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Seventh Personnel Dosimetry Intercomparison Study

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SEVENTH PERSONNEL DOSIMETRY INTERCOMPARISON STUDY

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SEVENTH PERSONNEL DOSIMETRY INTERCOMPARISON

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HIGHLIGHTS

The Seventh Personnel Dosimetry Intercomparison Study was conducted March 31-April 10, 1981, at the Oak Ridge National Laboratory. Dosimeters from 34 participating agencies were mounted on anthropomorphic phantoms and exposed to a range of low-level dose equivalents (1.5-15.0 mSv neutron and 0.1-2.8 mSv gamma) which could be encountered during routine personnel monitoring in mixed radiation fields. The Health Physics Research Reactor, operating in the steady-state mode, served as the source of radiation for two equivalent sets of six separate exposures. Lucite and concrete shields along with the unshielded reactor provided three different neutron and gamma spectra for five of the exposures in each set. A Lucite-concrete shield combination was used to provide a spectrum which was unknown to participants prior to dosimeter evaluation. Results reported by the participating agencies showed that no single type of neutron dosimeter exhibited acceptable performance characteristics for all mixed-field environments encountered in this study. Film, TLD, and TLD-albedo dosimeters were found to be inadequate for neutron dose equivalent measurements when large numbers of slow neutrons are present unless significant corrections are made to measured results. Track dosimeters indicated the least sensitivity to spectral characteristics, but did not always yield the most accurate results. Gamma dose measurements showed that TLD-700 dosimeters produced significantly more accurate results than film dosimeters which tend to overestimate gamma doses in mixed radiation fields. Under the conditions of this study in which participants generally had information concerning experimental geometries, neutron energy spectra, and source characteristics prior to dosimeter analysis, only approximately one-fourth of the agencies reporting results met regulatory neutron monitoring accuracy standards for all experiments. Coupled with the variation of more than a factor of 2 observed between measurements of the same neutron and gamma doses made by different agencies, these results indicate that continued development and analysis of mixed-field personnel dosimetry is required both individually and collectively by concerned organizations.

INTRODUCTION

The Seventh Personnel Dosimetry Intercomparison Study (PDIS) was conducted at the Oak Ridge National Laboratory's (ORNL) Dosimetry Applications Research (DOSAR) Facility during the period March 31 through April 10, 1981. This study is the seventh in a series[1,2] of annual intercomparisons which started in 1974. During the PDIS, personnel dosimeters are mailed to the DOSAR Facility, exposed to a range of low-level (0.1-2.8 mSv gamma and 1.5-15.0 mSv neutron) mixed-field dose equivalents using the Health Physics Research Reactor (HPRR)[3] as the radiation source, and then returned to the participants for evaluation. This report is a summary and analysis of results reported by the study participants.

This intercomparison was unique relative to the previous studies for several reasons. First, the number of participating organizations was the highest of any PDIS conducted to date. To effectively accommodate the large number of dosimeters received from the participants, two equivalent sets of exposures were conducted over a two-week period instead of the usual one week. Second, one exposure was conducted using a shield configuration which was not known to the participating organizations. This represents a departure from previous intercomparison formats and provides a good indication of the participants' ability to measure radiation doses under conditions encountered during routine personnel monitoring. Finally, reference neutron dosimetry for the Seventh PDIS is based on a set of data[4] recently developed for this purpose at the DOSAR Facility. Techniques used to determine reference neutron dose equivalents in prior intercomparisons were not consistent and not as accurate as the method used in this study.

PARTICIPATION

A total of 34 different organizations, 23 domestic and 11 foreign, participated in the Seventh PDIS. This represents the largest number of participants in any of the studies conducted to date. A list of partici-panting agencies, cognizant personnel, and abbreviations by which the agencies are identified in this report is given in Appendix A.

Participation in personnel dosimetry intercomparison studies has been open to any organization legitimately interested in radiation dosimetry and willing to share results with other organizations. The participant is responsible to pay dosimeter shipping costs, to provide instructions concerning handling and placement of dosimeters, and to expeditiously furnish measurement results. The DOSAR personnel set up and conduct the specified exposures, promptly return irradiated dosimeters to participants, collect and evaluate resulting data, and prepare a report describing the experiment and results.

EXPERIMENT DESCRIPTION

To effectively accommodate the large number of dosimeters (approximately 700) received from the participating agencies, two equivalent sets of exposures were conducted for the Seventh PDIS: Set A on March 31—April 2 and Set B on April 7-9, 1981. Each of the sets consisted of six separate runs which provided neutron and gamma dose equivalents which could be encountered during routine personnel monitoring. Dose levels and radiation field characteristics were varied by controlling reactor power level and run duration and by utilizing four different shielding conditions: unshielded, a 12-cm-thick Lucite shield, a 20-cm-thick concrete shield, and a configuration which was unknown to the participants. This "unknown" shield, which provided the softest neutron spectrum produced in this study, consisted of the concrete and Lucite shields used simultaneously. The six separate runs per set included two each for unshielded and Lucite shielded cases and one each for the concrete and unknown shields.

Table 1 is a summary of experimental conditions for both sets of exposures conducted during the Seventh PDIS. Geometric configurations (reactor, shield, and phantom arrangements), reactor power levels, and run durations were the same for equivalent exposures. The number of fissions given in the table for each run is based on sulfur pellet activation analysis. Indicated reactor operating parameters and shields produced dose equivalents in the range 0.1-2.8 mSv gamma and 1.5-15.2 mSv neutron at 3 m from the reactor centerline.

Dosimeters were mounted on the front (surface facing the HPRR) and rear surfaces of trunk sections of six water-filled Bomab[5] phantoms. The trunk sections used in this study have elliptical cross sections with dimensions 20 cm × 30 cm and are 40 cm high. These sections were located with their front surfaces 3 m from the reactor vertical centerline and their horizontal centerlines 1.5 m above the floor. Figure 1 shows a front view of the experimental configuration of the six phantom sections with dosimeters attached.

Figures 2, 3, and 4 show overhead views of the experimental arrangements for the Lucite, concrete, and Lucite-concrete (unknown) shielded exposures, respectively. The Lucite shield, which is 2.7 m high and encompasses a 150° arc, was located 2 m from the reactor centerline. The concrete shield, which is 2.13 m high and encompasses an arc of 135°, was positioned 1 m from the HPRR centerline. These concrete and Lucite shields were placed at 1 m and 2 m, respectively, from the reactor centerline for the unknown configuration. The HPRR horizontal centerline was located 1.5 m above the floor for all exposures.

REFERENCE DOSIMETRY

The following text gives details of the reference neutron and gamma dose equivalents determined for the Seventh PDIS.

Neutron Dose Equivalent

For this study, reference neutron dose equivalents were obtained using fission yields measured by sulfur pellet activation analysis and calculated dose-equivalent-per-fission conversion factors at 3 m from the reactor for the various HPRR energy spectra.[4] The number of fissions produced during a particular run was measured by monitoring the ^{32}P beta activity induced in a 22 g sulfur pellet located at a fixed position near the reactor core.[6] Dose-equivalent-per-fission values are based on two-dimensional discrete-ordinates-transport calculations of HPRR neutron energy spectra for various shield configurations and fluence-to-dose-equivalent conversion factors for element 57 absorbed dose with the capture gamma ray [primarily due to the $^{1}H(n,\gamma)^{2}H$ reaction] component excluded. Element 57 refers to the central volume element of the Auxier phantom[7] used to calculate the radiation dose distribution in a tissue-equivalent cylindrical volume exposed to an external neutron field. The element 57 dose equivalent is the highest of all volume elements represented in this model and is considered to provide the best estimate of depth dose equivalent for neutron spectra encountered at reactor facilities.[8] Relative to this study, the reference neutron dose equivalents based on element 57 conversion factors represent the expected maximum measured values for each exposure.

Table 2 shows reference neutron dose equivalents and associated data for phantom front and rear exposures for all runs conducted during the Seventh PDIS. Reference values for rear exposures were obtained by applying a front-to-rear conversion factor developed from previous intercomparison study results.[2] Dose equivalents for corresponding exposures in sets A and B differed by less than 7% in all cases except for unshielded runs 1A and 1B where the difference was 12%.

Reference neutron dose equivalents for the unknown exposure were obtained using data for the concrete and Lucite shields. A net neutron dose equivalent attenuation factor of 0.026 relative to air was calculated for this configuration by multiplying the attenuation factors for the concrete and Lucite shields (0.22 and 0.12, respectively).[4] This value is in good agreement with HPRR neutron attenuation measurements made using the Lucite-concrete shield combination.[9] Multiplying this net attenuation factor by the element 57 dose-equivalent-per-fission for the unshielded reactor gives the conversion factor shown in Table 2 for the Lucite-concrete combination. The phantom front-to-rear conversion factor for this case is an average of the values for the individual component shields. Although this shield configuration provided the softest (lowest median energy) neutron energy spectrum produced in the Seventh PDIS, the spectrum contained more fast neutrons than most fields encountered at reactor facilities which consist almost exclusively of neutrons with energies below about 500 keV.[8]

Gamma Dose Equivalent

The potentially significant contribution of residual fission product and activation gamma-rays to the total gamma dose at the levels encountered in this intercomparison precludes the determination of an accurate reference gamma dose equivalent based on calculated data. Reference values were determined by direct measurements of integrated gamma doses on the front and rear surfaces of a cylindrical phantom. These measurements were made using ^{7}LiF (TLD-700) gamma dosimeters and small Geiger-Mueller (G-M) tubes[10] mounted directly on the phantom. The G-M tubes were covered by lithium shields and were calibrated with a ^{60}Co source.

Table 3 gives front and rear reference gamma dose equivalent data for the Seventh PDIS. Final reference values are an average of the gamma doses measured on the phantoms using TLD-700 dosimeters and the G-M tubes. Individual doses measured by these two methods were within 20% for all exposures. No G-M tube measurements on the front of the phantom were made during the first set of exposures (set A) so that the reference front gamma dose equivalents for these runs are those measured using TLD-700 dosimeters. Also, due to difficulties in evaluating the TLD's for the initial unknown shield exposure (run 5A), the reference gamma dose for this case was calculated based on the average measured values for run 5B and the ratio of fissions between the two exposures.

DOSIMETER TYPES

The types of neutron and gamma dosimeters used in the Seventh PDIS and the set in which the dosimeters were exposed are summarized in Table 4 for each participating organization. Dosimeter descriptions given in the table were furnished by participants with reported experimental data. Neutron dosimeter types included thermoluminescent dosimeters (TLD), TLD-albedo, film, and track-etch. For neutron measurements, approximately 60% of the participating organizations used TLD (24%) or TLD-albedo (36%) systems, about 18% used track, about 15% used film, and the remainder generally used some combination of these basic types. Gamma doses were measured using TLD systems (primarily TLD-700) by almost 70% of the participants with the remainder using film. Descriptions of these basic dosimeter types are available in the literature,[1,11,12] and detailed participant-prepared comments concerning particular systems used in this study are included in Appendix B of this report.

RESULTS AND ANALYSIS

This section presents an analysis of reported results for the Seventh PDIS. Measured neutron and gamma dose equivalents are summarized in Tables 5-10. Each table contains individual dosimeter measurements and the associated average dose equivalents reported by participating organizations for equivalent runs in sets A and B. Results are not reported by phantom since the variation in measured doses among dosimeters placed on different phantoms has been shown to be insignificant relative to other factors affecting dosimeter response.[13] The DOSAR reference values are included in the tables, but are not considered part of the intercomparison results in the following analysis. Dosimeter performance relative to regulatory criteria and the relationship of these results to information obtained during previous intercomparisons are discussed in subsequent sections.

Neutron Dose-Phantom Front

An analysis of neutron dose equivalent results from measurements made on the front of phantoms is presented in Table 11 for all runs conducted during the Seventh PDIS. Data given for each run include mean neutron dose equivalent, which indicates measurement accuracy, and the associated standard deviation, which reflects measurement precision, based on measured results for all neutron dosimeter types included in Tables 5-10. Table 11 also shows the number and range of reported results used to calculate the composite data.

To provide the best indication of the ability of all participants to measure neutron dose, statistical information shown in the table is based on a subset of reported results for all dosimeter types. This subset omits results reported by TAEC in the analysis of set B exposures for reasons associated with dosimeter calibration. Doses reported by this agency were not corrected for differences between calibration source and HPRR spectra. Reported values shown in Tables 5-10 for TAEC were significantly lower than data reported by all other organizations using TLD's to measure neutron doses.

Based on the composite of measured results, Table 11 shows that the mean reported dose equivalents are lower than the reference values for all unshielded runs, higher than the reference values for all Lucite and Lucite-concrete shielded runs, and closest to the reference values for the concrete shielded run. Standard deviations from the mean for exposures in set A are about 50% less than corresponding values obtained from equivalent exposures in set B due to the greater variation in dosimeter types and overall evaluation methods contained in set B relative to set A. Unshielded runs exhibited the lowest percent standard deviations followed in order by concrete, Lucite, and Lucite-concrete for both sets of exposures. Ranges of reported results shown in Table 11 indicate that the largest differences between measurements of the same dose equivalent made by different organizations vary from a factor of about 2 for run 1A to 2 orders of magnitude for run 6B. A more detailed analysis of these composite results based on a combination of data for equivalent runs is given later in this section.

An analysis of neutron dose equivalents measured using four different types of dosimeters is presented in Table 12 for all runs. Although the small number of participants who used certain types of dosimeters in some cases precludes a detailed statistical analysis of all data given in the table, some general trends are evident. Average doses for all four dosimeter types are lower than reference values for all unshielded runs. The TLD and TLD-albedo dosimeters exhibit average dose equivalents which are greater than reference values for all Lucite and Lucite-concrete shielded runs. Average film-measured dose equivalents are significantly lower than reference doses in all cases, and average track-measured results are generally between film and TLD values. A detailed evaluation of the performance of individual dosimeter types based on a combination of results for equivalent runs is given in the following text.

