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SUMMARY AND ANALYSIS OF NEUTRON MEASUREMENTS CONDUCTED DURING THE OAK RIDGE PERSONNEL DOSIMETRY INTERCOMPARISON STUDIES

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Abstract

Since 1974, neutron personnel dosimetry intercomparison studies (PDIS) have been conducted annually at the Oak Ridge National Laboratory's (ORNL) Dosimetry Applications Research Facility. During these studies, neutron dosimeters are mailed to ORNL, exposed to low-level (less than 15 mSv) dose equivalents in a variety of mixed-radiation fields produced using the Health Physics Research Reactor (HPRR), and then returned to the participants for evaluation. Beginning with the Seventh PDIS in 1981, interest and participation in the Oak Ridge intercomparisons increased significantly and consistent and documented techniques for determining reference neutron dose equivalents for the HPRR were introduced. This document presents a summary and analysis of approximately 3400 neutron dose equivalent measurements made using a variety of personnel dosimeters and reported for PDIS 7-12.

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INTRODUCTION

Interest in neutron personnel monitoring has increased significantly over the past several years primarily due to the advent of dosimetry accreditation programs[1] and proposed increases in neutron quality factors for radiation protection.[2] To provide an opportunity for dosimetrists to test and calibrate their personnel monitoring systems in a variety of mixed neutron and gamma radiation fields, the staff of the Dosimetry Applications Research (DOSAR) Facility at Oak Ridge National Laboratory (ORNL) has conducted personnel dosimetry intercomparison studies (PDIS) annually since 1974.[3-9] During these studies, neutron dosimeters are mailed to ORNL, mounted on phantoms and exposed to low-level (0.40 to 15.21 mSv) dose equivalents in mixed-radiation fields produced using the Health Physics Research Reactor (HPRR)[10], 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 agencies who made measurements under identical exposure conditions. A total of 116 different organizations (78 from the United States and 38 from foreign countries) has participated in the twelve ORNL intercomparisons conducted to date. These organizations consist of nuclear utilities, industrial and government laboratories, military agencies, universities, vendor services, and hospitals.

Beginning with the Seventh PDIS in 1981, interest and participation in the Oak Ridge intercomparisons increased significantly and have remained high. This study also marked the introduction of consistent and documented techniques for determining reference neutron dose equivalents for the HPRR[11,12]. The following text presents a summary and analysis of about 3400 neutron dose equivalent measurements conducted during PDIS 7-12 using the HPRR as the primary source of radiation. Particular factors examined include threshold effects (low dose equivalent sensitivity) for various neutron dosimeter types, and measurement accuracy and precision as a function of incident neutron energy spectrum and dosimeter type.

INTERCOMPARISON DATA

Most (about 90%) of the reported neutron dose equivalents with the HPRR as the primary source of radiation have been measured for four different fields: the unshielded HPRR and the reactor shielded with 13-cm of steel, 20-cm of concrete, and 12-cm of Lucite. Only results measured for these fields will be considered in the following analysis since they should provide the best indication of neutron dosimeter performance. Table 1 summarizes characteristics of these four radiation fields including neutron mean 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 U^{235} fission neutron spectrum with a relatively low thermal fluence and strong neutron component (unshielded HPRR) to a soft, hydrogen-moderated spectrum with a high thermal fluence and strong gamma component (Lucite-shielded HPRR). Data given in Table 1 are for the most recent (PDIS 11 and 12) HPRR irradiation configuration[12]. Radiation field characteristics[11] for PDIS 7-10 show qualitatively similar relationships between the spectra listed in the table.

Reference neutron dose equivalents for the HPRR are determined using fission yields measured by sulfur pellet activation analysis and dose-equivalent-per-fission conversion factors developed for various spectra[11,12]. In this analysis, reference neutron dose equivalents used for comparison with measured results are based on specifications given in ICRP 21[13]. Approximately 42% of all agencies reporting results used this convention for their neutron dose equivalents in PDIS 7-12. Two other conventions widely used by intercomparison participants to report neutron dose equivalents are described in NCRP 38[14] and by Auxier and Snyder (element 57 convention)[15]. These conventions were used by 26% and 16%, respectively, of the responding participants. The remaining 16% of the participating organizations either used some other convention (6%) to report neutron dose equivalents or didn't know (10%) what convention was associated with their reported results. For the four HPRR spectra considered in this analysis, reference dose equivalents based on NCRP or element 57 specifications typically differ from corresponding ICRP values by less than 10%[8,9].

