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NEUTRON MEASUREMENTS AT HANFORD'S PLUTONIUM FINISHING PLANT

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August 2009

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Summary

The Pacific Northwest National Laboratory (PNNL) conducted neutron measurements at Hanford's Plutonium Finishing Plant (PFP). The measurements were performed to evaluate the performance of the Hanford Standard Dosimeter (HSD) and the 8816 TLD component of the Hanford Combination Neutron Dosimeter (HCND) in the neutron fields responsible for worker neutron exposures.

For this study, TEPC detectors and multisphere spectrometers were used to measure neutron dose equivalent rate, and multispheres were used to measure average neutron energy. Water-filled phantoms holding Hanford dosimeters were positioned at each measurement location. The phantoms were positioned in the same location where a multisphere measurement was taken and TEPCs were also positioned there. Plant survey meters were also used to measure neutron dose rates at all locations.

Three measurement locations were chose near the HC-9B glovebox in room 228A of Building 234-5.

The multisphere spectrometers measured average neutron energies in the range of 337 to 555 keV at these locations. Personal dose equivalent, $H_p(10)_n$, as measured by the multisphere and TEPC, ranged from 2.7 to 9.7 mrem/h in the three locations. Effective dose assuming a rotational geometry (E_{ROT}) was substantially lower than $H_p(10)$, ranging from 1.3 to 3.6 mrem/h. These values were lower than the reported values from dosimeters exposed on a rotating phantom. Effective dose assuming an AP geometry (E_{AP}) was also substantially lower than $H_p(10)$, ranging from 2.3 to 6.5 mrem/h. These values were lower than the reported values from the dosimeters on slab phantoms. Since the effective dose values were lower than reported values from dosimeters, the dosimeters were shown to be conservative estimates of the protection quantities.

Acronyms and Abbreviations

AP or A-P	Anterior-posterior geometry
Cf	Californium
CFR	Code of Federal Regulations
DOE	United States Department of Energy
E_{AP}	Effective dose, anterior-posterior geometry
E_{ROT}	Effective dose, rotational geometry
$H^*(10)_n$	Ambient dose equivalent, neutrons
HCND	Hanford combination neutron dosimeter
$H_p(10)_n$	Personal dose equivalent, neutrons
HPS	Health Physics Society
HSD	Hanford standard dosimeter
ICRP	International Commission on Radiological Protection
keV	$1 \cdot 10^3$ electron volts
LIPEAK	Computer code for processing a peak in a pulse height spectrum
MAXED	Computer code for spectrum unfolding
MCA	Multichannel analyzer
MeV	$1 \cdot 10^6$ electron volts
n/cm^2s	Neutrons per square centimeter per second, units of neutron flux
PFP	Plutonium Finishing Plant
PNNL	Pacific Northwest National Laboratory
ROT	Rotational geometry
TEPC	Tissue Equivalent Proportional Counter
TEPCalc	Computer code for analysis of TEPC runs

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1.0 Introduction

Neutron measurements were performed at Hanford's Plutonium Finishing Plant (PFP) during the time frame of March 16 through March 20, 2009. The measurements were performed to evaluate the performance of the Hanford Standard Dosimeter (HSD) and the 8816 TLD component of the Hanford Combination Neutron Dosimeter (HCND) in the neutron fields responsible for worker neutron exposures. The measurements were similar to those performed at PFP in 1999, and reported in PNNL-13136 (Scherpelz et al. 2000); and those performed in 2003 and reported in (Scherpelz and Rathbone, 2003).

For this study, TEPC detectors and multisphere spectrometers were used to measure neutron dose equivalent rate, and multispheres were used to measure average neutron energy. Water-filled phantoms holding Hanford dosimeters were positioned at each measurement location. The phantoms were positioned in the same location where a multisphere measurement was taken and TEPCs were also positioned there. Plant survey meters were also used to measure neutron dose rates at all locations.

This study was the first dosimeter validation measurement to be performed after the neutron dosimeter algorithms and algorithms for analyzing TEPC and multisphere measurements were upgraded to reflect ICRP 60 dosimetric concepts incorporated into the June 8, 2007 revision to 10 CFR 835 (DOE 2007) . The HSD and 8816 dosimeter results were calculated using External Dosimetry dose calculation algorithm version 11.

2.0 Neutron Measurements

Measurements were made at the PFP in March, 2009 to verify the performance of Hanford personnel neutron dosimeters. The measurements were made near a glovebox containing residual plutonium. This location is significant for producing neutron dose among Hanford workers.

