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Eleventh ORNL Personnel Dosimetry Intercomparison Study: May 22-23, 1985

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ELEVENTH ORNL PERSONNEL DOSIMETRY INTERCOMPARISON STUDY: MAY 22-23, 1985

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Highlights

The Eleventh Personnel Dosimetry Intercomparison Study was conducted at the Oak Ridge National Laboratory (ORNL) during May 22-23, 1985. This study differed from previous ORNL intercomparisons in that the Health Physics Research Reactor, the source of radiation for this study, was operated over the storage pit which necessitated new reference dosimetry and participants could submit up to five badges per run so that measurement precision could be evaluated. Dosimeter badges from 44 participating organizations were mounted on Lucite block phantoms and exposed to four mixed-radiation fields with neutron dose equivalents around 5 mSv and gamma dose equivalents between 0.1 and 0.7 mSv. Results of this study indicated that no participants had difficulty obtaining measurable indication of neutron exposure at the provided dose equivalent levels, and very few had difficulty obtaining indication of gamma exposure at dose equivalents as low as 0.10 mSv. Average neutron results for all dosimeter types were within 20% of reference values with no obvious spectrum dependence. Different dosimeter types (albedo, direct interaction TLD, film, recoil track, and combination albedo-track) with 10 or more reported measurements provided average results within 35% of reference values for all spectra. With regard to precision, about 80% of the reported neutron results had single standard deviations within 10% at the means which indicates that precision is not a problem relative to accuracy for most participants. Average gamma results were greater than reference values by factors of 1.07 to 1.52 for the four exposures with TLD systems being more accurate than film. About 80% of all neutron results and 67% of all gamma results met regulatory standards for measurement accuracy and approximately 70% of all neutron data satisfied national dosimetry accreditation criteria for accuracy plus precision. In general, neutron dosimeter performance observed in this intercomparison was much improved compared to that observed in the prior studies while gamma dosimeter performance was about the same.

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INTRODUCTION

The eleventh in a series of annual mixed field personnel dosimetry intercomparison studies (PDIS)[1-6] was conducted at the Oak Ridge National Laboratory's (ORNL) Dosimetry Applications Research (DOSAR) facility during May 22-23, 1985. In this study, personnel neutron and gamma dosimeters were mailed to ORNL, exposed to a range of low-level (4.12 to 5.98 mSv neutron and 0.10 to 0.70 mSv gamma) dose equivalents using the Health Physics Research Reactor (HPRR)[7], and then returned to participants for evaluation. This document is a summary and analysis of results reported by the intercomparison participants.

This study differed from previous ORNL intercomparisons in two aspects. First, the HPRR was operated over Storage Pit 1 and was attached to a new hydraulic vertical positioning device. During previous studies, the reactor was operated over a concrete floor and was attached to a vertical and horizontal motorized positioner.[8] These changes, which were necessitated by recent administrative requirements, resulted in different neutron energy spectra, gamma components, and reference dosimetry relative to that previously recommended for the HPRR.[9] Reference dosimetry for this study was based primarily on multisphere measurements of neutron energy spectra with the reactor in the new experimental configuration instead of on previously recommended data. A new reference dosimetry document which summarizes neutron energy spectra, dose and dose equivalent data, and gamma characteristics of HPRR radiation fields is in preparation and should be issued sometime in 1986.

The second difference was in the basic format of the Eleventh PDIS. Previous studies usually included a low dose equivalent and a high dose equivalent irradiation for each spectrum with one to three badges permitted per run. In this intercomparison, five badges were permitted for each exposure to obtain a better indication of measurement precision than had been available in previous studies. To preclude measurement problems due to detection sensitivity, neutron dose equivalents were approximately 5 mSv for each run which is well above detection thresholds for commonly used personnel dosimeters.

PARTICIPATION

A total of 44 different organizations, 27 from the United States and 17 from abroad, participated in the Eleventh PDIS. Measured results were reported by a total of 39 organizations which consisted of 18 laboratories (national laboratories or industrial research laboratories), 11 utilities, 4 vendor services, 3 government agencies (military or regulatory), and 3 universities. To ensure anonymity, participating organizations are designated by numbers in the data summary tables.

DOSIMETER TYPES

The 44 participating agencies provided a total of 49 groups of badges since some of the agencies submitted more than one badge type. A total of 929 dosimeters were mounted on phantoms and exposed during this intercomparison. Adding the 147 control badges which accompanied the irradiated dosimeters, a total of 1076 badges were processed by the DOSAR staff. Measured results were reported for 660 of the exposed neutron dosimeters and for 671 of the exposed gamma dosimeters.

irradiations. Although few of the badge designs are the same, the basic detection mechanisms can be classified into six categories: TLD-albedo, direct interaction TLD, recoil track (CR-39), fission track (thorium converter), NTA film, and combination albedo and CR-39 track.[10] TLD-based albedo and direct interaction systems, which were the most popular neutron dosimeters in this study, were used by 38% and 34%, respectively, of the organizations reporting results. Recoil track dosimeters based on CR-39 material were the third most popular neutron detector and were used by 11% of the reporting agencies. Film, fission track, and combination systems were used 7%, 4%, and 4%, respectively, of the responders. One agency (2%) reported neutron data based on recommended neutron-to-gamma dose equivalent ratios for the HPRR.

Considering the reported gamma results, a total of 84% of the reporting organizations used TLD systems with the remaining 16% using film. About 55% of the TLD badges used TLD-700 (^{7}LiF) material with the remainder using $CaSO_4$ alone or in combination with another phosphor.

EXPERIMENT DESCRIPTION

The Eleventh PDIS consisted of four exposures using the HPRR as the source of radiation. Table 1 lists the date, shield type, reactor power level, run duration, and albedo ratio for these irradiations. Albedo ratios shown in the table are the ratios of BF_3 detector responses inside 23 cm (9 inch) and 7.6 cm (3 inch) diameter polyethylene spheres located with the centers at 3 m from the reactor. Ratio values given in the table differ by about 6 to 15% from previously reported data[11] for the HPRR because of the new reactor experimental configuration.

Runs 1 through 4 consisted of an approximately 5 mSv neutron dose equivalent irradiation for each of four shield conditions: unshielded, shielded by 13 cm of steel, shielded by 20 cm of concrete, and shielded by 12 cm of Lucite. The reactor horizontal centerline was 1.4 m above the floor level for all runs. During irradiation, dosimeters were mounted on Lucite blocks which had 40 cm x 40 cm exposure surfaces and were 15 cm thick.[12] These blocks were located with their front surfaces 3 m from the reactor vertical centerline and their horizontal centerlines 1.4 m above the floor. Participants were limited to five badges per exposure with badges from the same agencies mounted side-by-side on the same phantom.

REFERENCE DOSIMETRY

The following text gives details of reference neutron and gamma dose equivalents determined for this study.

Neutron Dose Equivalent

Reference neutron dose equivalents were obtained using fission yields measured by sulfur pellet activation analysis and dose-equivalent-per-fission conversion factors for the various HPRR spectra. The number of fissions produced during an irradiation (Table 1) was determined by measuring the ^{32}P beta activity induced in a 22 g sulfur pellet located at a fixed position near the reactor core. As previously discussed, dose-equivalent-per-fission values were based on multisphere measurements with the new HPRR experimental configuration and fluence-to-dose equivalent conversion factors for several conventions. Considering the dose equivalent convention specified in ICRP 21[13], the ratios of spectrum-averaged conversion factors which give the neutron dose equivalent per 10^{17} fissions for the Eleventh PDIS and previous PDIS are about 0.85, 0.86, 0.71, and 1.09 for the unshielded, steel-shielded, concrete-shielded, and Lucite-shielded spectra, respectively. These differences will cause participants using systems calibrated during previous ORNL intercomparisons to overestimate neutron dose equivalents by approximately 15 to 29% for the unshielded, steel-shielded, and concrete-shielded spectra and to underestimate neutron results by about 9% for the Lucite-shielded HPRR relative to the new reference values.

In this report, reference neutron dose equivalents used for comparison to measured results are based on specifications given in ICRP 21[13]. This convention consists of log-log interpolation of maximum dose-equivalent-per-fluence values calculated at discrete energies for a tissue-equivalent cylindrical phantom. The ICRP convention was used by 58% of the agencies who reported neutron dose equivalents in this study. Twenty-two percent of the responding organizations reported neutron results in terms of the NCRP 38 convention[14]. This method is based on linear interpolation of maximum dose-equivalent-per-fluence values calculated at discrete energies for a cylindrical phantom. The element 57 convention[15] was used by 13% of the organizations reporting results. Element 57 dose equivalent refers to the value calculated for the central volume element of a cylindrical phantom exposed to an external radiation field (log-log interpolation between discrete energies). Bases of the remaining 7% of the reported results were associated with some other convention.

Table 2 shows reference neutron dose equivalents based on ICRP, NCRP, and element 57 data for all exposures conducted during the

Eleventh PDIS. Reference ICRP dose equivalents varied between 4.12 and 5.98 mSv and were within 10% of corresponding NCRP and element 57 values for each exposure.

Gamma Dose Equivalent

Table 3 shows reference gamma dose equivalents and neutron-to-gamma dose equivalent ratios determined for the Eleventh PDIS. Reference gamma values were measured using a Philips Geiger-Mueller (G-M) detector[16] mounted directly on a phantom. The G-M detector was covered with a lithium shield and calibrated with a ^{137}Cs source. Gamma dose equivalents ranged from 0.10 to 0.70 mSv for the four exposures. Neutron-to-gamma dose equivalent ratios on a phantom varied from 8.54 to 46.00 with the lower value obtained for the Lucite shield and the higher value obtained for the steel shield.

