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FOURTH INTERCOMPARISON OF PERSONAL DOSEMETERS USED IN US DEPARTMENT OF ENERGY ACCELERATOR FACILITIES

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Abstract — Personal neutron dosemeters from seven US Department of Energy (DOE) laboratories were mailed to the European Laboratory for Particle Physics (CERN) and irradiated using the well-characterised CERN reference radiation facility (CERF). Neutron dose equivalents determined using the DOE personal dosemeters have been compared to the reference dose equivalent as determined using a tissue-equivalent proportional counter (TEPC). In the 0.5 to 5 mSv dose equivalent range, the comparison of results suggests that the neutron personal dosemeters in use at DOE facilities are capable of estimating dose equivalents for high energy neutrons to within a factor of at least 2 or 3. If a field-specific calibration factor is used to correct the dose equivalent responses, the agreement with the reference dose equivalent for these dosemeters can be improved to better than about 25 to 65%. Suggestions for future intercomparison studies and methods of improving personal dosimetry at accelerator facilities are discussed.

INTRODUCTION

The US Department of Energy administers the operation of twelve laboratories that perform research using high energy particle accelerators. The accelerators in use at these laboratories produce complex radiation fields with particle energies ranging from a few MeV up to several TeV. The accurate determination of the dose equivalent in complex radiation fields is very challenging, especially for neutrons, because currently available radiation detectors are quite energy dependent in their dose equivalent responses.

Despite the energy dependent dose equivalent response of personal dosemeters and area monitors, accurate estimates of dosimetric quantities can still be obtained at accelerator facilities if field-specific calibration factors are used and if the dosimetry system is not overly sensitive to small perturbations in the energy spectrum of the radiation field (e.g. small changes in the radiation field caused by scattering from the floor or walls). It would be useful to develop dosemeters that provide improved dose equivalent responses. However, the effort to develop improved personal dosimetry systems at DOE accelerator facilities is hampered by the lack of an appropriate national or international standard for high energy neutron dosimetry.

To help assess the performance of the dosimetry systems in use at DOE accelerator facilities, the Department of Energy periodically sponsors high energy neutron personal dosemeter intercomparison studies[1]. In this fourth intercomparison study, the results of a series of dosemeter irradiations, performed at the European Laboratory for Particle Physics (CERN) in the reference radiation facility (CERF) high energy neutron field, are presented. The European Commission has sponsored a reference radiation facility at CERN to provide a simulated workplace neutron field, as recommended in ISO Standard 12789[2]. From the data collected in the study, a set of CERN-specific calibration factors, or field correction factors, has been calculated for each dosimetry system. These correction factors would allow for the determination of dose equivalent values that are significantly more consistent with the reference dose equivalents derived from measurements performed by CERN personnel. Suggestions for future intercomparison studies and methods of improving personal dosimetry at accelerator facilities are also discussed.

EXPERIMENTAL PROCEDURE

Participants in the fourth DOE intercomparison study provided one, or more than one, type of neutron personal dosemeter from each of seven DOE laboratories: Argonne National Laboratory (ANL), Brookhaven National Laboratory (BNL), Lawrence Berkeley National Laboratory (LBNL), Los Alamos National Laboratory (LANL), Pacific Northwest National Laboratory (PNNL), Stanford Linear Accelerator Center (SLAC), and the Thomas Jefferson National Accelerator Facility (TJNAF). Each laboratory provided 20 replicate dosemeters for the intercomparison study. The dosemeters provided by two of the seven laboratories included both thermoluminescent detectors (TLD) and

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polyallyldiglycol carbonate plastic (often referred to by the trade name* CR-39) etched track detectors (TED), allowing for two independent estimates of the neutron dose equivalent.

Once the dosemeters from the participating laboratories arrived at PNNL, each dosemeter was assigned a unique identifying number. A group of 98 dosemeters was shipped to Geneva for irradiation at the CERN facility. A group of 42 dosemeters remained at PNNL to act as unirradiated controls. At CERN, the dosemeters were divided into three groups. Eight dosemeters from each institution were exposed in the reference high energy neutron radiation field. Two dosemeters from each laboratory were exposed to neutrons from a ^{238}Pu-Be(α,n) neutron source, and the remaining four dosemeters from each institution were used as controls to correct for background radiation encountered during transit to and from CERN. The dosemeters were irradiated at CERN and returned to PNNL. All 140 of the dosemeters were re-packaged and shipped back to the appropriate institutions so that dose equivalents could be determined using their normal analysis methods.

