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Los Alamos National Laboratory Results for the
2010 CALIBAN Criticality Accident Dosimetry Exercise
Preliminary Report

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Introduction

September 20-24, 2010, Los Alamos National Laboratory (LANL) participated in a criticality accident dosimetry exercise at 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 facilities represented included LLNL, Pacific Northwest National Laboratory, Y-12, Sandia National Laboratory, Savannah River Site, and Oak Ridge National Laboratory.

The exercise was conducted using the CALIBAN reactor, which is a fast burst assembly made of highly enriched uranium, operated in the pulse mode (Trompier, et. al., 2008). The exposures were performed as single blinds where the participants were not informed of the dose to be delivered. Participants were informed of the assembly, shielding, and operating mode (pulse, free evolution, or steady state). 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. For both exposures the CALIBAN assembly was operated in pulse mode with no shielding. The number of fissions, or assembly power output, was the only difference between the two exposures. On the last day of the exercise participants were requested to submit their preliminary dose estimates to CEA Valduc. The results from all participants were compiled and compared with each other the approximate delivered neutron and gamma absorbed doses. The latter were calculated by CEA Valduc based on calibration information for CALIBAN and the measured number of fissions.

The goals for LANLs participation were to: 1) test and validate the procedures and algorithms used to determine doses resulting from a criticality accident, including changes to the algorithms derived following the 2009 intercomparison exercise (Gadd and Homan, 2010) ; 2) evaluate alternative portable instrumentation for analysis of dosimeter materials; 3) evaluate the effects of individual orientation on dosimeter results; and 4) verify correction factors used to adjust readings obtained from intact sulfur tablets to crushed tablets. Additionally, measurements were performed on the LANL 8823 Whole Body thermoluminescent dosimeter (TLD) cases to evaluate screening measurements as a method to sort exposed individuals who were not wearing personal nuclear accident dosimeters (PNADs).

This report presents the methods and results for the LANL measurements as reported to CEA Valduc and the LLNL exercise coordinator. CEA Valduc will report the final delivered absorbed doses for each exposure and location. When those results are received, a final report will be generated.

Methods

The LANL PNAD contains four activation elements consisting of bare and cadmium shielded indium foils, a cadmium covered copper foil, and a bare sulfur tablet all contained in a plastic holder. A line drawing of the PNAD is shown in Figure 1 and the reactions of interest are summarized in Table 1. Detailed information on the PNAD can be found in the Los Alamos Personnel and Area Criticality Dosimeter Systems technical basis document (LANL, 2006).

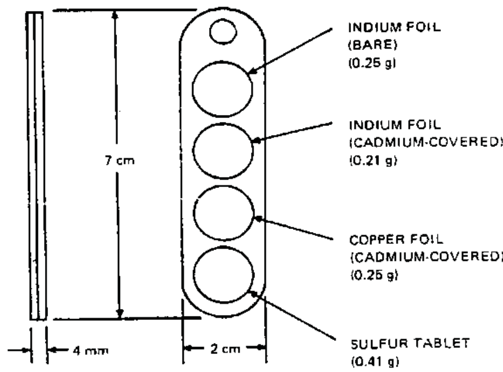

Figure 1. LANL Personnel Neutron Dosimetry (PNAD) packet.

Table 1. LANL PNAD Elements and Reactions

Neutron Energy	Reaction	Half Life	PNAD Element	Analysis
Thermal (<0.6 eV)	$^{115}In(n,\gamma)^{116m}In$	54 min.	Bare In Foil	1.293 MeV Gamma
3 keV – 1.1 MeV 1.2-20 MeV	$^{115}In(n,n')^{115m}In$	4.5 h	Cd Covered In Foil	0.336 MeV Gamma
0.6 eV – 3 keV	$^{63}Cu(n,\gamma)^{64}Cu$	12.8 h	Cd Covered Cu Foil	0.511 MeV Gamma
3.3 – 20 MeV	$^{32}S(n,p)^{32}P$	14.3 d	Sulfur Tablet	1.71 MeV Beta

Additionally, LANL 8823 Whole Body TLDs and Track-etch dosimeters (TED) were exposed. Descriptions of these dosimeters can be found in Hoffman and Mallett (1999). The TLD is used to measure the photon equivalent dose, H_γ, as well as provide an additional measure of the neutron equivalent dose (H_n). The TED is used to measure the dose resulting from high-energy neutrons with energies ranging from approximately 250 keV to several hundred MeV.

