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● *Paper*

NEUTRON PERSONNEL DOSIMETRY INTERCOMPARISON STUDIES AT THE OAK RIDGE NATIONAL LABORATORY: A SUMMARY (1981–1986)*

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Abstract—To provide an opportunity for dosimetrists to test and calibrate their neutron personnel monitoring systems, the staff of the Dosimetry Applications Research (DOSAR) Facility at the Oak Ridge National Laboratory (ORNL) has conducted personnel dosimetry intercomparison studies (PDIS) periodically since 1974. During these studies, personnel dosimeters are mailed to ORNL, exposed to low-level (less than 15 mSv) neutron dose equivalents in a variety of mixed-radiation fields, and then returned to the participants for evaluation. These intercomparisons have provided more data on neutron dosimeter performance than any other periodic test program conducted to date. This report presents a summary and analysis of about 3450 neutron dose equivalent measurements reported for PDIS 7 through 12 (1981–1986) with emphasis on low dose equivalent sensitivity, accuracy and precision, and performance relative to accreditation standards for the basic types of personnel dosimetry systems. Relationships of the PDIS results to occupational neutron monitoring, accreditation testing, and methods to improve personnel neutron dosimetry performance are also discussed.

INTRODUCTION

INTEREST in neutron personnel monitoring has increased significantly during the past several years primarily due to the advent of dosimetry accreditation programs (Gladhill et al. 1986) and proposed increases in neutron quality factors for radiation protection (International Commission on Radiological Protection 1985). To provide an opportunity for dosimetrists to test and calibrate their neutron monitoring systems in a variety of incident neutron energy spectra, the staff of the Dosimetry Applications Research (DOSAR) Facility at the Oak Ridge National Laboratory (ORNL) has conducted personnel dosimetry intercomparison studies (PDIS) periodically since 1974 and annually since 1976 (Sims and Swaja 1982, Swaja et al. 1981a, Swaja et al. 1981b, Swaja et al. 1983, Swaja et al. 1985a, Swaja et al. 1985b, Swaja et al. 1986, Swaja et al. 1987). During these studies, personnel dosimeters are mailed to ORNL, mounted on phantoms and exposed to low-level (less than 15 mSv) dose equivalents in mixed-radiation fields mainly produced using the Health Physics Research Reactor (HPRR) at ORNL (Auxier 1965), and then returned to the participants for evaluation. Reported dose equivalents are compared to reference values provided by the DOSAR staff and to results obtained by individual organizations which made measurements under identical irradiation conditions. These intercomparisons, which require no fee for participation and are open to any organization interested in external personnel dosimetry, have provided more data concerning neutron dosimeter performance characteristics in mixed-radiation fields than any other periodic open test program conducted to date.

A total of 116 different organizations (78 from the United States and 38 from other countries) has participated in the first twelve ORNL intercomparisons. These organizations include industrial and government laboratories (40%), nuclear utilities (20%), universities (14%), dosimetry vendor services (13%), military and regulatory agencies (12%) and hospitals (1%). Ninety facilities have participated in more than one study and 22 have participated in six or more. These 116 different organizations have submitted a total of 8018 badges which have been processed by the DOSAR staff (6644 exposed on phantoms and 1374 controls) and have reported a total of 4287 measured neutron dose equivalents.

Results of the first six ORNL intercomparisons have been summarized and reported in the open literature (Sims and Swaja 1982). Beginning with the seventh PDIS in 1981, interest and participation in the Oak Ridge intercomparisons increased significantly and have remained high. The average number of participants in the first six PDIS was 18 while the average number for PDIS 7 through 12 was 38. The seventh PDIS also marked the introduction

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of consistent and documented methods for determining reference neutron and γ dosimetry for the HPRR (Sims and Killough 1981, Sims 1986). Because of the demonstrated concern for personnel monitoring as indicated by the large numbers of participating organizations, and the consistency and reliability of techniques used to determine reference dose equivalents since 1981, the DOSAR staff considers that data obtained during the seventh and subsequent intercomparisons are more representative of performance characteristics of neutron personnel monitoring systems than results obtained during studies conducted prior to 1981. The following text presents a summary and analysis of about 3450 neutron dose equivalent measurements performed during PDIS 7–12 (1981–1986) primarily using the HPRR as the source of radiation. Particular factors examined include low dose equivalent sensitivity, measurement accuracy and precision, and performance relative to accreditation program standards for the basic types of neutron personnel dosimetry systems.

INTERCOMPARISON DATA

Table 1 summarizes information concerning PDIS 7–12 including dates of the exposures, total number of participating organizations, number of badges processed, number of badges exposed on phantoms, number of reported neutron results and the ORNL reference document describing each intercomparison. The total number of different participating organizations ranged from 31 to 49 for the six intercomparisons considered in this report. Participants submitted a total of 5750 personnel dosimetry badges which were processed by the DOSAR staff—4700 were mounted on phantoms and exposed while 1050 were controls. A total of 3451 measured neutron dose equivalents were reported for PDIS 7–12.

Each intercomparison was planned to provide data concerning some aspect of personnel neutron and γ dosimetry which may not have been considered in previous studies or which may have been of interest to participants. For example, PDIS 7, 11 and 12 contained irradiations with high (greater than 1.5 mSv) reference neutron dose equivalents so that dosimeter accuracy and precision could be evaluated without any lower limit of detection effects. Intercomparisons 8 (done in conjunction with the Commission of European Communities), 9 and 10 included low (about 0.5 mSv) and high (about 10.0 mSv) reference neutron dose equivalent irradiations for the same incident spectra so that dosimeter performance characteristics could be evaluated at significantly different levels. The tenth and twelfth PDIS contained exposures in which the HPRR irradiations were γ-enhanced by an additional 5 mSv to provide an indication of dosimeter performance in fields with significantly different neutron and γ components. The eighth and twelfth intercomparisons included exposures with neutron energy spectra which were outside the range of the HPRR fields normally considered in these studies (monoenergetic irradiations using accelerators, moderated and unmoderated isotopic sources) to determine if evaluation algorithms and calibration factors developed during prior PDIS were applicable to the new spectra. Instead of the usual three badges per exposure per participant, a limit of five badges per exposure was allowed in the eleventh PDIS to permit a better evaluation of measurement precision (reproducibility) for the individual organizations. Intercomparisons 9, 10 and 12 included irradiations for which the incident radiation fields were not explicitly known (except for some data such as sphere response ratios) to participants prior to dosimeter evaluation to provide an indication of system performance under conditions closer to those encountered during occupational monitoring.

The general format for the personnel dosimetry intercomparisons—badges are mailed to ORNL, mounted on phantoms and exposed to several radiation fields and returned to participants for evaluation—has been the same for all studies. Most (about 85%) exposures have used the HPRR with and without spectrum-modifying shields as the source of radiation. Most (about 90%) of the HPRR irradiations have been conducted for four different shield conditions: unshielded (bare reactor) and the reactor shielded with 13-cm of steel, 20-cm of concrete and 12-cm of Lucite.** Table 2 summarizes characteristics of these four radiation fields including mean neutron energies, ratios of thermal-to-fast neutron fluences and neutron-to-gamma dose equivalent ratios in air at the dosimeter exposure locations. The indicated fields range from a hard, almost equilibrium ^{235}U fission neutron spectrum with a relatively low thermal fluence and a small γ component (unshielded HPRR) to a soft, hydrogen-moderated neutron spectrum with a high thermal fluence and strong γ component (Lucite-shielded HPRR). The Lucite-moderated field, while having a relatively soft neutron energy spectrum with a high thermal component, is somewhat harder than spectra typically encountered during occupational monitoring at power reactor plants (Sanna et al. 1981). Data given in Table 2 are for the most recent (PDIS 11 and 12) HPRR irradiation configuration and are slightly different from spectra encountered during PDIS 7–10. In 1984, a change in the reactor operating geometry was necessitated by administrative requirements which altered the contribution to neutron and γ fields of materials located near the core. These changes were considered in the development of the latest recommended HPRR reference dosimetry (Sims 1986, Sims and Ragan 1987). Most of the analysis presented in the following text is based on data obtained for the four radiation fields listed in Table 2 since they provided the most measured results and should give the best indication of dosimeter performance.

Figure 1 shows a typical irradiation arrangement of the reactor, a spectrum-modifying shield, and dosimeters mounted on phantoms. For most PDIS, badges from each participating organization were mounted side-by-side on the front surface (side facing the radiation source) of a

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** Lucite, E. I. duPont de Nemours & Co., Wilmington, DE 19898.

Table 1. Summary of Oak Ridge National Laboratory (ORNL) personnel dosimetry intercomparison studies (PDIS) conducted between 1981 and 1986.

