nrad n^{-1} cm^2)	2.07	2.07	2.07	2.07	2.07
	Effective Cross Section‡	0.101	0.101	0.0103	0.0607	0.000693
	$\overline{Dn\gamma}$ (nrad n^{-1} cm^2) ††	0.255	0.255	0.255	0.255	0.255
	Φ = Fluence (n/cm^2)	1.79E+11	N/A	N/A	N/A	N/A
	D_{HP} = Absorbed Dose (rad)	3.71E+02	N/A	N/A	N/A	N/A
	$D_{n\gamma}$ = Capture Gamma Dose (rad)	4.56E+01	N/A	N/A	N/A	N/A
	D_n = Total Neutron Dose* (rad)	4.17E+02	N/A	N/A	N/A	N/A
	Uncertainty In Absorbed Dose	7.40E+01	N/A	N/A	N/A	N/A

† Heavy particle dose conversion factor. $D_{HP} = \Phi * \overline{D}$.
‡Values selected from Ward et al., 1996, Appendix A
†† Conversion factor for dose from gamma rays produced by $^1H(n,\gamma)^2H$ reaction. $D_{n\gamma} = \overline{Dn\gamma} * \Phi$
* $D_n = D_{HP} + D_{n\gamma}$

PNAD # 0364	SET UP: Pulse # 1, Free In-Air, 2 m from CALIBAN / Spectrum Type†: # 12 Godiva Bare	**Materials**				
		In	**Cu**	**Ti**	**Ni**	**Al**
	Foil Wt (g)	0.2286	0.6085	0.5245	0.8366	0.2719
	MDA (uCi)	2.42E-03	N/A	N/A	N/A	N/A
	Foil Activity (uCi)	2.68E-02	NDA	NDA	NDA	NDA
	Uncertainty in Foil Activity (2σ)	5.25E-03	N/A	N/A	N/A	N/A
	A=Specific Foil Activity (uCi/g)	1.17E-01	N/A	N/A	N/A	N/A
	$\overline{D}$† (nrad n^{-1} cm^2)	2.07	2.07	2.07	2.07	2.07
	Effective Cross Section‡	0.101	0.101	0.0103	0.0607	0.000693
	$\overline{Dn\gamma}$ (nrad n^{-1} cm^2) ††	0.255	0.255	0.255	0.255	0.255
	Φ = Fluence (n/cm^2)	1.94E+11	N/A	N/A	N/A	N/A
	D_{HP} = Absorbed Dose (rad)	4.01E+02	N/A	N/A	N/A	N/A
	$D_{n\gamma}$ = Capture Gamma Dose (rad)	4.95E+01	N/A	N/A	N/A	N/A
	D_n = Total Neutron Dose* (rad)	4.50E+02	N/A	N/A	N/A	N/A
	Uncertainty In Absorbed Dose	7.86E+01	N/A	N/A	N/A	N/A

† Heavy particle dose conversion factor. $D_{HP} = \Phi * \overline{D}$.
‡ Values selected from Ward et al., 1996, Appendix A
†† Conversion factor for dose from gamma rays produced by $^1H(n,\gamma)^2H$ reaction. $D_{n\gamma} = \overline{Dn\gamma} * \Phi$
* $D_n = D_{HP} + D_{n\gamma}$

PNAD #	SET UP: Pulse # 2, On Torso Phantom, Front, 2.5 m from CALIBAN	Materials				
0139	Spectrum Type†: # 12 Godiva Bare	**In**	**Cu**	**Ti**	**Ni**	**Al**
	Foil Wt (g)	0.2273	0.6099	0.5215	0.8303	0.2704
	MDA (uCi)	1.03E-02	N/A	N/A	N/A	N/A
	Foil Activity (uCi)	3.05E-02	NDA	NDA	NDA	NDA
	Uncertainty in Foil Activity (2σ)	8.95E-03	N/A	N/A	N/A	N/A
	A=Specific Foil Activity (uCi/g)	1.34E-01	N/A	N/A	N/A	N/A
	$\overline{D}$† (nrad n^{-1} cm^2)	2.07	2.07	2.07	2.07	2.07
	Effective Cross Section‡	0.101	0.101	0.0103	0.0607	0.000693
	$\overline{Dn\gamma}$ (nrad n^{-1} cm^2) ††	0.255	0.255	0.255	0.255	0.255
	Φ = Fluence (n/cm^2)	2.22E+11	N/A	N/A	N/A	N/A
	D_{HP} = Absorbed Dose (rad)	4.59E+02	N/A	N/A	N/A	N/A
	$D_{n\gamma}$ = Capture Gamma Dose	5.66E+01	N/A	N/A	N/A	N/A
	D_n = Total Neutron Dose*	5.16E+02	N/A	N/A	N/A	N/A
	Uncertainty In Absorbed Dose	1.35E+02	N/A	N/A	N/A	N/A