Except as noted below, the dosimeters placed at each location consisted of three or four PNADs, an 8823 TLD, and a TED. In the first exposure run, three sets of PNADs were placed on a polyethylene phantom located four meters from the assembly. To test the directional dependence of the PNAD response, sets were placed on the front of the phantom, facing the assembly; on the top, perpendicular to the assembly axis; and on the back of the phantom, facing away from the assembly. The last two sets would simulate someone facing at right angles to and away from a criticality, respectively. A TLD and TED were also placed on the front and rear of the phantom. Additionally, a set of dosimeters consisting of three PNADs, a TLD, and a TED, were placed in pockets on a plastic apron suspended free-in-air on a stand two meters from the assembly. For the second exposure all dosimeter sets were suspended free in air at distances of two, three, and four meters from the assembly. The dosimeter placements are summarized in Table 2.

Following the exposures the dosimeters were allowed to decay for approximately two hours prior to being delivered for analysis. At that time the TLD cards were removed from the 8823 holders and placed in a light tight box. This was done as the result of the 2009 intercomparison where it was found there was significant activation of the cadmium filters which surrounds the TLD card used to determine neutron dose (Gadd and Homan, 2010). The PNADs were opened by cutting a "window" in the plastic case and the foils removed and placed in paper envelopes labeled with the dosimeter ID and PNAD element.

Table 2. Dosimeter Placement

Run	Location Description	# Dosimeters
C1	4 m Phantom-Rear	4 PNAD 1 TED 1 TLD
	4 m Phantom-Front	4 PNAD 1 TED 1 TLD
	4 m Phantom-Top	3 PNAD
	2 m Free In Air	3 PNAD 1TED 1TLD
C2	2 m Free In Air	3 PNAD 1 TED 1 TLD
	3 m Free In Air	3 PNAD 1 TED 1 TLD
	4 m Free In Air	3 PNAD 1 TED 1 TLD

Analyses for gamma emitters were performed using either a 2"x2" NaI(Tl) detector[1] or a 1.5"x1.5" $LaBr_3$(Ce) detector[2] with spectra captured by the Genie™ 2000 Basic Spectroscopy Software[2]. To reduce the background the gamma detectors were shielded with a collimator consisting of approximately 1 cm thick lead and lined with 1 mm of copper. Samples were placed on the detector face on the central axis of the crystal.

The ^{32}P activity induced in the sulfur tablets was analyzed for using a 0.25 mm thick 43 mm diameter plastic scintillation detector with a 1.2 mg cm^{-2} thick window (Ludlum Instruments model 44-1)[3] connected to an Eberline E-600 Digital Survey Meter[4]. The beta detector was calibrated using sources with maximum beta energies ranging from 155 keV (^{14}C) to 2.32 MeV (^{234}Pa). A quadratic function was fit to the data to determine the efficiency at the beta energy of interest ($E_{\beta max}$ = 1.71 MeV). The intact sulfur tablets were centered on the detector window with the top of the tablet approximately 3 mm from the window. The tablets were also brought back to LANL and counted using a gas flow proportional counter both intact and crushed to a powder. The actual crushed mass of the sulfur tablets were used in all calculations.

The proper operation of the instruments was checked using a ^{60}Co source for the gamma detectors and a $^{90}Sr/^{90}Y$ source for the beta detectors. Due to large temperature variations in the room containing the gamma detectors it was necessary to periodically adjust the amplifier gain to maintain proper energy calibration. Typically this had to be done in the morning and again in the afternoon. The beta instruments were not significantly affected by temperature.