PDIS number	Dates of exposures	Number of participants	Number of badges	Number exposed	Reported results	Reference ORNL
7	31 Mar–10 Apr, 1981	34	714	612	392	TM-8080
8	19–23 Apr, 1982	48	1476	1024	901	TM-8697
9	19–21 Apr, 1983	33	654	558	404	6126
10	9–11 Apr, 1984	31	713	620	421	6143
11	22–23 May, 1985	44	1076	929	660	6296
12	14–17 Apr, 1986	49	1117	957	673	6378

phantom. Three different types of phantoms have been used since 1981 to simulate human body reflection and absorption characteristics. In PDIS 7 and 9, badges were mounted on water-filled polyethylene trunk sections of Bomab phantoms (Sanders and Poston 1962) which are 40-cm high and have elliptical cross sections (20-cm × 30-cm). Cylindrical (30-cm diameter × 60-cm high) water-filled polyethylene bottles were used in PDIS 8 to be consistent with phantoms used at the European facilities which conducted the monoenergetic and isotropic exposures. Solid 15-cm thick Lucite blocks with 40-cm × 40-cm square faces were used in PDIS 10–12. This type of mounting medium is presently recommended for neutron dosimeter calibration and testing by the National Bureau of Standards (Schwartz and Eisenhauer 1982). Performance tests conducted at the DOSAR Facility indicate that neutron and γ dosimeter responses for badges mounted on Lucite block and water-filled polyethylene phantoms using procedures normally followed in the ORNL intercomparisons do not vary by more than five percent for the HPRR radiation fields considered in these studies (Swaja and Greene 1983).

REFERENCE DOSIMETRY FOR THE HPRR

Reference neutron dose equivalents for the HPRR are determined using fission yields measured by S pellet activation analysis and dose-equivalent-per-fission conversion factors developed for the various reactor spectra (Sims and Killough 1981, Sims and Ragan 1987). The number of fissions produced during an irradiation is obtained by measuring the β activity induced in a 22 g S pellet located at a fixed position near the reactor core. The dose-equivalent-per-fission conversion factors are based on multisphere measurements and discrete-ordinates-transport calculations of the differential neutron energy spectra and fluence-to-dose-equivalent conversion factors specified for several reporting conventions (Sims and Ragan 1987).

Table 2. Health Physics Research Reactor (HPRR) radiation field characteristics at the dosimeter exposure locations.[a]

HPRR shield	Average neutron energy, MeV	Thermal-to-fast fluence ratio[b]	Neutron-to-gamma dose equivalent ratio
Unshielded	1.306	0.020	62.6
13-cm steel	0.780	0.030	86.6
20-cm concrete	0.885	0.257	22.0
12-cm Lucite	0.951	0.357	11.8

[a] Data at 3 m from the HPRR with the reactor operated over the storage pit at 1.4 m above the floor.

[b] Thermal neutron ($E_n \leq 0.5$ eV) fluence divided by the fast neutron ($E_n \gtrsim 1$ MeV) fluence.

In this report and in PDIS 7 through 12, reference neutron dose equivalents used for comparison to measured results are based on specifications given by the International Commission on Radiological Protection (ICRP) in their publication number 21 (International Commission on Radiological Protection 1973). This convention consists of log-log interpolation of maximum dose-equivalent-per-fluence values calculated at discrete energies for a tissue-equivalent cylindrical phantom. Approximately 42% of all organizations reporting results in PDIS 7–12 used this convention for their neutron dose equivalents. About 26% of all reporting organizations used data specified by the National Council on Radiation Protection and Measurements (NCRP) in their publication number 38 (National Council on Radiation Protection and Measurements 1971) to determine neutron dose equivalents for these studies. This method is based on linear interpolation of the maximum dose-equivalent-per-fluence values calculated at discrete energies for a cylindrical phantom. The "element 57" convention (Auxier et al. 1968) was used by approximately 16% of the organizations reporting results for PDIS 7–12. Element 57 dose equivalent refers to the value calculated for the central volume element (element number 57 in the calculational model) of a cylindrical phantom exposed to an external parallel radiation field (log-log interpolation between discrete energies). The remaining 16% of the reported results was either associated with some other convention (6%) or unknown (10%). For the four most used HPRR spectra, reference dose equivalents based on the NCRP or element 57 specifications typically differ from corresponding ICRP values by less than 10% (Sims and Killough 1983).

With regard to other dose equivalent conventions endorsed by various international committees, the ICRP-21 data gives values within about 10% of dose equivalents determined using the "depth dose equivalent" required

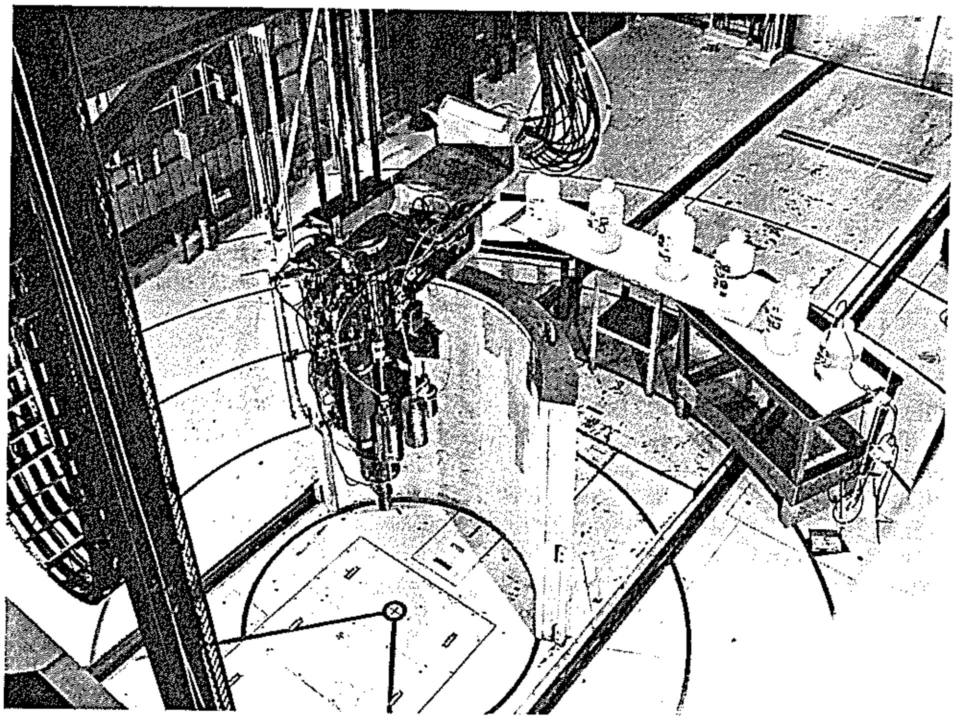

Fig. 1. Typical PDIS exposure arrangement of the Health Physics Research Reactor, a spectrum-modifying shield and dosimeters mounted on phantoms.

for neutron dosimetry accreditation programs in the United States (American National Standards Institute 1983). Dose equivalents determined using data specified for the "ambient dose equivalent" calculated in a tissue-equivalent 30-cm diameter spherical phantom as specified by the International Commission on Radiation Units and Measurements (ICRU) in their publication number 39 (International Commission on Radiation Units and Measurements 1985) are about 10% higher than ICRP-21 values for the four HPRR spectra. Neutron results based on the "effective dose equivalent" described by the ICRP in their publication number 26 (International Commission on Radiological Protection 1977) are about 60% of neutron dose equivalents determined using the ICRP-21 convention for the HPRR spectra considered in the ORNL comparisons. Spectrum-average conversion factors for HPRR spectra and other radiation sources have been calculated and compared in several previous publications (Sims and Killough 1983, Sims 1985, Sims and Ragan 1987).

NEUTRON DOSIMETER TYPES

Figure 2 shows the collection of neutron personnel dosimeters submitted by participants in the eleventh PDIS. This collection is typical of the variety of badges encountered in PDIS 7–12. Although few of the badge designs submitted by different organizations are the same, the basic detection mechanisms can be classified into six categories for neutrons: direct-interaction thermoluminescent (TLD), TLD-albedo, film, recoil track, fission track and combination albedo plus recoil track. These systems have been described in detail in previous open-literature publications (Brackenbush et al. 1980, Griffith et al. 1979, Ing and Piesch 1985).