† Heavy particle dose conversion factor. $D_{HP} = \Phi * \overline{D}$.
‡Values selected from Ward et al., 1996, Appendix A
†† Conversion factor for dose from gamma rays produced by $^1H(n,\gamma)^2H$ reaction. $D_{n\gamma} = \overline{Dn\gamma} * \Phi$
* $D_n = D_{HP} + D_{n\gamma}$

PNAD #	SET UP: Pulse # 2, On Torso Phantom, Front, 2.5 m from CALIBAN	Materials				
0039	Spectrum Type†: # 12 Godiva Bare	**In**	**Cu**	**Ti**	**Ni**	**Al**
	Foil Wt (g)	0.2259	0.6038	0.5261	0.8304	0.2713
	MDA (uCi)	5.71E-03	N/A	N/A	N/A	N/A
	Foil Activity (uCi)	2.87E-02	NDA	NDA	NDA	NDA
	Uncertainty in Foil Activity (2σ)	6.50E-03	N/A	N/A	N/A	N/A
	A=Specific Foil Activity (uCi/g)	1.27E-01	N/A	N/A	N/A	N/A
	$\overline{D}$† (nrad n^{-1} cm^2)	2.07	2.07	2.07	2.07	2.07
	Effective Cross Section‡	0.101	0.101	0.0103	0.0607	0.000693
	$\overline{Dn\gamma}$ (nrad n^{-1} cm^2) ††	0.255	0.255	0.255	0.255	0.255
	Φ = Fluence (n/cm^2)	2.10E+11	N/A	N/A	N/A	N/A
	D_{HP} = Absorbed Dose (rad)	4.35E+02	N/A	N/A	N/A	N/A
	$D_{n\gamma}$ = Capture Gamma Dose (rad)	5.36E+01	N/A	N/A	N/A	N/A
	D_n = Total Neutron Dose*	4.89E+02	N/A	N/A	N/A	N/A
	Uncertainty In Absorbed Dose	9.85E+01	N/A	N/A	N/A	N/A

† Heavy particle dose conversion factor. $D_{HP} = \Phi * \overline{D}$.
‡Values selected from Ward et al., 1996, Appendix A
†† Conversion factor for dose from gamma rays produced by $^1H(n,\gamma)^2H$ reaction. $D_{n\gamma} = \overline{Dn\gamma} * \Phi$
* $D_n = D_{HP} + D_{n\gamma}$

PNAD #	SET UP: Pulse # 2, On Torso Phantom, Back, 2.5 m from CALIBAN	Materials				
0372	Spectrum Type†: # 13 Godiva with 12 cm Lucite	**In**	**Cu**	**Ti**	**Ni**	**Al**
	Foil Wt (g)	0.2309	0.6088	0.5167	0.8312	0.2712
	MDA (uCi)	8.95E-03	N/A	N/A	N/A	N/A
	Foil Activity (uCi)	4.63E-03	NDA	NDA	NDA	NDA
	Uncertainty in Foil Activity (2σ)	5.59E-03	N/A	N/A	N/A	N/A
	A=Specific Foil Activity (uCi/g)	2.01E-02	N/A	N/A	N/A	N/A
	$\overline{D}$† (nrad n^{-1} cm^2)	1.4	2.07	2.07	2.07	2.07
	Effective Cross Section‡	0.0728	0.143	0.0064	0.0364	0.000257
	$\overline{Dn\gamma}$ (nrad n^{-1} cm^2) ††	0.228	0.228	0.228	0.228	0.228
	Φ = Fluence (n/cm^2)	4.60E+10	N/A	N/A	N/A	N/A
	D_{HP} = Absorbed Dose (rad)	6.44E+01	N/A	N/A	N/A	N/A
	$D_{n\gamma}$ = Capture Gamma Dose (rad)	1.05E+01	N/A	N/A	N/A	N/A
	D_n = Total Neutron Dose*	7.49E+01	N/A	N/A	N/A	N/A
	Uncertainty In Absorbed Dose	7.78E+01	N/A	N/A	N/A	N/A