RESULTS AND ANALYSIS OF NEUTRON MEASUREMENTS

Reported neutron results for the four irradiations conducted during the Eleventh PDIS are summarized in Tables 4-7. Data given in these tables for each participant include number organization identification, basic dosimeter type, reported neutron dose equivalents, the average of reported results, and the percent of the mean of one standard deviation of the reported data. Reference neutron dose equivalents in the ICRP 21 convention are included for each exposure. In the following text, neutron dosimeter performance characteristics are described based on results presented in these tables.

Tables 8-14 present analyses of reported neutron dose equivalents for the composite of all results and for each of the six basic dosimeter types considered in this study. Data given for each irradiation include the total number of reported results, the range of normalized (measured divided by reference) reported results, the mean and one standard deviation about the mean of all normalized results, and the average and range of standard deviations about the mean of reported results for each participating agency. None of the measured neutron results were reported as zero or below the minimum detectable value which indicates that, as expected, the monitoring systems used in this intercomparison had no problems providing indication of neutron exposure at dose equivalent levels of about 5 mSv.

An analysis of results for the composite of all neutron measurements (all dosimeter types) is presented in Table 8. Although performance characteristics of individual dosimeter types cannot be determined from these data, the following observations are noted concerning the ability of the collection of participants to measure neutron dose equivalents under identical conditions:

1. On the average, the collection of participants reported much more accurate results than those obtained in previous ORNL intercomparisons. Means of normalized results varied from 1.02 to 1.18 with standard deviations of about 35% of the means. No obvious correlation between average accuracy and incident neutron energy spectrum is evident from data shown in Table 8. These accurate results can be partly attributed to the easily detectable reference neutron dose equivalent levels of about 5 mSv provided for each run and the fact that 87% of the participants made some attempt to correct their results for differences between incident and calibration neutron spectra.

2. Although average normalized results were within 20% of the reference values, results reported by different organizations for the same irradiation differed by factors between 7 and 10 for each run. It was not unusual for neutron dose equivalent estimates made under identical conditions by different organizations to differ by a factor of two. Ranges of reported results given in Table 8 show no obvious correlation with incident neutron spectrum.

3. Single standard deviations about the mean (precision) for results reported by individual agencies averaged about 10% of the mean for all four irradiations. About 45% of the reporting organizations showed standard deviations of 5% or less of the mean values while about 80% indicated standard deviations of 10% or less of the means. Precisions for individual organizations ranged from less than 2% to approximately 60% of the means. In most cases, the individual standard deviations are based on measured results for five badges placed side-by-side on the same phantom. These data indicate that measurement precision is not a problem compared to accuracy for most participating organizations.

Table 9 presents a summary of results for TLD-albedo dosimeters, the most popular type (45% of all reported results and 34% of reporting organizations) used by intercomparison participants. The following observations concerning albedo dosimeter performance are based on data shown in this table:

1. Albedo dosimeter accuracy as reflected by the mean normalized results varied from 1.01 to 1.28 times reference values. Standard deviations associated with these values were about 30% of the

means. Neither accuracy nor standard deviations showed any obvious correlation with incident neutron spectrum. These indicated accuracies, which are much better than results obtained in previous intercomparisons[5,6], especially for moderated spectra, are partly due to the fact that about 88% of the organizations using albedo systems applied some correction factors to account for differences between incident and calibration spectra.

2. Ranges of reported normalized results varied from a minimum of about 0.40 to a maximum of about 2.50 times reference values for all runs. Thus, neutron dose equivalent measurements made under identical conditions by different organizations using albedo systems differed by factors of approximately 4 to 6 for this study. These differences are significantly less than the factors of more than ten observed in previous intercomparisons.[5,6]

3. With regard to measurement precision for the individual participants, single standard deviations ranged from less than 2% to about 23% of the means for the four irradiations. The average standard deviation was about 7.5% of the mean and approximately 80% of of the participants using albedo systems exhibited standard deviations of 10% or less. No obvious correlations between albedo measurement precision and incident spectrum are evident from these data.

A summary of results for direct interaction TL dosimeters, the second most popular type (34% of reporting agencies and 27% of all neutron data) used by PDIS 11 participants, is presented in Table 10. These systems use differences between responses of neutron plus gamma and gamma-only sensitive phosphors to obtain an estimate of the neutron dose equivalent in a mixed radiation field.[10] The following observations concerning direct interaction TLD performance are based on data shown in Table 10:

1. Mean normalized results for the direct interaction TL dosimeters varied from 1.05 to 1.35 times reference values which is comparable to the accuracy exhibited by TLD-albedo systems. Results for the harder energy spectra (unshielded and steel-shielded) were more accurate on the average (within 8% of reference values) than results obtained for softer spectra (concrete- and Lucite-shielded) which were 19 to 35% higher than references. These results are much more accurate than data obtained in previous intercomparisons[4-6] partly due to the fact that about 90% of the participants who used direct interaction TLD's applied some correction to account for differences between incident and calibration spectra. Standard deviations associated with these results were about 35% of the means for all runs except concrete which showed a standard deviation of 10% of the mean.

2. Reported normalized results ranged from a minimum of about 0.28 to a maximum of 2.40 times reference values for the few runs. For any particular irradiation, measurements made under identical conditions by different organizations differed by factors of about 2 to 6 which is also comparable to results obtained for TLD-albedo systems.

3. Measurement precision as indicated by one standard deviation of results reported by the individual participants averaged about 5.5%

of the mean which is slightly more precise than results obtained for albedo systems. Standard deviations ranged from 2 to 14% of the means for the four irradiations. Approximately 97% of the participants using direct interaction TLD's exhibited standard deviations of 10% or less of the mean reported dose equivalent. No obvious correlations between measurement precision and incident spectrum are evident from the data shown in Table 10.

An analysis of results obtained using recoil track (CR-39) dosimeters is presented in Table 11. This type of system was used by 11% of the participating agencies and for 10% of all neutron measurements. The following observations concerning CR-39 dosimeter performance are based on data shown in Table 11:

1. Average measured dose equivalents are within 23% of reference values for all spectra. Dose equivalents are overestimated by 23% for the unshielded spectra and underestimated by 9 to 19% for the moderated spectra. The underestimation is expected since most participants who used CR-39 monitors calibrated using an unmoderated encapsulated source (Cf or AmBe) and only 60% of these participants made any corrections to account for differences between incident and calibration spectra. Standard deviations associated with these results are about 25% of the means.

2. Ranges of measured results reported by different agencies for the same conditions varied between factors of 3 to 4 for all runs. Some organizations underestimated neutron dose equivalents by a factor of three relative to reference values while others overestimated by a factor of two. These variations are smaller than those observed for TL-based systems in this study.

3. With regard to measurement precision, standard deviations for individual organizations ranged from 3 to 30% of the mean values with an average precision of 7.8% of the mean for all irradiations. Although the average of reported standard deviations is consistent with results obtained for TL-based systems, two values for one organization were greater than 20% which significantly raised the average. About 83% of the CR-39 results reported in this study had precisions equal to or less than 5% of the mean values which is lower than corresponding standard deviations observed for albedo or direct interaction TL dosimeters.

Tables 12-14 summarize results for NTA film, thorium fission track, and combination albedo-track neutron dosimeters, respectively. Since each of these dosimeter types were used by less than 10% of the participating organizations, no detailed analysis of performance characteristics is possible. However, the following observations are evident from data shown in the tables:

Table 12 shows that the average of reported results for NTA film dosimeters were within 12% of reference values for all spectra. Dose equivalents for the unshielded spectrum were overestimated by only 2% on the average while values for the moderated spectra were underestimated by an average of 6 to 12%. Standard deviations associated with these results varied from 11 to 41% of the means. Neither accuracy nor precision indicates any obvious correlation with incident neutron energy spectrum. Results reported for the same irradiation varied by factors of about 1.5 to 4.0 among agencies who used film dosimeters. Measurement precision for each organization averaged 7.3%, which is similar to results obtained for TL and recoil track systems, and 90% of the reported mean dose equivalents had standard deviations of 10% or less for film dosimeters. Accuracy and precision performances for film dosimeters in this study were much better than performance characteristics observed in previous intercomparisons.[4-6] This is partly due to the fact that all agencies who calibrated with a hard source spectrum (AmBe or PuBe) applied corrections to account for incident and calibration spectrum differences, and those agencies who did not apply corrections used moderated spectra for calibration.

Reported data for thorium fission track dosimeters are presented in Table 13. These monitors were used by two organizations both of whom calibrated with unmoderated AmBe sources and made some attempt to account for spectrum effects in dose equivalent estimation. Average dose equivalents were within 38% of reference values with the hardest spectra (unshielded and steel-shielded) being less accurate than the softer spectra. However, one agency reported results which were low by 0.35 to 0.51 times reference values for all runs while the other reported results which were high by factors of 1.72 to 2.17 for all irradiations. Standard deviations for results reported by these organizations varied from 8 to 38% of the mean dose equivalents with an average precision of 23% of the mean for all runs. About 13% of the mean reported results had less than 10% standard deviations. These results indicate significant variation in measured neutron dose equivalents and much less precise results than those obtained for TL, film, or track systems.

Combination albedo-track dosimeters were also used by two participants who applied spectrum corrections and calibrated with a variety of sources (AmBe, Cf, and D_2O-moderated Cf). Table 14 shows that mean normalized results for combination dosimeters varied from 0.67 to 1.10 times reference values with the unshielded spectrum being overestimated and the moderated spectra being underestimated relative to reference dose equivalents. One organization underestimated neutron dose equivalents by 0.40 to 0.79 times reference while the other obtained higher results for each irradiation with a variation of from 0.93 to 1.52 times references. Standard deviations for each organization ranged from 6 to 24% of the means with an average of 14.8% for the four spectra. About 38% of the reported average results for combination dosimeters had standard deviations less than or equal to 10% of the means. Although only two agencies used combination dosimeters in this study, both organizations reported results which were much less accurate and precise than those exhibited by albedo, direct interaction TLD, film, or recoil track systems.