The TLD-based albedo and direct-interaction systems, the most popular types of neutron dosimeters used in PDIS 7–12, were used by 45% and 28%, respectively, of the organizations which reported results. Although both use pairs of thermoluminescent phosphors—one sensitive to neutrons (high thermal neutron sensitivity) plus γs and one sensitive essentially to γ rays only— to determine the neutron component of the incident field and both respond to albedo (reflected) neutrons, they differ in that direct-interaction dosimeters are affected by all incident neutrons including thermals while albedo systems either discriminate against incident thermal neutrons by using a thermal neutron absorber (e.g., Cd or B) or by measuring the incident thermal component separately using several thermoluminescent detectors in the same badge. Direct-interaction TLD's are very sensitive to thermal neutrons and TLD-albedo dosimeters are most sensitive to low and intermediate energy (lower than about 200 keV) neutrons. Neither system is very sensitive to fast neutrons with energies greater than about 500 keV.

Recoil track dosimeters, which were used by 11% of the reporting organizations, are based on counting tracks made by neutron interactions (mostly scattering with protons) in organic materials. Almost all recoil track systems used in PDIS 7–12 contained allyl diglycol carbonate

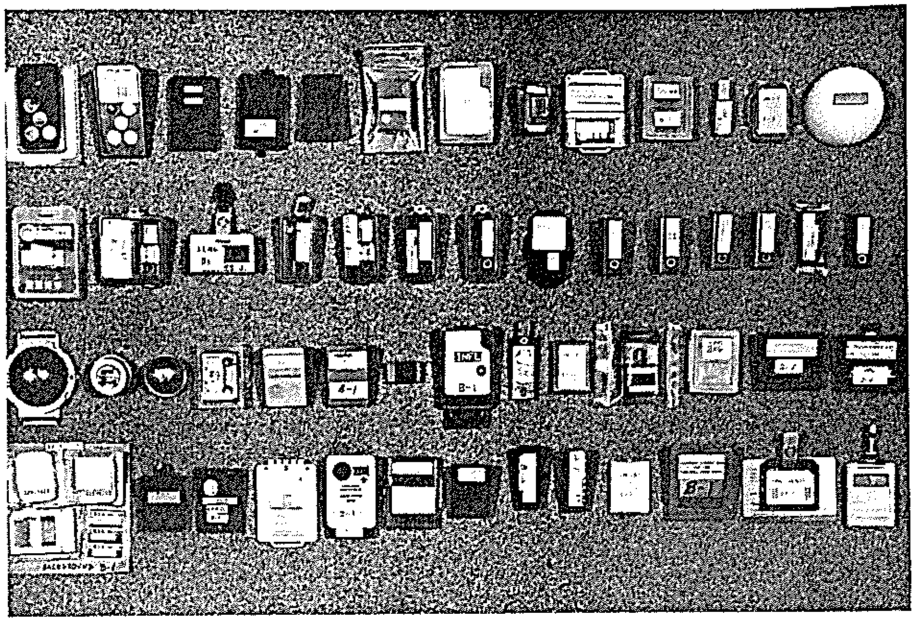

Fig. 2. Collection of personnel monitoring badges used for the Eleventh ORNL intercomparison.

(CR-39) plastic and were electrochemically etched to enhance track sizes. Results presented in this report are for CR-39 systems which were commercially available between 1981 and 1986 and do not include any data for recently developed dosimetry grade CR-39 and improved etching techniques (Hankins et al. 1987). Commercially available recoil track dosimeters typically have thresholds for neutron detection of about 200 keV.

Film, combination albedo-track, and fission track (Th convertor) neutron dosimetry systems were used by only 6%, 6% and 4%, respectively, of the reporting organizations. Film dosimeters (NTA film), which are based on counting tracks made by neutron interactions in a gelatin emulsion, have a threshold energy sensitivity of about 500 keV for neutrons. Combination albedo and recoil track systems were developed commercially in an attempt to combine the sensitivity of albedo dosimeters to intermediate energy neutrons with the sensitivity of recoil track materials to high energy neutrons so that a wide energy range could be monitored. Fission track dosimeters use a radiator material (Th convertor) to produce particles which make tracks in an adjacent organic medium. The tracks are larger than those produced in recoil track materials but, depending on the radiator material, the detection threshold can be relatively high (about 1 MeV for Th).

From 1981 to 1986, the percent use of TLDs (albedo and direct-interaction) increased with a slight trend toward use of direct-interaction systems especially among nuclear utilities. The use of film for neutron monitoring in the PDIS decreased slightly over this time. The percentages of participants using combination, recoil track and fission track systems, which have usually been low, have remained almost constant.

LOW DOSE EQUIVALENT SENSITIVITY

To determine the sensitivity of the basic personnel neutron dosimeter types at low dose equivalent levels of about 0.5 mSv (50 mrem), irradiations were conducted during PDIS 8, 9 and 10 for a variety of HPRR spectra. Figure 3 shows the percent of neutron results reported as greater than zero or the minimum detectable value (M) for each of the six basic dosimeter types used in these intercomparisons. The total number of reported measurements considered in this analysis for each dosimeter type is also included. In general, the figure shows that participants who used TLD-based systems had fewer problems obtaining measurable indication of neutron exposure at about 0.5 mSv than did those who used track-based systems. Albedo users had almost no problems obtaining measurable responses at low dose equivalents, and only a few of the participants who used combination albedo-track or direct-interaction TLD systems exhibited any difficulty obtaining measurable indication of neutron exposure. With regard to track-based systems, more than 25% of the fission track and film dosimeter results and almost half (47%) of the recoil track (CR-39) results were reported as zero or M. At a dose equivalent level of about 0.5 mSv, the percent of measurements greater than zero or M showed no obvious correlation with incident spectrum (Swaja et al. 1985b). The next lowest neutron dose equivalent level considered in the ORNL intercomparisons was about 1.5 mSv (150 mrem) which is the lowest limit specified for neutron dosimetry accreditation testing (American National Standards Institute 1983). None of the basic dosimeter types exhibited any difficulty providing measurable indication of neutron exposure at dose equivalent levels in this range (Swaja 1987).

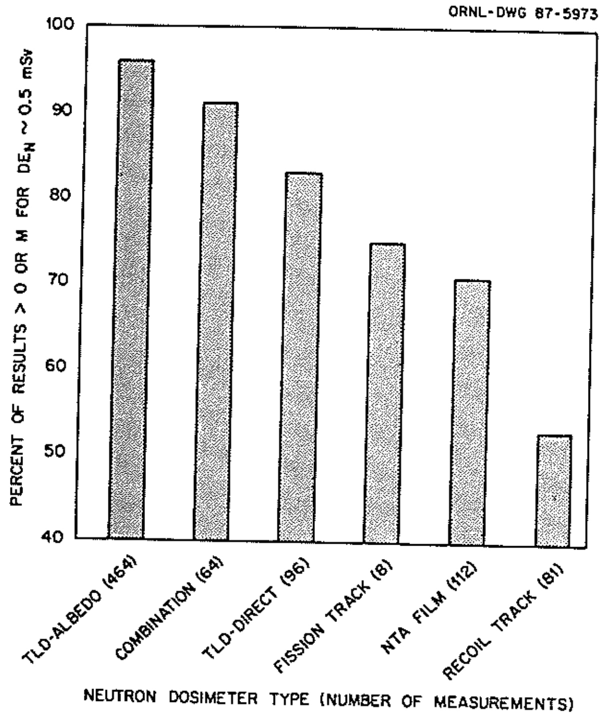

Fig. 3. Neutron dosimeter sensitivity at low dose equivalents.

MEASUREMENT ACCURACY AND PRECISION

The quantities of most concern to those involved in applied dosimetry or accreditation program testing are measurement accuracy and precision. In this analysis, accuracy is indicated by the mean normalized dose equivalent which is the average of all measured-divided-by-reference (ICRP-21 convention) dose equivalents for a particular incident spectrum reported for PDIS 7–12. Standard deviations associated with these data indicate the variation about the mean of the total sample of results reported by all participants who used the same basic dosimeter type. Measurement precision (reproducibility) is indicated by one standard deviation about the mean of measurements reported by an individual participant for a particular irradiation and is not directly related to the collection of results used to infer accuracy.

Figures 4–9 show measurement accuracy for each of the six basic neutron dosimeter types as a function of the four most used HPRR spectra: the unshielded HPRR and the reactor shielded with steel, concrete and Lucite. The spectra shown on the horizontal axes are ordered such that the neutron energies get increasingly softer (e.g., higher thermal neutron component as indicated by the thermal-to-fast fluence ratios) going from left to right. Points shown in the figures are accuracy values and represent the average normalized results reported for PDIS 7–12 by all participants who used a particular dosimeter type. Error bars are one standard deviation about the mean of all reported results for each spectrum.