All of the indium foils (bare and cadmium covered) were counted the same day as the exposure for ^{116m}In using the LaBr(Ce) detector and analyzing for the 1293 keV photon. All other measurements were performed the next

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[1] Model 2M2/2. Saint-Gobain Crystals. 17900 Great Lakes Parkway, Hiram, OH 44234
[2] Canberra Industries, Inc. 800 Research Parkway, Meriden, CT 06450
[3] Ludlum Measurements, Inc. 501 Oak Street, Sweetwater, TX 79556
[4] Thermo Scientific, 27 Forge Parkway, Franklin, MA 02038

day to allow for decay of short lived activation products that would interfere with the measurements. The ^{115m}In activity from the cadmium covered foil was measured by analyzing for the 336 keV photon using the LaBr(Ce) detector. Due to the relatively low activity present at the time of the count, the foils for all of the PNADs at a given position were counted at the same time. The copper foils were counted with 1 cm of polymethyl methacrylate, PMMA (e.g. Plexiglas™) placed between the foil and the NaI(Tl) detector to ensure the total annihilation of the ^{64}Cu positron and maximizing the signal from the 511 keV annihilation photon. If there was an apparent loss of material, the elements were weighed and the actual masses used in the calculations. Otherwise, the average mass of the element was used.

Calculation of the neutron fluence was performed using spectrum specific cross sections for the indium and sulfur elements (Devine, 2004) assuming threshold energies of 1.2 and 3.3 MeV, respectively. The spectra used in the calculations were those found in IAEA, 2001. Since the 2009 exercise, the intermediate/epithermal region has been divided into two portions. One covers 0.6 eV to 3 keV and is assessed based on the $^{63}Cu(n,\gamma)^{64}Cu$ reaction. The effective cross section for this reaction was adjusted until the relative proportions of the fluences in each energy region was similar to that found for the assumed spectrum. Fluence in the region from 3 keV to 1.2 MeV, $\Phi_{3\text{-}1.2}$, was calculated using:

$$\Phi_{3-1.2} = \Phi_{>1.2} \text{ x R}$$

where $\Phi_{>1.2}$ is the fluence calculated from the $^{115}In(n,n')^{115m}In$ reaction and R is the ratio of the fluences for the assumed spectrum. Spectrum specific fluence-to-dose conversion factors for the heavy particle recoil dose, DCF, were calculated for each energy region assuming an unshielded GODIVA spectrum and the methods described by Devine (2004).

In order to compare results obtained from the PNADs and the 8823 TLD badges it was necessary to convert the PNAD determined neutron absorbed dose, D_n, to dose equivalent, H_n. To do this a spectrum weighted radiation weighting factor, w_R, was calculated for each region based on the factors found in ICRP-60 (ICRP, 1999) and the HPRR spectrum data found in IAEA Report 318 (IAEA, 1990). A summary of the factors used are given in Table 3. Since both exposures were of the bare CALIBAN assembly, just with differing power levels, the same factors were used for each.

Table 3. Spectrum averaged cross sections, fluence to dose conversion, and radiation weighting factors.

Energy Region	Factor	CALIBAN
Thermal (<0.6 eV)	In(n,γ) σ_{eff}(b)	162.3
	DCF (pGy cm^2)	0.58
	w_R	5
0.6 eV – 3 keV	Cu(n,γ) σ_{eff}(b)	0.101
	DCF (pGy cm^2)	4.18
	w_R	5
3 keV – 1.2 MeV	R	1.25
	DCF (pGy cm^2)	13.7
	w_R	19
1.2 – 3.3 MeV	In(n,n') σ_{eff}(b)	0.295
	DCF (pGy cm^2)	33.9
	w_R	16
>3.3 MeV	S(n,p) σ_{eff}(b)	0.388
	DCF (pGy cm^2)	52.6
	w_R	10

The raw data from the counting instruments was entered into an in-house developed database which calculates the activity concentration for each element and applies the appropriate conversion factors to determine the fluence for each region and the associated absorbed doses. This database was developed following the 2009 intercomparison to expedite processing the quantity of data generated in the analysis of the PNADs and the complexity of the calculations necessary to calculate neutron fluences and doses. This database allows the user to select what data to include in calculations, select conversion factors for different assumed neutron spectra, and generate summary reports of fluence and dose results for individual dosimeters as well as averages for groups of dosimeters.