RESULTS AND ANALYSIS OF GAMMA MEASUREMENTS

Tables 15-18 summarize gamma results as reported by 35 different organizations who made gamma measurements. Data given in these tables for each participant include number organization identification, gamma dosimeter type, reported gamma dose equivalents, and the average of reported results. Reference gamma dose equivalents are also included for each run. Dosimeter performance characteristics described in the following text are based on results presented in these tables.

Analyses of reported gamma measurements are given in Tables 19-23 for the composite of all dosimeter types, all TLD's, TLD-700 phosphors, $CaSO_4$ phosphors, and film dosimeters, respectively. Data given for each irradiation include the reference gamma dose equivalent, the total number of reported results, the number of reported results greater than zero or the minimum detectable value, the range of normalized reported results, and the mean and one standard deviation about the mean of the normalized results. Data reported as zero or below the minimum detectable value were included in the calculation of the means and standard deviations shown in the analysis tables.

Table 19 presents an analysis of gamma results for all dosimeter types. The following observations concerning the ability of all participants to estimate gamma dose equivalents in mixed-radiation fields under identical conditions are based on data shown in this table:

1. Participants had almost no difficulty obtaining measurable indication of gamma exposure at dose equivalent levels less than 0.12 mSv. Only about 2% of all gamma measurements made below this level was reported as zero or below minimum detectable. Less than 1% of the measurements made of gamma dose equivalents greater than 0.26 mSv was reported as zero.

2. Average normalized results were greater than reference values for all exposure conditions. Mean results varied from 1.07 to 1.52 times references with the magnitude decreasing with decreasing neutron-to-gamma dose equivalent ratios. The most accurate average results were obtained for the irradiation with the highest gamma dose equivalent and the lowest neutron component (run 4) while the

least accurate results were obtained for the relatively low gamma dose equivalents and high neutron component (runs 1 and 2). These observed overestimates are primarily due to the effects of neutrons in the HPRR radiation fields on badge and gamma detection materials.[17] Standard deviations associated with these results were about 33% of the means for all runs.

3. Ranges of normalized results reported by individual organizations for the same irradiation varied from factors of about 2.2 to 6.7. The smallest differences were obtained for the run 4 which had the highest reference gamma dose equivalent (0.70 mSv). For this case, the range of results is almost the same as that obtained for corresponding neutron measurements. The largest differences were observed for runs 1 and 2 which had reference gamma dose equivalents of about 0.12 and 0.10 mSv, respectively. Maximum variations among results reported by different individual organizations for the same irradiations were about a factor of three greater than those obtained for corresponding neutron measurements in this study.

An analysis of data reported for all gamma TL dosimeters, which were used for 84% of the gamma measurements, is presented in Table 20. The following observations concerning gamma TLD performance are based on data shown in Table 20:

1. Participants who used TL gamma dosimeters had almost no difficulty obtaining measurable indication of gamma exposure. At dose equivalent levels greater than or equal to 0.12 mSv, none of the TLD-measured results were reported as zero or below the minimum

detectable. Only 4% of the reported measurements for a reference dose equivalent of 0.10 mSv was reported as zero.

2. Ranges, means, and standard deviations of the indicated data show the same qualitative trends observed for the composite of all results. Mean values are greater than reference dose equivalents for all irradiations and vary from 1.05 to 1.41 times references. Best accuracy and smallest differences among individual organizations were obtained for run 4 which had the highest reference gamma value and lowest neutron-to-gamma dose equivalent ratio, while poorest results were obtained for runs 1 and 2 which had the lowest reference dose equivalents and highest neutron components. Accuracy and spectrum effects observed for gamma TLD's this study are consistent with results obtained in previous ORNL intercomparisons.[4-6]

Among participants who used TLD systems for gamma measurements, 55% used TLD-700 material and the remaining 45% used $CaSO_4$ alone or in combination with another phosphor (usually $Li_2B_4O_7$). Tables 21 and 22 summarize results for participants who used TLD-700 and $CaSO_4$ materials, respectively. Neither phosphor indicated any difficulty providing measurable gamma response at dose equivalents above 0.12 mSv. At a reference value of 0.10 mSv, only about 1% of the $CaSO_4$ results and 7% of the TLD-700 measurements were reported as zero. Mean normalized dose equivalents for the TLD-700 phosphors were all greater than reference values and ranged from 1.14 to 1.47 times references. Average $CaSO_4$ results were more accurate than corresponding TLD-700 data and varied from 0.96 to 1.35 times reference values. With the exception of run 1, $CaSO_4$ results exhibited less variation among individual participants than did the TLD-700 data.

Table 23 presents an analysis of results obtained using film gamma dosimeters which were used for 16% of all reported results. The following observations are based on data presented in this table:

1. Participants who used film dosimeters had almost no problems obtaining measurable indication of gamma exposure at dose equivalents above 0.10 mSv. Only about 4% of all measured results was reported as zero or below minimum detectable.

2. Mean normalized dose equivalents were greater than reference values for all irradiations and varied from 1.16 to 2.20 times references. The most accurate average results were obtained for the spectrum with the lowest neutron-to-gamma ratio and the highest reference dose equivalent (run 4). Poorest results were obtained for spectra with the lowest reference dose equivalents and highest neutron components (runs 1 and 2). For every run, average film-measured results were higher than corresponding values obtained for TLD systems. Standard deviations associated with these results were about 30% of the mean values.

3. Ranges of results among different organizations for the same irradiation were similar to those observed for gamma TLD systems.

DOSIMETER PERFORMANCE RELATIVE TO REGULATORY CRITERIA

Guidelines specified by the United States Nuclear Regulatory Commission (NRC)[18] and the American National Standards Institute (ANSI)[19] suggest that personnel neutron and gamma dosimeters used in the dose equivalent range considered in this study should be accurate to within

±50% of reference values. Table 24 shows the percent of reported neutron and gamma dose equivalents which satisfy this criterion for each irradiation and the total of all exposures. Neutron results are presented for all dosimeters, albedo systems, and TLD's. Gamma data are shown for all dosimeters, TLD's, and film systems.

About 80% of all reported neutron results satisfied the NRC and ANSI standards. Percentages of results within ±50% of reference values varied between 76 and 87% for all dosimeter types with the highest percentage produced for the Lucite-shielded spectrum. About 78% of all albedo-measured results satisfied the subject standards while 77% of the direct interaction TLD data were within ±50% of references. For both dosimeter types, the Lucite-shielded irradiation provided the most accurate results with 93% and 83% of the albedo and TLD data, respectively, satisfying the criteria. These results are far superior to measurements made in previous ORNL intercomparisons[5,6] which indicated only about 50% of all neutron results within ±50% of reference values.

With regard to gamma measurements, about 67% of all reported results was within the accuracy limits for all spectra. Poorest results (about 55% of all measurements) were obtained for runs 1 and 2 which had the lowest reference dose equivalents and the highest neutron components. Best results were obtained for run 4 which had the highest reference values and lowest neutron components. About 89% of all gamma results were within ±50% of the references for this case. Approximately 74% of all TLD-measured results and 30% of all film results satisfied the standard for all irradiations. For both dosimeter types, poorest performance occurred for runs 1 through 3 (highest neutron components, lowest reference values) and best results were obtained for run 4 (lowest neutron component, highest reference dose equivalent). These results are consistent with those obtained in prior intercomparisons.[4-6]

Development of the National Voluntary Laboratory Accreditation Program (NVLAP) has provided standards for neutron personnel dosimetry based on ANSI criteria.[19] For mixed-field monitoring, NVLAP requirements specify that the sum of the accuracy (mean result minus reference) and precision (one standard deviation about the mean) must be equal to or less than 50%. Considering those organizations which submitted five dosimeters per run, 70% of all neutron measurements satisfied this criterion. Percent of results meeting this standard varied from 64 to 79% for all spectra with the Lucite-shielded run providing the best results.

CONCLUSIONS

The following conclusion are based on observations presented in the preceding text:

1. For neutron monitoring, TLD-based systems were the most popular in this study with 38% and 34% of the organizations reporting results using albedo and direct interaction TLD's, respectively. Recoil-track systems were used by 11% of the PDIS participants with film, fission-track, and combination albedo-track used by 7% or less of the participants.

2. Most (58%) participating agencies reported neutron dose equivalents in terms of the ICRP 21 convention. Twenty-two percent of the participants used the NCRP 30 convention while 13% reported dose equivalents in terms of element 57.

3. None of the measured neutron results was reported as zero or below minimum detectable which indicates that the monitoring systems used

in this study had no problems providing indication of neutron exposure at dose equivalent levels of about 5 mSv.

4. It is not unusual for neutron dose equivalents determined by different organizations under the same irradiation conditions to differ by a factor of two. For this study, variations as high as a factor of ten were obtained for the same run.

5. On the average, normalized results for all neutron measurements were within 20% of reference values with no obvious spectrum dependence. These results are much more accurate than those obtained in previous ORNL intercomparisons. All dosimeter types with 10 or more reported measurements provided average results within 35% of reference values for all spectra.

6. Neutron measurement precisions as reflected by one standard deviation about the mean of results were within 10% of the mean for 80% of the reporting organizations. These results indicate that for most participants, precision is not a problem relative to accuracy.

7. With regard to gamma dosimetry, most participants (84%) used TLD systems with the remainder using film. About 55% of the TLD's were TLD-700 phosphor with the remaining 45% being $CaSO_4$ alone or in combination with another phosphor.

8. Participants had no difficulty obtaining measurable indication of gamma exposure at dose equivalent levels as low as 0.10 mSv.