Two sets of data are shown in most figures—one set (open squares) for low dose equivalent irradiations of about 0.5 mSv and the other set (solid circles) for higher reference dose equivalents above about 1.5 mSv. For all basic dosimeter types, the low dose equivalent data show much greater variability among results reported by different participants and much higher standard deviations than corresponding measurements at higher dose equivalents. It was not unusual for neutron dose equivalents reported by different organizations for the same irradiation conditions to differ by more than a factor of three with variations of between 0 and 10 times reference values observed for some low dose equivalent runs. For the high dose equivalent irradiations, typical maximum variations in results reported by different organizations for the same irradiation were about a factor of two. The low dose equivalent data, although included in Figs. 4–9, will not be discussed further. Results from the high dose equivalent irradiations (1.48–15.21 mSv) are better indicators of dosimeter performance capabilities since almost no participants had any problems obtaining measurable dosimeter responses at dose equivalents in this range and many more measurements were available for analysis.

TLD-albedo dosimeters

Figure 4 shows average measured divided by reference neutron dose equivalents as a function of HPRR

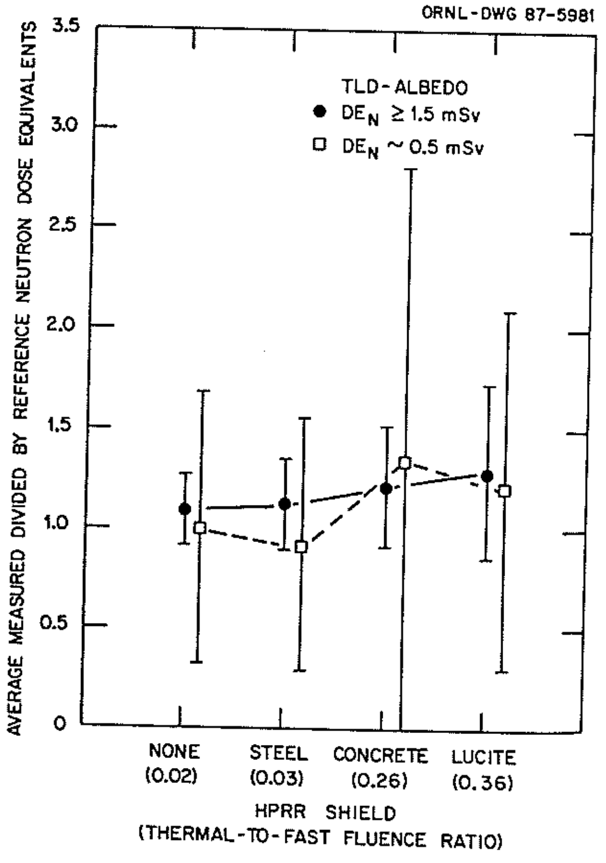

Fig. 4. Summary of PDIS results for TLD-albedo neutron dosimeters.

incident spectrum for TLD-albedo dosimeters based on 925 measurements reported for PDIS 7–12. There are at least 13 basic albedo dosimeter designs that have been documented in the literature (Griffith et al. 1979, Ing and Piesch 1985), and about 15 different badge types have been irradiated in the ORNL intercomparisons. Although the designs and evaluation methods can vary significantly, energy response characteristics are qualitatively similar for all albedo systems. For dosimeter types with more than 100 measurements, albedo dosimeters were overall the most accurate with mean reported results ranging from 9% to 28% higher than reference values for the four spectra. Single standard deviations associated with the albedo results are about 25% of the mean values. The hardest spectra (unshielded and steel-shielded) were measured more accurately than the softest spectra (concrete- and Lucite-shielded) with the average normalized values increasing monotonically with increasing spectrum softness as indicated by the thermal-to-fast fluence ratio. This qualitative performance is characteristic of albedo systems calibrated with hard neutron energy spectra (e.g., unmoderated Cf, PuBe or the unshielded HPRR) with no corrections applied to the dosimeter response to account for differences between incident and calibration spectra. Quantitative differences between mean measured and reference dose equivalents were consistent with results obtained in the most recent intercomparisons (PDIS 10–12) and were much lower than average results obtained in PDIS 7 (average overestimation of about 75% for soft spectra). This implies that in the most recent studies, more participants had calibrations for HPRR spectra or applied correction factors to dosimeter responses, but that some corrections were inadequate.

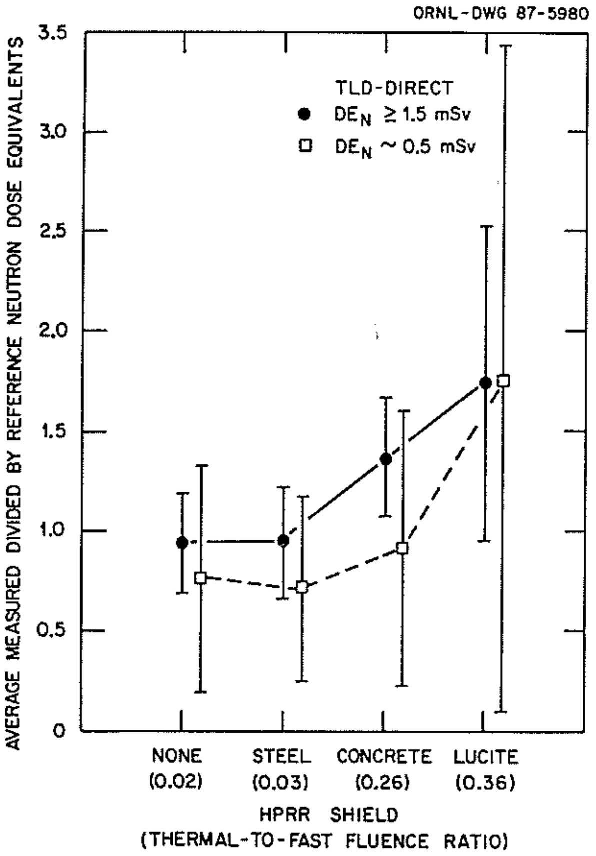

Fig. 5. Summary of PDIS results for direct-interaction TLD neutron dosimeters.

Direct-interaction TLDs

Normalized neutron dose equivalents as a function of HPRR spectrum are shown in Fig. 5 for the 420 measurements reported for direct-interaction TLD's used in PDIS 7–12. Most of these systems used either TLD-600 (^{6}LiF) plus TLD-700 (^{7}LiF) or $^6Li_2{}^{10}B_4O_7$ plus $^7Li_2{}^{11}B_4O_7$ phosphor pairs to determine the neutron component of the incident field. These systems exhibit the same qualitative behavior as albedo dosimeters in that hard spectra are measured more accurately than soft spectra with the average normalized values increasing monotonically with increasing spectrum softness. However, since direct-interaction TLD systems are much more sensitive to incident thermal neutrons than albedo dosimeters, the amount of overestimation for the soft spectra is much greater. For PDIS 7–12, average measured results for direct-interaction TLDs were within 6% of reference values for the hard spectra but were 36% and 75% higher than references for the softer concrete- and Lucite-shielded spectra, respectively. Some individual agencies which calibrated to hard neutron energy spectra overestimated Lucite-shielded dose equivalents by factors of three or more relative to reference data. Qualitative results shown in Fig. 5 are consistent with data obtained in the most recent PDIS and are much lower than values obtained in the earlier intercomparisons. This indicates that more participants in recent studies have calibrations to HPRR spectra and are applying corrections to the direct-interaction TLD responses. However, the large errors observed for soft spectra indicate that some corrections may not be adequate or applicable to their particular systems (Swaja and Yeh 1987). These results also show the magnitudes of errors that can be expected if TLD systems are used to monitor neutron spectra which are significantly different from those used for calibration. Standard deviations shown for the TLD dosimeters are about 20% of the mean values for the hard spectra and about 60% of the means for the softest spectrum.

NTA film dosimeters

Figure 6 shows normalized neutron results reported for 112 measurements made with NTA film dosimeters as a function of HPRR incident spectrum. On the average, film neutron dosimeters underestimated dose equivalents for all spectra and provided average results between 62% and 70% of the reference values with no obvious spectrum dependence. This performance has been observed in all ORNL intercomparisons and is a consequence of the threshold response characteristics of NTA film which is insensitive to neutrons with energies below about 500 keV

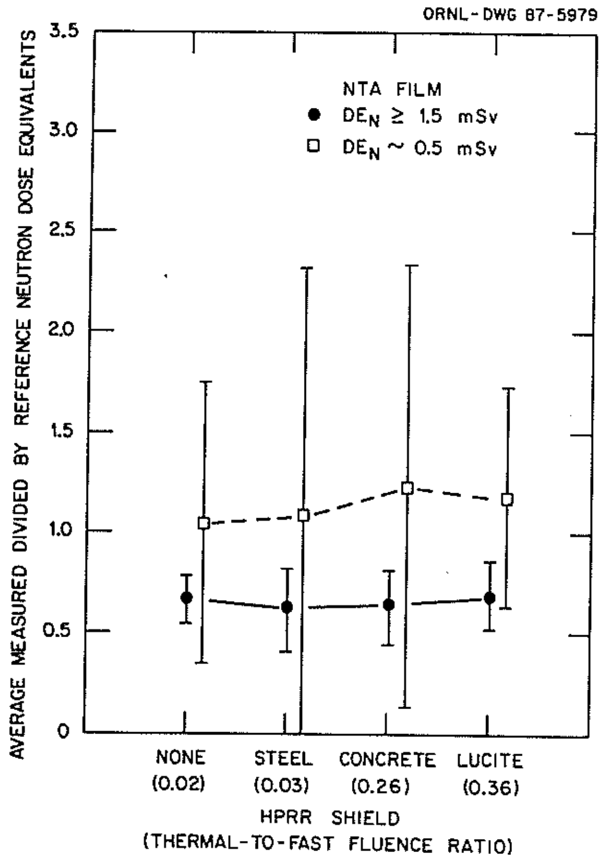

Fig. 6. Summary of PDIS results for NTA film neutron dosimeters.