† Heavy particle dose conversion factor. $D_{HP} = \Phi * \overline{D}$.
‡Values selected from Ward et al., 1996, Appendix A
†† Conversion factor for dose from gamma rays produced by $^1H(n,\gamma)^2H$ reaction. $D_{n\gamma} = \overline{Dn\gamma} * \Phi$
* $D_n = D_{HP} + D_{n\gamma}$

PNAD # 0385	SET UP: Pulse # 2, On Torso Phantom, Back, 2.5 m from CALIBAN	**Materials**				
	Spectrum Type†: # 13 Godiva with 12 cm Lucite	**In**	**Cu**	**Ti**	**Ni**	**Al**
	Foil Wt (g)	0.2310	0.6024	0.5248	0.8308	0.2724
	MDA (uCi)	4.28E-03	N/A	N/A	N/A	N/A
	Foil Activity (uCi)	3.07E-03	NDA	NDA	NDA	NDA
	Uncertainty in Foil Activity (2σ)	2.72E-03	N/A	N/A	N/A	N/A
	A=Specific Foil Activity (uCi/g)	1.33E-02	N/A	N/A	N/A	N/A
	$\overline{D}$† (nrad n^{-1} cm^2)	1.4	0.143	0.0064	0.0364	0.000257
	Effective Cross Section‡	0.0728	0.143	0.0064	0.0364	0.000257
	$\overline{Dn\gamma}$ (nrad n^{-1} cm^2) ††	0.228	0.228	0.228	0.228	0.228
	Φ = Fluence (n/cm^2)	3.05E+10	N/A	N/A	N/A	N/A
	D_{HP} = Absorbed Dose (rad)	4.27E+01	N/A	N/A	N/A	N/A
	$D_{n\gamma}$ = Capture Gamma Dose (rad)	6.95E+0	N/A	N/A	N/A	N/A
	D_n = Total Neutron Dose*	4.97E+01	N/A	N/A	N/A	N/A
	Uncertainty In Absorbed Dose	3.78E+01	N/A	N/A	N/A	N/A

† Heavy particle dose conversion factor. $D_{HP} = \Phi * \overline{D}$.
‡Values selected from Ward et al., 1996, Appendix A
†† Conversion factor for dose from gamma rays produced by $^1H(n,\gamma)^2H$ reaction. $D_{n\gamma} = \overline{Dn\gamma} * \Phi$
* $D_n = D_{HP} + D_{n\gamma}$

APPENDIX D: Quick-Scan Nomograms Technical Basis

The following example can be used to reproduce the nomogram shown in Figure 3 of the main report. Data used in the development of this nomogram is for a Bare Godiva – LANL Spectrum (Spectrum Type #12[6]). The only foil in the SNL PNAD that will have a sufficient level of activation that can be detected with portable health physics survey equipment is the Indium (In) foil. The following information is taken from the reference listed in footnote 4 below.