Table 13 gives neutron dose equivalent results for the composite of all measurements and individual dosimeter types normalized to reference values and combined for equivalent runs in sets A and B. Normalized mean dose equivalents and associated standard deviations were obtained by dividing unnormalized data given in Tables 11 and 12 by corresponding reference doses and then combining results for equivalent exposures using the number of measurements in each run as a weighting factor. These normalized data are representative of the ability of all Seventh PDIS participants to measure neutron dose equivalents under identical mixed radiation field conditions.

The composite of results for all dosimeter types indicates that, on the average, dose equivalents for the unshielded spectra were 36% lower than reference values. Mean measured dose equivalents for the concrete shielded spectrum were 14% lower than reference values. Lucite shielded runs, which provide the softest (lowest median neutron energy) single-shield HPRR spectrum, produced results higher than reference doses by an average of 28%. The most discrepant measured data were obtained for the Lucite-concrete shield combination which was unknown to participants and provided the softest neutron energy spectrum encountered in this study. Considering all dosimeter types, average measured dose equivalents for this configuration were 70% higher than reference values. Standard deviations from the mean were lowest for unshielded runs (average of 48%) followed in increasing order by concrete (78%), Lucite (90%), and Lucite-concrete (99%) shielded runs. These data indicate that the ratio of measured-to-reference neutron doses and the associated standard deviation of the composite of all participant results increases with increasing spectral softness.

Although the preceding analysis does not reflect performance characteristics of individual neutron dosimeter types, the following observations are noted concerning the ability of all participants to measure the same neutron dose under identical conditions:

(a) the poorest measurement accuracy and precision for exposures performed during the Seventh PDIS were exhibited for the Lucite-concrete shielded runs for which the shield configuration produced the softest neutron energy spectrum and was unknown to participants prior to dosimeter evaluation,

(b) doses resulting from the unshielded HPRR spectrum were more precisely measured than doses from shielded spectra, and

(c) the same neutron dose equivalents measured by different agencies can differ by more than two orders of magnitude.

An analysis of measured dose equivalents based on normalized and combined results is presented in Table 13 for the four types of neutron dosimeters used in this study. Average measured dose equivalents relative to the reference values as a function of neutron spectrum are also shown in Figure 5 for all four dosimeter types. Shield configurations indicated on the abscissa in the figure are arranged in order of decreasing median neutron energy; i.e., the neutron energy spectra become softer going from left to right.

Figure 5 shows that film measurements of neutron dose equivalents were significantly lower than reference values for all spectra encountered in the Seventh PDIS. Means of the reported film measurements were less than 40% of the reference doses in all cases with some individual measurements indicating zero dose. These low results, which have been observed for film in prior dosimetry studies,[1,8] can be partly attributed to the low sensitivity of film to neutrons having energies below 0.5 MeV and the low response of film to neutrons with energies less than 1.2 MeV.[11,14] Film can also have a fading problem which results in low measured dose values if it is not packaged carefully and read promptly after exposure.[11] Since only three organizations reported results using film dosimeters, a detailed analysis of the standard deviations associated with these measurements is not meaningful.

The TLD and TLD-albedo dosimeters yielded similar qualitative performance characteristics relative to variation of incident neutron spectra. For both types of dosimeters, Figure 5 shows that the ratio of measured-to-reference dose equivalents increases monotonically as the neutron spectra become softer. This behavior is due to the high sensitivity of TLD-based dosimeters to low energy neutrons.[11,12] On the average, TLD and TLD-albedo dosimeters produced measured doses which were 24% lower than reference values for unshielded HPRR spectra.

For the degraded (shielded) spectra, average TLD results are less accurate than corresponding TLD-albedo measurements in all cases. Least accurate results were obtained for the Lucite-concrete shielded run which produced average neutron dose equivalents that were 342% and 94% higher than reference values using TLD and TLD-albedo dosimeters, respectively. Average measurement accuracies exhibited by track dosimeters were within 40% of the reference values for all unshielded and shielded spectra. Figure 5 shows much less variation in normalized dose as a function of spectral energy for track dosimeters compared to TLD-based systems. By applying a constant correction factor to track-measured dose equivalents, average measured results within 13% of reference values could be obtained for all spectra considered in this study.

Data given in Table 13 shows that unshielded doses were more precisely measured than shielded doses for TLD and TLD-albedo dosimeter types. Standard deviations from the mean for TLD's ranged from an average of 26% for unshielded runs to an average of 88% for the shielded cases. Standard deviations for TLD-albedo measurements ranged from 32% for unshielded runs to 37% for shielded exposures. Average standard deviations from the mean for the reported track data ranged from 48 to 57% for the unshielded and shielded runs, respectively.

When incident neutron spectra are known, responses of all four types of neutron dosimeters used in this study can be corrected for differences between calibration and measured energy spectra. Failure to make adequate corrections for this effect was probably a major contributor to the inaccuracy of some of the results reported here. Basic dosimeter performance properties, interpretations of neutron dose equivalent, and differences in room scatter characteristics between the calibration locations and HPRR facilities also contributed somewhat to the overall measurement inaccuracies.

Neutron Dose-Phantom Rear

An analysis of neutron dose equivalent results measured on the rear of phantoms is presented in Table 14. Data shown in the table represent average measured dose equivalents and associated standard deviations normalized to reference values and combined for equivalent exposures in sets A and B. The relatively few neutron dose equivalent measurements made on the rear of phantoms precludes any meaningful statistical analysis of these results. However, trends inferred from these data are consistent with conclusions obtained from results measured on the front of phantoms. For instance, data based on the composite of all dosimeter types exhibited the poorest accuracy and precision for the Lucite-concrete (softest spectrum) shield configuration. Also, unshielded dose equivalents were measured more precisely than those for shielded spectra. With regard to individual dosimeter performance, film dosimeters yielded dose estimates significantly lower than reference values in every case. The TLD and TLD-albedo results indicate decreasing accuracy with increasing spectrum softness for the shielded cases with the most discrepant results obtained for the Lucite-concrete shielded runs.

Gamma Dose-Phantom Front

An analysis of gamma dose equivalent results from measurements made on the front of phantoms is presented in Table 15 for each run conducted during the Seventh PDIS. Average gamma dose equivalents and associated standard deviations are given for a subset of all reported measurements and for the two types of gamma dosimeters used in this intercomparison — TLD and film. The subset of reported results omits two sets of measured data to provide a better indication of the overall ability of participants to measure gamma dose. Results reported by BMI using TLD-100 dosimeters were omitted from the set A data analysis because this dosimeter type is extremely sensitive to neutrons and yields very high measured gamma doses in mixed radiation fields.[2] Gamma doses measured by UW using TLD's were omitted from the set B data because these results were significantly higher than doses measured by all other agencies using this dosimeter type in almost every case.

Considering the composite of all measurements included in the subset of reported results, mean measured gamma dose equivalents shown in Table 15 vary from 0.9 to 1.9 times the reference values for the 12 runs conducted during the Seventh PDIS. Standard deviations are between 23 and 69% of the mean with no significant differences between shielded or unshielded measurements. With regard to individual dosimeter types, average gamma dose equivalents measured using film were higher than corresponding values measured using TLD's in every case. Tables 5-10 show that the maximum differences between measurements of the same gamma dose equivalent made by different agencies in each run vary from a factor of about 2 for run 4A to a factor of approximately 13 for run 2B.

Table 16 summarizes gamma dose equivalent results on the fronts of phantoms normalized to reference values and combined for equivalent exposures. Normalized mean dose equivalents and associated standard deviations were obtained by dividing values shown in Table 15 by reference doses and then combining data for equivalent runs in sets A and B using the number of measurements in each set as a weighting factor. Data based on the subset of all results indicates that mean measured gamma doses varied from about 1.0 to 1.3 times the reference gamma dose equivalents for the six exposures. Standard deviations for the composite results are between 28 to 69% of the mean with shielded measurements being more precise (standard deviation = 38%) than unshielded measurements (standard deviation = 58%).

With regard to different gamma dosimeter types, average measured doses using TLD's were lower than and within 16% of the reference values for all exposures with mean reported results being within one standard deviation of the reference doses in every case. Table 16 also indicates that unshielded TLD-measured gamma doses were less precise (standard deviation = 58%) than shielded dose measurements (standard deviation = 32%). Figure 6, which is a graph of normalized gamma dose equivalent as a function of shield configuration for the Seventh PDIS, shows that there is very little spectral variation in the TLD-measured results. This is due to the TLD response, particularly for lithium-fluoride (LiF) material, being essentially constant for the range of photon energies encountered in the PDIS.[15] Of the TLD gamma dose measurements reported in the study, about 82% were made using LiF dosimeters (mostly TLD-700) with the remainder made using $CaSO_4$ material.

In contrast to film-measured neutron dose equivalents, average film-measured gamma dose equivalents were higher than reference values and TLD-measured results by factors of about 1.3 to 2.0 for the six runs. These high measured doses could be the result of the sensitivity of most radiation monitoring films to neutrons. Tests conducted on several commercial film types made to measure gamma dose showed that they were an average of four times more sensitive to thermal neutrons on a gray (or rad) basis than to ^{60}Co gamma-rays.[16] Average film response per gray to fast neutrons was about 5% of the response to a ^{60}Co source. Depending on the type of film and whether or not users corrected for the neutron response, this sensitivity could be a significant contributor to the high reported gamma doses. Measurement precisions based on data given in Table 16 were about equal for unshielded and shielded cases which exhibited average standard deviations of 21 and 22%, respectively. These values are lower than corresponding standard deviations for TLD-measured data.

Figure 6 shows the variation of film-measured gamma doses as a function of shield configuration for the Seventh PDIS. These data indicate that the accuracy of film-measured gamma doses improves with decreasing neutron-to-gamma dose ratio for the mixed-field spectra included in the figure. However, the total variation in average measured gamma doses relative to reference values is only 18% for film dosimeters compared to 10% for TLD's over the four shield configurations encountered in this study. While some spectral variation is indicated for film gamma dosimeters, the magnitude of this variation is small compared to the average amount of overmeasurement relative to reference doses. Based on results of this study, it therefore appears that the mere presence of neutrons is the primary contributor to inaccuracies in film-measured mixed-field gamma doses rather than neutron energy dependence or neutron-to-gamma dose ratios characteristic of the incident radiation field.

Gamma Dose-Phantom Rear

Table 17 presents an analysis of normalized and combined gamma dose measurements made on the rear of phantoms for composite, TLD, and film results. Data shown in this table omit results reported by BMI using TLD-100 dosimeters in set A for reasons previously discussed. Although a meaningful statistical analysis of these data is not possible because of the few gamma dose measurements made on the rear of phantoms and uncertainties in the reference doses, some observations which are consistent with results obtained from phantom front measurements are evident. The subset of reported results for all dosimeter types indicates that the mean gamma dose equivalents varied from approximately 1.0 to 1.7 times the reference values. As with the phantom front measurements, film-measured gamma doses were significantly higher than the reference values (1.1 to 2.9 times the reference) in every case due to the neutron sensitivity of the film. Mean gamma doses measured using TLD dosimeters (primarily TLD-700) were closer to the reference values (0.8-1.3 times the reference) than film-measured doses in every case.

DOSIMETRY PERFORMANCE RELATIVE TO REGULATORY CRITERIA

Guidelines established by the Nuclear Regulatory Commission (NRC)[17] for personnel neutron monitoring in mixed radiation fields suggest that dosimeters used in the dose equivalent range considered in this study should be accurate to within ±50% and that the associated standard deviations (measurement precision) should be within ±30% of the mean. Criteria proposed for gamma dosimeter testing by the American National Standards Institute (ANSI) suggest that the sum of the bias (accuracy) and standard deviation (precision) of the measured results relative to reference values should be equal to or less than 50% for spectra encountered in the Seventh PDIS.[18] The following text presents a discussion of the performance of neutron and gamma dosimeters used in this study relative to these criteria.

Neutron Dosimeters

Table 13, which is based on all reported results considering the composite of all measured data and individual neutron dosimeter types, shows that the ensemble of results satisfied the accuracy criteria for all exposures except the Lucite-concrete (unknown) shielded run. Criteria for measurement precision were not met for any of the runs. Accuracy requirements for TLD and TLD-albedo dosimeters were satisfied for unshielded and concrete shielded exposures while precision standards were met only for one unshielded run (TLD-run 2). Film neutron dosimeters failed to meet accuracy or precision requirements for any of the Seventh

PDIS exposures. Average results using track dosimeters were within 50% of the reference doses but failed to satisfy precision criteria for all six runs.

Table 18 summarizes personnel neutron dosimetry performance relative to the NRC criteria for the Seventh PDIS participants. Performance relative to accuracy standards (±50%) is based on the average of individual neutron dose equivalent measurements reported by each organization compared to the reference dose equivalents determined by the DOSAR staff. An evaluation of performance compared to precision criteria (±30%) is based on the distribution of individual measurements about the mean of all reported results for each agency. Individual reported results and associated averages are summarized in Tables 5-10 of this report.

Table 18 shows that the fraction of participants meeting accuracy standards varied between 58 to 69% for the unshielded, Lucite shielded, and concrete shielded spectra which were available and known to the evaluating organizations. Only 46% of the agencies reporting results satisfied accuracy standards for the Lucite-concrete shield which was unknown to participants prior to the evaluation of dosimeters. The table also shows that more than 88% of the participating agencies satisfied precision standards for every run. An average of 28% of the participants met accuracy standards for every run for which data were reported, and 76% of the participants satisfied precision standards for every run. Fourteen percent of the organizations did not meet accuracy standards for any of their average reported neutron measurements.