Results

Appendix A contains a summary of the average specific activity induced in the PNAD elements at each location and exposure run. Results for the analysis of the sulfur pellets for ^{32}P activity by counting of intact pellets using the 44-1 plastic scintillator, intact pellets counted with a gas flow proportional counter, and analysis of the pellets crushed to a fine powder and counted using the gas flow proportional counter are summarized in Appendix B. The neutron fluence and dose calculated for each pulse and location from PNAD data for the two exposure runs can be found in Table 4 and Table 5. At the end of the exercise participants were given preliminary dose results for each location based on calibration factors and the number of fissions occurring in the assembly. These results are presented in the following tables as the delivered values. The neutron doses, as measured by the LANL PNADs, were consistently greater than the delivered values reported by CEA Valduc but were within 53% of these values.

Table 4. PNAD Neutron Fluence and Dose Results for Exposure Run 1.

Run	Location	Energy	Fluence (n cm^{-2})	% Total Fluence	D_n (Gy)	H_n (Sv)	Delivered D_n (Gy)	D_n % Difference
C1	2 m Free-in-Air	< 0.6 eV	2.7E+10	11	0.02	0.08		
		0.6 eV - 3 keV	7.9E+09	3	0.03	0.2		
		3 keV - 1.2 MeV	1.2E+11	48	1.7	32		
		1.2 - 3.3 MeV	6.5E+10	26	2.2	35		
		> 3.3 MeV	3.2E+10	13	1.7	17		
		Total	**2.6E+11**		**5.6**	**85**	**5.1**	**+9.8**
C1	4 m Phantom-Front	< 0.6 eV	4.9E+10	36	0.03	0.1		
		0.6 eV - 3 keV	8.5E+09	6	0.04	0.2		
		3 keV - 1.2 MeV	4.5E+10	32	0.6	12		
		1.2 - 3.3 MeV	2.8E+10	20	0.9	15		
		> 3.3 MeV	7.5E+09	5	0.4	4		
		Total	**1.4E+11**		**2.0**	**31**	**1.7**	**+18**
C1	4 m Phantom-Top	< 0.6 eV	4.0E+10	31	0.02	0.1		
		0.6 eV - 3 keV	8.2E+09	6	0.03	0.2		
		3 keV - 1.2 MeV	4.4E+10	35	0.6	11		
		1.2 - 3.3 MeV	2.7E+10	21	0.9	15		
		> 3.3 MeV	7.9E+09	6	0.4	4		
		Total	**1.3E+11**		**2.0**	**31**	**1.7**	**+18**
C1	4 m Phantom-Back	< 0.6 eV	4.5E+10	60	0.03	0.1		
		0.6 eV - 3 keV	5.1E+09	7	0.02	0.1		
		3 keV - 1.2 MeV	1.4E+10	18	0.2	4		
		1.2 - 3.3 MeV	8.6E+09	12	0.3	5		
		> 3.3 MeV	2.2E+09	3	0.1	1		
		Total	**7.4E+10**		**0.6**	**10**	**1.7**	**-64**