Spectrum-Averaged Cross Section (barns)	Spectrum Type #12 GODIVA Bare, Measured at LANL
$^{63}Cu(n,\gamma)^{64}Cu$	0.101
$^{115}In(n,n')^{115m}In$	0.101
$^{58}Ni\ (n,p)^{58}Co$	0.0607
$^{47}Ti(n,p)^{47}Sc$	0.0103
$^{27}Al(n,\alpha)^{24}Na$	0.000693
$^{23}Na(n,\gamma)^{24}Na$	0.0191
$^{197}Au(n,\gamma)^{198}Au$	24.9
$\overline{K}$ $\frac{nrad}{n/cm^2}$	1.79
$\overline{D}$ $\frac{nrad}{n/cm^2}$	2.07
$\overline{DE}$ $\frac{nrem}{n/cm^2}$	20.7
$\overline{D_\gamma}$ $\frac{nrad}{n/cm^2}$	0.255

Average cross-section in barns, for the spectrum Type. The value for the $^{115}In(n,n')^{115m}In$ reaction is used for nomogram development.

$\overline{D}$ = Average recoil-particle dose to Auxier phantom element 57 (in nanorad/(n/cm^2)). For more information, see Page # 13, International Atomic Energy Agency (IAEA), Compendium Of Neutron Spectra In Criticality Accident Dosimetry. Technical Report Series No. 180. IAEA. 1978

Figure D-1: Extract of dosimetry information relevant to Spectrum Type # 12

[6] Appendix A – Dosimetry Data; Ward, D. C.; Mohagheghi, A., and Burrows, R., *Personal Nuclear Accident Dosimetry at Sandia National Laboratories*, Sand Report SAND96-2204, September 1996.

To develop a nomogram for a particular neutron spectrum, the average cross-section value for the $^{115}In(n,\gamma)^{116m}In$ reaction is also required. Values are provided in Table D-1 below.

Table D- 1: Average Cross-Section Values for the $^{115}In(n,\gamma)^{116m}In$ Reaction

Spectrum Type	Average Cross-Section (barns)	Spectrum Type	Average Cross-Section (barns)
#1 WATT	0.160	**#19** H_2O Solution, 5 cm Diameter	3.54
#2 GODIVA (Taken from Ing and Makra, 1990)	0.183	**#20** SPRIII, Central Cavity	0.245
#3 1/E + WATT	364.	**#21** Cf-252, from NBS Compendium	0.154
#4 ZPR-6, 4Z+, Thermal	43.2	**#22** Fission Neutrons through Concrete (10 cm)[a]	2.05
#5 FISSION through 10 cm Carbon	15.5	**#23** Fission Neutrons through Concrete (20 cm) [a]	11.5
#6 FISSION through 90 cm Water	59.9	**#24** Fission Neutrons through Concrete (30 cm) [a]	19.8
#7 20 cm Li-H Slab	25.4	**#25** Fission Neutrons through Concrete (40 cm) [a]	23.6
#8 Graphite Test Lattice	255.	**#26** Fission Neutrons through Polyethylene (5 cm)[b]	58.9
#9 FERMI Reactor Test	8.33	**#27** Fission Neutrons through Polyethylene (10 cm)	93.5
#10 SPR-III 17” Leakage	3.61	**#28** Fission Neutrons through Polyethylene (20 cm) [b]	97.2
#11 ACRR Central Cavity	114.	**#29** Fission Neutrons through Polyethylene (40 cm) [b]	86.9
#12 GODIVA Bare, Measured at LANL	40.4	**#30** Fission Neutrons through Polyethylene (60 cm) [b]	80.1
#13 GODIVA with 12 cm Lucite, Measured at LANL	140	**#31** Fission Neutrons through Iron (5 cm)[c]	0.186
#14 GODIVA with 20 cm Concrete Measured at LANL	166.	**#32** Fission Neutrons through Iron (10 cm) [c]	0.206

Spectrum Type	Average Cross-Section (barns)	Spectrum Type	Average Cross-Section (barns)
#15 SHEBA Bare, Measured at LANL	47.8	**#33** Fission Neutrons through Iron (20 cm) [c]	0.260
#16 H_2O Solution, 50 cm Diameter	7.00	**#34** Fission Neutrons through Iron (30 cm) [c]	0.275
#17 H_2O Solution, 30 cm Diameter	6.52	**#35** Fission Neutrons through Iron (50 cm) [c]	0.720
#18 H_2O Solution, 10 cm Diameter	5.76		

[a] Taken from page 88, Ing & Makra, 1978.
[b] Taken from page 80, Ing & Makra, 1978
[c] Taken from page 100, Ing & Makra, 1978

The following calculations will produce the estimated exposure rate reading for a PNAD exposed to a neutron fluence (spectrum Type # 12) that will deposit 100 rad recoil particle dose to phantom element #57. Estimated exposure rate readings for other doses can then be scaled to this value.