2.1 Measurement Locations

Measurements were made at the PFP in Room 228A of 234-5 near the HC-9B glove box. Measurements were taken at three locations near the glovebox. Location 1 was at the south face of the glovebox, near its east end. Location 2 was south of the glovebox, near the wall. Location 3 was off the west end of the glovebox. The three locations are illustrated in Figure 2-1.

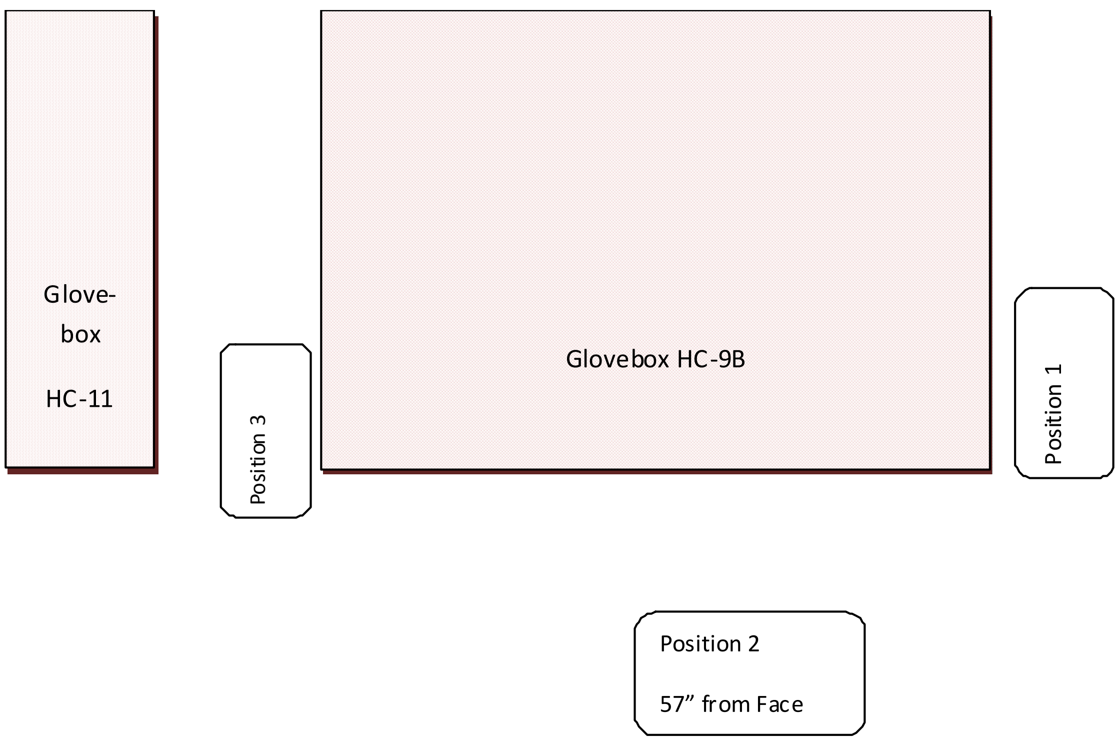

Figure 2-1. Measurement locations near Glovebox HC-9B in Room 228A (not to scale).

2.2 Measurement Methods

At each measurement location, the following measurements were made:

- A plant survey meter (remball) was placed on the multisphere stand to get a reading of dose equivalent rate
- A multisphere spectrum was measured

- Two tissue equivalent proportional counters (TEPCs) were positioned and spectra collected
- A water-filled slab phantom was set up with three 8816 and three HSD dosimeters on the face of the phantom that faced the glovebox
- A cylindrical phantom was positioned on a rotating table, with six 8816 and six HSD dosimeters distributed around the phantom.

Each measurement configuration was employed individually, with no other instruments nearby. The heights of the positioning stands were adjusted so that all instruments had their center of sensitive region at the same location.