9. Average gamma results were greater than reference values by factors of 1.07 to 1.52 for all exposure conditions. Mean TLD-measured dose equivalents varied from 1.05 to 1.41 for the four irradiations

with $CaSO_4$ systems being slightly more accurate than TLD-700 dosimeters. Film gamma monitors overestimated reference values by average factors of 1.16 to 2.20 with mean film results being higher than corresponding TLD data for each run. The most accurate average results were obtained for the spectrum with the lowest neutron-to-gamma dose equivalent ratio and highest reference value, and the poorest accuracies were exhibited for spectra with high neutron components and lowest reference dose equivalents.

10. Maximum variations among gamma results reported by different organization for the same irradiation were greater than those obtained for corresponding neutron measurements.

11. About 80% of all neutron and 67% of all gamma results reported for all dosimeter types were within ±50% at reference values which is the accuracy standard suggested by the NRC and ANSI for personnel dosimeters. In addition, approximately 70% of all neutron data satisfied NVLAP standards for personnel neutron dosimetry which specify that measurement accuracy plus precision must be equal to or less than 50% relative to reference values. Best performance was exhibited for the Lucite-shielded spectrum while poorest performance was obtained for the unshielded and steel-shielded spectra.

12. In general, neutron measurement accuracies for all dosimeter types were significantly better than those observed in prior ORNL intercomparisons. Gamma results relative to reference values were consistent with previous data. The improved accuracy of neutron measurements can be partly attributed to the easily measured reference

dose equivalent levels and the fact that about 87% of the participants made some attempt to correct their results for differences between incident and calibration spectra.

RECOMMENDATIONS

The large number of participants in the past several ORNL Personnel Dosimetry Intercomparison Studies indicates that dosimetrists are concerned with testing and evaluating performance characteristics of their personnel neutron and gamma monitoring systems. While average accuracies for neutron measurements were significantly improved for this study compared to prior intercomparisons, the wide range of results observed among individual participants for the same irradiation conditions indicates that a significant number of participants must continue to develop and test their monitoring systems so that deficiencies can be identified and corrected. To facilitate these efforts, the DOSAR staff plans to continue annual ORNL intercomparisons and to increase the scope of the radiation fields and exposure conditions. Plans are now underway to construct a comprehensive dosimeter-instrument calibration facility at ORNL to greatly expand DOSAR irradiation capabilities. In addition, the DOSAR staff is initiating plans for another external dosimetry symposium similar to the one conducted in Knoxville in 1984.[20] This conference will be aimed at combining information on research advances and practical needs and experience and will provide a valuable forum for information exchange and discussion among international dosimetrists.

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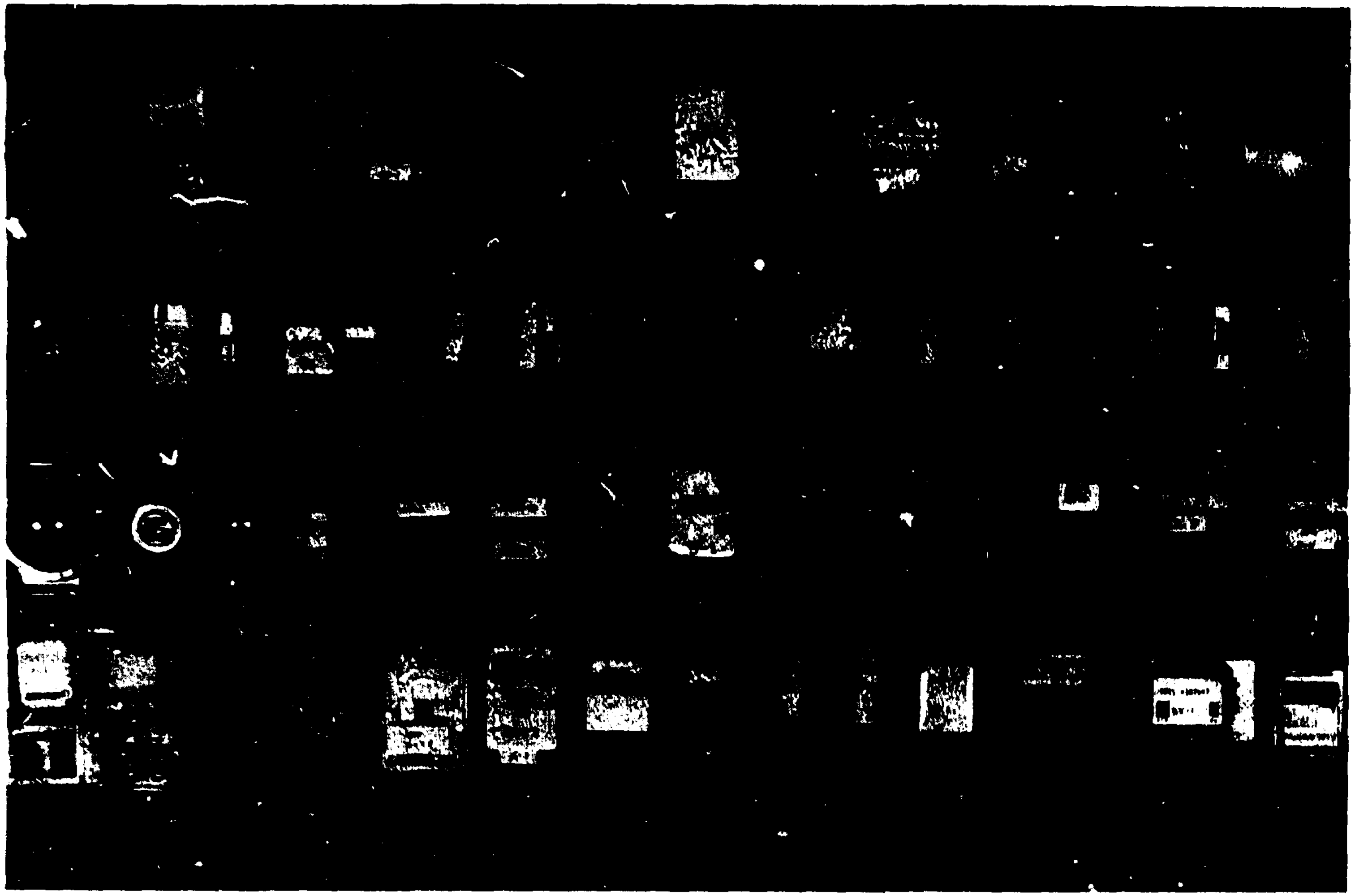

Figure 1. Collection of dosimeter badges for one exposure during the Eleventh PDIS

Table 1. Summary of experimental conditions for the Eleventh PDIS[a]

Exposure number	Date	Shield type	Reactor power, w[b]	Run duration, s	Number of fissions, x 10^{13} [c]	Albedo ratio[d]
1	5/22/85	None	1.0	350	1.04	0.90
2	5/23/85	12-cm steel	2.0	408	2.46	0.62
3	5/22/85	20-cm concrete	5.0	350	5.28	0.34
4	5/23/85	12-cm Lucite	5.0	558	8.66	0.50

[a]The horizontal centerlines of the reactor and the Lucite blocks on which the badges were mounted were 1.4 m above the floor level for all exposures. The HPRR was operated over Storage Pit 1 and was attached to a hydraulic positioning device.

[b]Based on reactor instrumentation.

[c]Based on sulfur pellet activation analysis.

[d]Ratio of BF^3 detector responses inside 23 cm and 7.6 cm diameter polyethylene spheres with centers located 3 m from the reactor.

Table 2. Reference neutron dose equivalents for the Eleventh PDIS.

Exposure number	Shield	Reference neutron dose equivalent, mSv		
		ICRP 21[a]	NCRP 38[b]	Element 57[c]
1	None	4.41	4.56	4.11
2	Steel	4.60	4.97	4.26
3	Concrete	4.12	4.28	3.82
4	Lucite	5.92	6.08	5.52

[a]Used for comparison to measured results in this report. Consists of ICRP 21 data with log-log interpolation between energy points.

[b]NCRP 38 data with linear interpolation.

[c]Element 57 data (capture gamma component excluded) with log-log interpolation.

Table 3. Reference gamma dose equivalents for the Eleventh PDIS

Exposure number	Shield	Reference gamma d.e., mSv[a]	Neutron-to-gamma d.e., ratio[b]
1	None	0.12	36.75
2	Steel	0.10	46.00
3	Concrete	0.26	15.85
4	Lucite	0.70	8.54

[a]Reference gamma dose equivalent based on measurements made with a Phillips Geiger-Mueller detector mounted on a phantom.

[b]Neutron-to-gamma dose equivalent ratio on a phantom at 3 m from reactor based on reference dosimetry

Table 4. Summary of reported neutron results - PDIS 11, run 1, unshielded exposure.