(Griffith et al. 1979). In addition, most film users (about 85%) calibrated their dosimeters with neutron sources which had much harder energy spectra than any of the HPRR fields. Performance characteristics of film dosimeters observed in these studies indicate that most participants are not making any corrections to their dosimeter response to account for dosimeter energy sensitivity or differences between measured and calibration spectra. Standard deviations associated with these data are about 25% of the mean values which is comparable to results observed for TLD-based systems.

Recoil track dosimeters

Normalized results as a function of HPRR spectrum are shown in Fig. 7 for participants who used recoil track (CR-39) systems. Indicated results represent a total of 81 reported dose equivalents for neutron reference values greater than 1.5 mSv. The CR-39 track systems, which also have a threshold energy sensitivity (insensitive to neutrons with energies below about 200 keV), provided underestimates of neutron dose equivalents for all spectra. Average measured results varied from 60% to 97% of reference values with results for the unshielded HPRR being the most accurate. This good accuracy for the hardest spectrum is expected since most recoil track users (about 75%) calibrated their dosimeters to hard spectra (unmoderated Cf, PuBe or the unshielded HPRR). Although average accuracies exhibited by recoil track systems are comparable to or significantly better than those exhibited for NTA film for each spectrum, the track results show more variation in mean normalized dose equivalents with incident spectrum than film. Standard deviations associated with the reported track results are about 25% of the means for each HPRR spectrum which is consistent with results obtained for TLD and NTA film systems.

Combination dosimeters

Combination albedo plus recoil track dosimeters are designed to provide a wide range of neutron energy sensitivity by combining the high sensitivity of albedo systems to intermediate energy neutrons with the high sensitivity of CR-39 material to fast neutrons. Figure 8 shows normalized results as a function of incident spectrum for 64 measured neutron dose equivalents reported for reference values greater than 1.48 mSv. Average results varied from 70% to 102% of the references for the four spectra with the unshielded HPRR being the most accurately measured. Qualitatively and quantitatively, variations in accuracy with incident spectrum for combination dosimeters were much closer to those observed for recoil track do-

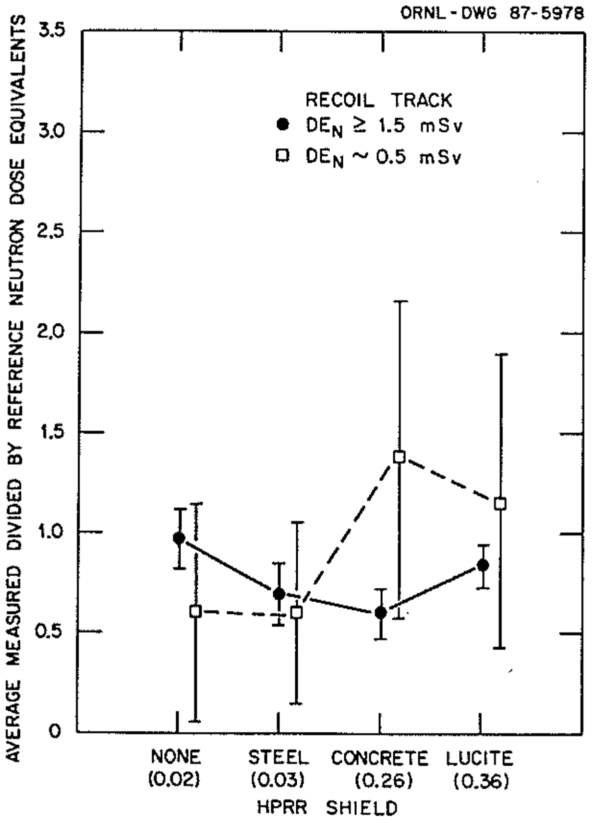

Fig. 7. Summary of PDIS results for recoil track neutron dosimeters.

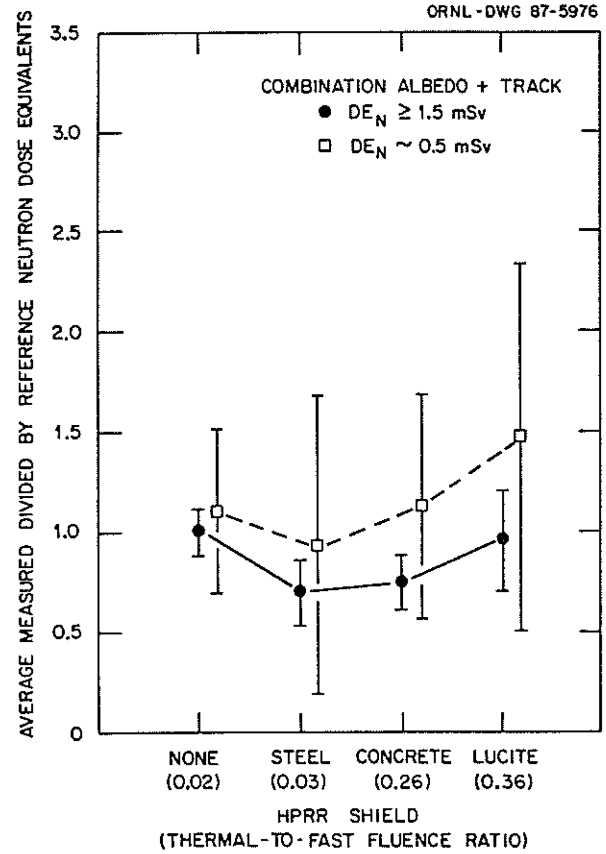

Fig. 8. Summary of PDIS results for combination albedo-track neutron dosimeters.

simeters than for albedo systems in that average normalized results were very close to reference values for the unmoderated HPRR and were lower than reference values for the moderated reactor spectra. Standard deviations associated with the combination dosimeter data are about 25% of the mean values which is also consistent with that obtained for recoil track systems. Based on these results, combining albedo and track systems did not significantly improve neutron dose equivalent estimation capability in the PDIS relative to that observed for recoil track systems alone.

Fission track dosimeters

Figure 9 shows normalized results as a function of incident HPRR spectrum for eight results reported for fission track (Th convertor) dosimeters for neutron dose equivalents above 1.5 mSv. These dosimeters, which also have threshold response characteristics (insensitive to neutrons with energies below about 1 MeV), produced average results which ranged from 0.95 to 1.20 times reference values with no obvious spectrum dependence. Standard deviations shown in the figure are about 40% of the mean reported results for each spectrum. While these data indicate that fission track systems can provide accurate dose equivalent estimates for the primary HPRR spectra, the small number of reported results for this dosimeter type prevents any conclusive comparisons between performance observed for fission track systems and any of the other basic neutron dosimeter types.