NEUTRON DOSIMETER TYPES

The 116 different organizations who participated in PDIS 7-12 submitted a total of 5750 neutron monitoring badges which consisted of 4700 which were mounted on phantoms and exposed to various spectra and 1050 control dosimeters. Measured results were reported for 3451 of the badges exposed to HPRR spectra. Although few of the badge designs submitted by different organizations were the same, the basic detection mechanisms can be classified into six categories: direct interaction thermoluminescent (TLD), TLD-albedo, NTA film, recoil track (mostly CR-39), fission track (mostly thorium convertors), and combination albedo plus recoil track[16]. The TLD-based albedo and direct interaction systems, the most popular types used in PDIS 7-12, were used by 45% and 28%, respectively, of the agencies who reported results. Recoil track systems were used by 11% of the reporting organizations. Film, combination, and fission track systems were used by 6%, 6%, and 4%, respectively, of the responding participants. From PDIS 7 to PDIS 12, the percentage use of recoil track, combination, and fission track systems has remained relatively constant while TLD (albedo and direct interaction) use has increased slightly and film has decreased slightly. In addition to these six basic dosimeter types, less than one percent of the neutron results for PDIS 7-12 were obtained using different methods such as other dosimeter types or estimating neutron dose equivalents from gamma results.

DOSE EQUIVALENT SENSITIVITY

To determine the sensitivity of the various neutron dosimeter types, irradiations were conducted during PDIS 8, 9, and 10[5-7] at dose equivalent levels of about 0.5 mSv (50 mrem). For each dosimeter type, Table 2 summarizes the total number of reported measurements, the number of reported measurements greater than zero or the minimum detectable value (M), and the percent of measurements greater than zero for all irradiations. In general, the table 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 indication of neutron exposure at low dose equivalents in that only 4% of all reported results were zero or below minimum detectable. Some of the participants who used combination albedo plus track and direct-interaction TLD systems exhibited slightly greater difficulty obtaining measurable indication of neutron exposure with approximately 9% and 17%, respectively, of the results being reported as zero or M. Although the small number of reported measurements precludes a comprehensive evaluation of dosimeter response at low dose equivalents, about 25% of the fission track results were reported as zero. Approximately 29% of the measurements reported for film dosimeters were zero or M for all spectra. Recoil track systems exhibited the most problems providing measurable results with about 47% of the data reported as zero. At this dose equivalent level, the percent of measurements greater than zero or M for the basic dosimeter types showed no obvious correlation with incident spectrum[7]. The next lowest neutron dose equivalent value considered in the ORNL intercomparisons was about 1.5 mSv (150 mrem)[9] which is the lowest limit specified for neutron accreditation tests[1]. None of the basic dosimeter types exhibited any difficulty providing measurable indication of neutron exposure at dose equivalent levels in this range.

ACCURACY AND PRECISION

The quantities of most concern to those involved in applied dosimetry or dosimetry accreditation testing are measurement accuracy and precision. In this analysis, accuracy will be indicated by a normalized dose equivalent which is the reported measured result divided by the reference neutron dose equivalent provided by the DOSAR staff. Measurement precision will be indicated by one standard deviation about the mean of all measured results for a particular irradiation.

Table 3 shows measurement accuracy for each of the six basic dosimeter types as a function of HPRR spectrum and the total number of measurements considered for each dosimeter type. Data given in the table are based on results obtained in PDIS 7 through 12[4-9] for reference neutron dose equivalents between 1.48 and 15.21 mSv. Accuracy values represent the average normalized results reported by all participants who used a particular dosimeter type for each spectrum. Standard deviations associated with the indicated data are about 25% of the means in each case.

For dosimeter types with more than 100 measurements, TLD-albedo dosimeters are overall the most accurate providing results within 28% of reference values for all spectra. The hardest spectra (unshielded and steel-shielded) are measured more accurately than the softest spectra (concrete- and Lucite-shielded) with the average normalized values increasing monotonically with increasing spectrum softness: i.e., increasing thermal-to-fast fluence ratio. This performance is characteristic of albedo systems calibrated with hard sources (unmoderated Cf, PuBe, or the unshielded HPRR) with no corrections applied to the dosimeter response to account for differences between incident and calibration spectra[4-9].

Direct interaction TLD 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 thermal neutrons than albedo dosimeters, the amount of overestimation for the soft spectra is much greater for direct interaction TLD's. Some individual agencies who use direct interaction systems calibrated to hard spectra overestimated Lucite-shielded dose equivalents by factors of three or more relative to reference values.

On the average, film neutron dosimeters underestimated dose equivalents for all spectra and provided results between 62% and 70% of reference values. This performance has been observed in all ORNL intercomparisons and is a consequence of the threshold response characteristics of NTA film dosimeters (insensitive to neutrons with energies below about 700 keV) and the fact that most reporting organizations calibrated with neutron sources much harder than any HPRR spectra; e.g., unmoderated Cf and PuBe. Recoil track (mostly CR-39) systems, which also have a threshold energy sensitivity (insensitive to neutrons below about 200 keV), also generally provided underestimates of neutron dose equivalents for all spectra. Average measured results varied from 60% to 97% of reference values with the unshielded HPRR spectrum being the most accurate. For each spectrum, average accuracies exhibited by recoil track systems are comparable to or significantly better than those exhibited by film dosimeters. Fission track dosimeters (thorium converter), which also have threshold response characteristics (insensitive to neutrons with energies below about 1 MeV), produced the most accurate results with average normalized values within 21% of reference dose equivalents for all spectra. However, the small number of reported results for this dosimeter type prevents any conclusive comparisons between fission track dosimeters and accuracies observed for other basic systems used in these studies.