CERN reference radiation field

At the CERN super proton synchrotron, a beam of hadrons (protons and pions) with an approximate energy of 120 GeV impacts on a copper target to produce a cascade of high energy secondary particles, including neutrons. The radiation produced at a 90° angle to the plane of the copper target then passes through an 80 cm thick concrete shield. The cascade of secondary radiation that passes through the concrete shield includes an intense neutron fluence strongly peaked around 100 MeV with another evaporation peak around 1 to 2 MeV. This neutron energy spectrum is similar to the neutron spectrum produced by the cosmic radiation encountered during commercial airline flights[3].

A grid pattern has been established on top of the shielding surrounding the beam line, and measurements have been performed at various places on this grid using a Bonner sphere spectrometer system and a TEPC. Monte Carlo calculations[4] of the neutron energy spectrum at grid locations CT7 and CT11 on the concrete shield are shown in Figure 1. The data in Figure 1 indicate that the neutron energy spectrum is strongly peaked in the 100 MeV region and decreases rapidly for higher and lower energies. Dosemeters were mounted on the face of a $30 \times 30 \times 15$ cm^3 polymethylmethacrylate (PMMA) phantom for irradiations both at grid locations CT7 and CT11 as well as the ^{238}Pu-Be reference irradiations.

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HANDI-TEPC

The HANDI system has been described in detail in an earlier publication[5]. It consists of a tissue-equivalent proportional counter (TEPC), supporting electronics and a computer to evaluate various dosimetric parameters. This system was used to measure the event-size[6] distribution as a function of lineal energy, y, produced by the high energy neutrons incident upon the TEPC. Within the precision of the TEPC, lineal energy y closely approximates linear energy transfer L (or LET). Multiplication of the event size distribution with the L-dependent quality factor Q(L) as defined in ICRP Publication 21[7], or the more recent values from ICRP Publication 60[8], yields the dose equivalent to a microscopic volume of tissue. A lineal energy of approximately 10 keV.μm^{-1} was used to differentiate between events resulting from low L radiation (e.g. photons and muons) and high L radiation (hadrons including neutrons). The dose equivalent thus obtained for high L radiation behind the concrete shielding at CERF compares very well with FLUKA simulations of the dose equivalent due to neutrons in the same positions[4]. Also, for high energy neutron fields such as the one used in this study, the dose equivalent values obtained using the ICRP 21 and ICRP 60 quality factors are approximately equal to the ICRU's dose equivalent index[9] and the personal dose equivalent[10] operational quantities, respectively.

During the dosemeter irradiations, the intensity of the hadron beam generating the radiation field was monitored with an ionisation chamber. In a separate measurement, the ratio of charge collected in the ionisation chamber to dose equivalent in positions CT7 and CT11 was determined using the TEPC. Calibration of the HANDI system was based on uniform irradiation of the detector with gamma rays from a ^{60}Co source. Regular verification tests were also performed using an alpha particle source within the counter.

Descriptions of the dosimetry systems

The seven study participants reported nine independent determinations of the dose equivalent for each radiation exposure (for convenience, labelled A to I). The readings of dosemeters used by two of the seven participants yielded values for dose equivalent based on the response of TLD and CR-39 TED dosemeters. Because the dose equivalent response of each dosemeter is dependent, to some extent, on neutron energy and because the characteristics of the radiation field at each DOE accelerator facility differ, the calibration factors used by a particular accelerator facility (although appropriate for their own facility) may or may not be appropriate for the CERN reference radiation field. Brief descriptions of the DOE personal dosemeters used in the study are given below. As mentioned earlier, some participants submitted two dosemeter types. For these cases, the dosemeters are described together.

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Dosemeter A

This dosemeter consists of the Panasonic model 810 (Panasonic Industrial Company, Secaucus, NJ). It incorporates both $^{6}Li_2{}^{10}B_4O_7$ and $^{7}Li_2{}^{11}B_4O_7$ elements. A CR-39 TED is also attached behind the Panasonic dosemeter to detect high energy neutrons. A fully automated system, developed by the laboratory, was used to read out the CR-39 foils that had undergone electrochemical processing. The dosemeters were calibrated to an unmoderated ^{252}Cf neutron fission source.

Dosemeters B and H

The dosemeter B neutron dose equivalent values were estimated using the TLD chip readings from a Harshaw model 8816 neutron TLD/TED dosemeter (Bicron-NE, Solon, OH). The 8816 dosemeter includes a TLD-700 chip and three TLD-600 chips filtered (front/back) by a layer of Sn/Sn, Cd/Sn, Sn/Cd and Sn/Sn, respectively. Neutron dose equivalent values were determined from the TLD chip readings by applying a set of energy dependent calibration factors. The calibration algorithm uses ratios of filtered chip readings to determine the relative importance of low and high energy neutrons in a radiation field. The dosemeter B calibration algorithm has been tuned to provide accurate results for a wide range of moderated and unmoderated ^{252}Cf fission neutron sources. The dosemeter B photon dose equivalent values were determined using a Harshaw model 8825 beta-gamma TLD dosemeter consisting of four TLD 700 chips filtered by copper, tin and plastic. The etched track detector foils included in the 8816 dosemeter were also used to obtain an independent estimate of the neutron dose equivalent. The dosemeter H results were the dose equivalent values determined using the electrochemically etched TED foils and a calibration factor appropriate for unmoderated ^{252}Cf fission neutrons.