Multisphere Spectrometer: For each multisphere measurement, seven moderator/detector configurations were used. For each of these measurements, a pulse-height spectrum was collected in a multichannel analyzer (MCA). This spectrum was analyzed by a PNNL analysis routine called "LIPEAK", which fits a Gaussian distribution to the region of interest, including the peak of neutron counts. It then uses this distribution to find the full integral of counts under the peak, a background count, and the net area under the peak. The net area is used to find the neutron count rate, and an uncertainty value is derived from the counting statistics uncertainty of the integral and of the background. The neutron count rates and uncertainties are input to the computer code MAXED (Reginatto and Goldhagen, 1998) to determine the binned neutron flux. This binned neutron flux is then input into a post-processing spreadsheet to determine the following quantities:

- Total flux
- Average energy
- $H_p(10)_n$ (personal dose equivalent at 10 mm depth in tissue for neutrons)
- $H^*(10)_n$ (ambient dose equivalent at 10 mm depth in tissue for neutrons)
- Effective dose, rotational geometry (E_{ROT})
- Effective dose, anterior-posterior (A-P or AP) geometry (E_{AP})

The values for $H_p(10)$, $H^*(10)$ and effective dose were found by multiplying the binned fluxes by conversion factors derived from ICRP-74 (ICRP, 1996).

Multisphere Uncertainty: The results of measurement studies in calibration laboratories at PNNL and at Los Alamos National Laboratory (LANL) were used to estimate the uncertainty involved in a multisphere measurement. In this study, 17 different measurements were made with multisphere spectrometers exposed in a variety of well-characterized neutron fields (Scherpelz and Conrady, 2008). The comparison of measured dose equivalent rates to accepted dose equivalent rates was used to derive a bias and precision, following the guidelines of Sections 3.4.2 and 3.4.3 of the HPS N13.30 standard (Health Physics Society, 1996). The bias was estimated to be -0.018, and the precision was estimated to be 0.12.

Tissue Equivalent Proportional Counter (TEPC): For each TEPC measurement, a pulse-height spectrum was collected in the MCA, and the spectrum was analyzed using a PNNL analysis routine called TEPCalc (Scherpelz and Conrady, 2008). This code converts the pulse height spectrum into a lineal energy spectrum, and uses this to determine the absorbed dose to the detector, and uses a routine based on ICRP-60 (ICRP 1990) to determine quality factor. The product of the absorbed dose and quality factor is a dose equivalent value that approximates (slightly over estimates) the delivered $H_p(10)$ from bare and moderated ^{252}Cf under parallel beam calibration conditions. TEPC results are reported as the quantity $H_p(10)$. Since two detectors were used at the measurement location, the average of the two measurements are reported as the TEPC result for that location. The measurements were all within 10% of the reported average for that location.

TEPC Uncertainty: The results of measurements studies in calibration laboratories at PNNL and at LANL were used to estimate the uncertainty involved in a TEPC measurement. In this study, 36 different measurements were made with TEPC detectors exposed in a variety of well-characterized neutron fields (Scherpelz and Conrady, 2008). The comparison of measured dose equivalent rates to accepted dose equivalent rates was used to derive a bias and precision, following the guidelines of Sections 3.4.2 and 3.4.3 of the standard HPS N13.30 (Health Physics Society, 1996). The bias was estimated to be 0.17, and the precision was estimated to be 0.086.

Dosimeters on Rotating Phantom: For exposures of dosimeters on a rotating phantom, the phantom was a cylindrical water-filled polyethylene bottle, 28 cm in diameter and 38 cm tall. Six 8816 dosimeters were strapped around the bottle, just above the bottle's vertical centerline, evenly spaced around the bottle. Six HSD dosimeters were strapped around the bottle, just below the 8816s. The bottle was placed on a rotating table, with the table rotating slowly to expose all dosimeters to the same radiation field. Exposure times ranged from 24 to 114 hours, with the goal of exposing the dosimeters to at least 100 mrem.

Dosimeters on Slab Phantom: For exposures of dosimeters on a slab phantom, the phantom was a polyethylene water-filled bottle with large flat faces, dimensions 37 cm by 36 cm by 15 cm. Three 8816s and three HSDs were affixed to one face of the bottle. Exposures ranged from 22 to 115 hours.

Dosimeter Readout: All dosimeters were processed in the Hanford External Dosimetry laboratory using standard procedures and ICRP 60 based algorithms to determine $H_p(10)_n$ values for the entire exposure. These values were divided by the exposure time to determine a dose equivalent rate. For dosimeters exposed on the rotating phantom, dose equivalent rates from all six identically-exposed dosimeters were averaged to get the reported dose; for dosimeters exposed on the slab phantom, three identically-exposed dosimeters were averaged for the reported value.

3.0 Measurement Results

Results of the PFP measurements are presented in this section.

3.1 Dose Equivalent Rates

Measured neutron dose equivalent rates in PFP are given in Table 3-1.