Required fluence for 100 rad recoil particle dose:

$$Neutron\ fluence\ \left(\frac{n}{cm^2}\right) = \frac{100\ rad}{\bar{D}} \qquad \text{Eqn D-1}$$

$$\text{Neutron fluence } \left(\frac{\text{n}}{\text{cm}^2}\right) = \frac{100 \text{ rad}}{2.07 \text{ x } 10^{-9}\ \frac{\text{rad}}{\text{n/cm}^2}} \qquad \text{Eqn D-2}$$

$$\text{Neutron fluence } \left(\frac{\text{n}}{\text{cm}^2}\right) = 4.83 \text{ x } 10^{10} \qquad \text{Eqn D-3}$$

Number of ^{115}In atoms in a SNL In foil:

Atomic wt of In:	114.818 g/mole
Average Indium foil weight:	0.228 g
Foil purity:	99.9%
% abundance of ^{115}In atoms:	95.71%

$$No. of\ ^{115}\text{In atoms in a foil} = \frac{(0.228\ \text{g}) \times (0.999) \times (0.9571)}{114.818\ \text{g/mole}} \times 6.027 \text{ x } 10^{23}\ \text{atoms/mole} \qquad \text{Eqn D-4}$$

$$1.14 \text{ x } 10^{21}\ \text{atoms} \qquad \text{Eqn D-5}$$

Determination of ^{116m}In Initial Activity in a Counting foil

Number of ^{116m}In atoms in foil immediately after irradiation = $N_{o\text{-}116m}$

Cross Section for $^{115}In(n,\gamma)^{116m}In$ reaction,

Spectrum type # 12 = 40.4 barns (Table D-1)

$$N_{o-116m} = (4.83 \text{ x } 10^{10}\ \text{n/cm}^2) \times (1.14 \text{ x } 10^{21} \text{atoms}) \times (40.4 \text{ x } 10^{-24}\ \text{cm}^2) \qquad \text{Eqn D-6}$$

$$2.22 \text{ x } 10^{9}\ \text{nuclei} \qquad \text{Eqn D-7}$$

Activity of ^{116m}In in foil immediately after irradiation = $A_{o\text{-}116m}$

Decay constant for ^{116m}In (λ_{116m}) = $2.12 \text{ x } 10^{-4}$ Bq s^{-1} $nuclei^{-1}$

$$A_{o-116m} = \frac{(2.22 \text{ x } 10^{9}\ \text{nuclei}) \times (2.12 \text{ x } 10^{-4}\ \text{Bq s}^{-1}\ \text{nuclie}^{-1})}{3.7 \text{ x } 10^{4}\ \text{Bq s}^{-1}\ \mu\text{Ci}^{-1}} \qquad \text{Eqn D-8}$$

$$1.27 \text{ x } 10^{1}\ \mu\text{Ci} \qquad \text{Eqn D-9}$$

Determination of ^{115m}In Initial Activity in a Counting foil

Number of ^{115m}In atoms in foil immediately after irradiation = $N_{o\text{-}115m}$

Cross Section for $^{115}\text{In}(n,n')^{115m}\text{In}$ reaction,

Spectrum type # 12 = 0.101 barns (Fig. D-1)

$$N_{o-115m} = (4.83 \text{ x } 10^{10} \text{ n/cm}^2) \times (1.14 \text{ x } 10^{21} \text{atoms}) \times (0.101 \text{ x } 10^{-24} \text{ cm}^2) \quad \text{Eqn D-10}$$

$$5.56 \text{ x } 10^6 \text{ nuclei} \quad \text{Eqn D-11}$$

Activity of ^{116m}In in foil immediately after irradiation = $A_{o\text{-}116m}$