Dosemeters C and E

The TLD portion of this dosemeter (dosemeter E) is the Harshaw (Bicron-NE, Solon, OH) model 8814 with three ^{7}LiF:Mg,Ti chips and one ^{6}LiF:Mg,Ti chip. The dosemeter also has an exterior plastic pouch, attached in the back, containing a commercially available CR-39 TED detector processed by Landauer Inc. (Glenwood, IL). The TLD portion of the dosemeter has been calibrated using unmoderated ^{252}Cf, D_2O-moderated ^{252}Cf, and ^{238}Pu-Be neutron sources. The TED was calibrated using a ^{241}Am-Be source.

Dosemeter D

This dosemeter employs CR-39 for the detection of neutrons with energies greater than 2 MeV. The CR-39 TED methodology is an adaptation of the Hankins system[11] and is based on electrochemical

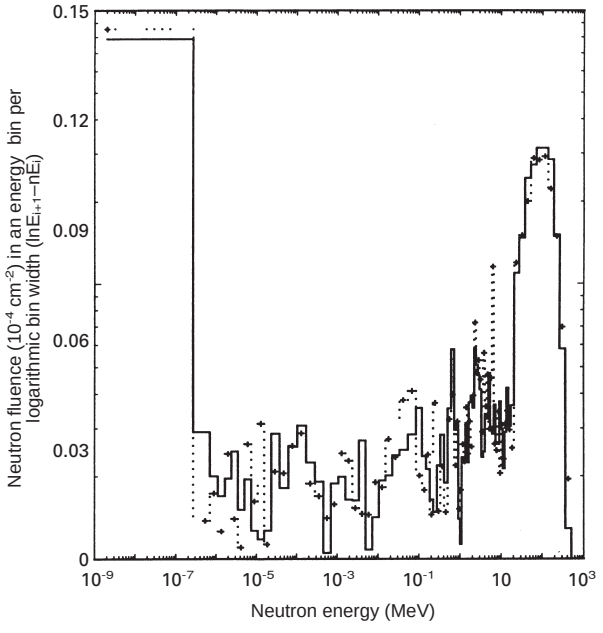

Figure 1. Calculated neutron fluence spectral distributions at grid locations CT7 (solid line), and CT11 (dotted line and crosses) on the concrete shield[14]. Each spectrum is plotted as a histogram and normalised to the number of particles incident on the copper target.

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etching of dosimetry grade CR-39 plastic at elevated temperatures. The foils are 2.85 cm by 1.6 cm by 0.064 cm thick and are covered with a 0.008 cm thick polyethylene covering to exclude alpha track production from radon. After etching the foil, tracks are counted using an optical microscope attached to an automated counting system. Calibration of this dosemeter is also carried out using an unmoderated ^{252}Cf neutron source.

Dosemeter F

Personal dosimetry system F uses a plastic, hemispherical case that encloses a pyramidal shaped polystyrene holder for the TED foils. By averaging the readings from the three foils, the angular dependence normally associated with a planar dosemeter is minimised. An Autoscan 60 (NE Technologies Ltd, Reading, UK) automated reading system is used to count the number of damage sites created by recoil protons in the CR-39 plastic. The TED foils are processed using a two step chemical etching procedure. The dose equivalent is obtained by multiplying the number of tracks per cm^2 by a calibration factor (Sv.cm^2 per track or mrem.cm^2 per track). The calibration factor used for the present intercomparison study is based on the quality factors reported in ICRP 21[7].

Dosemeter G

This dosemeter is distributed by ICN (ICN Dosimetry Service, Costa Mesa, CA) and consists of a Harshaw (Bicron-NE, Solon, OH) dosemeter that incorporates three TLD-700 (^{7}LiF:Mg,Ti) chips, one TLD-600 (^{6}LiF:Mg,Ti) chip and a CR-39 TED. The electrochemical etching process used in the readout of the TED element is performed manually. The TED element of the dosemeter was calibrated using unmoderated fission neutrons from a ^{252}Cf source. Testing of the ^{252}Cf calibration algorithm for the TED element, the component used for routine dose reporting, indicates that this calibration is also accurate for neutrons from a ^{241}Am-Be source. For the present study, the dosemeter G dose equivalent values were computed using the TED element reading and the standard ^{252}Cf calibration algorithm.