Table 3-1. Measured neutron dose equivalent rates

		(mrem/h)		
Instrument	*Measured Quantity*	*Location 1*	*Location 2*	*Location 3*
Remball	Dose equivalent rate	6.5	3.14	2.67
TEPC	$H_p(10)_n$	7.63	3.63	2.88
Multisphere	$H_p(10)_n$	9.68	3.85	3.32
Multisphere	$H^*(10)_n$	9.38	3.73	3.21
Dosimeters: 8816 on rotating phantom	$H_p(10)_n$	5.16	2.67	2.26
Dosimeters: HSD on rotating phantom	$H_p(10)_n$	8.43	6.97	6.08
Multisphere	Effective dose: ROT geometry	3.63	1.46	1.28
Dosimeters: 8816 on slab phantom	$H_p(10)_n$	11.0	4.67	3.04
Dosimeters: HSD on slab phantom	$H_p(10)_n$	14.2	9.35	7.59
Multisphere	Effective dose: AP geometry	6.51	2.61	2.28

The effects of the uncertainties inherent in the dosimeters and instruments are shown in Table 3-2. For each measurement, a one-standard-deviation range is given. For the TEPC and multisphere, the lower- and upper-bound values were found by applying the bias factor to derive an unbiased estimate, then subtracting and adding the precision value. For dosimeters, the bounds were found using the means and standard deviations of the six (or three) readings reported for identically exposed dosimeters.

Table 3-2. Estimated uncertainty bounds for instruments and dosimeters

Instrument	*Dosi-meter Type*	*Estimated bounds of dose equivalent rates (mrem/h)*		
		Location 1	*Location 2*	*Location 3*
TEPC		5.77 – 6.87	2.74 – 3.26	2.18 – 2.59
Multisphere		8.69 – 11.04	3.46 – 4.39	2.98 – 3.79
Dosimeters on Rotating Phantom	8816	4.41 – 5.90	2.29 – 3.05	2.09 – 2.42
	HSD	8.25 – 8.61	6.77 – 7.17	5.87 – 6.29
Dosimeters on Slab	8816	9.15 – 12.85	4.53 – 4.80	2.82 – 3.26
	HSD	13.3 – 15.2	8.97 – 9.72	7.38 – 7.80

3.2 Neutron Spectra

Summaries of the measured neutron spectra in PFP are given in Table 3-3. Graphs of the measured neutron flux distributions are presented in Figures Figure 3-1, Figure 3-2, and Figure 3-3. Table 3-4 presents the binned fluxes for the three measurement locations.

Table 3-3. Summary of neutron spectra measured by the multisphere

Location	*Neutron Flux (n/cm^2s)*	*Average Neutron Energy (keV)*
Location 1	113	555
Location 2	70	337
Location 3	62	337