Decay constant for ^{115m}In (λ_{115m}) = $4.29 \text{ x } 10^{-5}$ Bq s^{-1} nuclei^{-1}

Gamma constant for ^{115m}In = $1.97 \text{ x } 10^{-4}$ mrem/h/µCi @ 1m

$$A_{o-115m} = \frac{(5.56 \text{ x } 10^6 \text{ nuclei}) \times (4.29 \text{ x } 10^{-5} \text{ Bq s}^{-1} \text{ nuclie}^{-1})}{3.7 \text{ x } 10^4 \text{ Bq s}^{-1} \text{ µCi}^{-1}} \quad \text{Eqn D-12}$$

$$6.45 \text{ x } 10^{-3} \text{ µCi} \quad \text{Eqn D-13}$$

Expected initial exposure rate from foil due to ^{116m}In activity = $\dot{X}_{o-116m}$.

NOTE: This calculation is based upon equipment and measurement geometry shown in Figure 2 of the main report. The measured distance from the foil to the center of the active detector volume is 1 cm. Based upon the relative size of the foil and the detector, point source geometry is assumed.

Gamma constant for ^{116m}In = $1.354 \text{ x } 10^{-3}$ mrem/h/µCi @ 1m

$$\dot{X}_{o-116m} = \frac{(1.27 \text{ } x \text{ } 10^1 \text{ } \mu Ci) \times (1.354 \text{ } x \text{ } 10^{-3} \text{ mrem/h/µCi @ 1m})}{0.01 \text{ } m^2} \quad \text{Eqn D-14}$$

$$1.72 \text{ x } 10^2 \text{ mrem h}^{-1} \quad \text{Eqn D-15}$$

Expected initial exposure rate from foil due to ^{115m}In activity = $\dot{X}_{o-115m}$.

NOTE: This calculation is based upon equipment and measurement geometry shown in Figure 2 of the main report. The measured distance from the foil to the center of the active detector volume is 1 cm. Based upon the relative size of the foil and the detector, point source geometry is assumed.

Gamma constant for ^{115m}In = 1.97×10^{-4} mrem/h/µCi @ 1m

$$\dot{X}_{o-115m} = \frac{(6.45\ x\ 10^{-3}\ \mu Ci) \times (1.97\ x\ 10^{-4}\ \text{mrem/h/µCi @ 1m})}{0.01\ m^2} \qquad \text{Eqn D-16}$$

$$1.27 \times 10^{-2}\ \text{mrem h}^{-1} \qquad \text{Eqn D-17}$$

Comparison of Initial Exposure Rates

$$\text{The ratio of } \frac{\dot{X}_{o-116m}}{\dot{X}_{o-115m}} = \frac{1.72 \text{ x } 10^2 \text{ mrem h}-1}{1.27 \text{ x } 10^{-2} \text{ mrem h}-1} = 1.35\ x\ 10^4 \qquad \text{Eqn D-18}$$

This ratio indicates that any measurable exposure rate values will be determined essentially by the ^{116m}In component. The half-life of ^{116m}In is 54.4 min and the half-life of ^{115m}In is 4.36 h. As time passes, the ^{116m}In component will decay faster than the ^{115m}In component resulting in a bigger fraction of the total exposure eventually coming from the ^{115m}In component. It is the ^{115m}In component that is used for dosimetry purposes.

This also has implications for the use of sensitive counting room equipment. There will need to be a few hours of foil decay time to allow the ^{116m}In component to be reduced to help minimize system dead-time.

Expected total In foil exposure rate, due to activation products,

as a function of time = $\dot{X}(t)_{In}$

$$\dot{X}(t)_{In=} [(\dot{X}_{o-116m}\ e^{-\lambda_{116m} t}) + (\dot{X}_{o-115m}\ e^{-\lambda_{115m} t})] \qquad \text{Eqn D-19}$$

Where t is the time since the foil was exposed to neutrons.

Equation D-19 is then used within a spreadsheet program to plot exposure rate vs. time for a 100 rad exposure. This yields a single line. Additional lines for different doses are easily added, as the amount of foil activation (exposure rate) scales linearly with dose (fluence).

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