Dosemeter I

Dosemeter I is a Panasonic model UD-802 dosemeter (Panasonic Industrial Company, Secaucus, NJ). This dosemeter employs two phosphor materials with different dopings. Lithium tetraborate ($LiBO_4$) or $Li_2B_4O_7$:Cu and calcium sulphate ($CaSO_4$) or $CaSO_4$:Tm are used. The two $LiBO_4$ elements are prepared with lithium and boron in their naturally occurring isotopic abundances. The $LiBO_4$ elements are sensitive to gamma, beta, X ray, and neutron radiations. $LiBO_4$ is approximately tissue equivalent with respect to beta and photon radiations. The $LiBO_4$ elements are significantly more sensitive to low energy (thermal) neutrons than to higher energy neutrons, and these chips are thus suitable for use as an albedo neutron dosemeter. The $CaSO_4$ elements over-respond to X rays (compared to gamma radiation) and are very insensitive to neutrons, making a separation of neutron and non-neutron dose equivalents possible. For the present study, the response of the dosemeter was calibrated using an unmoderated ^{252}Cf fission spectrum and ICRP 21[7] quality factors.

ANALYSIS OF RESULTS

The participating institutions were asked to report the neutron dose equivalent for each personal dosemeter, corrected for the dose equivalent received from background radiation. Study participants were also asked to report neutron dose equivalent estimates for the dosemeters used as controls as well as the dose equivalent resulting from the non-neutron component of the radiation field. An average dosemeter response for each irradiation group was calculated using the formula

$$\overline{H} = \frac{1}{N}\sum_{i=1}^{N} H_i \qquad (1)$$

where N is the number of irradiated dosemeters and H_i is the dose equivalent (mSv) for the ith dosemeter. Equation 1 was used to calculate the average dose equivalent for all dosemeters, including those used as controls. The sample variance associated with the average dose equivalent $\overline{H}$ was calculated using the formula

$$s^2 = \frac{1}{N-1}\sum_{i=1}^{N} (H_i - \overline{H})^2 \qquad (2)$$

The sample standard deviation is the square root of s^2.

Tables 1(a) and 1(b) summarise the dose equivalent estimates obtained for the dosemeters used as unirradiated controls in the study. The ‘PNNL controls’ are the dosemeters that were stored at PNNL for the duration of the experiment and the ‘CERN controls’ are the dosemeters that were shipped to CERN. The response of the purposely irradiated dosemeters was corrected for background radiation using the CERN controls. The laboratory-averaged dose equivalent per transatlantic flight from PNNL (Richland, WA) to CERN (Geneva, Switzerland), as determined from the control dosemeters, is 0.1 ± 0.3 mSv per flight from neutrons, 0.02 mSv $\pm$ 0.05 mSv pe flight from photons, for a total of 0.1 ± 0.3 mSv per flight. Although it was never intended that these dosemeters would be used to perform a primary measurement of in-flight dose equivalent, it is interesting to note that a typical value for the effective dose resulting from a transatlantic flight, derived from data given in the Eurados report on *Exposure of Air Crew to Cosmic Radiation*[12], is 0.06 mSv.

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Figures 2 and 3 and Table 2 summarise the intercomparison study results for irradiation positions CT7 and CT11 at the CERN reference facility. The ICRP 21[7] reference dose equivalent values, as determined with the TEPC, are 2.7 ± 0.3 and 4.9 ± 0.5 mSv for positions CT7 and CT11, respectively. The corresponding ICRP 60[8] dose equivalent values are 3.2 mSv (CT7) and 5.9 mSv (CT11). The error associated with the TEPC dose equivalent values corresponds to an estimated 10% (1 sigma) standard deviation. The results reported for the DOE personal dosemeters are most appropriately compared to the ICRP 21[7] reference dose equivalents.

Figures 2 and 3 show that, in general, the reported dose equivalents for all DOE personal dosemeters were systematically low in comparison to the reference values (dosemeters A, B, C, D, G, and H), except for the high results recorded for dosemeters F and I. The results for dosemeter E appeared to be anomalous in the sense that the average dose equivalent value for position CT7 was about 4% lower than the reference (TEPC) value, while the average dose equivalent for position CT11 was 220% higher than the reference value. Several factors may have contributed to the observed behaviour of the E-type dosemeter. The information available to the authors does not warrant making strong conclusions about the reason for the anomalous behaviour of the E-type dosemeters, although it seems unlikely that a systematic error could have occurred in the processing of all four of the dosemeters irradiated in one position and not the other.

Table 1. Neutron (a) and photon (b) dose equivalent (mSv) for PNNL and CERN controls. The 'transit' dose equivalent is calculated by subtracting the PNNL dose equivalent from the CERN dose equivalent. For calculation purposes only, results are reported to 3 decimal places.

