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Blind Intercomparison of Nuclear Accident Dosimetry using the Flattop Reactor at NCERC

Hickman, D. P.[1], Wilson, C.[2], Trompier, F.[3]

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IER-253 CED-4 Report

[1]Lawrence Livermore National Laboratory
[2]Atomic Weapons Establishment
[3]Institut de Radioprotection et de Sûreté Nucléaire

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Executive Summary

The purpose of this exercise was to continue United States, United Kingdom, and France collaborative activities performing Nuclear Accident Dosimetry intercomparison. IER 148 was the inaugural intercomparison exercise using the Godiva reactor at the DAF. In contrast to IER 148, in the current exercise participants were "blind" to the known doses during the exercise, to simulate the dosimetry response to a real criticality incident. This document is the Final Exercise (CED-x) Report for IER-253, "International Intercomparison Exercise for Nuclear Accident Dosimetry at the DAF Using Flattop." The report describes the structure and results of the exercise consisting of two irradiations. The details of all dosimetry elements and their placement in proximity to Flattop on support stands or phantoms was unknown to participating laboratories. The participating laboratories in this report are deidentified and the report summarizes participant results from the intercomparison. The exercise occurred during the week of May 21, 2018.

Introduction

IER-253 is part of a "Non-Classified Research Program under the CEA-DOE Agreement, Cooperation in Fundamental Science Supporting Stockpile Stewardship," for joint US/French nuclear accident dosimetry (NAD) exercises in the DAF. IER-253 builds on:

- Start-up of the Flattop reactor (IER-195) and
- Establishment of reference values for the Flattop radiation field in DAF (IER-252).

Ten laboratories participated in this NAD exercise at the NNSS including all six US participants (LANL, LLNL, PNNL, SNL, SRS and Y12) in the previous SILENE and CALIBAN exercises at CEA-Valduc. The additional participants are the Atomic Weapons Establishment (United Kingdom), the Institute for Radiological Protection and Nuclear Safety (France), Pacific Northwest National Laboratory, Missions Support and Test Services (MSTS), and the Naval Dosimetry Center and Norfolk Naval Shipyard, by special invitation. CEA (Valduc) is no longer participating due to change of mission. MSTS dosimeters were irradiated but not reported or tallied as part of the exercise.

Methods

Two critical excursions using the Flattop Reactor were performed on May 22 and May 23, 2018 at the Nuclear Criticality Experiments Research Center (NCERC) facility. Dosimeters were positioned at 2 and 3 meters from the Flattop core. After each excursion dosimeters were transported to LLNL's NAD Lab at Mercury for processing by dosimetry personnel. For each excursion, dosimeters were placed on bottle manikin (BOMAB) phantoms and on aluminum plates for "free-in-air" dose measurements. The focus of the exercise was the dosimetry using the BOMABs because the response of dosimeters on phantoms is a good simulator of dosimeters worn by workers. Free-in-air stations were placed alongside the BOMABs to provide additional information and make a measure of the air kerma associated with the absorbed dose in the phantom. Four BOMABs were used in each irradiation.

Each BOMAB was able to accommodate up to 11 dosimeters on the front and 11 dosimeters on the back for a total of 22 dosimeters per BOMAB. The placement of dosimeters and the designation of orientation of the phantoms was performed by the exercise coordinators and kept private from the participants. The position of each dosimeter was noted by the coordinators as it was placed on a phantom. The BOMABs contained saline solution (Ringer's Lactate) to simulate blood and small packets containing hair were taped to the surface of the BOMAB so that participants could utilize biological dosimetry methods. All activated BOMABs will be set up for quick sort measurements at the NAD lab and multiple 10 ml samples of Ringer's Lactate were taken for analysis by participants.

The free-in-air stands accommodated up to 11 dosimeters per plate for a total of 33 dosimeters per stand. A maximum of 3 dosimeters per laboratory were able to be placed on the stand at a height as close as possible to the height of the corresponding dosimetry placed on the adjacent

BOMAB phantom. The placement of dosimeters on the free air plates was performed by the exercise coordinators and kept private from the participants. The position of each dosimeter was noted by the coordinators as it was placed on a plate.

On receipt of the free air stand plates and the BOMABs the coordinators removed the dosimeters and sorted them according to participant. Each participant was then presented with their irradiated dosimeters.

As the dosimeter results became available, participants were requested to report their results. During the first 24 hours post excursion, limited information about the irradiations was provided to participants to simulate the expected changing of circumstances surrounding a nuclear criticality accident. After 24-hours participants were requested to provide their best dosimetry determinations[1]. On conclusion of the exercise, the locations of all dosimeters including their position on each BOMAB phantom and its orientation and location relative to Flattop were given to participants and they were requested to provide a revised estimate of the dose within 3 weeks of receipt of their dosimeters at the home laboratory.

The inter-comparison was designed to compare whether participants could accurately estimate the maximal dose to the phantoms regardless of orientation. For consistency participants were asked to use dose factors from the ANSI N13.3 standard. The phantom (simulating a person) was centered at the dose point (either 3, or 4 meters). A dosimeter on the front of a person who is oriented with his/her back to the event was simulated by placing the dosimeter on the back of the phantom. Some dosimeters do not provide orientation information, but other methods can be used to determine the orientation (e.g. hair samples from different sides of the head). Information on the orientation of the phantom and the placement of dosimeters on the phantom were provided to the participants after the exercise so that they could apply any necessary corrections for orientation of the person (phantom) in the three weeks after the event. Figures 1 and 2 show the positioning and orientation of the free in air trees and phantoms. In the first irradiation the phantoms were oriented tangential to the core at the 3 or 4-meter mark. Dosimeters on the backs of the phantoms simulate the dose reading expected for a person facing away from the criticality event.

[1] Twenty-four hour reporting requirements are commonly required by National and International standards or regulations.

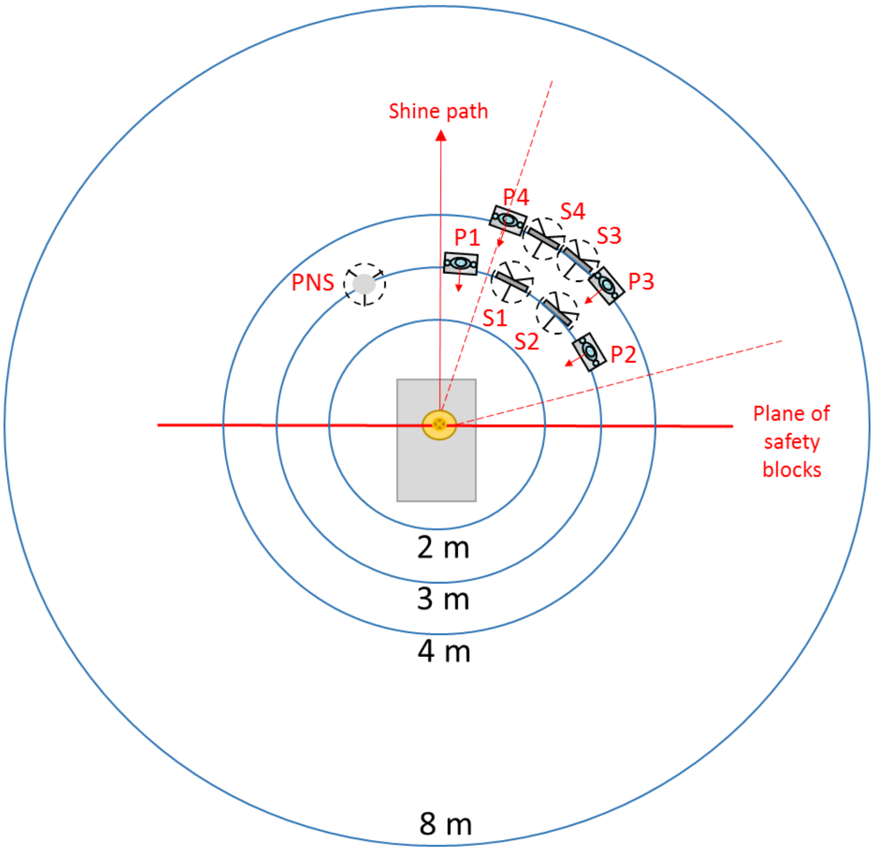


Figure 1: Location of dosimetry phantoms (P#) and stands (S#) for irradiation 1.