Table 5. PNAD Neutron Fluence and Dose Results for Exposure Run 2

Run	Location	Energy	Fluence (n cm^{-2})	% Total Fluence	D_n (Gy)	H_n (Sv)	Delivered D_n (Gy)	D_n % Difference
C2	2 m Free-in-Air	< 0.6 eV	2.8E+10	8	0.02	0.08		
		0.6 eV - 3 keV	1.3E+10	4	0.05	0.3		
		3 keV - 1.2 MeV	1.7E+11	49	2.3	43		
		1.2 - 3.3 MeV	9.2E+10	27	3.1	50		
		> 3.3 MeV	4.1E+10	12	2.1	21		
		Total	**3.4E+11**		**7.6**	**115**	**7.2**	**+5.6**
C2	3 m Free-in-Air	< 0.6 eV	2.9E+10	11	0.02	0.08		
		0.6 eV - 3 keV	1.2E+10	4	0.05	0.2		
		3 keV - 1.2 MeV	1.2E+11	47	1.7	32		
		1.2 - 3.3 MeV	7.9E+10	30	2.7	43		
		> 3.3 MeV	2.0E+10	8	1.1	11		
		Total	**2.6E+11**		**5.5**	**86**	**3.6**	**+53**
C2	4 m Free-in-Air	< 0.6 eV	3.2E+10	18	0.02	0.09		
		0.6 eV - 3 keV	1.1E+10	6	0.04	0.2		
		3 keV - 1.2 MeV	7.4E+10	42	1.0	19		
		1.2 - 3.3 MeV	4.8E+10	27	1.6	26		
		> 3.3 MeV	1.2E+10	7	0.6	6		
		Total	**1.8E+11**		**3.3**	**52**	**2.4**	**+38**

The 8823 Whole Body TLD badges were processed using the standard algorithm with no corrections for supralinearity applied. Table 6 contains a summary of the results obtained from the TLDs. Due to the dose delivered it was necessary to install light filters in the TLD readers to ensure proper readout of the elements and to prevent damage to the reader components. However, in the case of the photon card (elements 1 through 4) for exposure C1 at 2-meters , the correct filter was not used and there was incomplete collection of the light output[5]. For this exposure location the photon dose was estimated based on the net corrected reading for element seven on the neutron card. This element has the same composition (TLD-700) and effective filtration as element 1 on the photon card.

Table 6. TLD Equivalent Dose Results Summary

Pulse	Location	Equivalent Dose (Sv)	
		Photon	Neutron
C1	2 m	0.85	13.3
C1	4 m Phantom-Front	1.3	22.1
C1	4 m Phantom-Rear	0.94	17.4
C2	2 m	1.3	17.2
C2	3 m	1.5	18.2
C2	4 m	1.7	19.6

In order to compare the neutron doses measured by the PNADs and the TLDs it is necessary to convert the PNAD absorbed dose (D_n) results to equivalent dose (H_n) using the spectrum averaged radiation weighting factors found in Table 3. A comparison of the H_n results can be found in Table 7. For the dosimeters placed on the front and rear of the phantom the results are within ±40% of each other. However, for those dosimeters placed "free-

[5] Mallett, M. Personal communication , Jan. 3, 2011.

in-air" the TLD results are greater than those from the PNADs by factors of 2.7 to 6.7. These results are to be expected since the LANL 8823 Whole Body TLD algorithm calculates the neutron dose based on the albedo and anti-albedo response of the neutron card (Hoffman and Mallett, 1999). For the dosimeters suspended in air the albedo response is under-represented.

Table 7. Comparison of PNAD and TLD Neutron Equivalent Dose Results

Pulse	Location	PNAD (Sv)	TLD (Sv)	PNAD:TLD
C1	2 m	85	13.3	6.4
C1	4 m Phantom-Front	31	22.1	1.4
C1	4 m Phantom-Rear	10	17.4	0.6
C2	2 m	115	17.2	6.7
C2	3 m	86	18.2	4.7
C2	4 m	52	19.6	2.7

A summary of the measured results and comparison with the delivered dose reported by CEA Valduc can be found in Table 8. With the exception of the results for the dosimeters placed on the phantom the photon doses measured by the TLDs are within 180 percent of delivered photon dose.

Table 8. Comparison of Photon Dose Equivalent Results

Pulse	Location	Delivered H_γ (Sv)	Measured H_γ (Sv)	H_γ % Difference
C1	2 m	0.7	0.85	+21
	4 m Phantom-Front	0.4	1.3	+230
	4 m Phantom-Rear		0.94	+140
C2	2 m	1.0	1.3	+30
	3 m	0.7	1.5	+110
	4 m	0.6	1.7	+180

The TEDs were processed by the LANL RP-2 External Dosimetry Team using their standard procedures[6]. On completion it was found the density of the developed tracks rendered the foil completely opaque. Therefore, no dose information could be determined from the foils.