Accuracy summary

To summarize performance of the different basic neutron dosimetry systems, Fig. 10 shows normalized results for reference dose equivalents greater than about 1.5 mSv as a function of incident HPRR spectrum for the four most popular dosimeter types used in the PDIS—direct-interaction TLD, TLD-albedo, recoil track and NTA film. The indicated points represent average accuracy values for each basic dosimeter system. Qualitative variations for each dosimeter type were discussed in the preceding text. With regard to overall performance, direct-interaction TLD's, albedos and recoil track dosimeters provide average results within about 10% of reference values for the hardest (unshielded) HPRR spectrum. Since most of these dosimeters were calibrated with hard neutron energy spectra, this performance is expected. As the spectra become softer, TLD-based systems tend to overestimate reference dose equivalents with direct-interaction systems overresponding more than albedos with increasing spectrum softness. Dosimeter types with threshold detec-

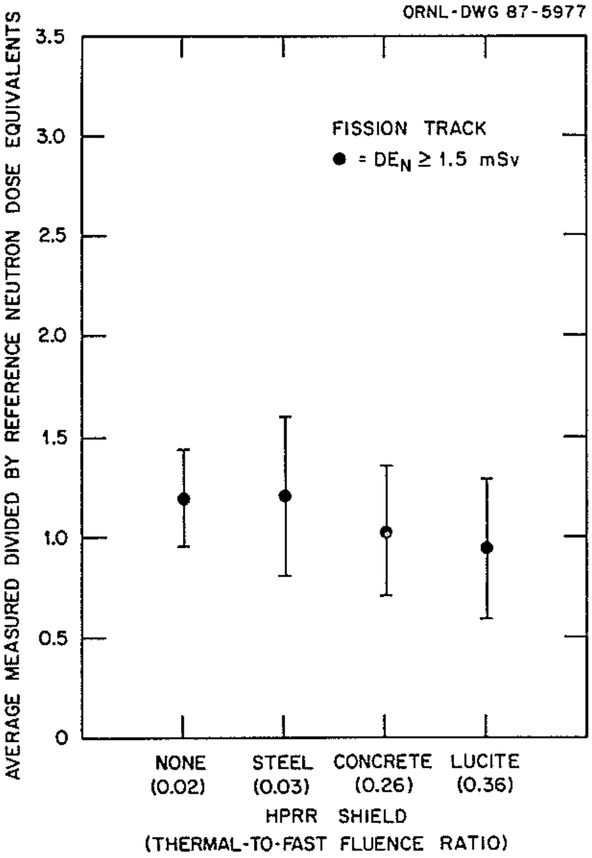

Fig. 9. Summary of PDIS results for fission track neutron dosimeters.

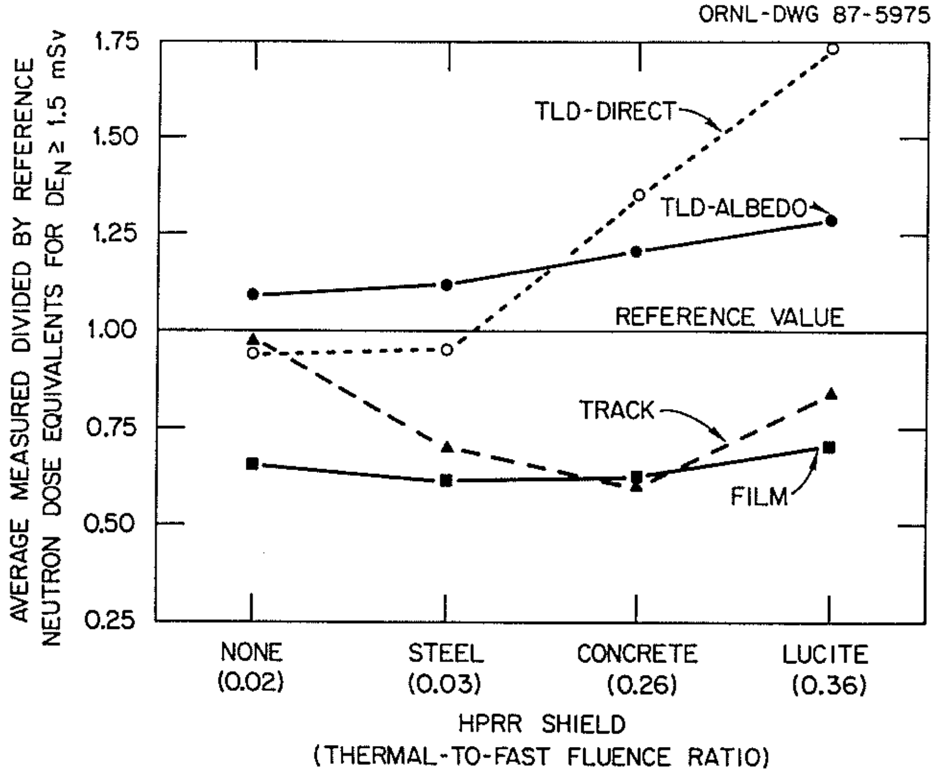

Fig. 10. Neutron dosimeter accuracy as a function of incident spectrum for dose equivalents greater than 1.5 mSv.

tion energies such as recoil track and film underestimate reference dose equivalents for moderated spectra by more than 20%. Film neutron dosimeters, which were generally calibrated in spectra much harder than the unshielded HPRR, also underestimate reference dose equivalents for the unmoderated reactor spectrum. These observed variations in accuracy as a function of incident spectrum are qualitatively the same as would be expected if the dosimeters were calibrated in hard energy spectra on the order of the unshielded HPRR and no corrections were made to dosimeter responses to account for energy response characteristics and differences between incident and calibration spectra. This suggests that many PDIS participants are not making corrections to dosimeter responses or are using inadequate corrections. Surveys conducted in conjunction with the intercomparisons support this premise in that about 52% of all reporting participants indicated that they made no corrections to their measured dosimeter responses. Despite this inadequacy, average reported results for all the basic dosimeter types included in Fig. 10 are within 40% of reference values with the exception of the direct-interaction TLD data for the softest incident spectrum (Lucite-shielded HPRR).

One other observation evident in Fig. 10 is that with the exception of direct-interaction TLD's, the variation of average accuracy with incident spectrum is not very severe for the basic dosimeter types. Applying a uniform correction factor of 0.83 to the albedo data would yield average measured dose equivalents within 10% of the reference values for all spectra. Applying a uniform correction factor of 1.52 to the film-measured results, which show the smallest variation in accuracy with incident spectrum, would provide measured dose equivalents within 6% of reference values for all of the four reactor spectra. Average recoil track measurements within 22% of reference dose equivalents could be obtained by applying a uniform correction factor of 1.26. Results obtained for combination dosimeters, which are not included in Fig. 10, could be within 16% of reference values if a factor of 1.14 were applied to average measured results. Due to the severe variation of measurement accuracy with incident spectrum exhibited by direct-interaction TLD systems, application of a constant correction factor to the average reported results would not provide such accurate data as observed for the other basic dosimeter types. This indicates the need for very careful calibration and application of TLD systems especially in incident spectra with greatly different thermal neutron components than that encountered during calibration. Thus, with careful calibration and development of evaluation algorithms, any of the basic neutron dosimetry systems can provide accurate dose equivalent estimates for the exposure conditions and radiation fields considered in the ORNL intercomparisons. This conclusion also applies to accreditation testing and those occupational monitoring situations where the incident spectra and exposure conditions are well known. It should be emphasized that the data presented in the preceding text is based on average results reported by several agencies for a variety of dosimeter types. Correction factors and evaluation algorithms applicable to a particular system must be developed by the individual processor based on performance characteristics of his system.

Measurement precision

With regard to measurement precision (reproducibility for each measurement for each participant), single standard deviations about the mean of results reported by individual organizations for each irradiation condition averaged about 11% of the means for exposures in which three or more badges from each participant were mounted side-by-side on a phantom. About 36% of all reporting organizations showed standard deviations of 5% or less of the mean values while about 68% indicated standard deviations of 10% or less of the means. Albedo and direct-interaction TLD's exhibited the best precision with average standard deviations of about 9% of the means. About 75% of all organizations using these dosimeter types showing single standard deviations of 10% or less. Fission track systems produced the poorest precision with average standard deviations of about 18% of the means and approximately 25% of all reporting organizations showing standard deviations of 10% or less. Film, recoil track and combination systems showed precisions close to but slightly higher in magnitude than results obtained for TLDs. These data indicate that for well over half of the participants in the ORNL intercomparisons, measurement precision is not a problem relative to accuracy (Swaja 1987).

PERFORMANCE RELATIVE TO ACCREDITATION CRITERIA

Development of national dosimetry accreditation programs has provided standards for neutron personnel dosimetry based on criteria suggested by the American National Standards Institute (American National Standards Institute 1983). For mixed-field monitoring (moderated Cf neutron source enhanced with ^{137}Cs γs) at neutron dose equivalent levels equal to or greater than 1.5 mSv, these requirements specify that the sum of the measurement accuracy (percent deviation of the mean result from the reference value) and precision (percent of one standard deviation about the mean of measured results) must be equal to or less than 50% for 15 dosimeters submitted by a single processor. Table 3 shows the percent of reported results which satisfy this criterion for each basic neutron dosimeter type used in the ORNL intercomparisons and for the collection of all results as a function of incident spectrum and the composite of results for all spectra. Data shown in the table are for reference neutron dose equivalents greater than about 1.5 mSv and for organizations which submitted three or more badges per irradiation. Considering all reported neutron results, about 77% of all measurements satisfied the subject standard. Best performance was exhibited for the hardest neutron energy spectrum (unshielded HPRR) with an average of 92% of all measurements meeting the criterion, and poorest performance was obtained for the softest spectrum (Lucite-shielded) in which an average of 59% of all reported measurements met the standard. With regard to the individual dosimeter types, TLD-albedo, recoil track and combination albedo-track systems all averaged over 80% of the measurements within the suggested limits for all spectra. For the unshielded HPRR spectrum, over 90% of the measurements made with these three dosimeter types were within 50% of reference values. Performance relative to the accreditation standard decreased with increasing spectrum softness especially for direct-interaction TLDs. These systems performed well for the hardest spectrum with over 90% of the reported results satisfying suggested limits, but TLD performance decreased rapidly with increasing spectrum softness with only 32% of the reported results meeting the standard for the softest neutron energy spectrum. Film neutron dosimeters exhibited the poorest performance of all the basic dosimeter types relative to the accreditation standards for almost all spectra. An average of 74% of all reported film-measured dose equivalents satisfied the subject limits.