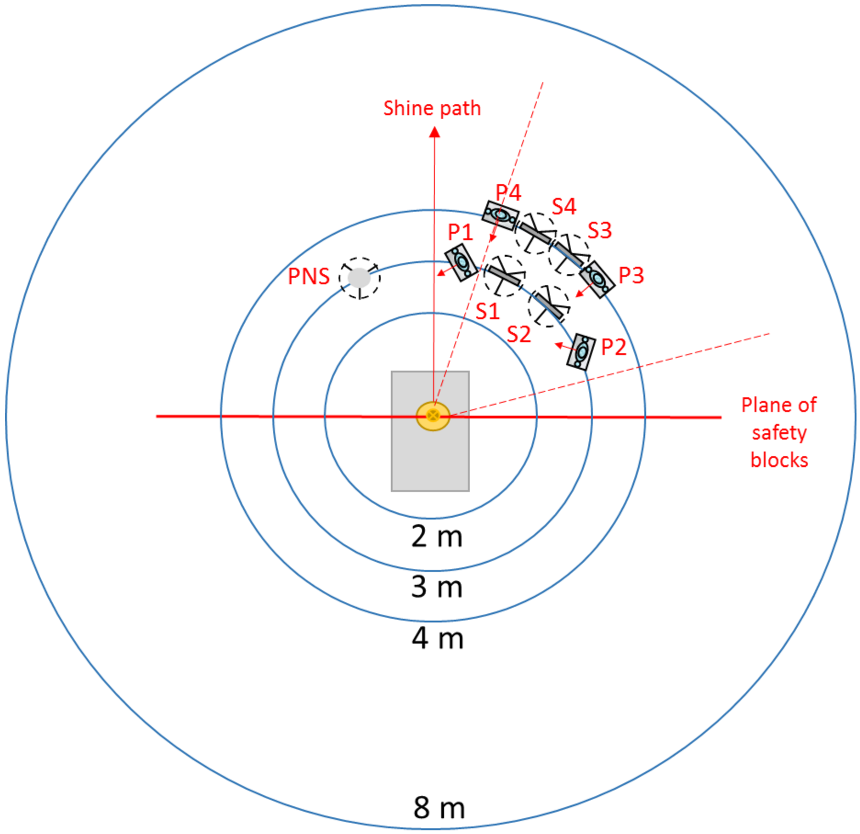


Figure 2: Location of dosimetry phantoms (P#) and stands (S#) for irradiation 2 (note phantoms 1 and 2 are rotated clockwise 45°)

Results

Participants were asked to provide doses using the ANSI N13.3-2013 dose factors, however some laboratories reported doses based on IAEA Technical Series 211 (Dosimetry for Criticality Accidents) or tissue kerma dose conversion factors. The performance statistic was calculated in accordance with the ANSI standard using the following:

$$B = \frac{(Measured\ Dose - Delivered\ Dose)}{Delivered\ Dose} \times 100$$

For reported values using IAEA 211 or tissue kerma dose factors, the performance statistic was calculated using the known IAEA 211 or kerma delivered dose.

The ANSI N13.3-2013 performance test criteria are as follows:

Total absorbed dose range (Gy)	Test Statistic (B)
0.1 to 1	±50%
1 to 10	±25%

The reference 'known' dose values based on previous Flattop characterization studies (IER-252) are provided in Table 1. Appendix A contains additional known dose values for various reference dose conversions as well as verification data.

Table 1. Known doses for the blind exercise using ANSI/HPS N13.3- 2013 dose conversion factors.

		Neutron Dose (Gy)[2]			Gamma Dose (Gy)			Total Dose (Gy)		
	Distance (m)	Known Value	+1s	-1s	Known Value	+1s	-1s	Known Value	+1s	-1s
Irradiation #1	3	0.92	0.08	-0.07	0.17	0.01	-0.01	1.09	0.08	0.07
	4	0.61	0.04	-0.04	0.15	0.01	-0.01	0.76	0.04	0.04
Irradiation #2	3	3.71	0.32	-0.30	0.67	0.05	-0.06	4.48	0.33	0.30
	4	2.50	0.16	-0.15	0.59	0.04	-0.04	3.09	0.16	0.15

Total Dose Results

Final results were provided approximately three weeks post irradiation. Figures 3 through 6 show the performance of each laboratory relative to the ANSI N13.3 Limits. These limits are not applicable to foreign participants, but the ANSI N13.3-2013 limits provide a reasonable benchmark for all participants.

[2] Using ANSI N13.3 $D_P(10)$ dose conversion values.

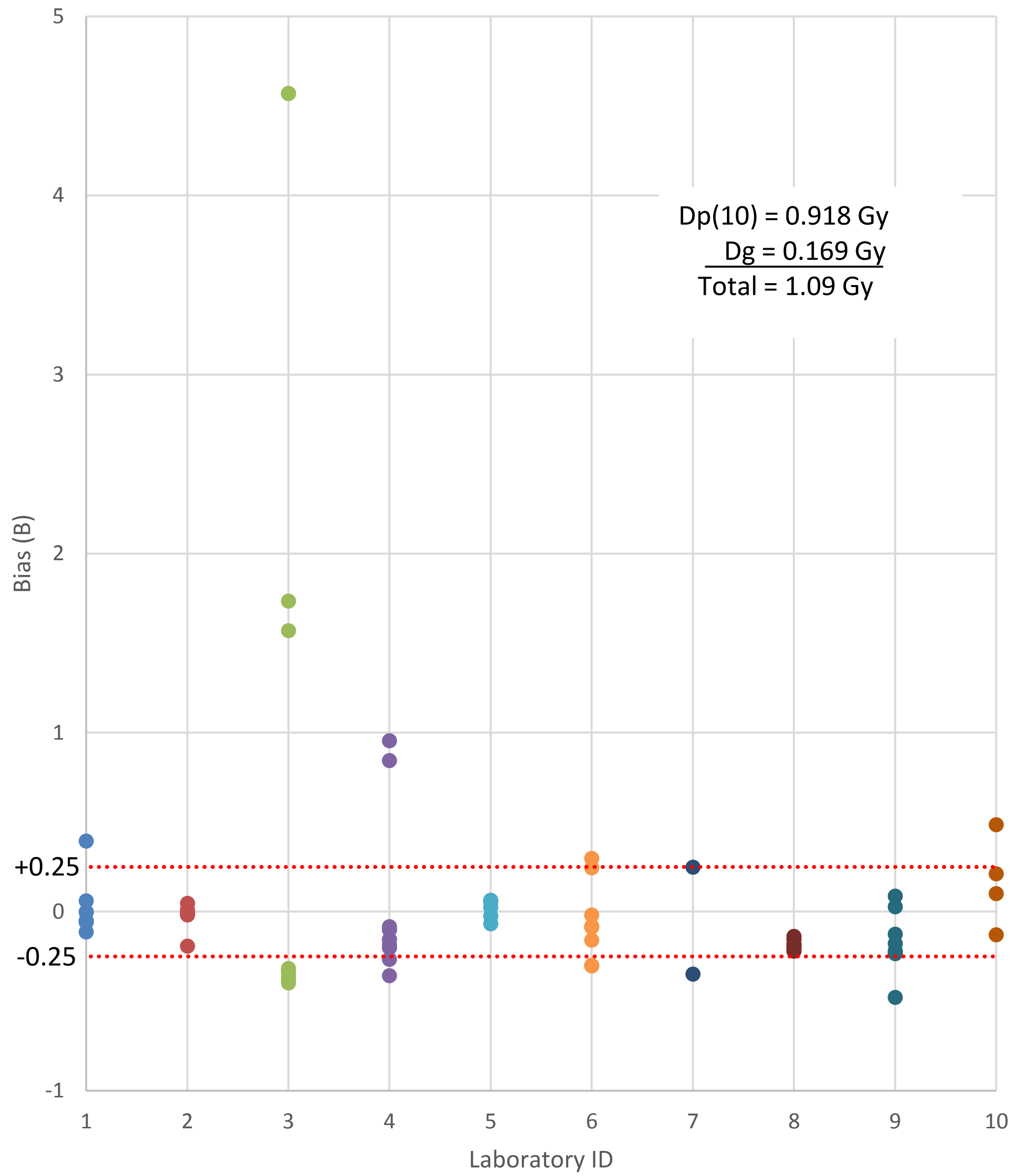


Figure 3. Irradiation No.1 - Comparison of final total dose results to ANSI N13.3 Limits @ 3m.