During the 2009 exercise significant activation of components in the 8823 TLD case was observed (Gadd and Homan, 2010). This activity is believed to result from activation of the cadmium "box" which surrounds the neutron card with the primary activation products of being ^{115}Cd and to some extent ^{117}Cd. At the end of the experiment the cases were measured with a pancake Geiger-Mueller detector to determine if the cases could be used to screen individuals involved in a criticality incident who were not wearing PNADs. The results of the counts are presented in Table 9. Due to the relatively short (2.4 hour) half-life of ^{117}Cd and low abundance of its target nucleus, ^{116}Cd (7.6%), it was assumed that the measured activity more than 24-hours after the exposure was from ^{115}Cd the count rates were decay corrected back to the time of exposure. In all cases the net beta count rates were greater than background. However, the count rates are not representative of the total dose as shown by the results for C2 where the count rate increases with greater distance from the assembly. However, the count rates are proportional to the thermal absorbed dose for the dosimeters suspended in air. This indicates that the 8823 Whole Body badge could be used to screen exposed individuals but the results may not be indicative of the dose the individual received.

[6] Issuing, Receiving, and Procssing Track-Etch Dosimeters. RP2-ED-DP-33, R7. Oct. 29, 2010.

Table 9. 8823 Case Beta Counts Rate

Exposure	Location	Time Post Exposure (h)	Net Count Rate (cps)	Decay Corrected Count Rate (cps)	cps/Gy_{Th}
C1	2 m	49	7.9 ± 0.3	14.9	930
	4 m Phantom Front	49	6.1 ± 0.3	11.5	410
	4 m Phantom Rear	49	3.3 ± 0.2	6.2	240
C2	2 m	25	12.7 ± 0.4	17.6	1100
	3 m	25	13.7 ± 0.4	18.9	1100
	4 m	25	14.9 ± 0.4	20.6	1100

Conclusions

Based on the preliminary delivered doses reported by CEA Valduc neutron doses calculated from the LANL PNAD were within 53 percent of the reported true values with the exception of the dosimeters placed on the back of a polyethylene phantom. This is to be expected since the neutron spectrum would be modified by the presence of the phantom between the source and the dosimeters. Indications are that modifications to the algorithms, conversion factors, and data processing techniques made following the 2009 exercise did not degrade, and possibly improved the results obtained from the PNADs. The use of a database to store the data and perform the calculations greatly eased and accelerated processing of the data.

For dosimeters placed on the polyethylene phantom, the LANL 8823 Whole Body TLD badge neutron dose equivalent results were within ±40% of those measured by the PNAD. However, for those dosimeters suspended "free-in-air" the TLD badge under reported the neutron doses by factors of 2.7 to 6.7. When compared to the "True" photon does reported by CEA Valduc, the biases in the photon equivalent doses, measured by the LANL 8823 Whole Body TLD badge, ranged from 21 to 230 percent. Measurement of the neutron dose using track etch dosimeters was unsuccessful as the high neutron fluence rendered the developed foils completely opaque.

Unlike measurements with a pancake Geiger-Mueller tube, the thin plastic scintillator used for field measurement of beta emitters did not exhibit any significant interference from gamma emitters. This is advantageous for field measurements where there may be a high gamma background, such as from activation foils placed in the vicinity. The use of a multi-channel analyzer for the measurement of gamma emitters proved advantageous over the single-channel analyzer used in 2009. Being able to view the spectrum allowed the user to compensate for drift in the gain caused by temperature changes. The LaBr(Ce) detector performed well and was able to discriminate the peaks of interest. However, it did not have a sufficient peak-to-compton ratio to determine ^{115m}In in the presence of ^{116m}In. It should be noted that even higher resolution high-purity germanium detectors had difficulty accomplishing this in certain circumstances.