(a)

Laboratory	CERN control		PNNL control		Transit dose equivalent (mSv)	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
A	0.467	0.126	0.492	0.291	–0.025	0.317
B	0.290	0.032	0.063	0.019	0.227	0.037
C						
D	0.040	0.022	–0.053	0.010	0.093	0.024
E	0.097	0.016	0.062	0.015	0.035	0.022
F						
G	0.145	0.029	0.087	0.024	0.058	0.038
H	0.014	0.005	0.007	0.021	0.007	0.022
I						
				Laboratory average	0.055	0.323

(b)

Laboratory	CERN control		PNNL control		Transit dose equivalent (mSv)	
	Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
A	0.317	0.029	0.303	0.008	0.013	0.030
B	0.238	0.015	0.177	0.016	0.061	0.022
C						
D						
E	0.213	0.015	0.182	0.017	0.031	0.023
F	0.001	0.000	0.000	0.000	0.001	0.000
G	0.525	0.019	0.512	0.016	0.013	0.025
H						
I						
				Laboratory average	0.024	0.050

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To provide an additional reference point for the intercomparison study, two of each type of the DOE personal dosemeters were irradiated at the CERN facility using a ^{238}Pu-Be neutron source. The dose equivalent from this source was determined with a transfer instrument, i.e. a rem counter of the type EG&G Berthold LB 6411 calibrated using ^{252}Cf and ^{241}Am-Be neutron sources located at the Physikalisch-Technische Bundesanstalt (PTB) in Germany. The fluence and dose equivalent values for the CERN ^{238}Pu-Be source were then determined using the methods described in International Standard ISO 10647[13]. For this transfer calibration, it was assumed that the response of the rem counter to neutrons from ^{241}Am-Be is the same as that for neutrons from a ^{238}Pu-Be source. The results of the ^{238}Pu-Be irradiations to 1 mSv are summarised in Figure 4. Although the statistical power of the results for ^{238}Pu-Be experiment is low (because of practical constraints), these data suggest that the DOE personal dosemeters are better at estimating neutron dose equivalent values for ^{238}Pu-Be neutrons than for the CERN reference radiation field. The relative error in the DOE personal dose-

Table 2. Reported neutron dose equivalents (mSv) for DOE personnel dosemeters irradiated in the CERN accelerator. The reference ICRP 21 dose equivalent values for positions CT7 and CT11 are 2.7 and 4.9 mSv. For calculation purposes only, results are reported to 2 decimal places.

Dosemeter	Neutron dose equivalent (mSv)			
	CT7 irradiation		CT11 irradiation	
	Average	Standard deviation	Average	Standard deviation
A	0.81	0.03	1.70	0.23
B	0.53	0.06	1.01	0.31
C	0.68	0.22	1.78	0.19
D	1.01	0.21	2.46	0.36
E	2.59	0.19	10.82	0.52
F	3.32	0.11	6.94	0.13
G	0.67	0.16	1.48	0.22
H	0.72	0.08	1.69	0.04
I	5.23	0.66	10.68	1.51

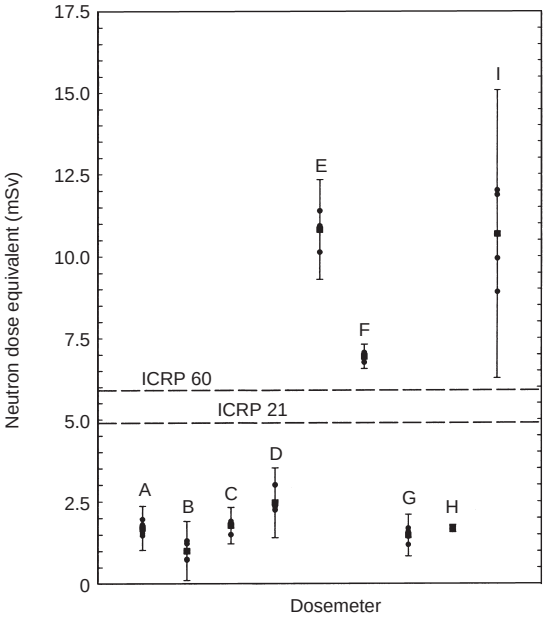

Figure 2. Summary of intercomparison study results for CERN irradiation position CT11. The average dose equivalent response for each dosemeter (■) is shown with a 99% confidence interval. The data points (●) used to calculate the average dosemeter response and the associated sample standard deviation are also shown. The reference ICRP 21 and 60 neutron dose equivalents, as determined with the TEPC, are 4.9 mSv and 5.9 mSv, respectively. The estimated 1 σ relative error in both reference TEPC measurments is 10%.