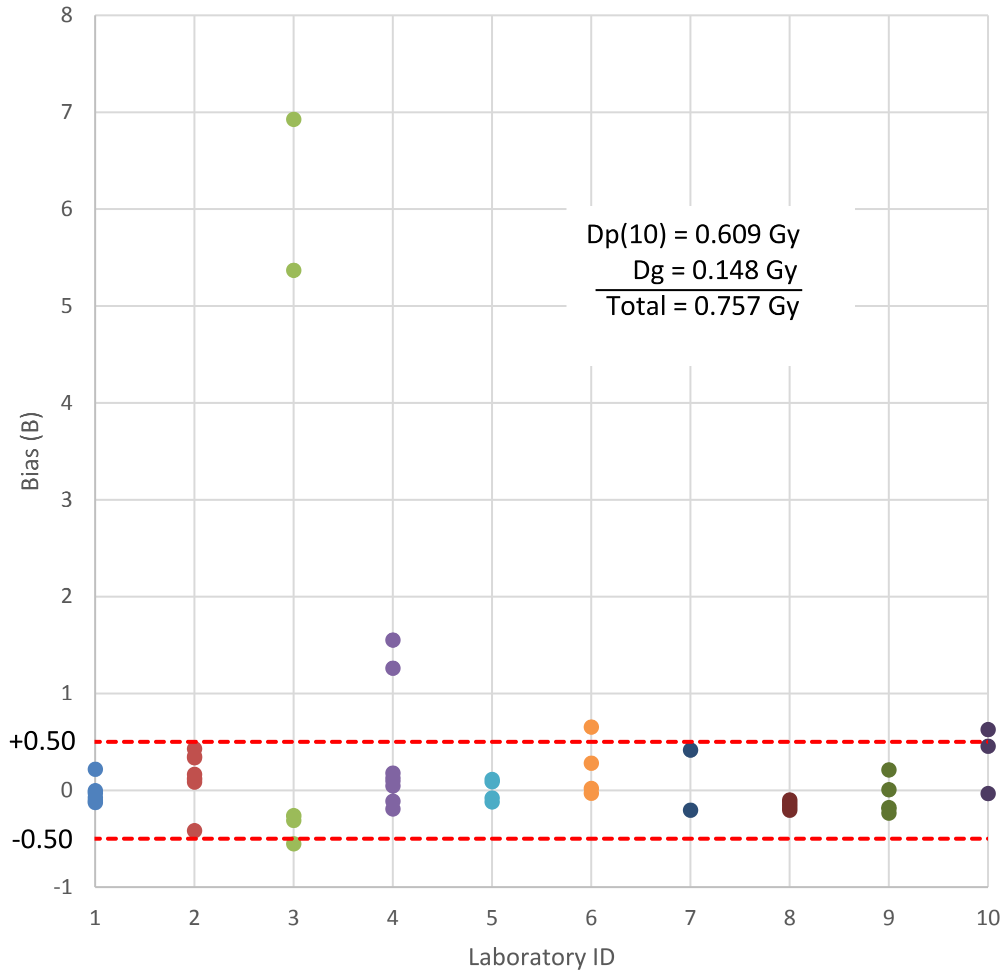


Figure 4. Irradiation No.1 - Comparison of final total dose results to ANSI 13.3 Limits @ 4m

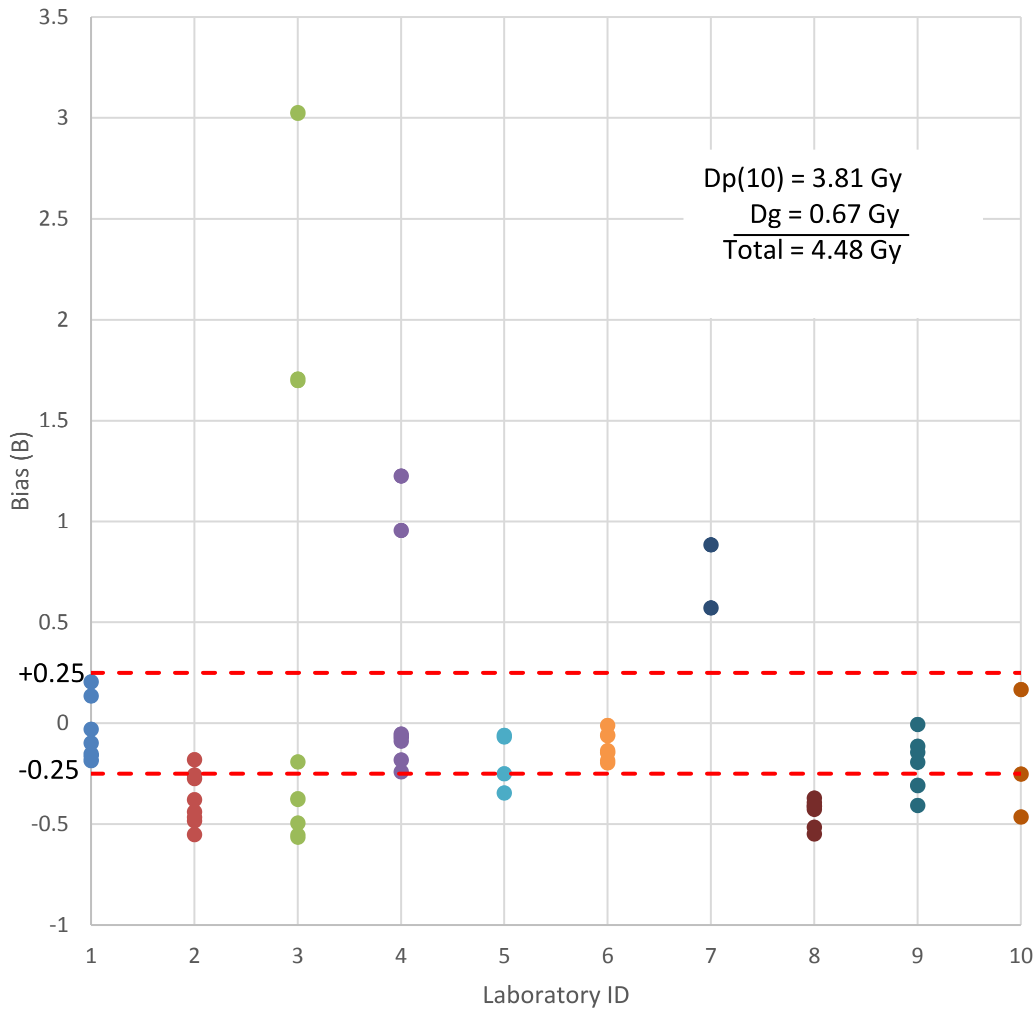


Figure 5. Irradiation No.2 - Comparison of final total dose results to ANSI 13.3 Limits @ 3m

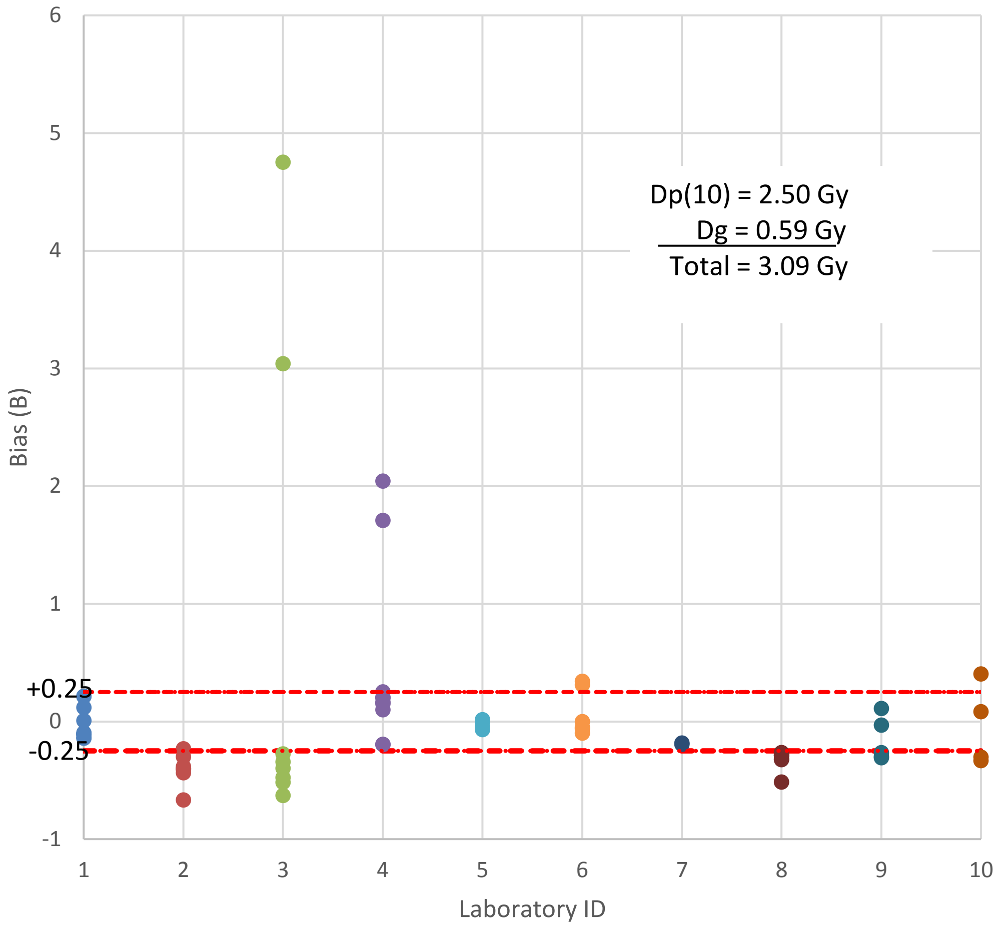


Figure 6. Irradiation No.2 - Comparison of final total dose results to ANSI 13.3 Limits @ 4m

The DOE Standard on Radiological Control (DOE-STD-1098-2017), Article 515 specifies that "Personnel Nuclear Accident Dosimeters should be capable of measuring an absorbed dose in or on a phantom from 10 rads to approximately 1,000 rads with an accuracy of ± 20% for gamma radiation and ± 30% from neutron radiation. Comparison of laboratory performance for the DOE standard relative to the ANSI standard are provided in Tables 2 and 3.