Results for PNADs placed on a phantom indicated no significant difference in the results for the dosimeters placed on the front and the top of the phantom. This indicates that no correction is necessary for individuals who were facing perpendicular to the criticality; that is, for side exposures. However, the results for dosimeters placed on the back of the phantom were a factor of 3.3 lower than those on the front. A correction factor of 3.3 should be applied to the PNAD results for someone facing away from the criticality event to achieve a better estimate of the true dose.

The standard method for determining ^{32}P activity in the sulfur tablet is to melt the tablet and burn off impurities. This process minimizes the self absorption of the beta particles in the tablet. However, this procedure is time consuming and sensitive to operator technique. In 1969 a study was performed to determine the relative effect of measuring the activity with the tablet intact, crushed, and melted and burned (Hankins, 1969). This study established an activity ratio for burned to crushed tablets of 1.87 ± 0.18 and crushed to intact tablets of 1.41 ±

0.14. These ratios could be used to determine the true ^{32}P activity from intact or crushed tablets without the need to melt and burn them. Although the burning process was not performed in this intercomparison, the tablets were counted both intact and crushed. The ratio of crushed to intact tablet activity, as measured using the gas flow proportional counter, was 1.83 ± 0.05. This is significantly greater than that measured by Hankins however these measurements were performed on 27 samples as compared to the six used by Hankins. Therefore, the recommendation is to establish a correction factor for counting of an intact PNAD sulfur tablet of 3.42 (1.83 for crushed to intact times 1.87 for burned to crushed).

Measurements of the 8823 TLD cases showed measureable beta activity even 48 hours after the exposure. This indicates that the cases could be used to identify individuals who were exposed in a criticality accident even if they were not wearing PNADs. However, while the count rate appears to be proportional to the thermal neutron dose, it is not proportional to the total neutron dose. Therefore, the activity of the dosimeter case may not be able to be used to estimate the individual's dose.

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Appendix A

PNAD Element Specific Activities

Run	Location	Element/Isotope	Specific Activity ($Bq\ g^{-1}$)	Uncertainty ($Bq\ g^{-1}$)
C1	2 m	Bare In/^{116}In	5.5E+06	1.1E+06
		Cd Covered In/ ^{116}In	6.2E+03	3.1E+02
		Cd Covered In/ ^{115m}In	1.8E+06	5.5E+04
		Cd Covered Cu/^{64}Cu	2.5E+03	4.0E+02
		Sulfur/^{32}P	1.2E+02	7.5E+00
	4 m Phantom-Front	Bare In/^{116}In	8.8E+06	9.0E+05
		Cd Covered In/ ^{116}In	2.3E+03	1.7E+02
		Cd Covered In/ ^{115m}In	2.1E+06	7.6E+04
		Cd Covered Cu/^{64}Cu	2.7E+03	3.5E+02
		Sulfur/^{32}P	2.9E+01	3.2E+00
	4 m Phantom-Rear	Bare In/^{116}In	7.5E+06	3.6E+05
		Cd Covered In/ ^{116}In	6.9E+02	1.1E+02
		Cd Covered In/ ^{115m}In	1.4E+06	8.2E+04
		Cd Covered Cu/^{64}Cu	1.6E+03	3.0E+02
		Sulfur/^{32}P	8.6E+00	6.3E-01
C2	2 m FIA	Bare In/^{116}In	5.5E+06	3.7E+05
		Cd Covered In/ ^{116}In	8.4E+03	4.0E+02
		Cd Covered In/ ^{115m}In	1.7E+06	2.1E+05
		Cd Covered Cu/^{64}Cu	3.9E+03	4.4E+02
		Sulfur/^{32}P	1.6E+02	3.4E+00
	3 m FIA	Bare In/^{116}In	5.6E+06	1.7E+05
		Cd Covered In/ ^{116}In	6.3E+03	3.4E+02
		Cd Covered In/ ^{115m}In	1.7E+06	1.3E+05
		Cd Covered Cu/^{64}Cu	3.7E+03	2.7E+02
		Sulfur/^{32}P	7.8E+01	4.9E+00
	4 m FIA	Bare In/^{116}In	5.9E+06	2.2E+05
		Cd Covered In/ ^{116}In	3.8E+03	2.0E+02
		Cd Covered In/ ^{115m}In	1.6E+06	4.7E+05
		Cd Covered Cu/^{64}Cu	3.4E+03	1.7E+02
		Sulfur/^{32}P	4.7E+01	1.1E+00