Regarding the performance of individual neutron dosimeter types, film dosimeters met accuracy requirements for only one participant in one exposure for the spectra considered in this intercomparison. Thermoluminescent and TLD-albedo dosimeters exhibited the best overall performance for the hardest neutron spectrum (unshielded) encountered in this study in that 73 and 89%, respectively, of the average results reported using these types were within ±50% of the reference values. Sixty-four percent of the reported results measured using track dosimeters satisfied NRC accuracy standards for the unshielded spectrum. However, track dosimeters produced the most accurate results for the Lucite and Lucite-concrete (softest) spectra with accuracy criteria being met by 73 and 67% of the reported measurements, respectively. Thermoluminescent and TLD-albedo dosimeters satisfied accuracy criteria for less than 63% and 33% of the agencies using these monitors for the Lucite and Lucite-concrete shields, respectively. The fraction of users of a particular dosimeter type which met accuracy criteria is above 60% for all runs for track dosimeters while TLD and TLD-albedo performance decreases markedly with increasing spectral softness. Two agencies using track, two agencies using TLD-albedo, and one agency using TLD monitors satisfied accuracy standards for all runs. None of these basic dosimeter types exhibited significant problems relative to measurement precision for any of the spectra encountered in this study.

Gamma Dosimeters

Table 16 summarizes results of gamma dose equivalent measurements made during the Seventh PDIS. Data for the composite of all dosimeter types satisfied the proposed accuracy plus precision guideline of ±50% for runs 4 and 5 (Lucite and Lucite-concrete shields, respectively). An analysis of results for individual dosimeter types shows that TLD's met the suggested criteria for three of the six runs while film dosimeters satisfied the guidelines for only one run. No further analysis of the gamma results will be presented since TLD monitors (mostly TLD-700) clearly indicates superior accuracy relative to film for mixed-field personnel dosimetry.

COMPARISON TO PREVIOUS INTERCOMPARISON STUDIES

Results presented in the preceding text for the Seventh PDIS are consistent with the following statements which are based on results of the previous six studies:[1]

1. The most popular types of dosimeters used by participants are TLD-albedo for neutron measurements and TLD-700 for gamma measurements.

2. Film dosimeters yield lower neutron dose equivalents than TLD (including albedo) and track monitors independent of spectrum. Summary results show that film measured dose equivalents are less than about 50% of the reference values for all spectra considered in these studies.

3. Thermoluminescent (including TLD-albedo) dosimeters yield higher values of neutron dose equivalent than track film monitors independent of spectrum. Summary results indicate that TLD and TLD-albedo dosimeters can grossly overestimate neutron dose equivalents in spectra containing large numbers of thermal neutrons. Average response of TLD monitors is consistently higher than TLD-albedo dosimeters for the same neutron spectra.

4. Without significant spectral corrections, film, TLD, and TLD-albedo dosimeters are inadequate for neutron personnel monitoring applications where large numbers of low energy (<0.7 MeV) neutrons are present.

5. Neutron dose equivalents measured using track dosimeters are higher than film results and lower than TLD and TLD-albedo results for all spectra. Response of track dosimeters also exhibits less variation with neutron spectrum characteristics than do TLD and film monitors.

6. It is not unusual for neutron dose equivalents measured under the same conditions by different agencies to differ by more than a factor of 2.

7. Neutron dose equivalents are more accurately measured for unshielded exposures than for shielded exposures.

8. The TLD-measured gamma doses are more accurate than film-measured doses when relatively large numbers of neutrons are present.

9. Gamma dose equivalents measured using film are generally higher than reference values.

10. The TLD-100 dosimeters yield gamma doses which are significantly higher than reference values and are unsuitable for measurement of gamma dose equivalents in mixed radiation fields unless adequate correction factors can be applied.

11. It is not unusual for measurements of the same gamma dose by different agencies to differ by more than a factor of 2.

CONCLUSIONS

Performance characteristics of neutron and gamma dosimeters inferred from data measured during the Seventh PDIS were consistent with results obtained during the previous six intercomparison studies. With regard to neutron dose equivalent measurements, film dosimeters were shown to be inadequate for personnel monitoring applications where large numbers of low energy neutrons are present. The TLD and TLD-albedo dosimeters are also inadequate for neutron personnel monitoring in soft energy spectra unless significant corrections are made to measured results. Track dosimeters indicate the least sensitivity to neutron spectrum variations for the spectra considered in this study. Gamma dose results show that TLD-700 dosimeters yield significantly more accurate results (within 16% of reference doses) than film dosimeters regardless of spectra. In mixed radiation fields, film dosimeters overestimate gamma doses by more than 50% primarily due to the sensitivity of film to neutrons.

Intercomparison results continue to show that no single type of neutron dosimeter exhibits acceptable performance characteristics for all mixed-field conditions encountered in these studies. Variations of more than a factor of 2 between measurements of the same neutron exposure made by different agencies are exhibited for all spectra. For cases where experimental geometries, neutron energy spectra, and source characteristics were known to evaluators, only about 60% of the agencies reporting results satisfied NRC guidelines for neutron dose measurement accuracy in mixed radiation fields. When the neutron energy spectrum was not known in advance — which is generally the case in routine personnel monitoring — less than half of the participants met neutron dose accuracy criteria. Precision does not appear to be a significant problem since more than 88% of the participants reporting neutron dose measurements satisifed NRC criteria for all spectra.

The accuracy of personnel dose measurements in mixed radiation fields could be improved for some participating agencies by using dosimeters more suited to the particular spectral characteristics encountered at specific facilities. Improvements could also be obtained by applying correction factors to account for dosimeter performance associated with anticipated radiation fields, by calibrating dosimeters with sources appropriate for the energy spectrum to be measured, and by standardizing the basis of reported dose equivalents.

RECOMMENDATIONS

Results from all intercomparison studies conducted to date indicate that regulatory standards concerning accuracy and precision of neutron personnel monitoring systems represent realistically obtainable criteria. However, only about one-fourth of the participating agencies satisfy existing standards for the range of spectra considered in these studies. Measurement inaccuracies of the magnitude exhibited in dosimetry intercomparison studies can produce adverse consequences with regard to personnel safety and the implementation of ALARA (as-low-as-reasonably-achievable) radiation protection programs.

Improved dose estimates for personnel monitoring will require continued efforts by individual organizations to evaluate and implement items to improve measurement accuracy as discussed in this report. Efforts will also be required by the collection of agencies to participate in future intercomparison studies to determine dosimetry performance and refine measurement techniques. To facilitate these efforts, the DOSAR staff plans to implement the following items:

1. In 1982, an international personnel dosimetry intercomparison study will be conducted with one or more European organizations. The primary objective of this study will be to provide the most comprehensive evaluation of neutron and gamma dosimeter performance of any personnel dosimetry intercomparison study conducted to date. Dosimeters will be exposed to a variety of mixed radiation fields using the HPRR and to a range of mono-energetic neutrons and degraded californium spectra using facilities at the European agencies. Study coordinators will endeavor to provide mixed-radiation fields consistent with those encountered at

nuclear facilities and neutron energies of interest to clinical and laboratory personnel. General advertising for this international intercomparison will begin late in 1981.

2. A week-long radiation dosimetry training course to be conducted at the DOSAR facility will be designed and implemented in 1982. The primary objective of the course will be to provide lectures and experimental studies which will acquaint participants with the various types of neutron and gamma personnel dosimeters and their performance characteristics. Emphasis will be placed on proper choice of dosimeter type for the anticipated measurement environment, application and determination of correction factors to account for dosimeter performance and spectral response, calibration techniques, dosimeter testing, and methods of estimating dose equivalents. The course will be designed for personnel associated with radiation monitoring at nuclear, medical, and university facilities. Advertising for this course will begin early in 1982.

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Fig. 1. Front view of typical experimental arrangement of phantoms and dosimetry.

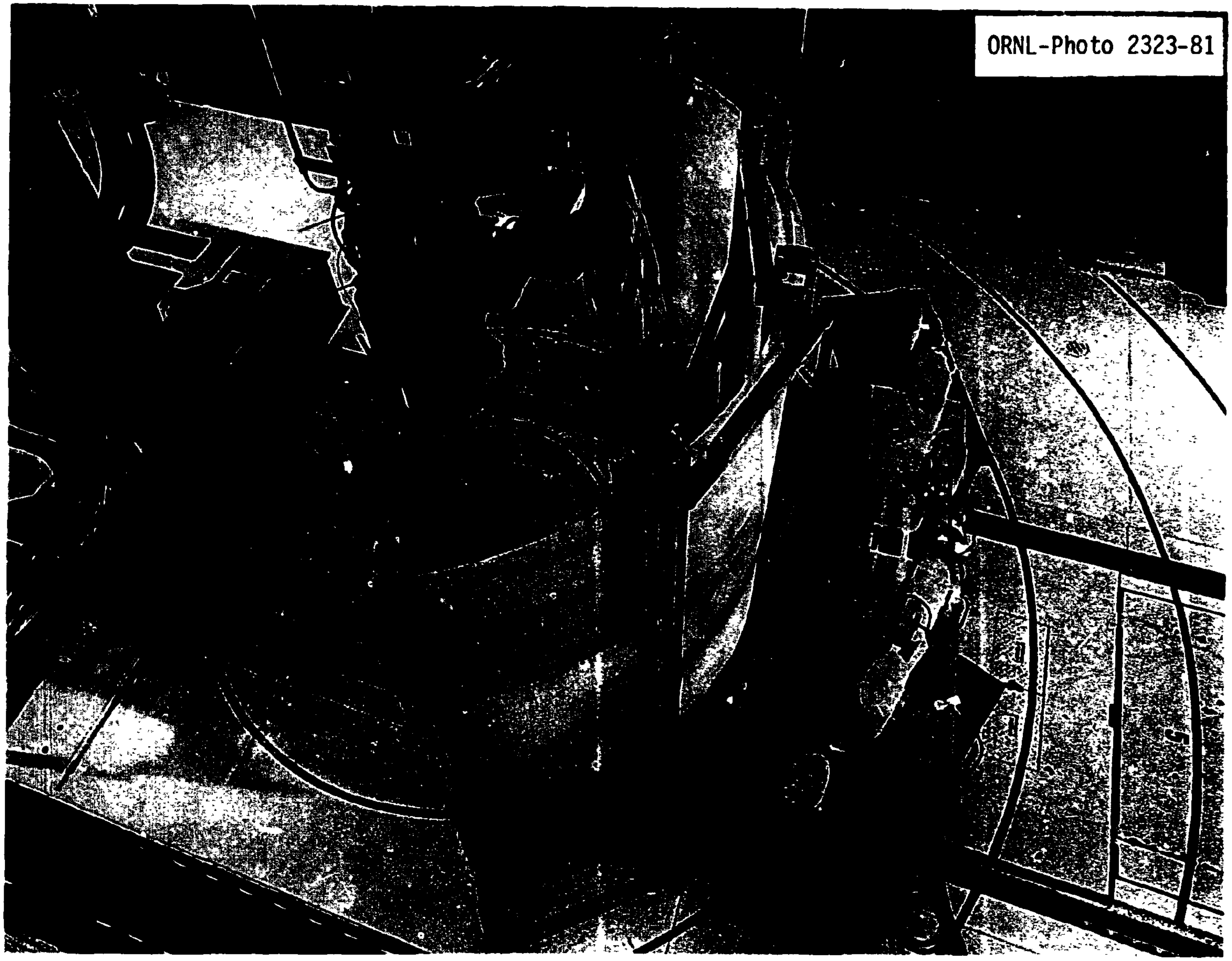

Fig. 2. Top view of experimental arrangement for Lucite shielded exposures.

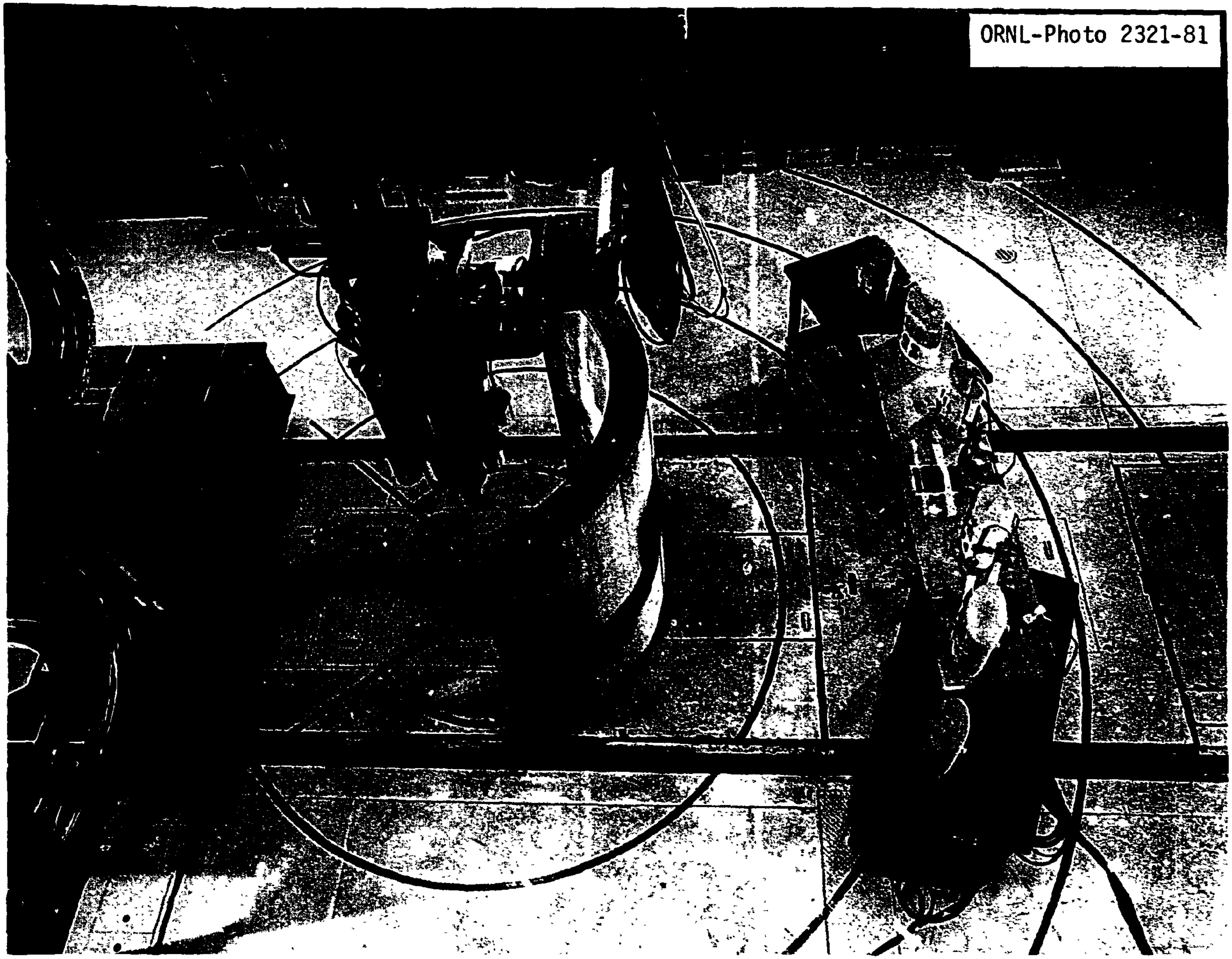

Fig. 3. Top view of experimental arrangement for concrete shielded exposures.