Group[a]	Neutron dosimeter type	Neutron dose equivalent, mSv[b] 1[c]	2	3	4	5	Average	Percent Standard Deviation[e]
Dosar Reference[d,e]		4.41	-	-	-	-	-	-
1	TLD	4.31	4.60	4.89	4.15	4.80	4.55	7
2	CR-39	5.52	5.18	5.29	5.08	-	5.27	4
3	Albedo	6.63	6.59	6.57	6.59	6.97	6.67	3
4	TLD	2.16	2.31	1.96	1.56	1.90	1.98	14
5	TLD	5.83	5.62	5.99	6.11	5.65	5.84	4
6	Albedo	3.97	4.45	4.13	3.86	4.46	4.17	7
7	Albedo	4.44	4.71	5.25	5.39	5.46	5.05	9
8	TLD	5.60	5.96	5.63	6.53	6.08	5.96	6
9	Albedo	3.50	3.80	4.00	3.85	3.65	3.76	5
10	TLD	4.92	4.80	5.15	4.75	4.45	4.81	5
11	Film	6.60	5.20	5.20	5.10	4.30	5.28	16
12	Film	2.60	3.10	3.10	-	-	2.93	10
12	TLD	3.90	4.10	-	-	-	4.00	4
13	TLD	6.56	6.36	6.60	6.53	6.84	6.58	3
14	CR-39	5.10	9.05	6.30	6.90	7.05	6.88	21
15	Albedo	4.98	4.69	4.85	5.18	5.08	4.96	4
16	Albedo	-	-	-	3.32	3.33	3.33	0
17	TLD	5.80	4.65	5.50	5.55	5.55	5.41	8
18	Albedo	0.00	4.70	5.60	3.70	6.10	4.02	60
19	TLD	0.06	0.07	0.07	0.06	0.07	0.07	5
20	Fission track	7.70	8.30	8.30	8.30	4.60	7.44	22
21	Albedo	9.18	8.79	7.49	9.01	8.64	8.62	8
23	Albedo	0.18	0.21	0.22	0.19	-	0.20	10
25	Albedo	7.25	8.38	8.72	8.84	8.78	8.39	8
26	TLD	1.41	1.26	1.24	1.25	1.42	1.32	7
27	Combination[f]	6.30	6.70	5.20	5.00	5.30	5.70	13
28	Other	-	-	2.92	-	-	2.92	-
28	Albedo	2.18	2.38	-	-	-	2.28	6
28	Fission track	-	-	-	2.53	2.25	2.39	8
30	TLD	5.39	5.81	5.88	5.39	5.80	5.65	4
31	CR-39	5.00	5.20	4.60	5.20	5.10	5.02	5
31	Film	4.30	4.80	4.80	4.50	4.80	4.64	5
32	CR-39	2.15	-	-	-	-	2.15	-
33	Albedo	3.76	4.13	-	-	-	3.95	7
33	CR-39	4.10	-	-	-	-	4.10	-
34	Albedo	6.30	6.71	6.01	6.81	7.29	6.62	7
34	Albedo	6.60	6.62	6.79	6.28	7.73	6.80	8
35	Albedo	4.97	4.23	5.06	4.37	4.96	4.72	8
36	Combination	3.80	4.30	4.50	3.50	4.00	4.02	10
37	Albedo	10.40	10.98	-	-	-	10.64	4
38	Albedo	6.10	5.85	6.36	5.15	6.13	5.93	8
39	Albedo	3.30	3.90	3.50	4.00	3.75	3.69	8

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values are reported by participants.
[c]Participants were permitted to submit five badges per exposure.
[d]Percent of the mean of one standard deviation of reported results.
[e]Reference values given in the ICRP 21 convention.
[f]TLD-albedo and CR-39 recoil tracks.
[g]Based on neutron-to-gamma dose equivalent ratio.

Table 5. Summary of reported neutron results – PDIS 11, run 2, 13-cm steel-shielded exposure.

Group[a]	Neutron dosimeter type	Neutron dose equivalent, mSv[b] 1[c]	2	3	4	5	Average	Percent Standard Deviation[e]
Dosar Reference[d,e]		4.60	–	–	–	–	–	–
1	TLD	4.74	5.02	4.76	4.03	4.18	4.55	9
2	CR-39	3.30	3.63	3.50	3.74	3.53	3.54	5
3	Albedo	6.04	6.02	5.78	6.21	6.26	6.06	3
4	TLD	2.28	2.26	2.22	2.46	2.21	2.29	4
5	TLD	6.68	6.65	6.34	6.70	6.62	6.60	2
6	Albedo	3.10	3.97	3.50	3.13	4.10	3.56	13
7	Albedo	5.94	4.85	5.15	5.32	5.30	5.31	7
8	TLD	5.02	4.72	5.09	5.50	5.46	5.16	6
9	Albedo	4.05	4.20	4.00	4.80	5.00	4.41	10
10	TLD	5.63	5.51	5.55	6.07	5.49	5.65	4
11	Film	4.20	4.50	4.20	4.90	5.10	4.53	9
12	Film	1.40	1.50	1.70	–	–	1.53	10
12	TLD	6.50	6.00	–	–	–	6.25	6
13	TLD	8.50	8.50	7.62	6.83	7.03	7.70	10
14	CR-395.10	4.60	4.65	4.65	4.75	4.75	14	
15	Albedo	6.27	6.20	6.34	6.86	5.50	6.23	8
16	Albedo	2.71	2.60	2.61	2.53	2.46	2.58	4
17	TLD	4.70	4.70	4.61	3.98	4.98	4.59	8
18	Albedo	6.60	7.00	6.80	0.00	6.10	5.30	56
19	TLD	0.08	0.08	0.08	0.09	0.08	0.03	3
20	Fission track	9.30	9.30	10.00	6.70	5.30	8.1[illegible]	25
21	Albedo	6.65	6.95	7.22	7.15	7.19	7.03	3
23	Albedo	0.26	0.26	0.24	0.23	–	0.25	7
25	Albedo	7.27	6.09	7.53	6.27	7.55	6.94	10
26	TLD	1.63	1.79	1.76	1.67	1.85	1.74	5
27	Combination[f]	4.30	3.20	3.70	2.60	2.60	3.28	22
28	Other	–	–	3.05	–	–	3.05	–
28	Albedo	1.86	1.92	–	–	–	1.89	2
28	Fission track	–	–	–	2.30	1.60	1.95	25
30	TLD	5.67	5.33	6.10	5.86	5.71	5.73	5
31	CR-39	4.30	4.50	4.60	4.30	4.70	4.48	4
31	Film	5.00	5.10	5.30	4.70	4.80	4.98	5
32	CR-39	1.45	–	–	–	–	1.45	–
33	Albedo	4.84	5.14	–	–	–	4.99	4
33	CR-39	4.10	–	–	–	–	4.10	–
34	Albedo	6.15	6.77	6.49	6.96	6.58	6.59	5
34	Albedo	6.65	6.15	6.91	6.34	7.00	6.61	5
35	Albedo	4.28	5.17	3.90	4.52	4.16	4.41	11
36	Combination	2.70	3.40	2.40	3.10	3.00	2.92	13
37	Albedo	9.43	10.85	–	–	–	10.14	10
38	Albedo	6.85	8.30	8.42	6.40	7.38	7.47	12
39	Albedo	3.90	2.80	3.20	3.45	3.50	3.37	12

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values are reported by participants.
[c]Participants were permitted to submit five badges per exposure.
[d]Percent of the mean of one standard deviation of reported results.
[e]Reference values given in the ICRP 21 convention.
[f]TLD-albedo and CR-39 recoil tracks.
[g]Based on neutron-to-gamma dose equivalent ratio.

Table 6. Summary of reported neutron results - PDIS 11, run 3, 20-cm concrete-shielded exposure.

Group[a]	Neutron dosimeter type	Neutron dose equivalent, mSv[b] 1[c]	2	3	4	5	Average	Percent Standard Deviation[e]
Dosar Reference[d,e]		4.12	-	-	-	-	-	-
1	TLD	4.74	4.57	4.89	4.93	4.63	4.75	3
2	CR-39	3.28	3.21	3.12	2.98	3.01	3.12	4
3	Albedo	5.32	5.18	5.67	5.59	5.43	5.44	4
4	TLD	6.80	6.98	7.11	6.36	6.41	6.73	5
5	TLD	5.00	4.87	5.11	4.99	5.23	5.04	3
6	Albedo	3.25	3.67	3.44	3.89	3.78	3.61	7
7	Albedo	4.48	4.80	4.96	4.97	5.57	4.96	8
8	TLD	5.85	5.67	5.37	5.51	6.18	5.72	6
9	Albedo	3.95	3.80	3.80	4.20	5.30	4.21	15
10	TLD	4.71	4.75	4.96	4.72	4.78	4.78	2
11	Film	5.20	4.30	5.20	5.50	5.00	5.04	9
12	Film	2.20	2.20	2.20	-	-	2.20	-
12	TLD	7.20	6.90	-	-	-	7.05	3
13	TLD	5.56	5.22	5.23	5.27	5.64	5.38	4
14	CR-39	4.30	5.50	2.90	-	6.10	4.70	30
15	Albedo	6.30	7.39	6.48	7.88	8.21	7.25	12
16	Albedo	2.19	2.37	2.47	2.44	2.31	2.36	5
17	TLD	5.75	6.31	6.11	6.89	5.82	6.18	7
18	Albedo	6.90	8.40	4.90	8.40	5.80	6.88	23
19	TLD	0.21	0.21	0.22	0.26	0.28	0.24	14
20	Fission track	7.40	11.00	2.70	4.00	4.00	5.82	58
21	Albedo	5.22	5.17	5.15	5.44	5.17	5.23	2
23	Albedo	0.51	0.48	0.46	0.50	-	0.49	5
25	Albedo	5.31	6.21	6.43	5.90	6.31	6.03	7
26	TLD	4.72	4.63	4.41	4.77	5.01	4.71	5
27	Combination[f]	5.30	4.50	4.80	5.20	4.50	4.86	8
28	Other[g]	-	-	3.50	-	-	3.50	-
28	Albedo	1.63	1.58	-	-	-	1.61	2
28	Fission track	-	-	-	1.59	2.17	1.88	22
30	TLD	6.33	5.62	6.06	6.08	6.36	6.09	5
31	CR-39	4.20	4.20	3.90	3.70	4.10	4.02	5
31	Film	3.90	3.60	3.70	3.90	3.60	3.74	4
32	CR-39	1.47	-	-	-	-	1.47	-
33	Albedo	4.76	4.88	-	-	-	4.82	2
33	CR-39	4.20	-	-	-	-	4.20	-
34	Albedo	6.86	7.01	6.97	6.48	6.96	6.86	3
34	Albedo	6.11	6.18	5.63	5.94	5.98	5.97	4
35	Albedo	3.81	3.95	4.19	4.15	3.13	3.85	11
36	Combination	3.20	1.70	2.60	2.60	2.40	2.50	22
37	Albedo	9.26	10.54	-	-	-	9.90	9
38	Albedo	-	5.36	5.74	-	6.71	6.94	10
39	Albedo	2.45	3.00	3.20	3.15	3.10	2.98	10

[a]Participants designated by numbers to preserve anonymity.
[b]Background corrected values are reported by participants.
[c]Participants were permitted to submit five badges per exposure.
[d]Percent of the mean of one standard deviation of reported results.
[e]Reference values given in the ICRP 21 convention.
[f]TLD-albedo and CR-39 recoil tracks.
[g]Based on neutron-to-gamma dose equivalent ratio.