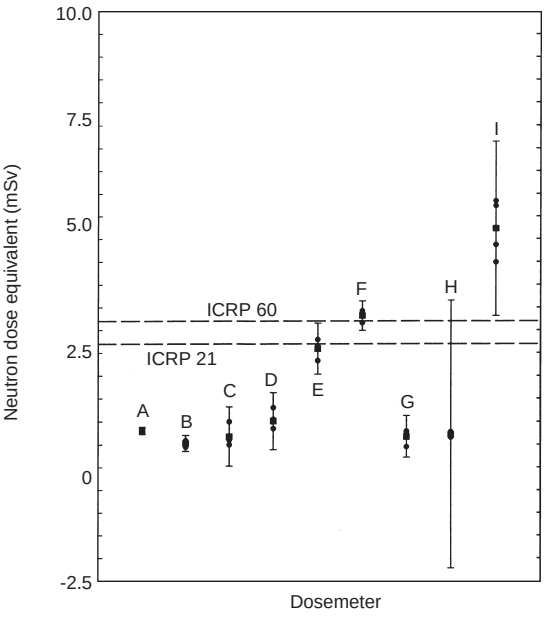

Figure 3. Summary of intercomparison study results for CERN irradiation position CT7. The average dose equivalent response for each dosemeter (■) is shown with a 99% confidence interval. The data points (●) used to calculate the average dosemeter response and the associated sample standard deviation are also shown. The reference ICRP 21 and 60 neutron dose equivalents, as determined with the TEPC, are 2.7 mSv and 3.2 mSv, respectively. The estimated 1 σ relative error in both reference TEPC measurments is 10%.

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meter results, when irradiated with ^{238}Pu-Be neutrons, ranged from a low of 2.5% to a high of 63% (compared with a 4 to 300% relative error for the accelerator irradiations).

One way to improve the performance of DOE personal dosemeters for a specific radiation field, or facility, is to multiply the dose equivalent reading obtained using a standardised dose estimation algorithm and a specific calibration source (e.g. ^{252}Cf or ^{241}Am-Be) by a field-specific correction factor. This procedure can be expressed mathematically as

$$\overline{H}'(k) = f_k\overline{H}(k) + c_k = \frac{1}{N}\sum_{i=1}^{N}[f_kH_i(k)] + c_k \qquad (3)$$

where $\overline{H}'(k)$ is the field-corrected mean dose equivalent value for the kth type of radiation field (Sv), f_k is a dose equivalent multiplication factor for the kth type of radiation field (Sv.Sv^{-1}), and c_k is the projected dose equivalent response at zero dose (Sv). The dose equivalent values $\overline{H}'(k)$ and $\overline{H}(k)$ are implicit functions of the intensity of the kth radiation field (i.e. the magnitude of the particle fluence). The quantity $f_kH_i + c_k$ is the field-corrected dose equivalent value for the ith dosemeter irradiated in the kth radiation field.

To help improve the performance of DOE personal dosemeters in future studies, estimates of the parameters f_k and c_k for the ^{238}Pu-Be and CERN reference neutron radiation field have been obtained by performing an inverse linear regression[14] of the intercomparison study results. This regression analysis was performed using software based on the IMSL RONE and RINPF statistical analysis routines (Visual Numerics, http://www.vni.com/). The dose equivalent values determined using the TEPC were taken as the 'conventional true' dose equivalent with an associated standard deviation of zero. An inverse regression analysis was performed using the general form of Equation 3 as well as for the special case when c_k is forced equal to zero (i.e. the intercept is not included in the model). For the case when $c_k = 0$, the multiplication factor f_k is approximately equal to the 'conventional true' dose equivalent divided by the dose equivalent obtained using the standard dose estimation algorithm. Because only two of each of the dosemeter types were irradiated with the ^{238}Pu-Be source, f_k for the ^{238}Pu-Be source was estimated by dividing the 1 mSv 'conventional true' dose equivalent value by the average of the two reported dose equivalent readings.

Table 3 summarises the results of the regression analysis of the calibration equation, Equation 3. A non-zero value for c_k indicates that the dose estimation algorithm responds in a non-linear fashion with the dose of radiation, i.e. because of non-linearities in the dose-response of the dosemeter, or other unknown spurious effects (i.e. so-called 'outliers' in the reported dose equivalent values). For all of the dosemeters used in the study, the regression analysis of the general form of the calibration equation yielded positive values for c_k. In all cases except one (dosemeter E), analysis of the variance suggests that outliers had a significant effect on the regression analysis, i.e. a much larger F-statistic[14] was obtained for the calibration with the intercept forced through zero ($c_k = 0$) than the one obtained for the general calibration equation which allows for non-zero values of c_k. With the exception of dosemeter E, the preferred calibration parameters for the CERN simulated workplace neutron field are those obtained when the regression analysis is based on the model without an intercept, e.g. the preferred calibration parameters for dosemeter A in the CERN workplace neutron field are $f_{CERN} = 2.982$ and $c_{CERN} = 0$. For dosemeter E, the preferred calibration parameters for the CERN reference facility field are $f_{CERN} = 0.268$ and $c_{CERN} = 2.00$. While these parameters are applicable for use in the present experiment, they are not necessarily appropriate for other experiments or dosemeters.