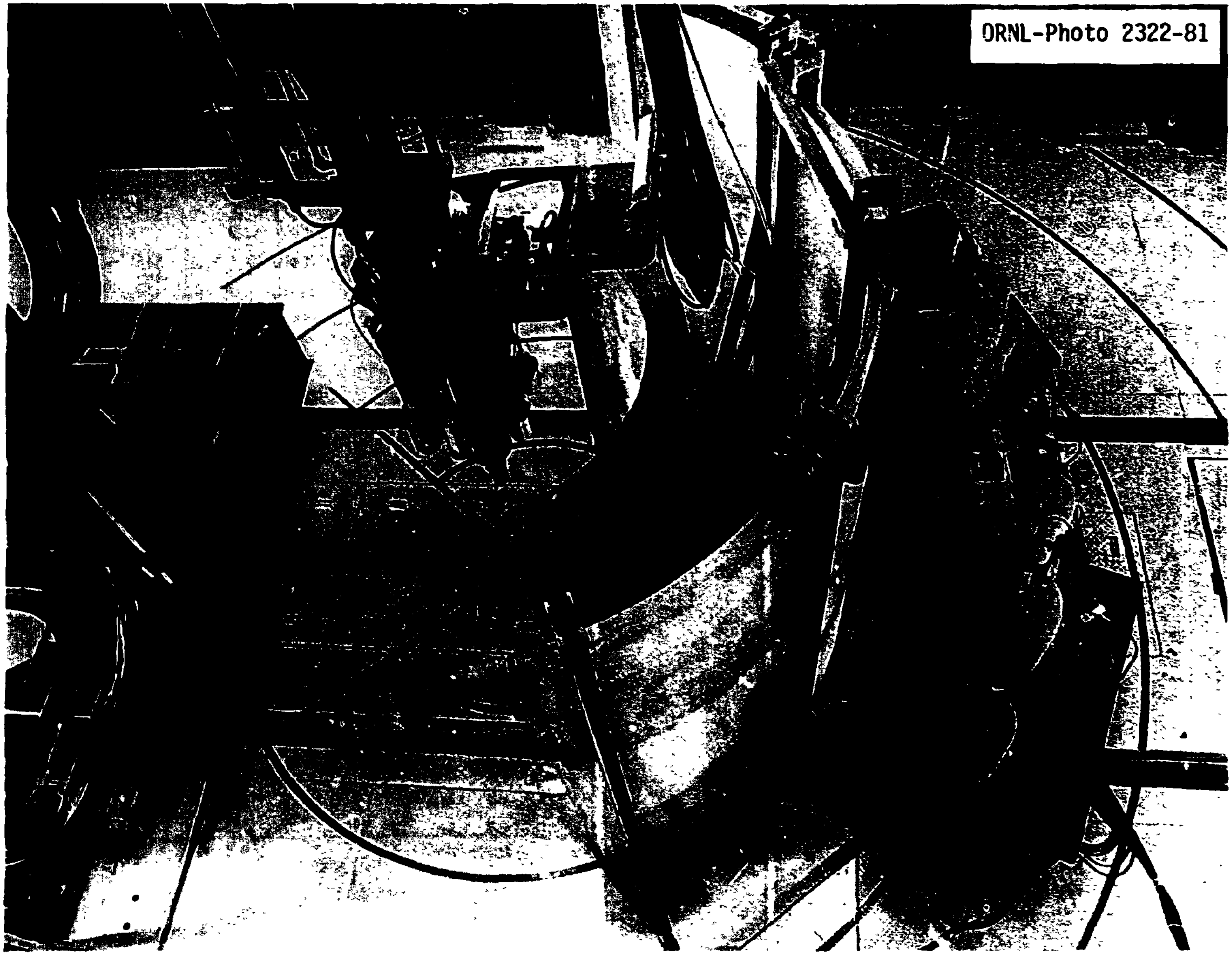

Fig. 4. Top view of experimental arrangement for Lucite-concrete shielded (unknown) exposures.

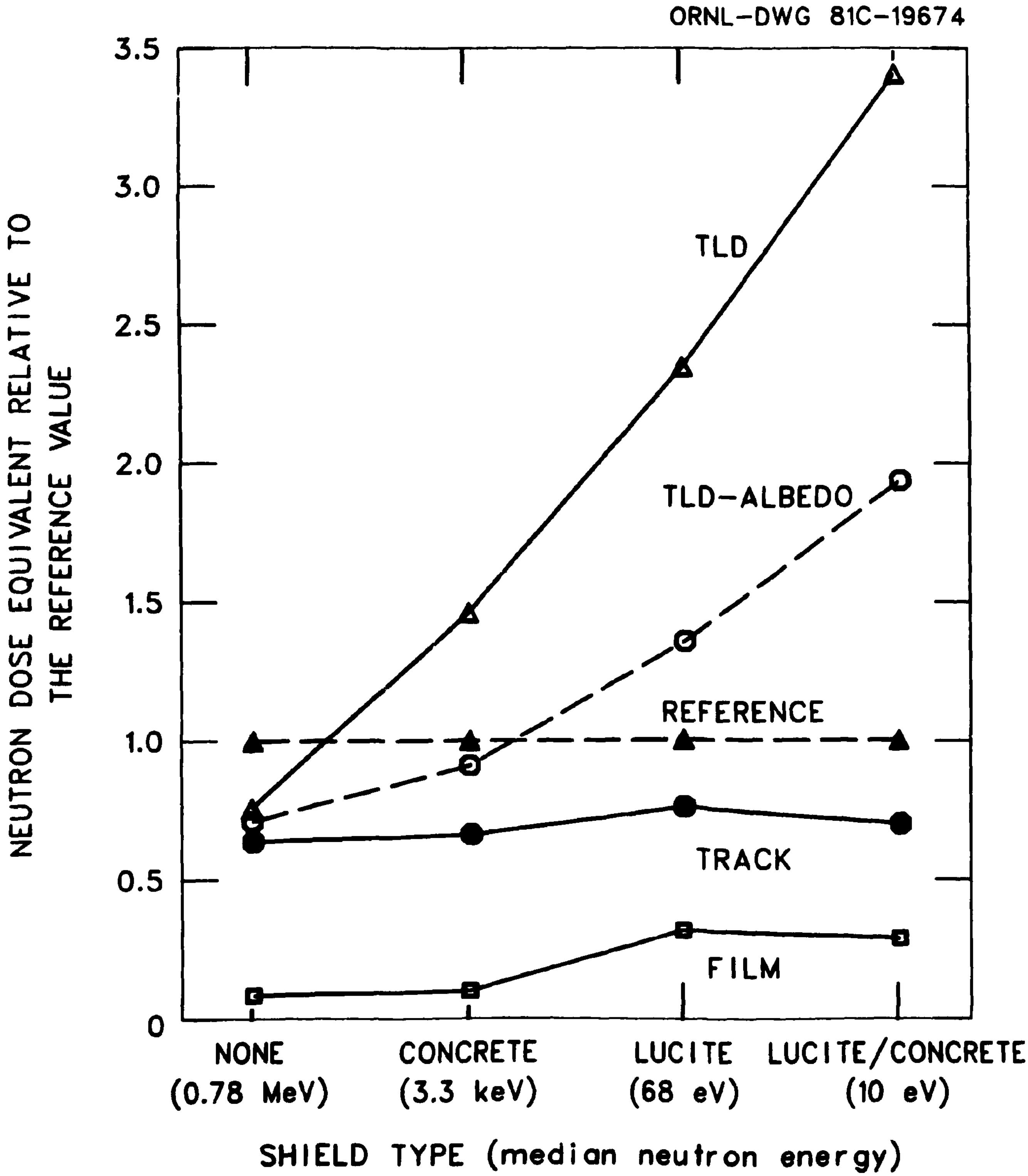

Fig. 5. Neutron dose equivalents for various HPRR spectra by dosimeter type normalized to reference values for the Seventh PDIS.

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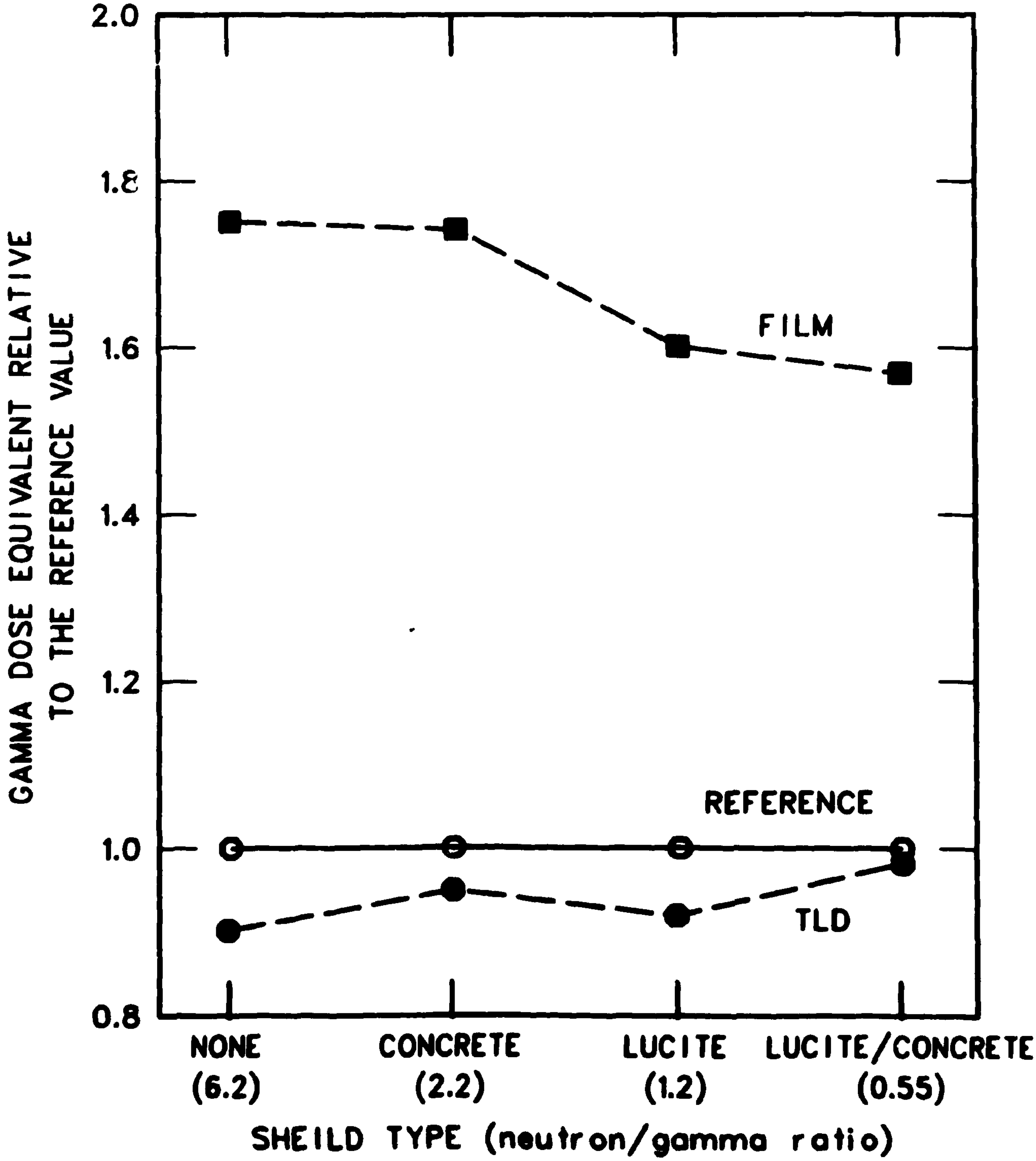

Fig. 6. Gamma dose equivalents for various HPRR spectra by dosimeter type normalized to reference values for the Seventh PDIS.