Table 2. Percent of all dosimeter results (total dose) outside the bias limits for all laboratories.

	Irradiation #1		Irradiation #2	
Known Total Dose (Gy)	**0.76**[3]	**1.09**	**3.09**	**4.48**
% outside ANSI Limits	12%	45%	52%	50%
% outside DOE STD Limits	51%	53%	52%	48%

[3] ANSI N13.3-2013 limit for <1Gy is ±50%

Table 3. Percent of dosimeter results (total dose) outside of bias limits by laboratory.

Lab ID	% outside ANSI Limits	% outside DOE STD Limits[4]
1*	2.8%	11%
2*	47%	41%
3	88%	81%
4*	33%	32%
5	10%	23%
6*	27%	58%
7[5]*	50%	100%
8	59%	26%
9	38%	36%
10*	57%	78%

*DOE laboratory

24-Hour Neutron Results

All laboratories reported initial 24-hour neutron dose results. Six (out of 10) laboratories were able to provide gamma doses within the first 24 hours. The remaining four laboratories provided gamma results with the final dose values.

Final neutron dose values were received approximately 3 weeks after the exercise. Figures 7 and 8 show the comparison of the 24-hour neutron dose results to the final neutron dose results. In the both irradiations, eight laboratories improved their neutron 24-hour results (i.e., moved results closer to a zero bias) after having time to make corrections based on released information about the irradiations after the exercise. Four of the laboratories demonstrated improvements in the neutron dose determination for one irradiation but not for the other irradiation, thus showing an inconsistency among laboratories on improvement with additional time and information.

[4] These limits only apply to DOE Laboratories. Gamma and neutron criteria were evaluated.

[5] Measurement equipment failures hindered ability to report results properly.

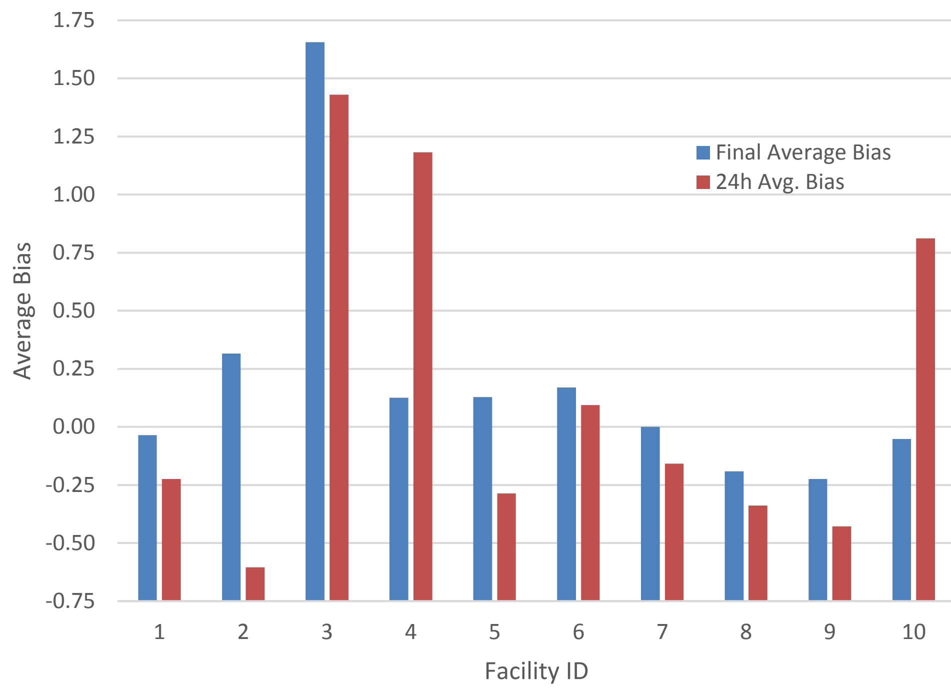


Figure 7. Final and 24-hour neutron dose bias for irradiation #1.

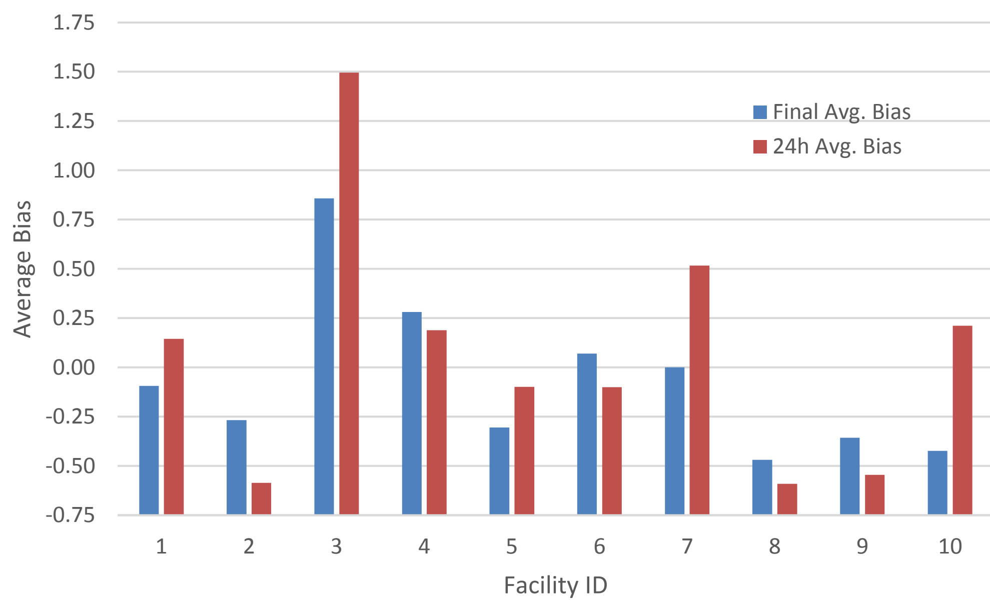


Figure 8. Final and 24-hour neutron dose bias for irradiation #2.

24-hour and final Gamma Dose Results

Most of the participants needed to process gamma dosimeters back at their home laboratories where the proper processing equipment was available. Two laboratories were unable to report gamma doses, one of which was unable to process dosimeters with such high doses without risking damage to their DOELAP accredited equipment used to read the gamma dosimeters. Fifty one percent of all the gamma dose results were unable to meet the DOE Standard on Radiological Control §515 limits for gamma dose determination using Personnel Nuclear Accident Dosimeters. The final gamma dose performance statistics ranged from approximately -0.75 and 3.5. Four of the 10 laboratories were able to provide gamma doses within the first 24 hours. Only one of the five laboratories made refinements to their 24-hour gamma dose estimates during the three weeks after receiving final information about the irradiations. Most of the refinements increased the performance statistic away from zero. Figures 9 through 12 provide individual laboratory performance for gamma dosimetry relative to the DOE standard.