Figure 3-1. Neutron spectrum measured at PFP Location 1

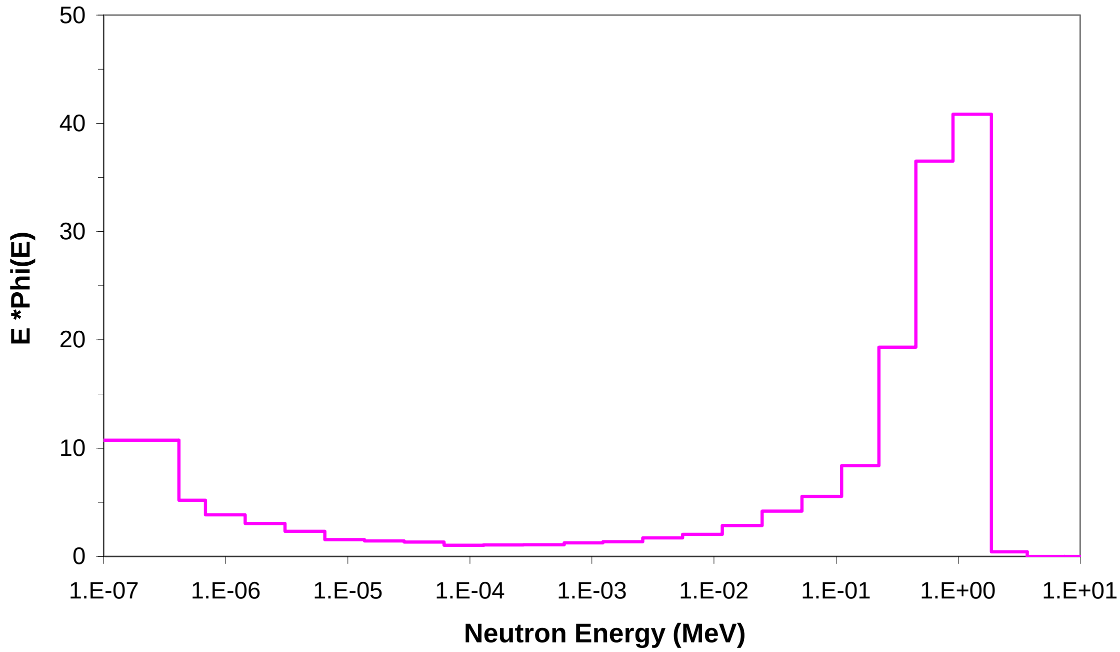

Figure 3-2. Neutron spectrum measured at PFP Location 2

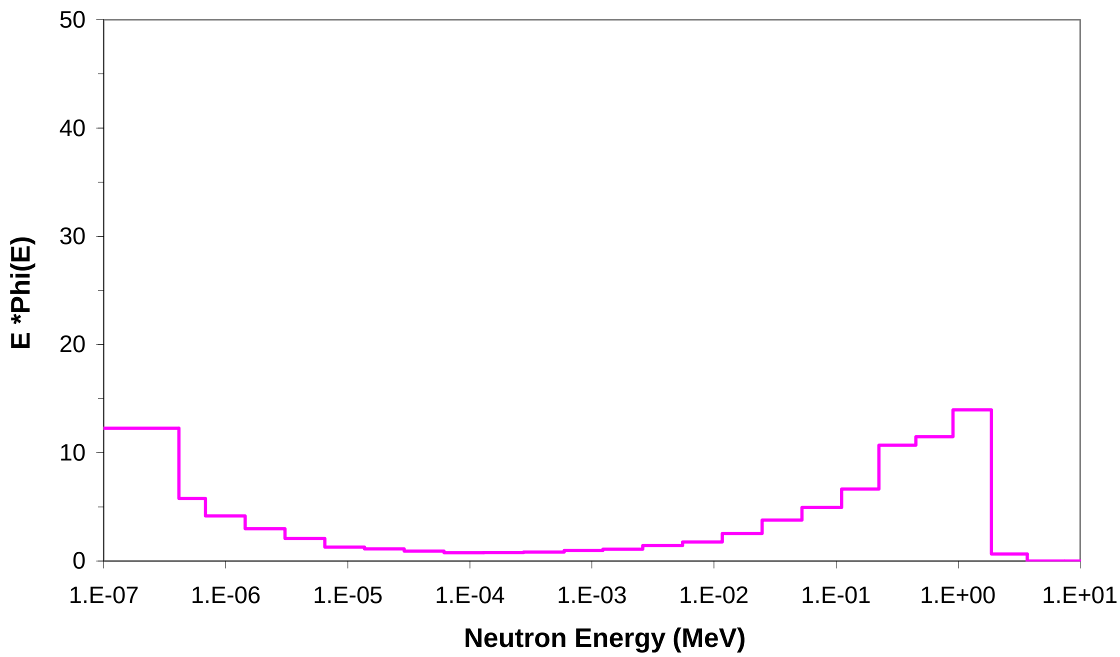

Figure 3-3. Neutron spectrum measured at PFP Location 3

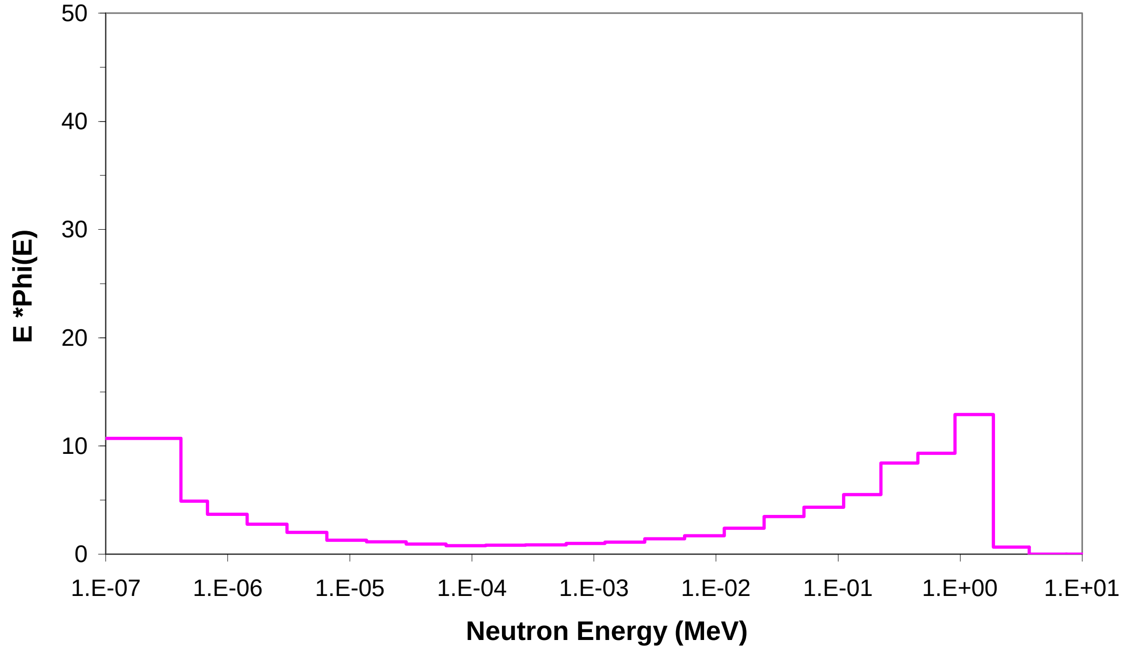

Table 3-4. Neutron spectra measured by the multisphere

Energy-low (MeV)	*Energy-high (MeV)*	*Binned neutron flux (n/cm^2·s)*		
		Location 1	*Location 2*	*Location 3*
1.00E-07	4.14E-07	13.097	14.978	13.068
4.14E-07	6.83E-07	2.545	2.832	2.393
6.83E-07	1.45E-06	2.751	2.981	2.630
1.45E-06	3.06E-06	2.177	2.134	1.983
3.06E-06	6.48E-06	1.652	1.495	1.445
6.48E-06	1.37E-05	1.110	0.922	0.917
1.37E-05	2.90E-05	1.032	0.804	0.817
2.90E-05	6.14E-05	0.944	0.649	0.664
6.14E-05	1.30E-04	0.738	0.542	0.563
1.30E-04	2.75E-04	0.762	0.564	0.585
2.75E-04	5.93E-04	0.796	0.604	0.622
5.93E-04	1.23E-03	0.876	0.680	0.693
1.23E-03	2.61E-03	0.977	0.787	0.790
2.61E-03	5.53E-03	1.233	1.028	1.014
5.53E-03	1.17E-02	1.463	1.260	1.217
1.17E-02	2.48E-02	2.046	1.819	1.715
2.48E-02	5.25E-02	2.993	2.714	2.483
5.25E-02	0.1111	3.970	3.544	3.108
0.1111	0.2237	5.632	4.475	3.704
0.2237	0.4508	13.011	7.198	5.670
0.4508	0.9072	24.538	7.713	6.265
0.9072	1.872	28.354	9.698	8.955
1.872	3.679	0.284	0.429	0.421
3.679	7.408	4.36E-04	4.75E-03	4.31E-03
7.408	14.92	1.73E-10	3.06E-09	2.67E-09
14.92	25.81	1.33E-20	5.50E-20	4.65E-20

4.0 Discussion