Table 1. Summary of experimental conditions for exposures[a]

Run[b]	Date of exposure	Start time[c]	Exposure duration, s	Reactor power, W[d]	Number of fissions × 10^{13}[e]	Shield thickness and type	Shield distance from reactor, m
1A	3/31/81	0943	807	0.3	0.88	None	--
1B	4/7/81	1018	807	0.3	0.99	None	--
2A	3/31/81	1345	484	1.0	1.79	None	--
2B	4/7/81	1324	484	1.0	1.83	None	--
3A	4/1/81	0945	525	1.5	2.68	12-cm Lucite	2
3B	4/8/81	0951	525	1.5	2.70	12-cm Lucite	2
4A	4/1/81	1326	784	10.0	25.64	12-cm Lucite	2
4B	4/8/81	1340	784	10.0	26.34	12-cm Lucite	2
5A	4/2/81	0930	866	30.0	73.89	Unknown[f]	--[f]
5B	4/9/81	0951	866	30.0	75.79	Unknown	--
6A	4/2/81	1404	808	2.0	4.59	20-cm concrete	1
6B	4/9/81	1324	808	2.0	4.89	20-cm concrete	1

[a]The horizontal centerlines of the reactor and of the phantom sections on which the dosimeters were mounted were 1.5 m above the concrete floor for all exposures. The distance from the reactor to the front surfaces of the phantoms was 3 m for all exposures.

[b]Runs designated A were performed during March 31-April 2, 1981, and those designated B were performed during April 7-9, 1981.

[c]Eastern Standard Time.

[d]Based on reactor instrumentation.

[e]Based on sulfur pellet activation analysis.

[f]Configuration not known to participants prior to evaluation. Arrangement consisted of a 20-cm concrete shield at 1 m and a 12-cm Lucite shield at 2 m from the HPRR.

Table 2. Reference neutron dose equivalent values

Run[a]	Shield	Dose equivalent conversion, mSv/10^{15} fissions[b]	Phantom front[c]		Phantom rear	
			Number of fissions × 10^{13}	Reference neutron dose equivalent, mSv	Front-to-rear conversion	Reference neutron dose equivalent, mSv
1A	None	465.37	0.883	411	0.16	66
1B	None	465.37	0.994	463	0.16	74
2A	None	465.37	1.787	832	0.16	133
2B	None	465.37	1.827	850	0.16	136
3A	12-cm Lucite	57.75	2.680	155	0.21	32
3B	12-cm Lucite	57.75	2.703	156	0.21	33
4A	12-cm Lucite	57.75	25.64	1481	0.21	311
4B	12-cm Lucite	57.75	26.34	1521	0.21	319
5A	Unknown[d]	12.10[e]	73.89	894	0.20[f]	179
5B	Unknown[d]	12.10[e]	75.79	917	0.20[f]	183
6A	20-cm concrete	100.27	4.59	460	0.19	87
6B	20-cm concrete	100.27	4.89	490	0.19	93

[a]Runs designated A were performed during March 31-April 2, 1981, and those designated B were performed during April 7-9, 1981.

[b]Element 57 neutron dose equivalent with the capture gamma contribution excluded.

[c]Side of phantom facing the HPRR.

[d]Co[illegible]ion of concrete shield at 1 m and Lucite shield at 2 m.

[e]Product of the neutron dose equivalent attenuation factors relative to air for the concrete and Lucite shields multiplied by the dose equivalent per fission value for the unshielded HPRR.

[f]Average of front-to-rear conversion factors for the concrete and Lucite shields.

Table 3. Reference gamma dose equivalent values

Run[a]	Shield	Phantom front[b]: Measured dose equivalent, mSv: TLD-700	Phantom front[b]: Measured dose equivalent, mSv: G-M tube[c]	Phantom front[b]: Reference gamma dose equivalent, mSv	Phantom rear: Measured dose equivalent, mSv: TLD-700	Phantom rear: Measured dose equivalent, mSv: G-M tube[c]	Phantom rear: Reference gamma dose equivalent, mSv
1A	None	13.0	--[d]	13.0	4.6	5.8	5.2
1B	None	13.9	12.2	13.1	3.7	5.7	4.7
2A	None	26.0	--[d]	26.0	9.5	9.3	9.4
2B	None	19.0	17.8	18.4	6.1	8.9	7.5
3A	12-cm Lucite	26.9	--[d]	26.9	8.0	10.8	9.4
3B	12-cm Lucite	18.8	23.6	21.2	8.1	9.7	8.9
4A	12-cm Lucite	279.9	--[d]	279.9	80.8	94.8	87.9
4B	12-cm Lucite	226.6	221.6	274.1	88.0	91.8	89.9
5A	Unknown[e]	--[f]	--[d]	252.6[g]	--[f]	135.7	135.7
5B	Unknown[e]	238.5	279.6	259.1	--[f]	133.6	133.6
6A	20-cm concrete	26.0	--[d]	26.0	8.0	11.0	9.5
6B	20-cm concrete	27.1	21.4	24.3	--[f]	10.8	10.8

[a]Runs designated A were performed during March 31-April 2, 1981, and those designated B were performed during April 7-9, 1981.

[b]Side of phantom facing the HPRR.

[c]Phillips Geiger-Mueller tube mounted directly on the phantom.

[d]No G-M tube measurements made on phantom front during the initial set of exposures.

[e]Combination of concrete shield at 1 m and Lucite shield at 2 m.

[f]No results available due to difficulties with TLD-700 evaluation.

[g]Based on measured results of run 5B and the relative number of fissions between exposures.

Table 4. Dosimeter types used by the participants

Organization[a]	Exposure set[b]	Neutron dosimeter	Gamma dosimeter
AIRP	A	TLD (Harshaw TL 6/7 cards)	TLD (TLD-700)
APS	A	TLD-albedo ($Li_2B_4O_7$ and $CaSO_4$)	TLD ($Li_2B_4O_7$ and $CaSO_4$)
BMI	A		Film (Landauer)
BMI	A		TLD (Harshaw TLD-100)
BNL	A	TLD-albedo (TLD-600)	TLD (TLD-700)
CEER	B	Film (Kodak Type A)	Film (Kodak Type 3)
DOSAR	A,B	See reference dosimetry section	
EGG	A	Activation (Au, As, W, S)	
EIR	A	Track (Makrofol, Th-232)	TLD (Harshaw TLD-700)
EML	A	TLD-albedo	TLD
EML	A	Combination (Albedo, film, track)	Film
GAC	A		TLD (Harshaw LiF)
IAEA	A	Film	Film
IAEA	A	TLD	TLD
IPEN	B	TLD (LiF:Mn,Ti)	TLD (LiF:Mn,Ti)
IPEN	B		TLD ($CaSO_4$:Dy)
IPEN	B		Film
KJ	-[c]	Film	Film
KK	B	TLD-albedo (Karlsruhe design)	TLD-700
KK	B	TLD-600 (30-cm sphere)	TLD-700
LAND	A	NEUTRAK-ER (TLD-albedo plus CR-39 track)	
LLNL	A	Track (CR-39 plus polycarbonate)	TLD-700
LLNL	A	TLD-albedo	TLD-700
MIT	A	TLD	TLD
NLO	A		Film (Kodak Type 2)
NNMC	A	TLD-albedo (Harshaw TL 6/7)	TLD (TLD-700)
NRC	A	Track (Landauer NEUTRAK-144)	Film (Landauer)
NTHU	B		Film
NTHU	B		TLD ($CaSO_4$:Dy)
OPPD	B	TLD-600	TLD-700
ORNL	B	TLD-albedo	TLD
OSU	B	Film (Landauer NTA)	Film (Landauer)
PPPL	B	Film (NTA)	Film (Landauer H-1)
PPPL	B	Track (CR-39)	
RFP	B	TLD-albedo (Harshaw)	TLD (Harshaw TLD-700)
RPB	B	TLD-albedo (RPB design)	TLD (TLD-700)
SNL	B	TLD-albedo (Harshaw)	TLD (Harshaw TLD-700)
TAEC	B	TLD ($CaSO_4$:Dy)	TLD ($CaSO_4$:Dy)
TPC	B	TLD-albedo (Harshaw NG-67)	TLD (Harshaw NG-67)
TVA	B	TLD (Harshaw G7 and N6)	TLD (Harshaw G7 and N6)
UW	B	Track (Landauer NEUTRAK-144)	TLD (Landauer)
WPPS	B	TLD-albedo (Teledyne $CaSO_4$:Dy)	TLD (Teledyne $CaSO_4$:Dy)
YALE	B	Track	Film

[a]Identifying acronyms are defined in Appendix A.

[b]Set A exposures were conducted during March 31-April 2, 1981, and those designated B were conducted during April 7-9, 1981.

[c]Dosimeters received after April 9, 1981. These badges were exposed to bare reactor spectra corresponding to runs 1 and 2 in Table 1 on April 23, 1981. Evaluation of the badges indicated no detectable exposure.

Table 5. Tabulation of reported results — PDIS 7, runs 1A and 1B, unshielded

Group[a]	Neutron dosimeter	Neutron dose equivalent,[b] 10^{-5} Sv				Gamma dosimeter	Gamma dose equivalent,[b] 10^{-5} Sv			
		1[c]	2	3	Average		1	2	3	Average
					Run 1A - 0.883 × 10^{13} fissions					
DOSAR	Reference				411/66[d]	Reference				13.0/5.2[d]
AIRP	TLD	215	249	275	246	TLD	14	13	15	14
APS	TLD-albedo	342	357		350	TLD	16	16		16
BMI						Film	60	40[d]		60/40[d]
BMI						TLD	339			339
BNL	TLD-albedo	210	225	55[d]	218/55[d]	TLD	10	15	5[d]	12/5[d]
EGG	Activation	358[e]			358[e]					
EIR	Track	360			360	TLD	20			20
EML	TLD-albedo	412	392		402	TLD	22	18		20
EML	Combination[f]	464	350		407	Film	40	25		32
GAC						TLD	13.0	5.2[d]	11.8	12.4/5.2[d]
LAND	TLD, track	240	260	260	253					
LLNL	Track	558	682	384	541	TLD[g]				
NLO						Film	23	13	23	20
NNMC	TLD-albedo	439	509	515	488	TLD	15	10	16	14
NRC	Track	280	350	190	273	Film	50	50	70	57
					Run 1B — 0.994 × 10^{13} fissions					
DOSAR	Reference				463/74[d]	Reference				13.1/4.7[d]
CEER	Film	0	0	0	0	Film	25	10	0[d]	12
IPEN	TLD[i]	405	402	85[d]	404/85[d]	TLD[h]	18	17	8[d]	18/8[d]
IPEN						TLD[i]	16	13	6[d]	14/6[d]
IPEN						Film	18	18	12[d]	18/12[d]
KK	TLD-albedo	402			402	TLD	13			13
KK	TLD, sphere	408			408	TLD	12			12
NTHU						Film	18.5	8.1[d]		18.5/8.1[d]
NTHU						TLD[i]	16.6	7.0[d]		16.6/7.0[d]
OPPD	TLD	212	187	78	159	TLD	0	1	0	0
ORNL	Albedo, film	200	210	200	203	TLD	0	0	0	0
OSU	Film	80	110	20[d]	95/20[d]	Film	20	20	10[d]	20/10[d]
PPPL	Track	210	250		230	Film	20	M[j]	20	20
PPPL	Film	M[k]			M[k]					
RFP	TLD-albedo	251	307	67[d]	279/67[d]	TLD	12	12	2[d]	12/2[d]
RPB	TLD-albedo	261	57[d]		261/57[d]	TLD	13	5[d]		13/5[d]
SNL	TLD-albedo	291	272	284	282	TLD	7	7	7	7
SNL	TLD-albedo	49[d]	60[d]	46[d]	52[d]	TLD	0.4[d]	1[d]	1[d]	0.8[d]
TAEC	TLD[i]	14.44	5.77[d]		14.44/5.77[d]	TLD	10.05	4.53[d]		10.05/4.53[d]
TPC	TLD-albedo	279.6	471.1	424.3	425.0	TLD	12.9	11.8	14.9	13.2
TVA	TLD	367	330	351	349	TLD	12.8	14.9	12.7	13.5
UW	Track	60	80	100	80	TLD	110	120	90	107
WPPS	TLD-albedo	166	130	185	160	TLD	33	27	27	29
YALE	Track	220	<20[d]		220/<20[d]	Film	<10	<10[d]		<10/<10[d]

[a]Identifying acronyms are defined in Appendix A.

[b]Dose equivalents are background corrected and reported in units of 10^{-5} Sv (mrem). Measurements were made on the fronts of phantoms (side facing HPRR) unless otherwise indicated.

[c]Each group was allowed to expose three dosimeters per run.

[d]Dosimeter on rear of phantom (side opposite HPRR).

[e]Measurement made at 2 m from HPRR and extrapolated to 3 m.

[f]Combination of TLD-albedo, film, and track dosimeters.

[g]Results not reported due to high background.

[h]LiF:Mn,Ti TLD.

[i]$CaSO_4$:Dy TLD.

[j]Less than measurement threshold of 10^{-4} Sv.

[k]Less than measurement threshold of 4 × 10^{-4} Sv.