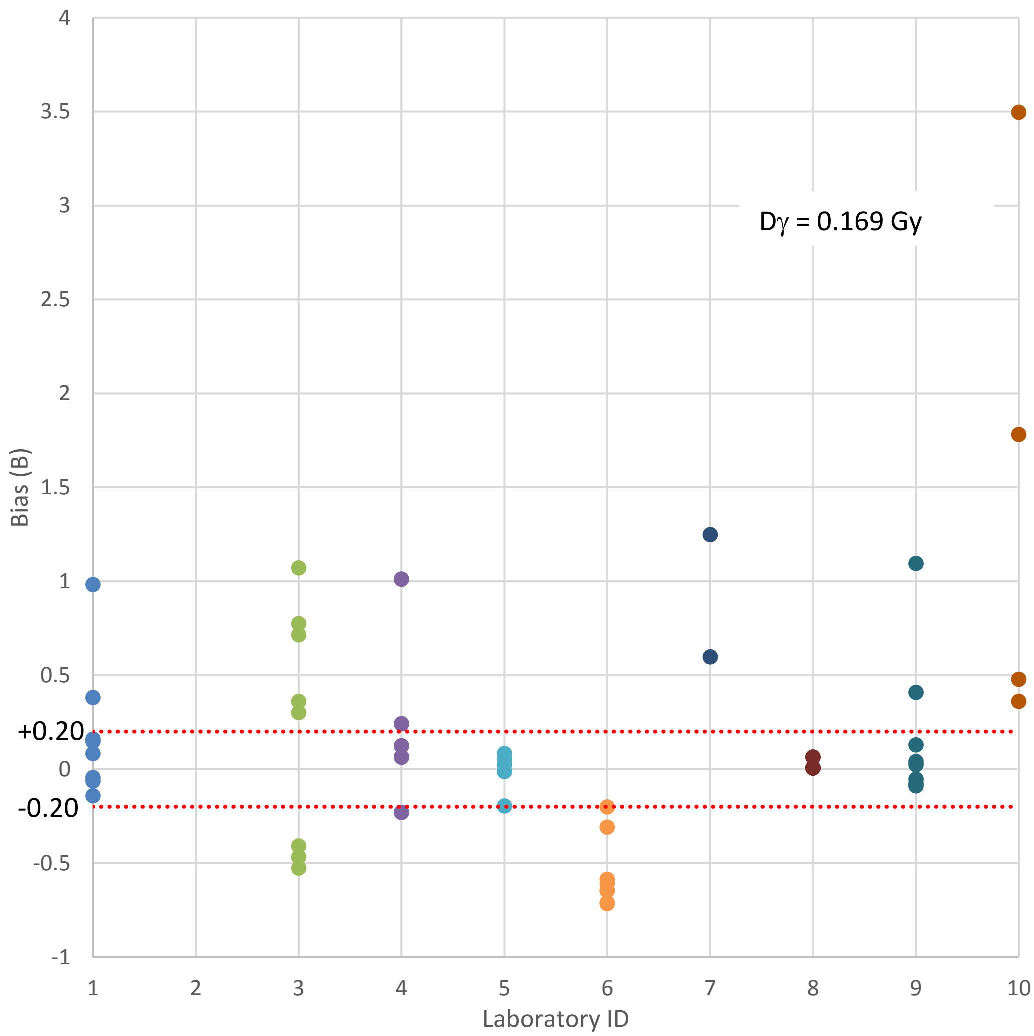


Figure 9. Irradiation No.1 - Comparison of final gamma dose results to DOE Limits @ 3m.

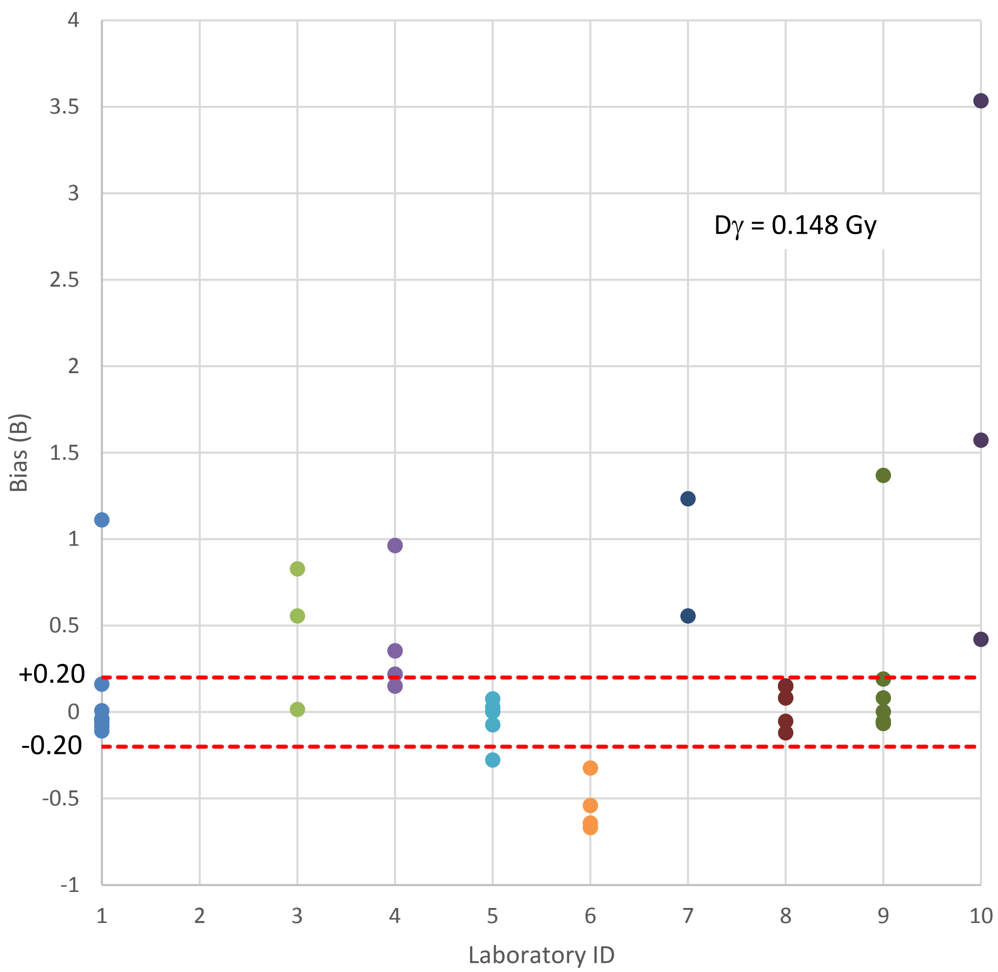


Figure 10. Irradiation No.1 - Comparison of final gamma dose results to DOE Limits @ 4m.

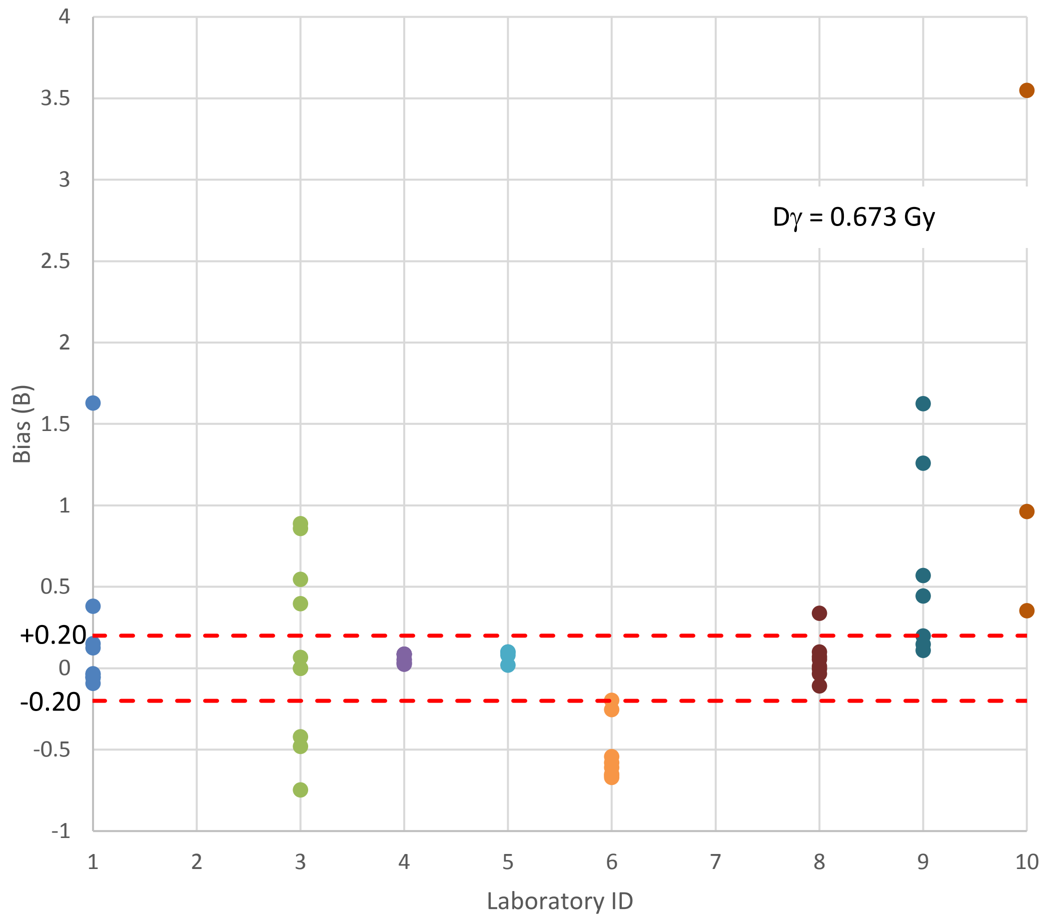


Figure 11. Irradiation No.2 - Comparison of final gamma dose results to DOE Limits @ 3m.