APPENDIX B: Sulfur Tablet Count Data

Exposure	Exposure Date	Location	PNAD ID	44-1 Whole (Bq g^{-1})	Berthold Whole (Bq g^{-1})	Berthold Crushed (Bq g^{-1})	Crushed: 44-1	Crushed: Whole
C1	21-Sep-10	4 m Rear	097941	1.42E+00	2.75E+00	4.91E+00	3.47E+00	1.78E+00
			100878	9.26E-01	2.55E+00	4.57E+00	4.93E+00	1.79E+00
			106252	1.43E+00	2.57E+00	4.78E+00	3.34E+00	1.86E+00
			178559	1.38E+00	3.02E+00	4.15E+00	2.99E+00	1.38E+00
		4 m Front	083727	6.36E+00	9.95E+00	1.67E+01	2.63E+00	1.68E+00
			105567	6.45E+00	7.21E+00	1.62E+01	2.51E+00	2.25E+00
			113020	5.89E+00	8.18E+00	1.31E+01	2.23E+00	1.60E+00
			184610	7.45E+00	9.19E+00	1.67E+01	2.24E+00	1.81E+00
		4 m Top	0285	6.46E+00	1.18E+01	1.67E+01	2.59E+00	1.42E+00
			320022	5.65E+00	1.03E+01	1.64E+01	2.90E+00	1.59E+00
			320074	5.94E+00	1.05E+01	1.61E+01	2.72E+00	1.53E+00
		2 m FIA	0344	2.27E+01	3.35E+01	6.25E+01	2.76E+00	1.86E+00
			117806	1.95E+01	3.05E+01	6.99E+01	3.58E+00	2.29E+00
			195735	2.18E+01	3.67E+01	6.98E+01	3.20E+00	1.90E+00
			320006	2.90E+01	4.12E+01	6.34E+01	2.18E+00	1.54E+00
C2	22-Sep-10	2 m FIA	114740	2.98E+01	4.44E+01	8.31E+01	2.79E+00	1.87E+00
			114962	3.29E+01	4.19E+01	8.66E+01	2.63E+00	2.07E+00
			186648	9.64E+00	1.03E+01	2.34E+01	2.43E+00	2.28E+00
			191157	2.81E+01	4.74E+01	8.44E+01	3.00E+00	1.78E+00
		3m FIA	108534	2.20E+01	2.31E+01	4.26E+01	1.94E+00	1.84E+00
			175003	1.60E+01	2.19E+01	4.41E+01	2.75E+00	2.01E+00
			175594	1.59E+01	2.00E+01	3.91E+01	2.46E+00	1.95E+00
			212369	2.76E+01	5.00E+01	8.80E+01	3.19E+00	1.76E+00
		4m FIA	107030	1.01E+01	1.18E+01	2.49E+01	2.46E+00	2.11E+00
			109915	8.89E+00	1.27E+01	2.44E+01	2.75E+00	1.92E+00
			170906	2.43E+01	1.46E+01	2.56E+01	1.05E+00	1.75E+00
			212239	1.49E+01	2.36E+01	4.38E+01	2.94E+00	1.85E+00

	Crushed:44-1	Crushed:Whole
Mean	2.77	1.83
Standard Error	0.13	0.05
Median	2.75	1.84
Standard Deviation	0.67	0.24
Sample Variance	0.45	0.06
Kurtosis	4.39	-0.11
Skewness	0.73	0.16
Range	3.88	0.92
Minimum	1.05	1.38
Maximum	4.93	2.29
Count	27	27