Although it appears that outliers in the reported dose equivalent values had a significant effect on the regression analysis of parameters for Equation 3, further analysis of the data suggests that all of the dosemeters used in the study may also respond in a non-linear fashion to irradiation in the CERN simulated workplace neutron field. Figure 5 shows the corrected dose equivalent values, $H'_i(k) = f_kH_i(k)$, obtained when the reported dose equivalent values for positions CT7 (●) and CT11 (▼) are extrapolated to a dose of 1 mSv. For an 'ideal' dosemeter, the extrapolated data from position CT7 (2.7 mSv) and CT11 (4.9 mSv) would be randomly distributed about 1 mSv. However, the data shown in Figure 5 clearly indicate that for all of the dosemeters, with the possible exception of dosemeter B, the extrapolated dose equivalent values obtained from positions CT7 and CT11 appear to be clustered in a binary fashion about two different values.

Table 3. Summary of calibration equation (Equation 3) parameters for ^{238}Pu-Be fission neutrons and the CERN simulated workplace neutron field. For calculation purposes only, results are reported to 2 decimal places.

Laboratory	General calibration equation (CERN field)		Calibration equation ($c_k = 0$)	
	f_k	c_k	CERN field f_k	^{238}PuBe f_k
A	2.47	0.71	2.98	1.26
B	4.65	0.23	4.92	2.70
C	2.00	1.35	2.98	1.18
D	1.52	1.16	2.11	1.82
E	0.27	2.01	0.52	0.88
F	0.61	0.69	0.73	1.03
G	2.73	0.86	3.46	1.82
H	2.26	1.08	2.99	1.28

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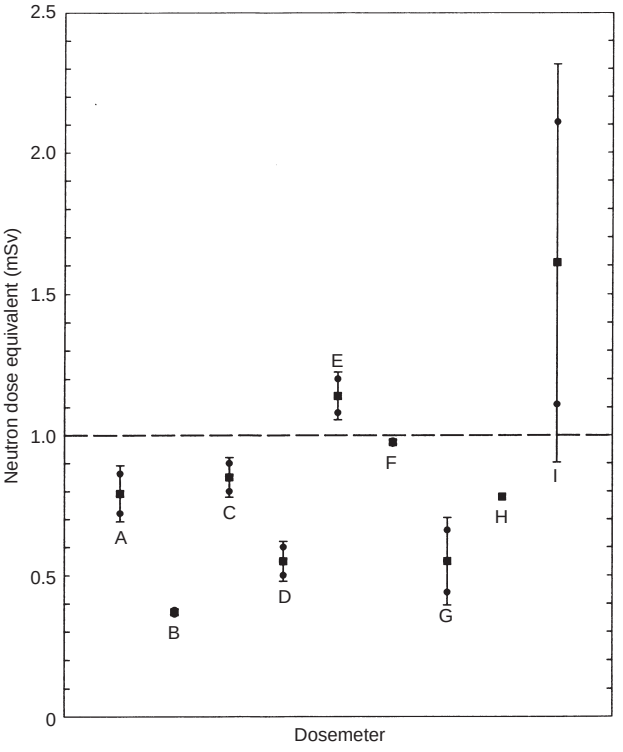

Figure 4. Neutron dose equivalents for a 1 mSv ^{238}Pu-Be neturon source. The average dose equivalent response for each dosemeter (■) is shown with a 68% (1 σ) confidence interval. The data points (●) used to calculate the average dosemeter and the associated sample standard deviation are also shown.

For some of the dosemeters, the apparent clustering of extrapolated dose equivalent values may be attributed to outliers, e.g. the data for dosemeters C and I. For other dosemeters such as dosemeter F and especially E, the clustering of dose equivalent values is not easily attributed to outliers. The clustering of extrapolated dose equivalent values may either be caused by actual differences in the radiation field at positions CT7 and CT11 in the field, or they may be caused by non-linearities in the dose estimation algorithm (e.g. the correction for background radiation). Although the statistical power of the study is too low to make a definitive judgement, the lack of a systematic pattern to the clustering effects among the dosemeter types argues in favour of the latter explanation.