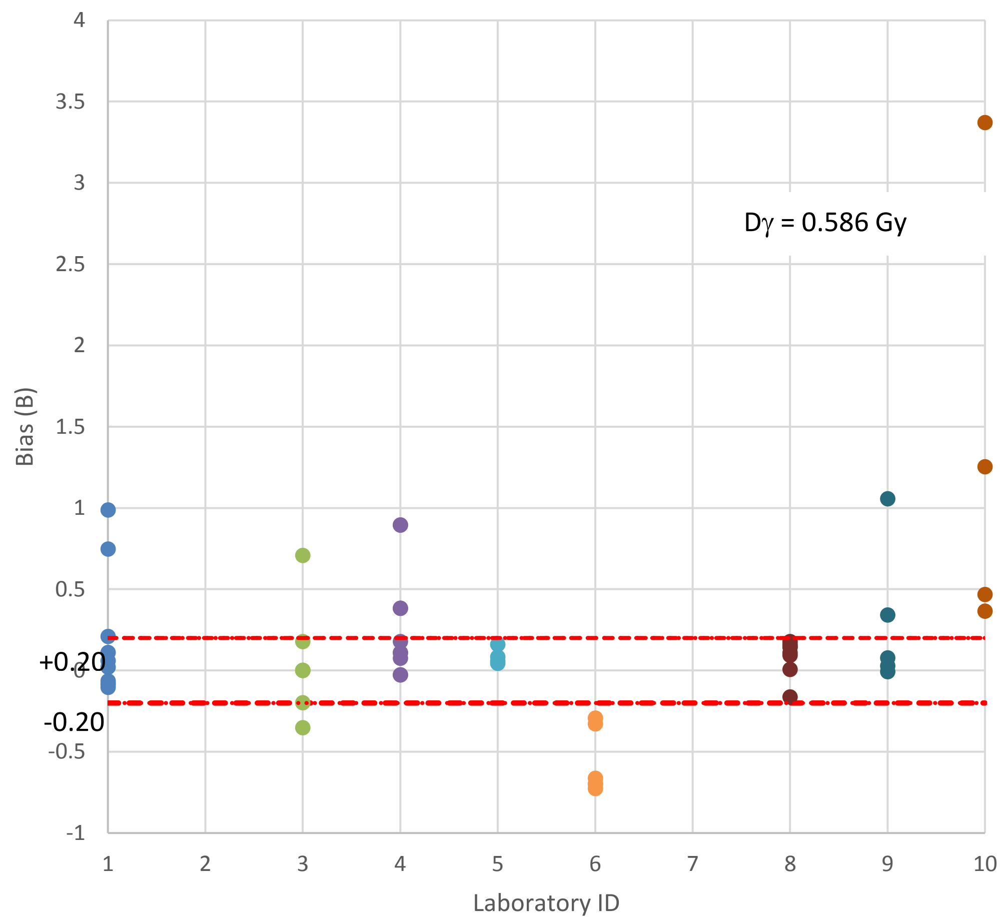


Figure 12. Irradiation No.2 - Comparison of final gamma dose results to DOE Limits @ 4m.

Biological Dosimetry Neutron Dose Results

Four Laboratories provided neutron dose results using biological dosimetry (i.e., hair and/or simulated blood). A limited number of results and the lack of a one-to-one correspondence with any specific dosimeter result limits the statistical significance or comparison to dosimeter results, however the number of dose results within the ANSI and DOE standard bias limits appear to be better than doses predicted by other dosimetry methods, as shown in Table 4. Figures 13 and 14 shows individual laboratory performances for the neutron biological dosimetry used in this exercise.

Table 4. Percent of all dosimeter results (total dose) outside the bias limits for all laboratories.

	Irradiation #1	Irradiation #2
% outside ANSI Limits	14%	33%
% outside DOE STD Limits	14%	17%

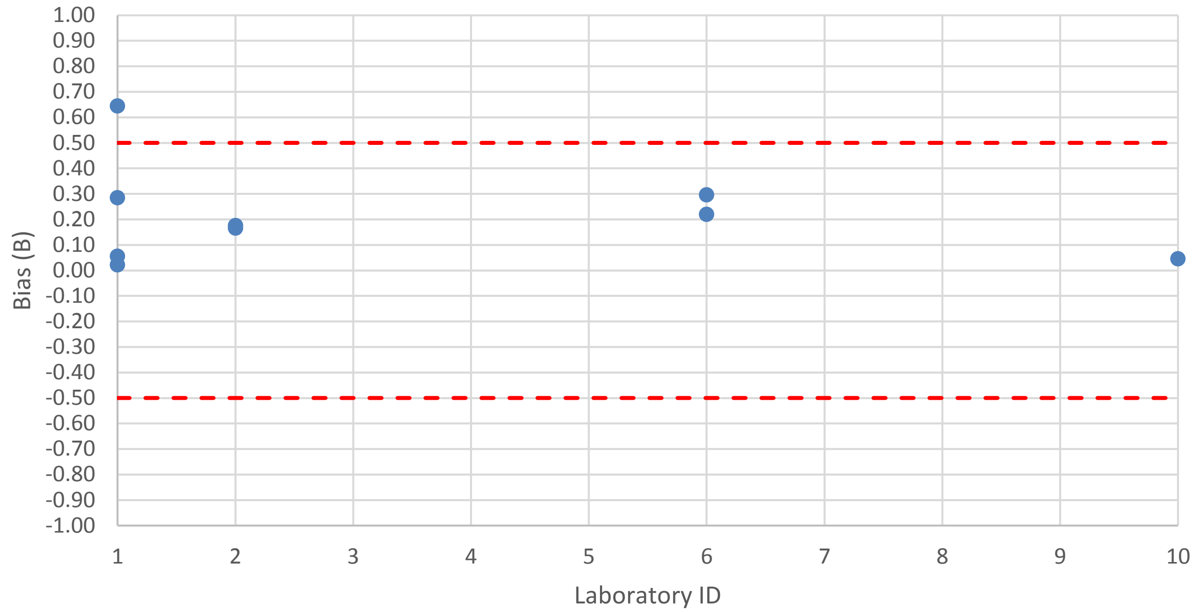


Figure 13. Biological neutron dosimetry performance for Irradiation #1.

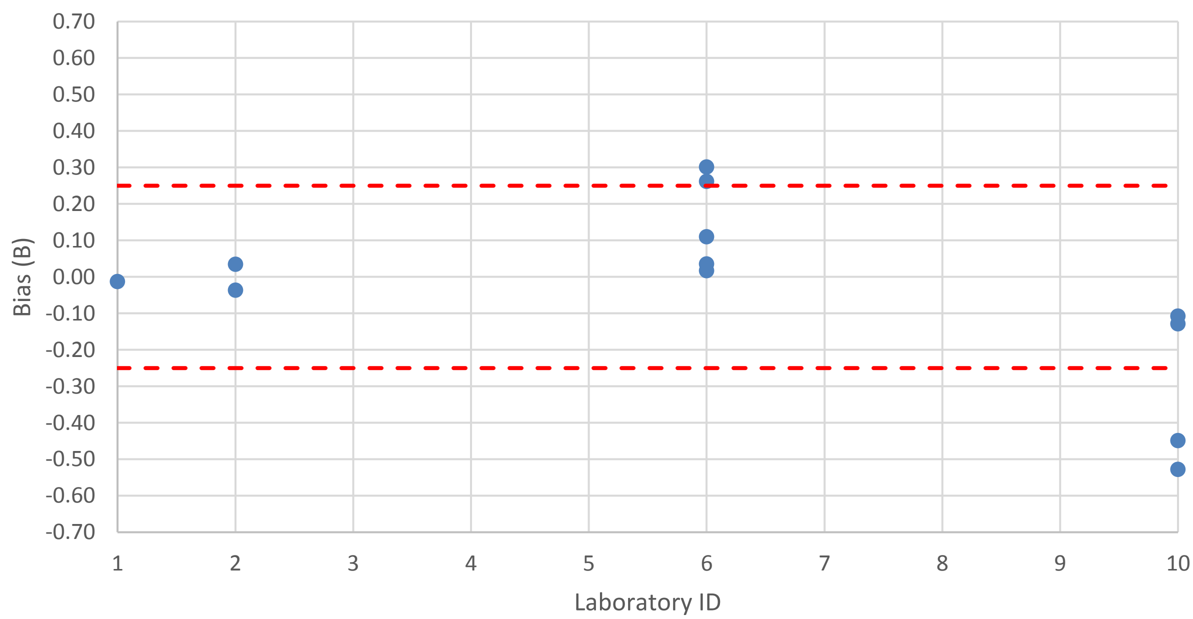


Figure 14. Biological neutron dosimetry performance for Irradiation #2.

Rotation results

The inter-comparison was designed to compare whether participants could accurately estimate the maximal dose. BOMAB phantoms filled with Ringers Lactate solution were used to emulate the human body. Phantom rotations in irradiation #1 were at 180° (Figure 1) while phantoms for irradiation #2 were rotated clockwise as 45°, 180°, and 225° (Figure 2). Dosimeters mounted on the back of the phantoms represented a person wearing a dosimeter and rotated at either 180° or 225°. Table 5 shows the percent of doses meeting the ANSI and DOE standard requirements when the dosimeter was mounted on the phantom to emulate rotation of personnel at the known dose location.

Table 5. Percent of all dosimeter results (total dose) outside the bias limits for all laboratories with dosimeters on rotated phantoms simulating personnel not facing the event.