These data indicate that under the irradiation conditions of the ORNL intercomparisons which are similar to those used in accreditation testing (e.g., direct irradiation, known spectrum, opportunity for a calibration irradiation), most participants have no difficulty meeting the 50% accuracy plus precision standard presently specified for neutron monitoring. If the performance criteria were reduced to 40% or 30% relative to reference values, about 61% and 47%, respectively, of the PDIS results measured at dose equivalents above 1.5 mSv would satisfy the reduced standards. If data obtained for irradiations with reference neutron dose equivalents less than 1.5 mSv were included, performance would decrease significantly with only 58% of all measurements satisfying the 50%

Table 3. Percent of neutron results with accuracy plus precision within 50% of reference values for dose equivalents greater than 1.5 mSv.

HPRR spectrum	All neutron dosimeters	TLD-albedo	Direct TLD	NTA film	Recoil track	Combination
Unshielded	92	95	91	82	92	90
13-cm steel	86	89	88	65	81	80
20-cm concrete	72	79	61	68	67	81
12-cm Lucite	59	61	32	81	88	82
All spectra	77	81	68	74	82	83

standard and percentages of measured results meeting the criterion for the individual basic dosimeter types varying from 38% (film) to 70% (albedo). This decrease is expected based on the low dose equivalent detection problems exhibited by some dosimetry systems at neutron dose equivalents around 0.5 mSv.

ADDITIONAL INTERCOMPARISON RESULTS

In addition to irradiations conducted for the four HPRR spectra discussed in the preceding text, other exposures were conducted during the ORNL intercomparisons to provide data concerning neutron dosimeter performance for conditions of interest to various participants. These exposure conditions included irradiations using very high energy (greater than 5 MeV) neutrons, exposure to spectra outside the range of the four primary HPRR fields, γ-enhanced HPRR exposures and incident spectra which were not explicitly known to participants prior to dosimeter evaluation. Although the numbers of results reported for these irradiations were less than those reported for the four primary HPRR spectra, the data available for these exposures do indicate some definite neutron dosimeter performance characteristics.

High energy monoenergetic neutrons

In PDIS 8, several irradiations were conducted using accelerators to obtain neutrons with energies of 5.3 and 15 MeV—much higher than those produced by the HPRR and typical isotopic sources used for calibration. For occupational monitoring, some neutrons with energies in this range can be encountered around fusion energy systems or high energy accelerators. Results reported for these irradiations showed that at dose equivalent levels around 0.5 mSv all basic neutron dosimeter types exhibited significant variations in results reported by individual agencies and generally poor accuracy relative to reference values. This is consistent with the performance observed for the HPRR spectra at low dose equivalents. At levels of about 10 mSv, average dose equivalents measured with film neutron dosimeters were within 20% of reference values for both energies. Combination albedo-track systems also provided average results within about 20% of reference dose equivalents but with significantly fewer reported measurements. Albedo and direct-interaction TLDs, which have very low sensitivity to neutrons in this energy range, underestimated dose equivalents by an average of about 60% of reference values at both energies. The CR-39 recoil track systems used in the eighth PDIS provided an average overestimate of about 25% relative to reference values at 5.3 MeV and an average underestimate of about 75% of the reference dose equivalent for 15 MeV neutrons. This behavior is expected based on energy response characteristics of CR-39 material at high energies (Brackenbush et al. 1980). Thus, for neutrons with energies greater than those produced by typical fission sources, NTA film dosimeters provided more accurate dose equivalent estimates than TLD-based systems or recoil track dosimeters in this intercomparison. These results support the application of film dosimeters for high energy neutron monitoring in stable environments (Hofert and Piesch 1985).

Additional neutron spectra

Besides the accelerator irradiations in PDIS 8, two exposures were conducted in PDIS 12 using neutron energy spectra outside the range of the HPRR fields considered in previous intercomparisons. These exposures were included to determine how calibration factors developed during prior PDIS performed for spectra outside the range of those normally considered for HPRR irradiations. One such exposure involved a steel-concrete-Lucite shield combination with the HPRR in which dosimeters were irradiated to reference neutron dose equivalents of about 1.5 mSv. The neutron energy spectrum resulting from this configuration was softer (average energy = 659 keV) than any considered in intercomparisons conducted prior to 1986. Based on dosimeter energy sensitivities and incident spectrum characteristics, this irradiation was expected to produce the highest dose equivalent overestimates for TLD systems and the largest underestimates for NTA film dosimeters. The second exposure used a PuBe isotopic source to irradiate dosimeters to a reference dose equivalent of about 1.5 mSv. The PuBe neutron energy spectrum was significantly harder (average energy = 4.5 MeV) than any HPRR spectrum considered in the ORNL intercomparisons conducted prior to 1986. For this exposure, it was expected that TLD-albedo, direct-interaction TLD and recoil track dosimeters would yield average results very close to the reference values since about 60% of these systems were calibrated using multiple sources with hard neutron spectra such as the unshielded HPRR, PuBe, AmBe and unmoderated Cf. It was also expected that NTA film dosimeters, most of which were calibrated to unmoderated Cf (average energy = 2.4 MeV) or the unshielded HPRR, would overestimate reference dose equivalents for the PuBe spectrum. Measurement precision was expected to be about the same as results observed for other HPRR irradiations. For both exposures, the expected performance was observed in PDIS 12 which supports the fact that many participants apply no or inadequate corrections to dose equivalents based on measured dosimeter responses and predetermined calibration factors to account for differences between incident and calibration spectra and dosimeter energy response characteristics.

Gamma-enhanced irradiations

The tenth and twelfth PDIS contained exposures in which the HPRR irradiations were supplemented by an additional γ dose equivalent of about 5 mSv from a ^{137}Cs source. By comparing results reported for the HPRR-only and the γ-enhanced HPRR irradiations, an indication of dosimeter performance in radiation fields with the same neutron component but significantly different γ components can be obtained. In the tenth PDIS, two sets of exposures were conducted for the concrete- and Lucite-shielded reactor at neutron dose equivalents of about 0.5 mSv. The first set (HPRR-only) had neutron-to-gamma

(n/γ) dose equivalent ratios greater than 6.0 while the second set (γ-enhanced) had n/γ ratios less than 0.1. At these low neutron dose equivalents, average normalized neutron results and standard deviations for the γ-enhanced runs were within about 20% of values obtained for HPRR-only runs. Considering all neutron dosimeter types, about twice as many measurements were reported as zero or M for the γ-enhanced runs compared to the reactor-only irradiations. Also, the percent of reported results within 50% of reference neutron dose equivalents for the γ-enhanced runs was about half of the value obtained for the HPRR-only exposures. The greatest problems in determining low neutron dose equivalents in strong γ fields were exhibited by TLD-based systems which had increased difficulty providing measurable indication of exposure to neutrons and a significantly lower percentage of reported results within 50% of reference values for the γ-enhanced exposures relative to the reactor-only runs. In PDIS 12, a set of exposures was conducted for the Lucite-shielded reactor with reference neutron dose equivalents of about 1.5 mSv and n/γ ratios of 6.7 (reactor-only) and 0.3 (γ-enhanced). At this reference neutron dose equivalent, average accuracies obtained for the collection of reported neutron results and for the individual dosimeter types were within about four percent for both irradiations. None of measured neutron dose equivalents was reported as zero or M for either of these exposures, and the percents of all results within 50% of reference values were the same (71%) for these two runs. These data indicate that γ radiation can affect neutron measurement accuracy and dose equivalent sensitivity, especially for TLD systems, at low neutron dose equivalents (about 0.5 mSv) in mixed-fields with strong γ components (n/γ less than about 0.1). However, at neutron dose equivalents above about 1.5 mSv, no degradation in dosimeter average accuracy was observed for mixed-fields with n/γ ratios greater than 6.0 and less than 0.3 with the same neutron energy spectra.