Table 7. Summary of reported neutron results - PDIS 11, run 4, 12-cm Lucite-shielded exposure.

Group[a]	Neutron dosimeter type	Neutron dose equivalent, mSv[b] 1[c]	2	3	4	5	Average	Percent standard deviation[d]
DOSAR	Reference[e]	5.98	-	-	-	-	-	-
1	TLD	5.27	5.23	5.54	5.10	5.67	5.36	4
2	CR-39	4.19	4.70	4.33	4.66	4.63	4.50	5
3	Albedo	7.94	7.95	7.99	8.33	8.58	8.16	4
4	TLD	12.63	13.50	13.10	14.35	12.91	13.30	5
5	TLD	5.84	6.14	6.00	6.16	5.56	5.94	4
6	Albedo	9.11	6.91	7.95	8.33	6.68	7.80	13
7	Albedo	4.44	5.45	5.51	5.11	4.73	5.05	9
8	TLD	6.81	7.04	7.01	7.71	7.22	7.16	5
9	Albedo	5.00	5.75	4.55	3.90	4.50	4.74	14
10	TLD	5.17	5.07	5.68	5.16	6.17	5.45	9
11	Film	11.50	12.30	10.90	14.10	10.20	11.80	13
12	Film	4.50	5.40	5.10	-	-	5.00	9
12	TLD	8.40	22.80	-	-	-	15.60	65
13	TLD	5.29	4.81	5.04	5.52	5.31	5.19	5
14	CR-39	5.05	4.70	5.05	5.00	5.05	4.97	3
15	Albedo	5.46	4.94	5.74	4.97	6.15	5.45	9
16	Albedo	4.30	4.16	4.27	4.53	5.10	4.47	8
17	TLD	26.03	25.58	23.62	24.69	24.77	24.94	4
18	Albedo	10.20	10.90	7.60	8.70	7.80	9.04	16
19	TLD	0.40	0.38	0.38	0.40	0.39	0.39	3
20	Fission track	10.30	10.30	7.60	4.90	5.40	7.70	34
21	Albedo	5.22	5.63	5.24	5.35	5.32	5.35	3
23	Albedo	0.78	0.76	0.80	0.74	-	0.77	3
25	Albedo	5.65	5.91	6.10	5.88	5.67	5.84	3
26	TLD	9.15	8.28	8.39	8.91	9.39	8.82	5
27	Combination[f]	5.80	6.30	6.80	6.50	6.00	6.28	6
28	Other[g]	-	-	4.48	-	-	4.48	-
28	Albedo	2.89	2.91	-	-	-	2.90	0
28	Fission track	-	-	-	2.49	2.89	2.69	11
30	TLD	5.63	6.30	5.45	5.91	5.29	5.72	7
31	CR-39	5.20	5.40	5.00	5.30	5.10	5.20	3
31	Film	6.30	5.70	5.70	5.90	5.80	5.88	4
32	CR-39	2.03	-	-	-	-	2.03	-
33	Albedo	5.28	5.89	-	-	-	5.59	8
33	CR-39	6.50	-	-	-	-	6.50	-
34	Albedo	7.71	7.23	7.73	7.85	7.89	7.68	3
34	Albedo	5.58	5.89	6.49	6.30	5.46	5.94	7
35	Albedo	5.04	4.41	5.34	4.34	4.47	4.72	9
36	Combination	2.80	2.90	2.40	4.30	3.70	3.22	24
37	Albedo	8.51	8.44	-	-	-	8.48	1
38	Albedo	-	6.38	6.75	6.73	6.81	6.67	3
39	Albedo	5.00	3.95	4.10	4.95	5.25	4.65	13

a. Participants designated by numbers to preserve anonymity.
b. Background corrected values as reported by participants.
c. Participants were permitted to submit five badges per exposure.
d. Percent of the mean of one standard deviation of reported results.
e. Reference values given in the ICRP 21 convention.
f. TLD-albedo and CR-39 recoil track.
g. Based on neutron-to-gamma dose equivalent ratio.

Table 8. Analysis of reported neutron results for all dosimeter types.

Run number	Shield	N[a]	Normalized dose equivalent[b]		Standard deviation[c]	
			Range	Mean ± σ[d]	Range	Mean
1	None	166	0.28–2.49	1.18 ± 0.35	0–60	9.7
2	Steel	170	0.30–2.36	1.08 ± 0.38	2–56	9.2
3	Concrete	166	0.36–2.56	1.18 ± 0.33	2–58	11.1
4	Lucite	158	0.34–2.40	1.02 ± 0.34	0–65	10.7

[a]Number of reported results.

[b]Measured divided by reference values (ICRP convention).

[c]Percent of the mean of one standard deviation about the mean of results reported for each organization.

[d]Mean of normalized results ± one standard deviation about the mean.

Table 9. Analysis of neutron results for TLD-Albedo dosimeters.

Run number	Shield	N[a]	Normalized dose equivalent[b]		Standard deviation[c]	
			Range	Mean $\pm$ σ^d	Range	Mean
1	None	72	0.49-2.49	1.28 $\pm$ 0.34	0-60	7.1
2	Steel	75	0.40-2.36	1.20 $\pm$ 0.33	2-13	7.4
3	Concrete	74	0.38-2.56	1.24 $\pm$ 0.35	2-23	7.9
4	Lucite	75	0.48-1.82	1.01 $\pm$ 0.27	0-16	7.4

[a]Number of reported results.

[b]Measured divided by reference values (ICRP convention).

[c]Percent of the mean of one standard deviation about the mean of results reported for each organization.

[d]Mean of normalized results $\pm$ one standard deviation about the mean.

Table 10. Analysis of neutron results for direct interaction TL dosimeters.

Run number	Shield	N[a]	Normalized dose equivalent[b]		Standard deviation[c]	
			Range	Mean $\pm$ σ[d]	Range	Mean
1	None	47	0.28–1.55	1.05 $\pm$ 0.37	3–14	6.2
2	Steel	47	0.35–1.85	1.08 $\pm$ 0.37	2–10	6.1
3	Concrete	47	1.07–1.75	1.35 $\pm$ 0.14	2–7	4.2
4	Lucite	40	0.80–2.40	1.19 $\pm$ 0.37	4–9	5.6

[a]Number of reported results.

[b]Measured divided by reference values (ICRP convention).

[c]Percent of the mean of one standard deviation about the mean of results reported for each organization.

[d]Mean of normalized results $\pm$ one standard deviation about the mean.

Table 11. Analysis of neutron results for recoil track dosimeters.

Run number	Shield	N[a]	Normalized dose equivalent[b]		Standard deviation[c]	
			Range	Mean ± σ[d]	Range	Mean
1	None	16	0.49–2.05	1.23 ± 0.27	4–21	9.8
2	Steel	17	0.32–1.11	0.89 ± 0.21	4–5	4.3
3	Concrete	16	0.36–1.48	0.91 ± 0.29	4–30	13.2
4	Lucite	17	0.34–1.09	0.81 ± 0.18	3–5	3.7

[a]Number of reported results.

[b]Measured divided by reference values (ICRP convention).

[c]Percent of the mean of one standard deviation about the mean of results reported for each organization.

[d]Mean of normalized results ± one standard deviation about the mean.

Table 12. Analysis of neutron results for film dosimeters.

Run number	Shield	N[a]	Normalized dose equivalent[b] Range	Normalized dose equivalent[b] Mean $\pm\ \sigma$[d]	Standard deviation[c] Range	Standard deviation[c] Mean
1	None	13	0.59–1.50	1.02 ± 0.24	5–16	10.2
2	Steel	13	0.30–1.15	0.88 ± 0.36	5–10	7.9
3	Concrete	13	0.53–1.33	0.94 ± 0.30	4–9	4.3
4	Lucite	8	0.75–1.05	0.93 ± 0.10	4–9	6.7

[a]Number of reported results.

[b]Measured divided by reference values (ICRP convention).

[c]Percent of the mean of one standard deviation about the mean of results reported for each organization.

[d]Mean of normalized results ± one standard deviation about the mean.

Table 13. Analysis of neutron results for fission track dosimeters.

Run number	Shield	N[a]	Normalized dose equivalent[b]		Standard deviation[c]	
			Range	Mean $\pm$ σ[d]	Range	Mean
1	None	7	0.51–1.88	1.36 $\pm$ 0.47	8–22	15.0
2	Steel	7	0.35–2.17	1.38 $\pm$ 0.54	25	25.0
3	Concrete	5	0.39–1.80	0.93 $\pm$ 0.59	22–38	30.0
4	Lucite	7	0.42–1.72	1.05 $\pm$ 0.52	11–34	22.0

[a]Number of reported results.

[b]Measured divided by reference values (ICRP convention).

[c]Percent of the mean of one standard deviation about the mean of results reported for each organization.

[d]Mean of normalized results $\pm$ one standard deviation about the mean.

Table 14. Analysis of neutron results for combination albedo-track dosimeters.