Table 6. Tabulation of reported results — PDIS 7, runs 2A and 2B, unshielded

Group[a]	Neutron dosimeter	Neutron dose equivalent,[b] 10^{-5} Sv 1[c]	2	3	Average	Gamma dosimeter	Gamma dose equivalent,[b] 10^{-5} Sv 1	2	3	Average
					Run 2A — 1.787 × 10^{13} fissions					
DOSAR	Reference				832/133[d]	Reference				26.0/9.4[d]
AIRP	TLD	131[d]	118[d]	128[d]	126[d]	TLD	11[d]	9[d]	9[d]	10[d]
APS	TLD-albedo	483			483	TLD	15			15
BMI						Film	40			40
BMI						TLD	87	316[d]		87/316[d]
BNL	TLD-albedo	610	130[d]	60[d]	610/95[d]	TLD	30	10[d]	10[d]	30/10[d]
EIR	Track	570			570	TLD	<10			<10
EML	Combination[e]	1002	971		986	Film	40	40		40
GAC						TLD	20.6	18.9	6.6[d]	19.8/6.6[d]
LAND	TLD, track	420	410	350	393					
LLNL	Track	921	987	739	882	TLD[f]				
NLO						Film	34	25	23	27
NNMC	TLD-albedo	929	938	814	894	TLD	22	20	30	24
NRC	Track	310	340	240	297	Film	50	40	50	47
					Run 2B — 1.827 × 10^{13} fissions					
DOSAR	Reference				850/136[d]	Reference				18.4/7.5[d]
CEER	Film	0	0	0	0	Film	25	27	20	24
IPEN	TLD[g]	776	745	203[d]	760/203[d]	TLD[g]	24	25	15[d]	24/15[d]
IPEN						TLD[h]	15	11	10[d]	13/10[d]
IPEN						Film	27	27	14[d]	27/14[d]
KK	TLD-albedo	823			823	TLD	22			22
KK	TLD, sphere	855			855	TLD	17			17
NTHU						Film	26.1	10.3[d]		26.1/10.3[d]
NTHU						TLD[h]	24.1	9.6[d]		24.1/9.6[d]
OPPD	TLD	549	543	489	527	TLD	0	3	5	3
ORNL	Albedo, film	330	250	330	303	TLD	20	20	20	20
OSU	Film	190	190	20[d]	190/20[d]	Film	40	30	M[d,i]	35/M[d,i]
PPPL	Track	570	590		580	Film	30	30	M[i]	30
PPPL	Film			70	70					
RFP	TLD-albedo	639	468	125[d]	554/125[d]	TLD	14	15	4[d]	14/4[d]
RPB	TLD-albedo	612	121[d]		612/121[d]	TLD	22	10[d]		22/10[d]
TAEC	TLD[h]	22.43	14.08[d]		22.43/14.08[d]	TLD[h]	6.07	6.56[d]		6.07/6.56[d]
TPC	TLD-albedo	844.2	817.8	722.6	794.9	TLD	22.8	22.1	18.7	21.2
TVA	TLD	682	727	680	696	TLD	20.0	22.1	20.9	21.0
UW	Track	130	240	200	190	TLD	260	280	250	263
WPPS	TLD-albedo	192	340	396	309	TLD	36	41	41	39

[a]Identifying acronyms are defined in Appendix A.

[b]Dose equivalents are background corrected and reported in units of 10^{-5} Sv (mrem). Measurements were made on the fronts of phantoms (side facing HPRR) unless otherwise indicated.

[c]Each group was allowed to expose three dosimeters per run.

[d]Dosimeter on rear of phantom (side opposite HPRR).

[e]Combination of TLD-albedo, film, and track dosimeters.

[f]Results not reported due to high background.

[g]$LiF:Mn,Ti$ TLD.

[h]$CaSO_4:Dy$ TLD.

[i]Less than measurement threshold of 10^{-4} Sv.

Table 7. Tabulation of reported results — PDIS 7, runs 3A and 3B, Lucite shield

Group[a]	Neutron dosimeter	Neutron dose equivalent,[b] 10^{-5} Sv				Gamma dosimeter	Gamma dose equivalent,[b] 10^{-5} Sv			
		1[c]	2	3	Average		1	2	3	Average
					Run 3A — 2.680 × 10^{13} fissions					
DOSAR	Reference				155/32[d]	Reference				26.9/9.4[d]
AIRP	TLD	607	664	543	605	TLD	23	24	27	25
APS	TLD-albedo	339	356		348	TLD	21	24		22
BMI						Film	90	40[d]		90/40[d]
BMI						TLD	134			134
BNL	TLD-albedo	140	90	60[d]	115/60[d]	TLD	30	25	30[d]	28/30[d]
EIR	Track	120			120	TLD	10			10
EML	TLD-albedo	197	210		204	TLD	32	44		38
EML	Combination[e]	213	206		210	Film	55	60		58
GAC						TLD	31.6	23.1	10.3[d]	27.4/10.3[d]
LAND	TLD, track	140	140	120	133					
LLNL	Track	241	498	307	349	TLD[f]				
NLO						Film	44	44	44	44
NNMC	TLD-albedo	257	222	257	245	TLD	24	25	31	27
NRC	Track	150	80	120	117	Film	50	70	60	60
					Run 3B — 2.703 × 10^{13} fissions					
DOSAR	Reference				156/33[d]	Reference				21.2/8.9[d]
CEER	Film	0	30	20	17	Film	32	30	25	29
IPEN	TLD[g]	549	969	110[d]	759/110[d]	TLD[g]	33	31	13[d]	32/13[d]
IPEN						TLD[h]	25	22	13[d]	24/13[d]
IPEN						Film	27	32	14[d]	30/14[d]
KK	TLD-albedo	230			230	TLD	23			23
KK	TLD, sphere	228			228	TLD	16			16
NTHU						Film	30.3	15.4[d]		30.3/15/4[d]
NTHU						TLD[h]	25.8	10.4[d]		25.8/10.4[d]
OPPD	TLD	93	103	109	102	TLD	7	14	5	9
ORNL	Albedo, film	160	150	190	167	TLD	30	30	30	30
OSU	Film	90	90	M[d,i]	90/M[d,i]	Film	30	40	10[d]	35/10[d]
PPPL	Track	110	90		100	Film	40	30	40	33
PPPL	Film	70			70					
RFP	TLD-albedo	121	124	18[d]	122/18[d]	TLD	21	21	8[d]	21/8[d]
RPB	TLD-albedo	166	45[d]		166/45[d]	TLD	28	12[d]		28/12[d]
SNL	TLD-albedo	160	128	139	142	TLD	14	13	17	15
TAEC	TLD[h]	37.59	8.04[d]		37.59/8.04[d]	TLD[h]	15.81	7.77[d]		15.81/7.77[d]
TPC	TLD-albedo	336.2	266.9	305.4	302.8	TLD	32.2	27.4	21.5	27.0
TVA	TLD	173	165	167	168	TLD	25.9	28.6	27.6	27.4
UM	Track	40	30	30	33	TLD	410	270	380	353
WPPS	TLD-albedo	115	125	115	118	TLD	43	44	43	43
YALE	Track	80	<20[d]		80/<20[d]	Film	50	20[d]		50/20[d]

[a]Identifying acronyms are defined in Appendix A.

[b]Dose equivalents are background corrected and reported in units of 10^{-5} Sv (mrem). Measurements were made on the fronts of phantoms (side facing HPRR) unless otherwise indicated.

[c]Each group was allowed to expose three dosimeters per run.

[d]Dosimeter on rear of phantom (side opposite HPRR).

[e]Combination of TLD-albedo, film, and track dosimeters.

[f]Results not reported due to high background.

[g]LiF:Mn,Ti TLD.

[h]$CaSO_4$:Dy TLD.

[i]Less than measurement threshold of 2×10^{-4} Sv.

Table 8. Tabulation of reported results – PDIS 7, runs 4A and 4B, Lucite shield

Group[a]	Neutron dosimeter	Neutron dose equivalent,[b] 10^{-5} Sv				Gamma dosimeter	Gamma dose equivalent,[b] 10^{-5} Sv			
		1[c]	2	3	Average		1	2	3	Average
					Run 4A – 25.64 × 10^{13} fissions					
DOSAR	Reference				1481/311[d]	Reference				279.9/87.8[d]
AIRP	TLD	878[d]	958[d]	828[d]	888[d]	TLD	101[d]	104[d]	100[d]	102[d]
APS	TLD-albedo	3660			3660	TLD	250			250
BMI						Film	370			370
BMI						TLD	533	19,000[d]		533/19,000[d]
BNL	TLD-albedo	2630	520[d]	505[d]	2630/512[d]	TLD	250	100[d]	120[d]	250/110[d]
EIR	Track	1900			1900	TLD	270			270
EML	TLD-albedo	1866	1734		1800	TLD	310	307		308
EML	Combination[e]	2038	1848		1943	Film	400	380		390
GAC						TLD	200.4	208.4	86.0[d]	204.4/86.0[d]
LAND	TLD, track	1400	1270	1290	1320					
LLNL	Track	632	1150	999	927	TLD[f]				
NLO						Film	413	407	426	415
NNMC	TLD-albedo	3216	2854	3157	3046	TLD	257	249	243	250
NRC	Track	1090	560	1070	907	Film	300	300	320	307
					Run 4B – 26.34 × 10^{13} fissions					
DOSAR	Reference				1521/319[d]	Reference				274.1/89.9[d]
IPEN	TLD[g]	9114	9726	1266[d]	9420/1266[d]	TLD[g]	262	242	122[d]	252/122[d]
IPEN						TLD[h]	198	211	87[d]	204/87[d]
IPEN						Film	410	450	108[d]	430/108[d]
KK	TLD-albedo	2190			2190	TLD	205			205
KK	TLD, sphere	2200			2200	TLD	130			130
NTHU						Film	250.5	110.7[d]		250.5/110.7[d]
NTHU						TLD[h]	243.0	109.7[d]		243.0/109.7[d]
OPPD	TLD	559	1330	909	933	TLD	123	183	220	175
ORNL	Albedo, film	1730	1860	1890	1827	TLD	280	280	270	273
OSU	Film	480	650	80[d]	565/80[d]	Film	280	280	140[d]	280/140[d]
PPPL	Track	930	1050		990	Film	400	360	410	390
PPPL	Film	240			240					
RFP	TLD-albedo	871	1290	174[d]	1080/874[d]	TLD	183	177	65[d]	180/65[d]
RPB	TLD-albedo	1402	267[d]		1402/267[d]	TLD	227	102[d]		227/102[d]
SNL	TLD-albedo	340[d]	299[d]	375[d]	338[d]	TLD	74[d]	74[d]	99[d]	82[d]
TAEC	TLD[h]	332.45	66.64[d]		332.45/66.64[d]	TLD[h]	167.15	68.01[d]		167.15/68.01[d]
TPC	TLD-albedo	3166.6	2791.7	2869.4	2942.6	TLD	219.2	228.4	223.8	223.8
TVA	TLD	1519	1567	1550	1545	TLD	284	279	280	281
UN	Track	410	270	460	380	TLD	3250	3690		3470
WPPS	TLD-albedo	1040	1104	1091	1078	TLD	321	327	318	322

[a]Identifying acronyms are defined in Appendix A.

[b]Dose equivalents are background corrected and reported in units of 10^{-5} Sv (mrem). Measurements were made on the fronts of phantoms (side facing HPRR) unless otherwise indicated.

[c]Each group was allowed to expose three dosimeters per run.

[d]Dosimeter on rear of phantom (side opposite HPRR).

[e]Combination of TLD-albedo, film, and track dosimeters.

[f]Results not reported due to high background.

[g]LiF:Mn,Ti TLD.

[h]$CaSO_4$:Dy TLD.

Table 9. Tabulation of reported results — PDIS 7, runs 5A and 5B, Lucite and concrete shield (unknown)

Group[a]	Neutron dosimeter	Neutron dose equivalent,[b] 10^{-5} Sv				Gamma dosimeter	Gamma dose equivalent,[b] 10^{-5} Sv			
		1[c]	2	3	Average		1	2	3	Average
					Run 5A — 73.89×10^{13} fissions					
DOSAR	Reference				894/179[d]	Reference				252.6/135.7[d]
AIRP	TLD	3989	3473	3771	3744	TLD	258	231	245	245
APS	TLD-albedo	2340	2290		2315	TLD	260	270		265
BMI						Film	410	250[d]		410/250[d]
BMI						TLD	402			402
BNL	TLD-albedo	2870	1960	2260	2363	TLD	230	270	250	250
EIR	Track	1300			1300	TLD	280			280
EML	TLD-albedo	1401	1590		1496	TLD	290	282		286
EML	Combination[e]	1077	1115		1096	Film	420	410		415
GAC						TLD	231.8	239.4	100.0[d]	235.6/100.0[d]
LAND	TLD, track	680	620	690	663					
LLNL	Track	926	1040	889	952	TLD[f]				
NLO						Film	394	404	394	397
NMMC	TLD-albedo	2111	1943	1608	1887	TLD	279	302	279	287
NRC	Track	520	420	620	520	Film	390	360	390	380
					Run 5B — 75.79 × 10 fissions					
DOSAR	Reference				917/183[d]	Reference				259.1/133.6[d]
IPEN	TLD[g]	7672	7305	1573[d]	7488/1573[d]	TLD[g]	280	248	130[d]	264/130[d]
IPEN						TLD[h]	244	256	132[d]	250/132[d]
IPEN						Film	476	501	209[d]	488/209[d]
KK	TLD-albedo	1920			1920	TLD	245			245
KK	TLD, sphere	1850			1850	TLD	165			165
NTHU						Film	301.2	150.7[d]		301.2/150.7[d]
NTHU						TLD[h]	277.8	135.4[d]		277.8/135.4[d]
OPPD	TLD	1494	915	1192	1200	TLD	123	126	222	157
ORNL	Albedo, film	1230	1360	1110	1233	TLD	290	260	280	277
OSU	Film	360	270	40[d]	315/40[d]	Film	410	410	210[d]	410/210[d]
PPPL	Track	580	460		520	Film	440	410	370	407
PPPL	Film	190			190					
RFP	TLD-albedo	731	987	296[d]	859/296[d]	TLD	193	187	88[d]	190/88[d]
RPB	TLD-albedo	1204	331[d]		1204/331[d]	TLD	283			283
TAEC	TLD[h]	267.69	99.3[d]		267.69/ 99.3[d]	TLD[h]	176.10	83.33[d]		176.10/83.33[d]
TPC	TLD-albedo	2829.1	2884.1	2753.3	2822.2	TLD	247.2	258.5	263.1	256.2
TVA	TLD	1173	1407	1231	1270	TLD	289	324	295	303
UM	Track	240	250	200	230	TLD	1950	2780	2540	2423
WPPS	TLD-albedo	943	929	995	956	TLD	354	333	347	345
YALE	Track	230	50[d]		230/50[d]	Film	410	220[d]		410/220[d]

[a]Identifying acronyms are defined in Appendix A.

[b]Dose equivalents are background corrected and reported in units of 10^{-5} Sv (mrem). Measurements were made on the fronts of phantoms (side facing HPRR) unless otherwise indicated.