	Irradiation #1		Irradiation #2	
Known Total Dose (Gy)	0.76[6]	1.02	3.09	4.26
% outside ANSI Limits	15%	57%	27%	44%
% outside DOE STD Limits	54%	57%	55%	81%

Neutron Quick Sorting results

The ANSI/HPS N13.3-2013 standard requires laboratories to be able to perform quick sort for doses above 0.5 Gy and should be capable for sorting personnel according to total estimated dose. The DOE Standard requires that there be a method to conduct initial screening of potentially exposed individuals to identify those who have received medically significant doses. There are no accuracy requirements by DOE or ANSI for quick sorting.

Nine of the ten participants provided quick (sorting) results within a matter of hours after irradiated dosimeters and phantoms were delivered to the NAD Lab facility for irradiation #1 and eight of the ten participants provided quick sorting results for irradiation #2.

One of the intercomparison participants routinely establishes a triage priority ranking for potentially exposed personnel. The primary method for evaluating the triage priority is by direct measurement of body sodium activation, however the participant also attempted to establish a triage priority using the TLD holder of its dosimetry system. These triage measurements were ranked and reported for each dosimeter.

Another participant initially used incorrect dose conversion units for its reported quick sort calculations and provided corrections during the three weeks after the exercise.

[6] ANSI N13.3-2013 limit for <1Gy is ±50%

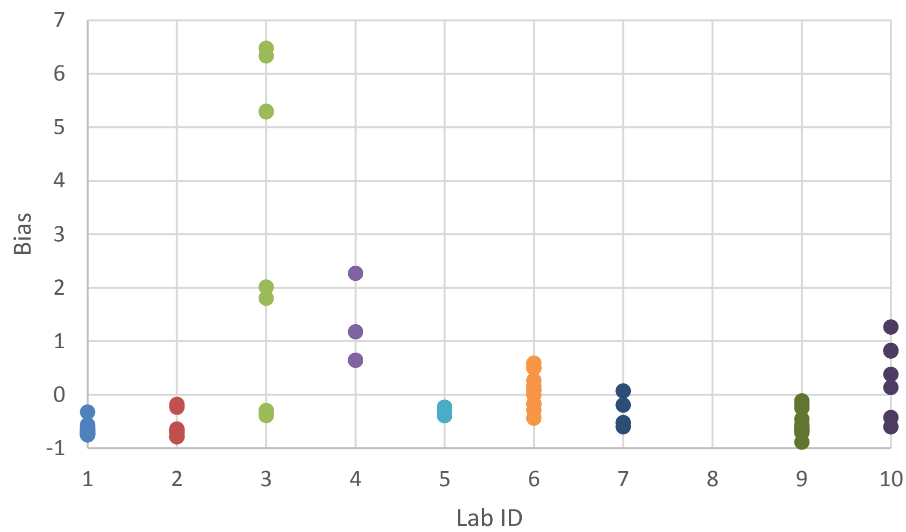


Figure 15. Neutron dose quick sort bias for irradiation #1.

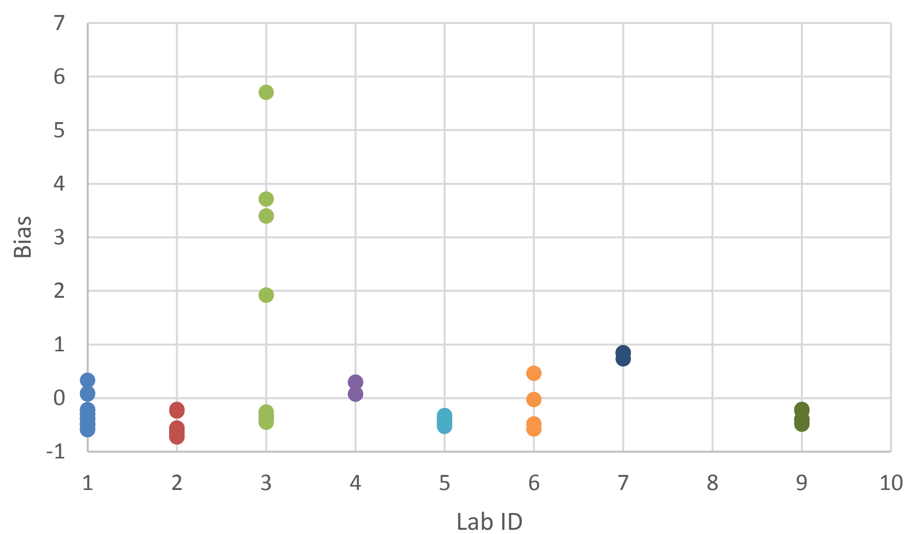


Figure 16. Neutron dose quick sort bias for irradiation #2.

Discussion and Conclusions

This was the first blind test of nuclear accident dosimeters at the NCSP NCERC/NAD Lab facilities. A considerable number of PNAD dosimeter results were outside the ANSI limits. A larger number of dosimeter results tended to be outside the DOE limits. Additional work and testing are required to improve current performances under blind conditions.

At least two laboratories used hair to determine rotation of the body. The evaluation of the degree of rotation was fairly accurate for these two laboratories. Laboratories with dosimeters distributed on a belt in the middle of the phantom also tended to perform well with rotations.

Sixty-seven to ninety percent of the biological (blood simulate) neutron dose results were within DOE and ANSI accuracy limits. These results were irrespective of rotation of the phantom.

Some quick sort methods rely on the measurement of metals such as indium that may not respond properly due to the low energy distribution of the spectrum. When triaging, the change in spectrum and body rotations make the quick sorting and triage ranking very difficult. Improvement in quick sorting with more consistency is needed.

References

American National Standards Institute Inc., Dosimetry of Criticality Accidents, Health Physics Society, McLean, VA, ANSI/HPS 13.3-2013, 2013.

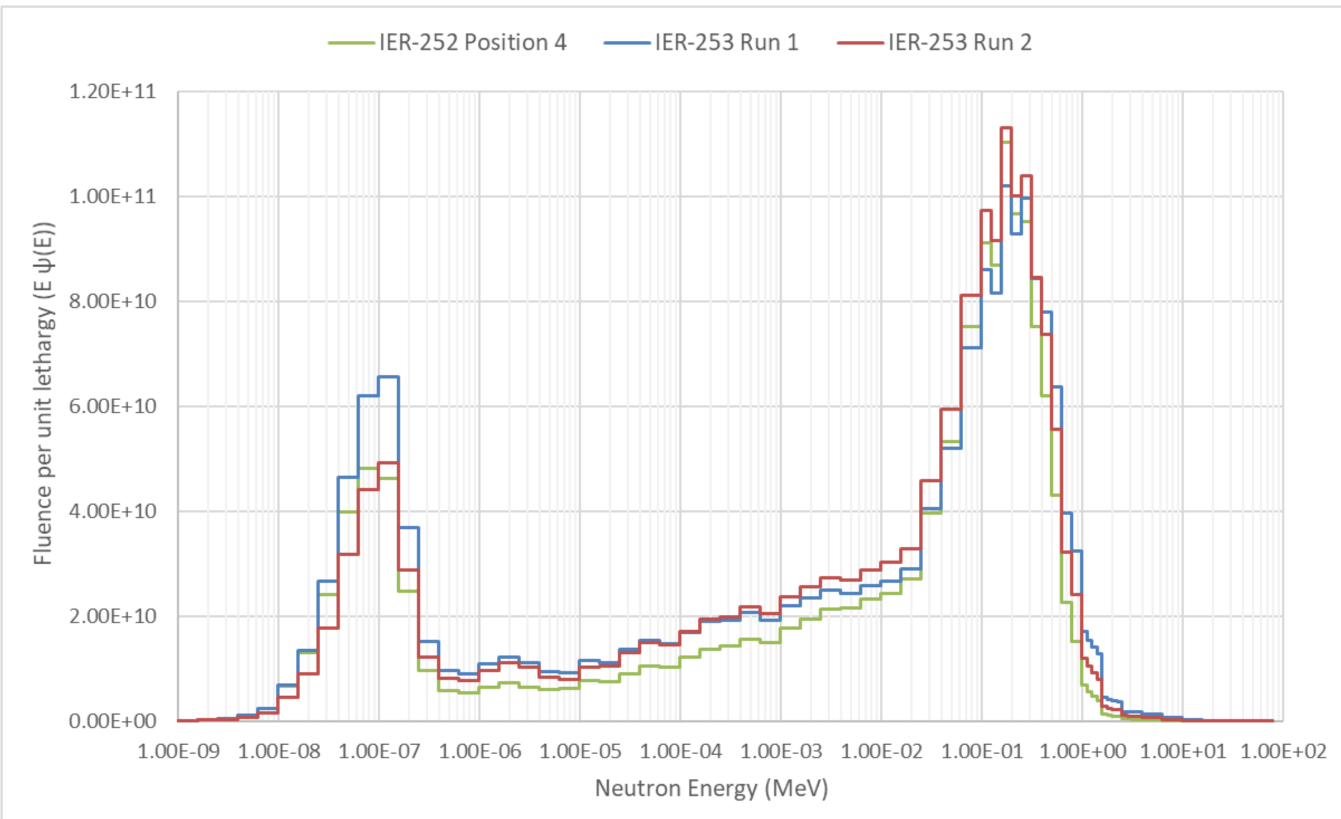
U.S. Department of Energy, DOE Standard Radiological Control, Washington D.C., DOE-STD-1098-2017, 2017.