The above concerns about outliers in the reported dose equivalent values tend to decrease confidence in the accuracy of the calibration parameters summarised in Table 3. Nevertheless, the corrected and re-normalised dose equivalent values shown in Figure 5 suggest that the accuracy of the measurements of dose equivalent values in the CERN simulated workplace neutron field could be improved by a factor of 3 to 12 if a field-specific calibration procedure were to be used. That is, the relative error in the dose equivalent values determined using the DOE personal dosemeters could be decreased from a factor of 200 to 300%, for the uncorrected values, to less than about 25 to 65% for the field-corrected values.

CONCLUSIONS AND SUGGESTIONS FOR FUTURE WORK

Although practical constraints limited the statistical power of the intercomparison study, useful results and conclusions can still be drawn from the data. Analysis of the dose equivalent values reported for the CERN simulated workplace neutron field suggests that (1) some of the reported dose equivalent values are too high or too low for unknown reasons and (2) the dose equivalent values for most of the dosemeters display an anomalous clustering of dose equivalent values that indicates the standard dosemeter and dose-estimation algorithms in use at DOE accelerator facilities may not respond in a linear fashion to the CERN simulated workplace neutron field. The apparent non-linear response of these dosemeters in the high energy neutron field generated by the CERN reference facility is not particularly surprising in light of the fact that personal

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dosemeters are usually optimised for the characteristics of the specific radiation field where they are used.

Analysis of the intercomparison study results suggests that the use of a field- or facility-specific calibration procedure could significantly improve the accuracy of values obtained by DOE personal dosemeters. For the CERN reference facility, the use of a field-specific calibration procedure could improve the accuracy of some personal dosemeters by as much as an order of magnitude, i.e. decrease the relative error in dose equivalent estimates from about 200 to 300% to the range of 25 to 65%. Intercomparison studies, such as this one, offer a useful method for improving dosemeter calibrations because the direct comparison of results for different dosemeters irradiated in identical fields can provide information that helps to identify inconsistencies in the experimental protocol and reported results, as well as help identify the strengths and weaknesses of specific personal dosemeters.

To improve the usefulness of future intercomparison studies, the number of dosemeters irradiated at each dose of interest should be increased to improve the statistical power of the study. The authors recommend the irradiation of at least 10 dosemeters for each dose of interest. To better test for non-linearities in dosemeter response, irradiations should be conducted for at least three different dose equivalent values (e.g. 0.5, 2.5, and 5.0 mSv). Information on the angular response of the participant's dosemeters should also be provided so that variations of the neutron fluence as a function of angle can be accounted for. In order to generate more accurate calibration factors for each DOE facility, it is suggested that additional intercomparison studies should be conducted at DOE accelerator facilities. TEPC dose equivalent determinations and Bonner sphere spectrometer measurements of the neutron energy spectrum should always be included in future intercomparison studies in order to provide a common reference dose equivalent value for estimating field-specific calibration procedures.

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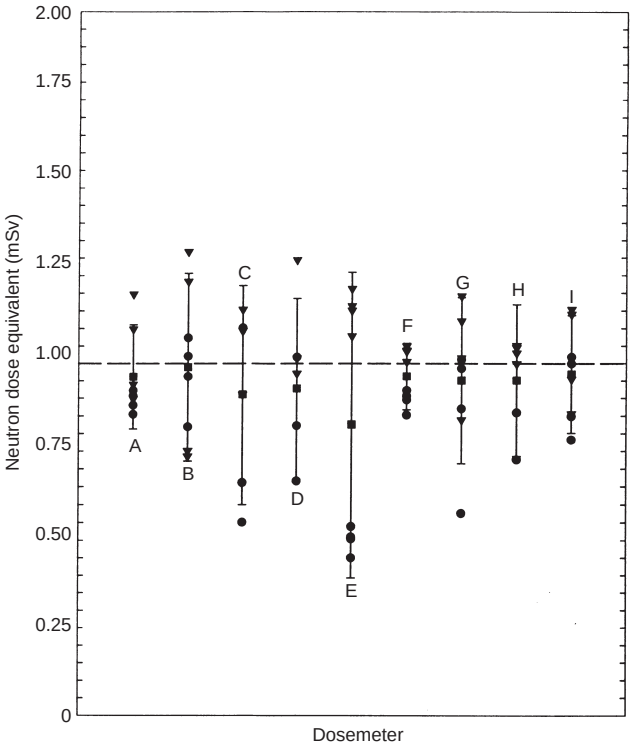

Figure 5. Neutron dose equivalents for position CT7 (●) and CT11 (▼) linearly extrapolated to a dose equivalent of 1 mSv. The average dose equivalent response for each dosemeter (■) is shown with a 99% confidence interval. The data points used to calculate the average dosemeter response and the associated sample standard deviation are also shown.

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