[c]Each group was allowed to expose three dosimeters per run.

[d]Dosimeter on rear of phantom (side opposite HPRR).

[e]Combination of TLD-albedo, film, and track dosimeters.

[f]Results not reported due to high background.

[g]LiF:Mn,Ti TLD.

[h]CaSO :Dy TLD.

Table 10. Tabulation of reported results — PDIS 7, runs 6A and 6B, concrete shield

Group[a]	Neutron dosimeter	Neutron dose equivalent,[b] 10^{-5} Sv				Gamma dosimeter	Gamma dose equivalent,[b] 10^{-5} Sv			
		1[c]	2	3	Average		1	2	3	Average
					Run 6A — 4.59×10^{13} fissions					
DOSAR	Reference				460/87[d]	Reference				26.0/9.5[d]
AIRP	TLD	921	985	875	927	TLD	24	31	29	28
APS	TLD-albedo	512	496		504	TLD	20	21		20
BMI						TLD	3460	37[d]		3460/37[d]
BMI						Film	70			70
BNL	TLD-albedo	670	340	590	533	TLD	30	25	25	27
EIR	Track	430			430	TLD	10			10
EML	TLD-albedo	476	440		458	TLD	37	39		38
EML	Combination[e]	420	421		420	Film	60	55		58
GAC						TLD	23.3	24.4	8.0[d]	23.8/8.0[d]
LAND	TLD, track	230	240	200	223					
LLNL	Track	586	630	569	595	TLD[f]				
NLO						Film	55	55	54	55
NMMC	TLD-albedo	389	409	407	402	TLD	27	21	45	31
NRC	Track	200	160	210	190	Film	30	50	40	40
					Run 6B — 4.89×10^{13} fissions					
DOSAR	Reference				490/93[d]	Reference				24.3/10.8[d]
CEER	Film	0	0	0	0	Film	27	30	30	29
IPEN	TLD[g]	1739	1457	275[d]	1598/275[d]	TLD[g]	28	22	10[d]	25/10[d]
IPEN						TLD[h]	22	26	12[d]	24/12[d]
IPEN						Film	22	22	14[d]	22/14[d]
KK	TLD-albedo	460			460	TLD	22			22
NTHU						Film	30.4	18.6[d]		30.4/18.6[d]
NTHU						TLD[h]	25.2	11.8[d]		25.2/11.8[d]
OPPD	TLD	258	326	127	237	TLD	18	16	0	11
ORNL	Albedo, film	370	410	430	403	TLD	30	30	30	30
OSU	Film	80	60	M[d,i]	70/M[d,i]	Film	40	30	10[d]	35/10[d]
PPPL	Track	240	280		260	Film	60	50	60	57
PPPL	Film	70			70					
RFP	TLD-albedo	319	396	60[d]	358/60[d]	TLD	12	17	7[d]	14/7[d]
RPB	TLD-albedo	300	74[d]		300/74[d]	TLD	30	12[d]		30/12[d]
TAEC	TLD[h]	61.51	11.68[d]		61.51/11.68[d]	TLD[h]	17.00	7.16[d]		17.00/7.16[d]
TPC	TLD-albedo	717.0	764.6	674.7	718.8	TLD	29.9	22.4	19.4	23.9
TVA	TLD	333	384	358	358	TLD	31.6	31.9	29.2	30.9
UN	Track	100	90	90	93.3	TLD	490	560	420	490
WPPS	TLD-albedo	210	196	214	207	TLD	53	55	55	54

[a] Identifying acronyms are defined in Appendix A.

[b] Dose equivalents are background corrected and reported in units of 10^{-5} Sv (mrem). Measurements were made on the fronts of phantoms (side facing HPRR) unless otherwise indicated.

[c] Each group was allowed to expose three dosimeters per run.

[d] Dosimeter on rear of phantom (side opposite HPRR).

[e] Combination of TLD-albedo, film, and track dosimeters.

[f] Results not reported due to high background.

[g] LiF:Mn,Ti TLD.

[h] $CaSO_4$:Dy TLD.

[i] Less than measurement threshold of 4×10^{-4} Sv.

Table 11. Analysis of neutron dose equivalent results on the fronts of phantoms for all dosimeter types

Run	Shield	No. of measurements	Neutron dose equivalent, 10^{-5} Sv[a]		
			Reference	Subset of reported results[b]	
				Range	Mean $\pm\sigma$ (%σ)
1A	None	11	411	218-488	354 ± 102 (29)
1B	None	17	463	0-425	233 ± 139 (60)
2A	None	8	832	297-986	639 ± 254 (40)
2B	None	15	850	0-795	484 ± 286 (59)
3A	Lucite	10	155	115-605	245 ± 155 (63)
3B	Lucite	17	156	17-759	170 ± 168 (99)
4A	Lucite	9	1481	907-3660	2015 ± 942 (47)
4B	Lucite	14	1521	240-9420	1914 ± 2290 (120)
5A	Lucite +	10	894	520-3744	1634 + 976 (60)
5B	concrete	15	917	190-7488	1486 ± 1817 (122)
6A	Concrete	10	460	190-927	468 ± 205 (44)
6B	Concrete	15	490	70-1598	372 ± 387 (104)

[a] 1 mrem = 10^{-5} Sv.

[b] This subset omits results reported by TAEC.

Table 12. Neutron dose equivalent on fronts of phantoms by type of dosimeter

Run	Shield	Mean neutron dose equivalent ±σ, 10^{-5} Sv[a] (%σ)				
		Reference	TLD[b]	TLD-albedo	Film	Track
1A	None	411	246[c]	364 ± 113 (31)	[d]	391 ± 137 (35)
1B	None	463	330 ± 117 (35)	301 ± 98 (32)	32 ± 54 (169)	177 ± 84 (47)
2A	None	832	[d]	662 ± 210 (32)	[d]	583 ± 293 (50)
2B	None	850	710 ± 138 (19)	619 ± 208 (34)	87 ± 96 (110)	385 ± 276 (72)
3A	Lucite	155	605[c]	228 ± 97 (42)	[d]	195 ± 133 (68)
3B	Lucite	156	314 ± 301 (96)	180 ± 73 (41)	59 ± 38 (64)	71 ± 34 (48)
4A	Lucite	1481	[d]	2784 ± 781 (28)	[d]	1245 ± 568 (46)
4B	Lucite	1521	3524 ± 3964 (112)	1738 ± 812 (47)	402 ± 230 (57)	685 ± 431 (63)
5A	Lucite +	894	3744[c]	2015 ± 407 (20)	[d]	924 ± 391 (42)
5B	concrete	917	2952 ± 3038 (103)	1552 ± 822 (53)	252 ± 88 (35)	327 ± 167 (51)
6A	Concrete	460	927[c]	474 ± 57 (12)	[d]	405 ± 204 (50)
6B	Concrete	490	659 ± 632 (96)	409 ± 196 (48)	47 ± 40 (85)	177 ± 118 (67)

[a] 1 mrem = 10^{-5} Sv.

[b] TAEC results not included.

[c] Used by only one participant.

[d] No neutron dose measurements made on front of phantom using this dosimeter type for this run.

Table 13. Neutron dose equivalent results on the fronts of phantoms normalized to reference values and combined for equivalent exposures[a]

Run	Shield	Normalized mean neutron dose equivalent ±σ (%σ)[b]				
		Subset[c]	TLD[c]	TLD albedo	Film	Track
1	None	0.64 ± 0.29 (45)	0.69 ± 0.22 (32)	0.75 ± 0.24 (32)	0.07 ± 0.12 (171)	0.66 ± 0.26 (39)
2	None	0.64 ± 0.33 (52)	0.83 ± 0.16 (19)	0.76 ± 0.24 (32)	0.10 ± 0.11 (110)	0.60 ± 0.34 (57)
3	Lucite	1.27 ± 1.05 (83)	2.38 ± 1.73 (73)	1.28 ± 0.53 (41)	0.38 ± 0.24 (63)	0.86 ± 0.69 (80)
4	Lucite	1.30 ± 1.27 (98)	2.32 ± 2.60 (112)	1.47 ± 0.53 (36)	0.26 ± 0.15 (58)	0.68 ± 0.34 (50)
5	Lucite + concrete	1.70 ± 1.69 (99)	3.42 ± 2.96 (87)	1.94 ± 0.74 (38)	0.28 ± 0.10 (36)	0.70 ± 0.31 (44)
6	Concrete	0.86 ± 0.67 (78)	1.47 ± 1.15 (78)	0.92 ± 0.31 (34)	0.10 ± 0.08 (80)	0.67 ± 0.37 (55)

[a]Normalized results combined for sets A and B of each run.

[b]Normalized values obtained by dividing mean measured results by the reference dose equivalents.

[c]These data omit results reported by TAEC.

Table 14. Neutron dose equivalent results on the rears of phantoms normalized to reference values and combined for equivalent exposures[a]

Run	Shield	Normalized mean neutron dose equivalent ±σ (%σ)[b]				
		Subset[c]	TLD[c]	TLD-albedo	Film	Track
1	None	0.66 ± 0.39 (59)	1.15[d]	0.80 ± 0.09 (11)	0.27[d]	0[d]
2	None	0.85 ± 0.46 (54)	1.22 ± 0.38 (31)	0.84 ± 0.02 (2)	0.15[d]	[e]
3	Lucite	1.19 ± 1.29 (108)	3.33[d]	1.26 ± 0.47 (37)	0[d]	0[d]
4	Lucite	1.59 ± 1.45 (91)	3.42 ± 0.78 (23)	1.02 ± 0.22 (22)	0.25[d]	[e]
5	Lucite + concrete	2.50 ± 3.48 (139)	8.6[d]	1.71 ± 0.13 (8)	0.22[d]	0.27[d]
6	Concrete	1.10 ± 1.29 (117)	2.96[d]	0.72 ± 0.11 (15)	0[d]	[e]

[a]Normalized results combined for sets A and B of each run.

[b]Normalized values obtained by dividing mean measured results by the reference dose equivalent.

[c]These data omit results reported by TAEC.

[d]Used by only one participant.

[e]No neutron dose measurements made on rear of phantom using this dosimeter type for this run.

Table 15. Analysis of gamma dose equivalent results on the fronts of phantoms

Run	Shield	Reference dose, 10^{-5} Sv[a]	Mean gamma dose equivalent ±σ (%σ), 10^{-5} Sv[a]		
			Subset[b]	TLD[b]	Film
1A	None	13.0	25.2 ± 17.4 (69)	12.6 ± 6.2 (49)	42.2 ± 19.4 (46)
1B	None	13.1	13.0 ± 7.3 (56)	12.7 ± 6.6 (52)	14.8 ± 7.8 (53)
2A	None	26.0	27.0 ± 14.5 (54)	17.8 ± 11.4 (64)	38.5 ± 8.3 (22)
2B	None	18.4	21.6 ± 9.0 (42)	16.6 ± 10.8 (65)	28.4 ± 4.3 (15)
3A	Lucite	26.9	39.0 ± 22.7 (58)	25.3 ± 8.4 (33)	63.0 ± 19.4 (30)
3B	Lucite	21.2	27.2 ± 9.5 (35)	21.9 ± 10.5 (48)	34.6 ± 7.9 (23)
4A	Lucite	279.9	301.4 ± 69.8 (23)	255.4 ± 33.7 (13)	370.5 ± 46.2 (12)
4B	Lucite	274.1	243.1 ± 90.1 (37)	221.8 ± 52.8 (24)	337.6 ± 86.0 (25)
5A	Lucite +	252.6	313.7 ± 71.2 (23)	264.1 ± 21.0 (8)	400.5 ± 15.6 (4)
5B	concrete	259.1	289.2 ± 93.0 (32)	245.3 ± 57.2 (23)	403.2 ± 66.5 (16)
6A	Concrete	26.0	36.3 ± 18.0 (50)	25.4 ± 8.8 (34)	55.5 ± 12.4 (22)
6B	Concrete	24.3	27.6 ± 13.0 (47)	22.6 ± 12.6 (56)	34.7 ± 13.3 (38)

[a] 1 mrem = 10^{-5} Sv.

[b] These data omit results reported by BMI using TLD-100 dosimeters in set A and by UW using TLD's in set B.

Table 16. Gamma dose equivalent results on the fronts of phantoms normalized to reference values and combined for equivalent exposures[a]

Run	Shield	Normalized mean gamma dose equivalent ±σ (%σ)[b]		
		Subset[c]	TLD[c]	Film
1	None	1.33 ± 0.92 (69)	0.97 ± 0.49 (50)	1.98 ± 0.48 (24)
2	None	1.13 ± 0.52 (46)	0.84 ± 0.56 (67)	1.52 ± 0.27 (18)
3	Lucite	1.34 ± 0.62 (46)	1.00 ± 0.44 (44)	1.91 ± 0.54 (28)
4	Lucite	0.96 ± 0.30 (31)	0.84 ± 0.16 (19)	1.28 ± 0.24 (19)
5	Lucite + concrete	1.16 ± 0.33 (28)	0.98 ± 0.18 (18)	1.57 ± 0.20 (13)
6	Concrete	1.24 ± 0.56 (45)	0.95 ± 0.46 (48)	1.74 ± 0.52 (30)

[a]Normalized results combined for sets A and B of each run.

[b]Normalized values obtained by dividing mean measured results by the reference dose equivalents.

[c]These data omit results reported by BMI (TLD-100) and UW (TLD).