Run number	Shield	N[a]	Normalized dose equivalent[b]		Standard deviation[c]	
			Range	Mean ± σ[d]	Range	Mean
1	None	10	0.79–1.52	1.10 ± 0.22	10–13	11.5
2	Steel	10	0.52–0.93	0.67 ± 0.19	13–22	17.7
3	Concrete	10	0.41–1.29	0.89 ± 0.36	8–22	14.7
4	Lucite	10	0.40–1.14	0.79 ± 0.36	6–24	15.1

[a]Number of reported results.

[b]Measured divided by reference values (ICRP convention).

[c]Percent of the mean of one standard deviation about the mean of results reported for each organization.

[d]Mean of normalized results ± one standard deviation about the mean.

Table 15. Summary of reported gamma results – PDIS 11, run 1, unshielded exposure.

Group[a]	Gamma dosimeter types	Gamma dose equivalent, mSv[b]					
		1[c]	2	3	4	5	Average
DOSAR	Reference	0.12	-	-	-	-	-
1	TLD-$CaSO_4$[d]	0.19	0.17	0.11	0.22	0.15	0.17
2	TLD-$CaSO_4$	0.17	0.13	0.16	0.13	-	0.15
3	TLD-700	0.18	0.23	0.14	0.28	0.15	0.20
4	TLD-$CaSO_4$	0.16	0.15	0.16	0.14	0.16	0.15
5	TLD-$CaSO_4$	0.14	0.12	0.12	0.11	0.11	0.12
6	TLD-700	0.22	0.26	0.25	0.30	0.27	0.26
7	TLD-700	0.10	0.11	0.13	0.12	0.12	0.12
8	TLD-$CaSO_4$	0.16	0.17	0.19	0.19	0.18	0.18
9	TLD-$CaSO_4$	0.10	0.10	0.10	0.05	0.05	0.08
10	TLD-$CaSO_4$	0.14	0.13	0.14	0.13	0.12	0.13
11	Film	0.30	0.25	0.20	0.25	0.30	0.26
12	Film	0.00	0.00	0.20	-	-	0.07
12	TLD-700	0.10	0.10	-	-	-	0.10
13	TLD-700	0.16	0.15	0.11	0.16	0.15	0.15
15	TLD-700	0.17	0.13	0.19	0.17	0.20	0.17
16	TLD-700	-	-	-	0.04	0.06	0.05
17	TLD-$CaSO_4$	0.19	0.19	0.19	0.15	0.22	0.19
18	TLD-700	0.20	0.20	0.20	0.20	0.20	0.20
19	TLD-700	0.18	0.20	0.20	0.23	0.20	0.20
21	TLD-700	0.14	0.12	0.15	0.14	0.15	0.14
22	TLD-700	0.18	0.15	0.15	0.17	0.14	0.16
23	TLD-$CaSO_4$	0.19	0.15	0.11	0.16	-	0.15
24	Film	0.25	0.35	0.20	0.10	0.20	0.22
25	TLD-700	0.18	0.16	0.16	0.11	0.18	0.16
26	TLD-$CaSO_4$	0.37	0.53	0.34	0.46	0.32	0.40
27	Film	0.30	0.30	0.30	0.20	0.20	0.26
28	TLD-700	-	-	0.22	-	-	0.22
29	TLD-$CaSO_4$	0.08	0.10	0.12	0.13	0.12	0.11
30	TLD-$CaSO_4$	0.14	0.13	0.16	0.15	0.13	0.14
31	Film	0.30	0.30	0.30	0.30	0.30	0.30
33	TLD-700	0.13	0.15	-	-	-	0.14
34	TLD-$CaSO_4$	0.09	0.15	0.14	0.13	0.09	0.12
34	TLD-$CaSO_4$	0.16	0.16	0.18	0.18	0.17	0.17
35	TLD-700	0.11	0.14	0.04	0.02	0.07	0.08
36	Film	0.20	0.80	0.40	0.10	0.10	0.32
37	TLD-700	-	-	0.30	0.35	-	0.33
38	TLD-700	0.35	0.36	0.28	0.34	0.23	0.31

[a]Participants designated by numbers to preserve anonymity.

[b]Background-corrected values as reported by participants.

[c]Participants were permitted to submit five badges per exposure.

[d]Includes $CaSO_4$ in combination with another phosphor.

Table 16. Summary of reported gamma results - PDIS 11, run 2, steel-shielded exposure.

Group[a]	Gamma dosimeter types	Gamma dose equivalent, mSv[b]					
		1[c]	2	3	4	5	Average
DOSAR	Reference	0.10	-	-	-	-	-
1	TLD-$CaSO_4$[d]	0.16	0.18	0.17	0.21	0.14	0.17
2	TLD-$CaSO_4$	0.09	0.14	0.08	0.12	0.08	0.10
3	TLD-700	0.15	0.13	0.12	0.14	0.14	0.14
4	TLD-$CaSO_4$	0.20	0.24	0.15	0.25	0.29	0.23
5	TLD-$CaSO_4$	0.09	0.08	0.10	0.09	0.10	0.09
6	TLD-700	0.21	0.24	0.23	0.23	0.23	0.23
7	TLD-700	0.09	0.07	0.08	0.10	0.08	0.08
8	TLD-$CaSO_4$	0.10	0.10	0.10	0.11	0.12	0.11
9	TLD-$CaSO_4$	0.05	0.05	0.10	0.05	0.00	0.05
10	TLD-$CaSO_4$	0.13	0.13	0.12	0.12	0.13	0.13
11	Film	0.30	0.30	0.30	0.35	0.40	0.33
12	Film	0.20	0.20	0.20	-	-	0.20
12	TLD-700	0.00	0.00	-	-	-	0.00
13	TLD-700	0.12	0.09	0.02	0.09	0.20	0.10
15	TLD-700	0.16	0.17	0.15	0.14	0.20	0.16
16	TLD-700	0.03	0.05	0.00	0.02	0.00	0.02
17	TLD-$CaSO_4$	0.08	0.11	0.11	0.14	0.09	0.11
18	TLD-700	0.20	0.20	0.20	0.20	0.20	0.20
19	TLD-700	0.18	0.16	0.15	0.16	0.15	0.16
21	TLD-700	0.12	0.15	0.16	0.15	0.16	0.15
22	TLD-700	0.18	0.17	0.11	0.14	0.13	0.15
23	TLD-$CaSO_4$	0.17	0.16	0.19	0.12	-	0.16
24	Film	0.10	0.20	0.25	0.10	0.25	0.18
25	TLD-700	0.19	0.14	0.07	0.06	0.17	0.13
26	TLD-$CaSO_4$	0.32	0.42	0.31	0.31	0.34	0.34
27	Film	0.30	0.30	0.30	0.30	0.10	0.26
28	TLD-700	-	-	0.20	-	-	0.20
29	TLD-$CaSO_4$	0.05	0.08	0.07	0.09	0.13	0.08
30	TLD-$CaSO_4$	0.16	0.14	0.15	0.13	0.13	0.14
31	Film	0.20	0.20	0.20	0.20	0.20	0.20
33	TLD-700	0.10	0.11	-	-	-	0.11
34	TLD-$CaSO_4$	0.09	0.09	0.09	0.07	0.06	0.08
34	TLD-$CaSO_4$	0.15	0.17	0.14	0.14	0.15	0.15
35	TLD-700	0.00	0.06	0.05	0.15	0.03	0.06
36	Film	0.30	0.10	0.10	0.10	0.10	0.14
37	TLD-700	-	-	0.41	0.52	-	0.47
38	TLD-700	0.18	0.16	0.10	0.10	0.10	0.13

[a]Participants designated by numbers to preserve anonymity.

[b]Background-corrected values as reported by participants.

[c]Participants were permitted to submit five badges per exposure.

[d]Includes $CaSO_4$ in combination with another phosphor.

Table 17. Summary of reported gamma results - PDIS 11, run 3, concrete-shielded exposure.

Group[a]	Gamma dosimeter types	Gamma dose equivalent, mSv[b]					
		1[c]	2	3	4	5	Average
DOSAR	Reference	0.26	-	-	-	-	-
1	TLD-$CaSO_4$[d]	0.39	0.41	0.33	0.28	0.25	0.33
2	TLD-$CaSO_4$	0.25	0.28	0.25	0.24	0.25	0.25
3	TLD-700	0.35	0.40	0.28	0.37	0.36	0.35
4	TLD-$CaSO_4$	0.44	0.44	0.46	0.38	0.48	0.44
5	TLD-$CaSO_4$	0.21	0.21	0.21	0.19	0.20	0.20
6	TLD-700	0.58	0.59	0.61	0.55	0.59	0.58
7	TLD-700	0.28	0.28	0.31	0.30	0.33	0.30
8	TLD-$CaSO_4$	0.26	0.28	0.28	0.30	0.31	0.29
9	TLD-$CaSO_4$	0.15	0.20	0.20	0.15	0.20	0.18
10	TLD-$CaSO_4$	0.27	0.30	0.28	0.30	0.28	0.29
10	Film	0.50	0.45	0.55	0.50	0.55	0.51
12	Film	0.40	0.50	0.50	-	-	0.47
12	TLD-700	0.60	0.60	-	-	-	0.60
13	TLD-700	0.32	0.21	0.25	0.27	0.22	0.25
15	TLD-700	0.30	0.27	0.26	0.26	0.28	0.27
16	TLD-700	0.25	0.18	0.18	0.15	0.20	0.19
17	TLD-$CaSO_4$	0.33	0.29	0.28	0.23	0.20	0.27
18	TLD-700	0.40	0.30	0.35	0.40	0.40	0.37
19	TLD-700	0.98	0.36	0.40	0.35	0.41	0.50
21	TLD-700	0.29	0.31	0.31	0.33	0.31	0.31
22	TLD-700	0.33	0.30	0.33	0.31	0.30	0.31
23	TLD-$CaSO_4$	0.40	0.45	0.37	0.39	-	0.40
24	Film	0.55	0.45	0.50	0.50	0.55	0.51
25	TLD-700	0.30	0.36	0.42	0.38	0.32	0.36
26	TLD-$CaSO_4$	0.53	0.43	0.43	0.44	0.54	0.47
27	Film	0.50	0.60	0.50	0.50	0.50	0.52
28	TLD-700	-	-	0.19	-	-	0.19
29	TLD-$CaSO_4$	0.22	0.25	0.18	0.20	0.16	0.20
30	TLD-$CaSO_4$	0.28	0.26	0.24	0.25	0.26	0.26
31	Film	0.30	0.40	0.40	0.40	0.40	0.38
33	TLD-700	0.27	0.35	-	-	-	0.31
34	TLD-$CaSO_4$	0.79	0.22	0.23	0.21	0.24	0.34
34	TLD-$CaSO_4$	0.33	0.30	0.24	0.27	0.25	0.28
35	TLD-700	0.18	0.35	0.12	0.09	0.23	0.19
36	Film	0.90	0.80	0.30	0.30	0.00	0.46
37	TLD-700	-	-	0.67	0.61	-	0.64
38	TLD-700	0.28	0.25	0.28	-	0.45	0.32