"Unknown" spectra

To provide an indication of system performance under conditions closer to those encountered during occupational monitoring, irradiations were conducted in PDIS 9, 10 and 12 for which the radiation fields were not explicitly known to participants prior to dosimeter evaluation. For most intercomparison exposures, the incident fields are explicitly identified (e.g., unshielded HPRR, concrete-shielded HPRR, etc.) so that participants can use published differential energy spectra to make corrections to their measured dosimeter responses, if desired. Although the exact irradiation condition for these "unknown" exposures was not given to participants until after their dose equivalent estimates were received at ORNL, some information necessary for dosimeter evaluation was provided such as sphere response ratios or other quantities that could be measured in the field. Thus, for some exposures, the incident neutron spectrum could be inferred from these characteristic quantities and the incident field was not totally "unknown".

At neutron dose equivalents greater than 1.5 mSv, average dosimeter accuracies were within about 5% of results obtained for the same spectra when explicitly known by participants. Standard deviations among results reported by all participants, ranges of reported results, and precisions indicated by the individual participants were about 20% higher for the unknown fields compared to corresponding results obtained for the same known spectra. At neutron dose equivalents around 0.5 mSv in the unknown fields, measurement accuracies and precisions were consistent with performance observed at low dose equivalents for the same incident spectra when known to participants. For cases where the unknown irradiations were γ-enhanced relative to known spectra, neutron dosimeter performances observed for the unknown exposures were consistent with results obtained for known γ-enhanced irradiations. Therefore, the fact that some incident radiation fields were not explicitly known to participants prior to dosimeter evaluation did not significantly affect neutron dosimeter performance relative to conditions where the incident spectra were identified in advance.

DISCUSSION

Since this paper is already a summary of ORNL intercomparison results, PDIS data presented in the preceding text will not be further summarized. Instead, the relationship of the PDIS results to occupational neutron monitoring, accreditation testing and methods to improve neutron personnel dosimetry will be discussed.

Occupational monitoring

With regard to occupational monitoring, one question of interest is what do the PDIS results imply about the neutron personnel dosimetry capabilities at participating organizations. Performance characteristics of the basic dosimetry systems presented in this paper are based on averages of dose equivalent estimates reported by a variety of facilities who used a variety of badge designs, detection mechanisms, evaluation methods, calibration techniques and dose equivalent reporting conventions. Some participants were relatively new at neutron personnel monitoring and did not have their systems adequately characterized. These persons were primarily interested in gaining experience with their dosimetry systems and obtaining some calibration data. Other participants were very experienced in neutron personnel dosimetry so that their systems were well characterized and some (those who had participated in previous PDIS) were even calibrated to several HPRR spectra. Most participants had neutron dosimetry capabilities somewhere between the new and very experienced organizations and were primarily interested in testing and further characterizing their monitoring systems. Considering the ranges of types of participating organizations and neutron dosimetry experience encountered in the Oak Ridge intercomparisons, the mean normalized dose equivalents used in the preceding analysis are probably good indications of the performance capabilities of the "average" neutron dosimetrist, and the associated standard deviations are probably good indications of the variation in capabilities among PDIS participants for the scope of irradiations considered in these studies.

One primary difference between occupational neutron monitoring and the PDIS exposures is that in the latter case, the irradiation conditions (incident radiation field, angular orientation and badge mounting medium) are essentially ideal in that they are known to the participants prior to dosimeter evaluation. Differential neutron energy spectra and other field characteristics of the HPRR are available in the open literature, and all exposures were conducted with the badges mounted on a specified phantom directly facing the source (no angular dependence). These items are not always known to dosimetrists during occupational monitoring. In view of the ideal exposure conditions and the variation in experience among participating organizations, the PDIS results represent the best performance, on the average, that can be expected by dosimetrists doing occupational neutron monitoring in spectra similar to those considered in this summary. Thus, for reference neutron dose equivalents above about 1.5 mSv, most dosimetrists can estimate dose equivalents within 50% of reference values in almost all of the radiation fields considered in the PDIS. At dose equivalents below about 0.5 mSv, some of the basic dosimeter types exhibit problems providing any indication of exposure to neutrons, and variations in accuracy among participating organizations are much larger than those observed at levels greater than 1.5 mSv.

The range of radiation fields provided during the ORNL intercomparisons does include some which are similar to spectra encountered during occupational monitoring. The four most used HPRR spectra are similar to neutron energy spectra encountered at nuclear research facilities (e.g., around research reactors or weapons testing areas), calibration facilities or laboratories containing isotopic sources, well logging operations, fuel storage areas and glove boxes. The hardest HPRR neutron energy spectrum (unshielded reactor) is softer than those around fusion devices and high energy accelerators. The softest reactor spectrum (Lucite-shielded reactor) is harder than those typically encountered inside pressurized water reactor containments or around boiling water reactor containments. The Lucite-shielded spectrum is also harder than that produced by the ^2H_2O-moderated Cf source used to calibrate neutron dosimeters used around reactor plants (Schwartz and Eisenhauer 1981). For radiation fields outside the range of those considered in the PDIS, errors in neutron dose equivalent estimates could be greater than those exhibited for the HPRR spectra. Larger errors would be expected especially for systems with threshold energy response characteristics (NTA film, recoil track) or for TLD-based systems (direct-interaction or albedo) calibrated using hard sources and used to monitor very soft spectra. In the former case, no response or very low dose equivalent estimates would be expected while in the latter case significant overestimates are expected.

Accreditation testing

With regard to accreditation testing, the PDIS irradiation format is basically the same as that used for dosimetry certification; i.e., known incident spectrum, known phantom and orientation and availability of pretest calibration to the incident spectrum. ORNL intercomparison results indicate that about 77% of all participants can meet the present 50% accuracy plus precision standard for neutron personnel monitoring for a much wider variety of spectra than specified in the performance criteria (American National Standards Institute 1983). If the accuracy plus precision standard were decreased to 40% relative to reference values, PDIS results indicate that about 61% of all participants could satisfy this criterion for the range of HPRR spectra. Even if the accuracy plus precision standard were further reduced to 30%, about half (47%) of the intercomparison participants could meet the accreditation specifications. Thus, in view of the format used for neutron dosimeter testing, accreditation criteria could be made even more restrictive than those presently recommended without significantly affecting the number of organizations able to satisfy the neutron monitoring requirements. The PDIS data also indicate that the presently recommended lower dose equivalent limit of 1.5 mSv for neutron testing is high enough to minimize low dose equivalent detection effects for all the basic neutron dosimetry systems. No intercomparison participants exhibited any problems obtaining measurable indication of exposure to neutrons at dose equivalents above this level. Lowering the low dose equivalent limit to 0.5 mSv would severely degrade performance for some of the basic neutron dosimeter types used for occupational monitoring.

Improvement of performance

Based on PDIS experience, what can be done to improve neutron personnel monitoring capabilities? Of primary importance is the selection of a basic dosimeter type which is sensitive to the energies of the neutrons to be monitored. To do this, the dosimetrist must have some knowledge of the neutron energy spectrum in the working environment. Second, the dosimetry system must be adequately calibrated and thoroughly characterized for the range of spectra to be monitored. If a calibration source which closely simulates the expected incident radiation fields is not available, then evaluation algorithms which correct measured dosimeter responses for differences between incident and calibration spectra and for dosimeter energy sensitivity must be developed based on empirical correlations or other applicable methods. Intercomparison results show that with suitable calibration and correction factors, any of the basic neutron dosimeter types can provide very accurate dose equivalent estimates well within accreditation specifications. Finally, one neutron dose equivalent convention and energy interpolation scheme should be specified for reporting occupational and accreditation results. The various international scientific committees (ICRP, ICRU, NCRP, etc.) should initiate an effort to review the many available neutron dose equivalent conventions and determine which has the strongest basis and satisfies the requirements for occupational monitoring and radiation protection. Differences in dose equivalents based on various conventions for the same incident spectrum can be significant (a factor of two or more) and can lead to artificially high occupational neutron dose equivalents and problems in meeting accreditation criteria.

RECOMMENDATIONS

The large numbers of participants in the ORNL Personnel Dosimetry Intercomparison Studies conducted since 1981 indicate that dosimetrists are concerned with testing and characterizing performance characteristics of their neutron monitoring systems. To facilitate these efforts, the DOSAR staff plans to continue the annual intercomparisons and to increase the scope of the radiation fields and exposure conditions. A comprehensive radiation calibration facility is being constructed at ORNL to greatly expand DOSAR irradiation capabilities. In general, communication between the applied dosimetrists, regulatory personnel, research organizations and scientific committees is necessary to ensure that the needs and objectives of all these organizations with regard to neutron dosimetry are recognized and considered.

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