Combination albedo plus recoil track dosimeters are designed to provide a wide range of neutron energy sensitivity by combining the strong sensitivity of albedo systems to intermediate energy neutrons with the strong sensitivity of recoil track dosimeters to fast neutrons. Table 3 shows that combination dosimeters provided average results from 70% to 102% of reference values for all spectra. Qualitatively, variations in accuracy as a function of incident spectrum for combination systems were closer to that observed for recoil track dosimeters than for albedo dosimeters in that average normalized results were very close to reference values for the unshielded HPRR spectrum and were lower than reference values for all moderated reactor spectra.

With regard to measurement precision, single standard deviations about the mean for results reported by individual organizations averaged about 11% for all irradiations 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 systems exhibited the best precisions with average standard deviations of about 9% of the means and about 75% of all reporting organizations showing single standard deviations of 10% or less of the means. Fission track systems produced the poorest precisions with average standard deviations of about 18% of the means and approximately 25% of all reporting organizations showing single standard deviations of 10% or less of the means. These results show that for well over half of the participants in these ORNL intercomparisons, measurement precision is not a problem relative to accuracy.

CONCLUSIONS

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

1. For neutron monitoring, TLD-based systems (albedo and direct interaction) are the most popular among participants in the ORNL personnel dosimetry intercomparisons. Between PDIS 7 and 12 (1981 to 1986), the percentage use of recoil track, combination albedo-track, and fission track systems has remained almost constant while TLD popularity has increased slightly and film has decreased slightly.

2. Most (42%) participating organizations reported neutron dose equivalents in the ICRP 21 convention. About 26% and 16% used the NCRP 38 and element 57 conventions, respectively. About 10% of all responding participants did not know what convention was associated with their reported results.

3. Participants who use TLD-based systems had fewer problems obtaining measurable indication of neutron exposure at dose equivalent levels of about 0.5 mSv than did those who used track-based systems. None of the basic dosimeter types exhibited any sensitivity problems at neutron dose equivalents greater than about 1.5 mSv.

4. Overall, TLD-albedo dosimeters were the most accurate with average results within 28% of reference values for all HPRR spectra. Best results were obtained for the hardest neutron energy spectrum while dose equivalents for moderated spectra were overestimated relative to reference values. Direct interaction TLD systems showed the same qualitative performance as albedo dosimeters but exhibited much greater overresponse for moderated spectra.

5. Track-based systems (film and recoil track) provided average dose equivalents which were lower than reference values for all spectra. Fission track dosimeters, which had the fewest reported measurements of all dosimeter types, exhibited good average

accuracy but the poorest precision. Performance characteristics of combination albedo-track dosimeters were qualitatively much closer to those observed for recoil track systems than for albedo systems.

6. Neutron measurement precision as reflected by one standard deviation about the mean of results were within 10% of the mean for 68% of the reporting organizations. These results indicate that for over half the participants, measurement precision is not a problem compared to accuracy.

RECOMMENDATIONS

The large number of participants in ORNL Personnel Dosimetry Intercomparison Studies conducted since 1981 indicates that dosimetrists are concerned with testing and evaluating performance characteristics of their personnel neutron and gamma monitoring systems. 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. In addition, a comprehensive radiation calibration facility is now being constructed at ORNL to greatly expand DOSAR irradiation capabilities.

Table 1. HPRR radiation field characteristics at the dosimeter exposure locations[a]

Shield	Average neutron energy, MeV	Ratio of thermal-to-fast fluence[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 meters from the HPRR with the reactor operated over the storage pit at 1.4 m above the floor.

[b]Thermal($\lesssim$ 0.5 eV) fluence divided by fast ($\gtrsim$ 1 MeV) fluence.

Table 2. Dose equivalent sensitivity for various neutron dosimeter types[a]

Dosimeter type	Total reported measurements	Number of results >0 or M[b]	Percent of results >0 or M
TLD-albedo	464	445	96
Combination albedo + track	64	58	91
TLD-direct interaction	96	80	83
Fission track	8	6	75
NTA film	112	80	71
Recoil track	81	43	53

[a]Based on data from PDIS 8, 9, and 10 for irradiations with reference neutron dose equivalents of about 0.5 mSv.

[b]M = minimum detectable value.

Table 3. Measurement accuracy for various neutron dosimeter types in HPRR radiation fields[a]

HPRR shield	Average normalized neutron dose equivalent[b]					
	TLD-albedo	TLD-direct	Film	Recoil track	Fission track	Combination albedo + trac
None	1.09	0.94	0.66	0.97	1.20	1.02
13-cm steel	1.12	0.95	0.62	0.68	1.21	0.70
20-cm concrete	1.21	1.36	0.63	0.60	1.03	0.75
12-cm Lucite	1.28	1.74	0.70	0.84	0.95	0.96
Number of measurements	1023	459	121	192	48	110

[a]Based on data from PDIS 7-12 for irradiations with reference neutron dose equivalents greater than 1.5 mSv.

[b]Average of measured divided by reference values for each spectrum. Associated standard deviations are about 25% of the means in each case.