Wilson, Chris, et. al., Characterisation of the leakage radiation field from the Flattop critical assembly machine at NCERC, IER-252 CED-4b Report/AWE Repot 122/18,

Hickman, D.P., Wilson, C., et. al., Final Design of an International Intercomparison Exercise for Nuclear Accident Dosimetry at the DAF Using the Flattop Critical Assembly Machine, IER-253 CED-2 Report, LLNL-TR-738674, Livermore, CA, September 2017.

Appendix A Verification and Spectral Information

A Passive Neutron Spectrometer (PNS) was used to verify the reactor output (neutron energy spectrum shape and intensity) during both inter-comparison exposures. The PNS was placed at 3 m from the center of the Flattop core (see Figures 1 and 2). During the experiment to characterize the neutron leakage field the energy spectrum at this location was found to be perturbed by nearby scattering surfaces therefore it is not representative of the spectrum where dosimeters were located. The PNS data cannot be used as a reference for the dosimetry measurements but can be used to check that for a given reactor "power" (integrated current in Amp seconds) the neutron fluence and energy spectrum was consistent with the data measured during the characterization experiment. The figure below shows the two spectra measured during the inter-comparison and the equivalent reference spectrum, all normalized to a reactor power of 0.02 As. There is good agreement between the spectra; the most significant difference occurs in the magnitude of the thermal peak, which tends to be sensitive to the activity measured in a single set of PNS foils and is subject to greater uncertainty than other regions of the spectrum.



Appendix A Figure 1: Neutron-energy spectra measured during both inter-comparison exposures, and the equivalent data from reference-field measurements

The values of total fluence derived from the measurements made during the inter-comparison are shown in the table below.

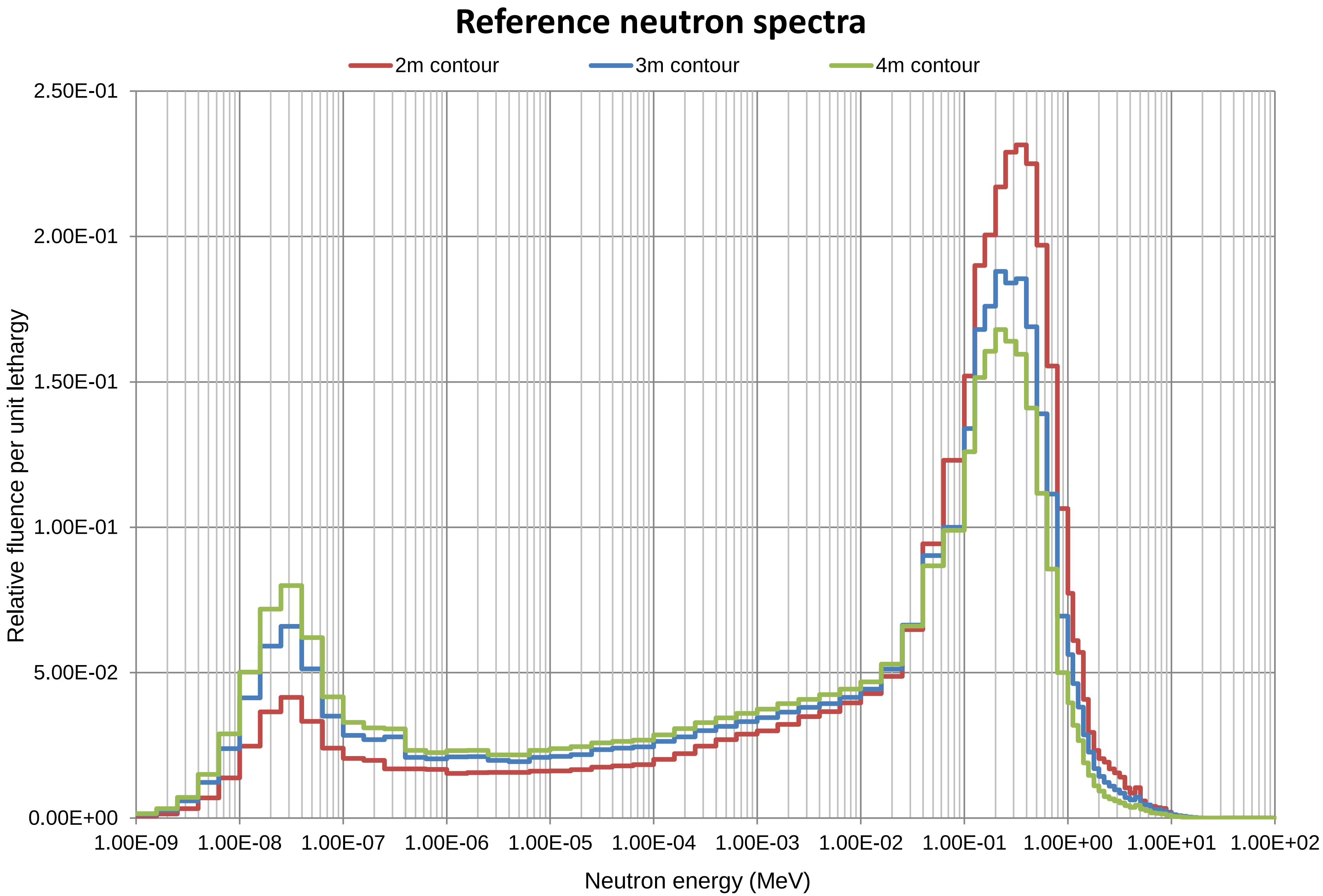
Appendix A Table 1: Integral quantities for spectra measured with the PNS

Integral Quantity	Run 1	Run 2	Reference
	0.005 As	0.02 As	0.029 As
Total fluence (n cm-2)	1.45E+11	5.59E+11	7.07E+11
ANSI N13.3 Ambient Absorbed Dose (Gy)	1.08	4.08	5.03

When the reference values are scaled to the power for runs 1 and 2 the fluence is 1.19 (run 1) and 1.15 (run 2) times larger, and the dose is 1.25 (run 1) and 1.18 (run 2) times larger. The cause of the bias may be due to the different gamma-ray spectrometers used in the two experiments; during the reference measurements the gold foils from the PNS were counted with Canberra Falcon 5000 detectors with an iSocs (computational) calibration; the equivalent measurements in the inter-comparison were performed with Ortec Trans-SPEC-100 detectors calibrated using a geometry-matched mixed-radionuclide source. It is expected that there will be differences between these two techniques, with the true value likely to lie somewhere between the two systems. The difference between the two inter-comparison exposures is not significant given the uncertainty on an individual PNS measurement (quantified at approximately 8 %, without including uncertainties associated with the positioning of the sphere or changes to the immediate environment). Since the reference spectrum is based on a single measurement it is also possible that the difference observed is statistical, and not a significant bias (there may also be a small bias within the statistics).

An alternative hypothesis is that the observed bias is a manifestation of the uncertainty in the reproducibility of the leakage field from the Flattop critical assembly machine. An analysis of LLNL's NAD data from the characterization experiment and the equivalent data for the second inter-comparison exposure does no support this supposition. There is no systematic difference between the two data sets. LLNL's NAD methodology and counting equipment was not changed between the two experiments therefore nothing was introduced that would mask the difference observed with the PNS. A similar analysis on the activity measured in components of AWE's NAD in the two experiments provides some evidence for a 5 – 10 % systematic difference but this could be due to changes in measurement equipment and methods.

In conclusion, the PNS exposed during the inter-comparison produced similar neutron energy spectra but systematically higher integral data than was measured during a previous characterization experiment. The difference is most likely due to uncertainties in the positioning of the sphere and changes in the equipment used to measure foils; analysis of other measurement devices does not support the hypothesis that the intensity of the neutron leakage radiation was greater than predicted, therefore the reference values used to assess the bias of the dosimeters in the inter-comparison are valid.



Reference neutron spectra
2m contour
3m contour
4m contour
Relative fluence per unit lethargy
2.50E-01
2.00E-01
1.50E-01
1.00E-01
5.00E-02
0.00E+00
1.00E-09
1.00E-08
1.00E-07
1.00E-06
1.00E-05
1.00E-04
1.00E-03
1.00E-02
1.00E-01
1.00E+00
1.00E+01
1.00E+02
Neutron energy (MeV)

Acknowledgements:

This work and report would not have been possible without the efforts of the following staff: Rebecca Hudson[1], David Heinrichs[1], Doug McAvoy[1], David Hayes[2], Tim Beller[2], Dann Ward[3], as well as all the participants of the intercomparison.

[1]Lawrence Livermore National Laboratory
[2]Los Alamos National Laboratory
[3]Sandia National Laboratory