Table 17. Gamma dose equivalent results on the rears of phantoms normalized to reference values and combined for equivalent exposures[a]

Run	Shield	Normalized mean neutron dose equivalent ±σ (%σ)[b]		
		Subset[c]	TLD[c]	Film
1	None	1.65 ± 1.94 (118)	0.98 ± 0.46 (47)	2.89 ± 1.01 (35)
2	None	1.12 ± 0.56 (50)	0.98 ± 0.58 (59)	1.08 ± 0.96 (89)
3	Lucite	1.73 ± 0.86 (50)	1.30 ± 0.84 (65)	2.18 ± 0.41 (19)
4	Lucite	1.02 ± 0.38 (37)	0.96 ± 0.38 (40)	1.33 ± 0.38 (29)
5	Lucite + concrete	1.16 ± 0.48 (41)	0.83 ± 0.17 (20)	1.55 ± 0.21 (14)
6	Concrete	1.04 + 0.30 (29)	0.82 ± 0.41 (50)	1.31 ± 0.40 (30)

[a]Normalized results combined for sets A and B of each run.

[b]Normalized values obtained by dividing mean measured results by the reference dose equivalents.

[c]These data omit results reported by BMI using TLD-100 dosimeters in set A.

Table 18. Neutron dosimetry performance of Seventh PDIS participants relative to NRC criteria[a]

Organization	Neutron dosimeter type	Performance of dosimeter relative to accuracy criteria[b]					
		1-None[c]	2-None	3-Lucite	4-Lucite	5-Lucite/Concrete	6-Concrete
AIRP	TLD	Y	*d*	N	*d*	N	N
IPEN	TLD	Y	Y	N	N	N	N
KK	TLD, sphere	Y	Y	Y	Y	N	Y
OPPD	TLD	N[e]	Y	Y	Y[e]	Y	N
TAEC	TLD	N	N	N	N	N	N
TVA	TLD	Y	Y	Y	Y	Y	Y
APS	TLD-albedo	Y	Y	N	N	N	Y
BNL	TLD-albedo	Y	Y	Y	N	N	Y[e]
EML	TLD-albedo	Y	*d*	Y	Y	N	Y
KK	TLD-albedo	Y	Y	Y	Y	N	Y
NNMC	TLD-albedo	Y	Y	N	N	N	Y
RFP	TLD-albedo	Y	Y	Y	Y	Y	Y
RPB	TLD-albedo	Y	Y	Y	Y	Y	Y
SNL	TLD-albedo	Y	*d*	Y	*d*	*d*	*d*
TPC	TLD-albedo	Y	Y	N	N	N	Y
WPPS	TLD-albedo	N	N[e]	Y	Y	Y	N
CEER	Film	N	N	N[e]	*d*	*d*	N
OSU	Film	N	N	Y	N	N	N
PPPL	Film	N	N	N	N	N	N
EIR	Track	Y	Y	Y	Y	Y	Y
LLNL	Track	Y[e]	Y	N[e]	Y[e]	Y	Y
NRC	Track	Y[e]	N	Y[e]	Y	Y	N
PPPL	Track	Y	Y	Y	Y	Y	Y
UW	Track	N	N[e]	N	N	N	N
YALE	Track	N	*d*	Y	*d*	N	*d*
EGG	Activation	Y	*d*	*d*	*d*	*d*	*d*
EML	Combination	Y	Y	Y	Y	Y	Y
LAND	TLD, track	Y	N	Y	Y	Y	N
ORNL	Albedo, film	N	N	Y	Y	Y	Y
Percent meeting accuracy criteria[f]	±50%	69	63	64	63	46	58
Percent meeting precision criteria[g]	±30%	90	92	89	88	100	92

[a]Personnel neutron dosimetry criteria specified in NUREG 8.14, Rev. 1 (1977): Accuracy = ±50%; Precision = ±30%.

[b]Y indicates the average of measurements was within ±50% of the reference dose equivalent for the run. N indicates the average of measurements was outside ±50% of the reference dose equivalent.

[c]Run number - shield.

[d]Did not report any measurements for this run.

[e]Standard deviation of the individual measurements about the mean was not within ±30% for this run.

[f]Based on an average of neutron dose equivalent results reported by each agency.

[g]Based on the distribution of individual measurements about the average reported by each agency.

APPENDIX A

SEVENTH PERSONNEL DOSIMETRY INTERCOMPARISON STUDY PARTICIPANTS

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PARTICIPANT COMMENTS CONCERNING DOSIMETRY AND MEASUREMENTS

Some of the Seventh PDIS participants reported comments concerning their dosimetry and measurement methods along with dose results. These comments, which are presented in this appendix, provide details concerning measurement, evaluation, and calibration techniques for individual participants. A list of participants and associated dosimeter types is given in Table 4 of this report, and identifying acronyms are defined in Appendix A. Dose equivalents were reported by participants in millirems (1 mrem = 10^{-5} Sv).

AIRP — Harshaw TL 6/7 cards were used for neutron and gamma measurements along with a Harshaw Model 2271 reader. Background dose equivalents were 7 mrem gamma and 0 neutron.

APS — The dosimetry system tested by Arizona Public Service Company (APS) in this intercomparison was at the Palo Verde Nuclear Generation Station (PVNGS) on a demonstration basis from Panasonic Corporation. We participated in order to begin evaluations of the system's characteristics and the neutron dosimetry potential of this type of dosimeter. Only eleven TLDs were available to send to DOSAR for this study and these were spread among the various exposure runs. These TLDs were comprised of unselected TL-elements having sensitivity correction factors ranging from 0.7 to 1.4. Combined with a $Li_2B_4O_7/CaSO_4$ calibration ratio, some TL-elements had to be corrected by almost a factor of 2.0 in order to equate the values to the average population sensitivity. The gamma calibration was accurate to about ±20% owing to the use of a borrowed source in a high level scatter field (PVNGS is not operating and has no sources onsite at this time). These problems were basically corrected after the readout of the intercomparison TLDs and should not be a large effect.

Calibration for neutron dose was completed in two phases: (1) Analysis of ^6LiF + ^7LiF exposures in PDIS and NAD studies; and (2) Analysis of $Li_2B_4O_7$ and $CaSO_4$ exposures in a Nuclear Accident Dosimetry study. These data have shown that, for the following dose equations, the calibration factors in mR/mrem are:

(1) For Lithium Fluoride: $$\frac{^6LiF\ (mR) - {}^7LiF\ (mR)}{\text{Calibration Factor}} = \text{Neutron Dose (mrem)}$$

	Calibration Factor (mR/mrem)
Bare HPRR	0.40
20-cm concrete shield	1.35
12-cm Lucite shield	0.90
5-cm steel shield	0.55

All data indicates that these values were appropriate for PDIS or Nuclear Accident Dosimetry work for typical LiF chips.

(2) For $Li_2B_4O_7$ and $CaSO_4$: $\frac{Li_2B_4O_7\ (mR) - CaSO_4\ (mR)}{\text{Calibration Factor}}$ = Neutron Dose (mrem)

	Calibration Factor (mR/mrem)
Bare HPRR	0.48
20-cm concrete shield	1.58
5-cm steel shield	0.56

There has been no Lucite shield data compiled as yet and the present data are limited. Correlation of these two systems would yield an estimate of the Lucite shield calibration factor of approximately 1.1 mR/mrem for this Panasonic system.

Our background dosimeters showed a control dose of 50 mrem, which is excessive. The effect of this would only be seen in the gamma dose measurements.

BML — Gamma film dosimeters were manufactured and evaluated by R. S. Landauer, Jr. and Company. The TLD dosimeters were Harshaw TLD-100's (2 each in a G-1 card) and were evaluated using a Harshaw Model 2271 reader.

BNL — The Hanford dosimeter is designed for determining "non-penetrating," penetrating, and fast and slow neutron doses. The neutron dosimeter consists of 2 TLD-600 chips with Cd and Sn filters, and the gamma dosimeter consists of 2 TLD-700 chips with an open window and an Al filter. Calibration sources are U, ^{137}Cs, PuF_4, and PuBe.

EGG — The data were obtained from a set of activation foils. The elements used were Au, Au(Cd), As, W, and S. Relatively large foils were employed in anticipation of a low total dose equivalent: 10 grams for Au, 100 grams for As, 200 grams for W and 150 grams for S. The Au, As, and W were spread out over a 12 by 12 inch (30.5 × 30.5 cm) area. The S was placed in a coffee cup sized aluminum can.

All of the activation products have half lives of 24 hours or greater thus allowing counting and analysis in Santa Barbara after shipment here. We used standard Ge(Li) detector techniques for counting the Au, As, and W. A least squares peak fitting code was employed for quantitative data. The S was counted with a plastic scintillator.

EIR — Neutron dose measurements were made using a track detector consisting of a Th-232 converter and a makrofol E detector. Tracks were counted by spark counter evaluation. An unshielded ^{252}Cf source was used for calibration.

EML — Two types of dosimeters were used during this intercomparison. The Type A dosimeter was a 3-component in-house construction, consisting of bare (actually a light-tight plastic package), cadmium-covered, and Hankins-type albedo dosimeters. In each component was a TLD-600/TLD-700 pair. All TLDs were read and evaluated at EML. The evaluations were based on EML calibrations with bare and moderated ^{252}Cf fission neutron spectra. The dose equivalent and specific dose equivalent of each of these calibration spectra were determined by Bonner sphere neutron spectrometry measurements unfolded using the TWOGO code (see USDOE Report EML-391). For each dosimeter component, a TL signal per unit neutron dose equivalent vs. specific dose equivalent curve was obtained. The HPRR spectra supplied in Appendices B and C of ORNL/TM-7615 were evaluated for specific dose equivalent and quality factor, and their appropriate TL signal per unit neutron dose equivalent were obtained from the calibration curves. The appropriate TL signal per unit neutron dose equivalent of the unknown spectrum was determined using dosimeter component response ratios. The neutron dose equivalents on the data report sheet are averages of the values found for each component.

The Type B dosimeter was a 4-component package obtained from R. S. Landauer, Jr. and Company. It consisted of TLD albedo, NTA film, Neutrak (polycarbonate) and Neutrak-144 (CR-39) detectors. These were processed by Landauer, and neutron exposures reported to EML assuming an unmoderated ^{252}Cf source calibration with detector on phantom. At EML, energy-response corrections, based on the HPRR spectra in Appendices B and C of ORNL/TM-7615 were made; the correction for the unknown spectrum was made as above. The values reported on the data sheets are again averages of the values determined for each component.

GAC — The gamma dosimetry system used is a Harshaw Model 2276 Automatic TLD system. The dosimeters are standard Harshaw TLD cards with three (3) LiF chips. The cards are placed in a badge and covered with various types of shielding. The system was calibrated with thirty (30) cards that were exposed to 100 mR gamma with the ^{60}Co calibration source at the Union Carbide Corporation Y-12 Plant. The accuracy of the system was computed to be ±7% which is two (2) standard deviations.

LAND — For the first time in the PDIS program, we used our new NEUTRAK-ER neutron dosimeter. NEUTRAK-ER contains both TLD albedo and CR-39 track etch type components. When evaluated in a complimentary manner, it permits energy compensating corrections which minimizes the severe energy dependence of albedo technology as well as the gamma interference at higher neutron energies. In addition, an overlap in response between the albedo components and the CR-39 threshold permits an interpretation of the neutron dose regardless of energy.

LLNL — The neutron dosimeter used in this study was a combination two component track detector — CR-39 and polycarbonate. TLD-albedo dosimeters were also used but high gamma background readings of 330 to 630 mR made an evaluation of these albedo neutron dosimeters impossible. Gamma measurements made with TLD-700 dosimeters were also not reported due to this high background.

NLO — Our dosimeter is the ORNL film badge type with Kodak Type 2 dosimetry film. Dosimeters were calibrated by exposing them to a ^{226}Ra source which has been calibrated at the National Bureau of Standards. Variations in dose are obtained by varying the distance between source and dosimeter. Films from the calibration dosimeters were developed along with the films which were to be evaluated. The density of the calibration films and test films were determined using a film densitometer. A least squares curve relating film density to dose was calculated for the calibration data. Doses for the test films were then calculated using the least squares calibration curve.

NRC — Neutron dosimeters used in this study were NEUTRAK 144 monitors manufactured by R. S. Landauer, Jr. and Company. Film dosimeters also manufactured by Landauer were used for gamma measurements.

OPPD — The neutron dosimeter is a Harshaw TLD-600 chip in an OPPD designed holder. The 3" to 9" (7.6 cm to 23 cm) sphere response ratio was used to determine a TLD response/dose correction factor. Gamma doses were measured with a Harshaw TLD-700 chip in an OPPD designed holder.

PPPL — Neutron dosimeters used for this study were NTA film and CR-39 track etch manufactured by R. S. Landauer, Jr. and Company. No corrections were made for the unknown spectrum. A standard Landauer conversion to an Am-Be source was used.

SNL — Neutron and gamma doses were measured using a Harshaw 2271 automated system with a dosimeter holder designed by SNL.

TAEC — Neutron and gamma dosimeters consisted of TAEC-made $CaSO_4$:Dy material. The TLD readers were Harshaw Model 2000B and 2000C systems. Background levels were 16.91 mrem neutron and 11.23 mrem gamma.

TPC — Dosimetry was based on a Harshaw NG-67 card system and a Harshaw 2271 reader. Background levels were 2.2 mrem neutron and 17.3 mR gamma.

TVA — The neutron and gamma dosimeters consisted of Harshaw cards G7 and N6 (4 chips total) in a slightly albedo-like badge arrangement.

UW — Neutron doses were measured using a NEUTRAK 144 dosimeter manufactured by R. S. Landauer, Jr. and Company. Gamma doses were measured using a 3 chip TLD badge also manufactured by Landauer. Some exposures were reported below the minimum quantity measurable for those systems (10 mRem for X and gamma and 20 mRem for fast neutron).

WPPS — The neutron dosimeter consisted of a Teledyne $CaSO_4$:Dy/$CaSO_4$:Dy^{6}LiF albedo TLD (PB-3 Personnel Badge Case) and a Teledyne Model 9100 reader. Gamma doses were determined using a Teledyne $CaSO_4$:Dy TLD system. Dose equivalents were calculated using current Teledyne calculations relating ^{137}Cs calibration dose to dose equivalents.