[a]Participants designated by numbers to preserve anonymity.
[b]Background-corrected values as reported by participants.
[c]Participants were permitted to submit five badges per exposure.
[d]Includes $CaSO_4$ in combination with another phosphor.

Table 18. Summary of reported gamma results – PDIS 11, run 4, Lucite-shielded exposure.

Group[a]	Gamma dosimeter types	Gamma dose equivalent, mSv[b]					
		1[c]	2	3	4	5	Average
DOSAR	Reference	0.70	–	–	–	–	–
1	TLD-$CaSO_4$[d]	0.65	0.77	0.63	0.57	0.59	0.64
2	TLD-$CaSO_4$	0.66	0.62	0.72	0.65	0.85	0.70
3	TLD-700	0.93	1.03	0.94	0.96	0.96	0.96
4	TLD-$CaSO_4$	0.68	0.78	0.85	0.68	0.75	0.75
5	TLD-$CaSO_4$	0.53	0.53	0.54	0.51	0.49	0.52
6	TLD-700	0.45	1.18	1.29	1.34	1.22	1.30
7	TLD-700	0.66	0.66	0.64	0.66	0.66	0.66
8	TLD-$CaSO_4$	0.80	0.88	0.81	0.83	0.78	0.82
9	TLD-$CaSO_4$	0.55	0.60	0.50	0.50	0.50	0.53
10	TLD-$CaSO_4$	0.82	0.72	0.76	0.70	0.76	0.75
11	Film	0.90	1.00	0.95	0.80	1.00	0.93
12	Film	0.90	0.90	0.90	–	–	0.90
12	TLD-700	0.20	0.10	–	–	–	0.15
13	TLD-700	0.69	0.53	0.56	0.68	0.73	0.64
15	TLD-700	0.76	0.85	0.75	0.82	0.70	0.78
16	TLD-700	0.64	0.66	0.62	0.56	0.57	0.61
17	TLD-$CaSO_4$	0.62	0.68	0.72	0.63	0.72	0.67
18	TLD-700	1.00	1.50	1.40	1.00	1.00	1.18
19	TLD-700	0.76	0.69	0.84	1.05	0.69	0.81
21	TLD-700	0.82	0.74	0.71	0.70	0.72	0.74
22	TLD-700	0.69	0.88	0.77	0.81	0.71	0.77
23	TLD-$CaSO_4$	0.72	0.76	0.78	0.79	–	0.76
24	Film	0.85	1.00	1.05	1.00	0.90	0.96
25	TLD-700	0.79	0.83	0.81	0.77	0.82	0.80
26	TLD-$CaSO_4$	0.87	0.85	0.77	0.93	0.97	0.88
27	Film	1.30	1.10	1.00	1.00	1.10	1.10
28	TLD-700	–	–	0.50	–	–	0.50
29	TLD-$CaSO_4$	0.52	0.47	0.56	0.51	0.49	0.51
30	TLD-$CaSO_4$	0.61	0.65	0.67	0.65	0.68	0.65
31	Film	0.70	0.80	0.80	0.70	0.80	0.76
33	TLD-700	0.64	0.65	–	–	–	0.65
34	TLD-$CaSO_4$	0.59	0.60	0.52	0.55	0.57	0.57
34	TLD-$CaSO_4$	0.65	0.72	0.66	0.66	0.69	0.68
35	TLD-700	0.75	0.78	0.71	0.64	0.58	0.69
36	Film	0.20	0.00	0.70	0.20	0.20	0.26
37	TLD-700	–	–	1.54	1.50	–	1.52
38	TLD-700	0.56	0.48	0.58	0.44	0.47	0.51

[a]Participants designated by numbers to preserve anonymity.
[b]Background-corrected values as reported by participants.
[c]Participants were permitted to submit five badges per exposure.
[d]Includes $CaSO_4$ in combination with another phosphor.

Table 19. Analysis of reported gamma results for all dosimeter types.

Run number	Shield	Reference d.e., mSv[a]	N[b]	N > 0[c]	Normalized dose equivalents[d]	
					Range	Mean ± σ[e]
1	None	0.12	165	163	0.00–6.67	1.52 ± 0.53
2	Steel	0.10	169	163	0.00–5.20	1.51 ± 0.58
3	Concrete	0.26	168	167	0.00–3.77	1.34 ± 0.42
4	Lucite	0.70	169	168	0.00–2.20	1.07 ± 0.32

[a]Reference gamma dose equivalent from Table 3.

[b]Number of reported results.

[c]Number of reported results greater than 0 or the minimum detectable value.

[d]Measured divided by reference values.

[e]Mean of normalized results ± one standard deviation about the mean.

Table 20. Analysis of reported gamma results for all TL dosimeters.

Run number	Shield	Reference d.e., mSv[a]	N[b]	N > 0[c]	Normalized dose equivalents[d] Range	Mean ± σ[e]
1	None	0.12	137	137	0.17–4.42	1.41 ± 0.45
2	Steel	0.10	141	135	0.00–5.20	1.37 ± 0.59
3	Concrete	0.26	140	140	0.35–3.77	1.24 ± 0.41
4	Lucite	0.70	141	141	0.14–2.20	1.05 ± 0.31

[a]Reference gamma dose equivalent from Table 3.

[b]Number of reported results.

[c]Number of reported results greater than 0 or the minimum detectable value.

[d]Measured divided by reference values.

[e]Mean of normalized results ± one standard deviation about the mean.

Table 21. Analysis of reported gamma results for TLD-700 dosimeters.

Run number	Shield	Reference d.e., mSv[a]	N[b]	N > 0[c]	Normalized dose equivalents[d]	
					Range	Mean ± σ[e]
1	None	0.12	69	69	0.17-3.00	1.47 ± 0.42
2	Steel	0.10	72	67	0.00-5.20	1.37 ± 0.62
3	Concrete	0.26	71	71	0.35-3.77	1.33 ± 0.42
4	Lucite	0.70	72	72	0.14-2.20	1.14 ± 0.35

[a]Reference gamma dose equivalent from Table 3.

[b]Number of reported results.

[c]Number of reported results greater than 0 or the minimum detectable value.

[d]Measured divided by referenc. values.

[e]Mean of normalized results ± one standard deviation about the mean.

Table 22. Analysis of reported gamma results for $CaSO_4$ dosimeters.

Run number	Shield	Reference d.e., mSv[a]	N[b]	N > 0[c]	Normalized dose equivalents[d] Range	Mean ± σ[e]
1	None	0.12	68	68	0.42-4.42	1.35 ± 0.49
2	Steel	0.10	69	68	0.00-4.20	1.38 ± 0.55
3	Concrete	0.26	69	69	0.58-3.04	1.15 ± 0.37
4	Lucite	0.70	69	69	0.67-1.34	0.96 ± 0.18

[a]Reference gamma dose equivalent from Table 3.

[b]Number of reported results.

[c]Number of reported results greater than 0 or the minimum detectable value.

[d]Measured divided by reference values.

[e]Mean of normalized results ± one standard deviation about the mean.

Table 23. Analysis of reported gamma results for film dosimeters.

Run number	Shield	Reference d.e., mSv[a]	N[b]	N > 0[c]	Normalized dose equivalents[d]	
					Range	Mean ± σ[e]
1	None	0.12	28	26	0.00-6.67	2.08 ± 0.58
2	Steel	0.10	28	28	1.00-4.00	2.20 ± 0.40
3	Concrete	0.26	28	27	0.00-3.46	1.83 ± 0.33
4	Lucite	0.70	28	27	0.00-1.86	1.16 ± 0.38

[a]Reference gamma dose equivalent from Table 3.

[b]Number of reported results.

[c]Number of reported results greater than 0 or the minimum detectable value.

[d]Measured divided by reference values.

[e]Mean of normalized results ± one standard deviation about the mean.

Table 24. Percent of reported neutron and gamma results within ±50% of reference values.

Run number	Shield	Percent of results within ±50% of reference values[a]					
		Neutron dosimeters			Gamma dosimeters		
		All[b]	Albedo	TLD	All[b]	TLD	Film
1	None	76	71	79	57	66	11
2	Steel	77	76	72	54	60	25
3	Concrete	78	72	77	65	76	11
4	Lucite	87	93	83	89	92	75
Total		80	78	77	67	74	30

[a]Percent of results reported for each dosimeter type and irradiation.

[b]Composite results for all dosimeter types

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