The neutron fluxes measured by the multisphere had relatively high energies for workplaces. Average energies ranged from 337 keV to 555 keV in the three locations near Glovebox HC-9B. In highly-moderated workplaces, average energies are often in the range of 100 keV. The measurements by HC-9B were all taken relatively near to the neutron sources, and the high average energies probably result from the influence of unscattered, or lightly-moderated neutrons relative to neutrons that experienced many scatters before reaching the dose point. In the 2003 PFP measurement study, a multisphere reading in the same room also showed a relatively high-energy spectrum for a workplace, with an average energy of 742 keV.

The $H_p(10)_n$ values for the multispheres in the three locations are somewhat higher than the corresponding $H_p(10)_n$ values determined by the TEPC. These values are also higher than the dose equivalent readings given by the neutron survey meter. These $H_p(10)_n$ values were more than double the E_{ROT} values determined by the multisphere, and substantially higher than the E_{AP} values determined by the multisphere, as would be expected. As an illustration, Tables A.41 and A.42 of ICRP-74 show similar differences for $H_p(10)_n$ compared to E_{ROT} and E_{AP}, depending on energy of the neutron.

There was no overlap in the one-standard-deviation uncertainty bounds for TEPC and multisphere measurements of $H_p(10)_n$ at each location. This result was disappointing, because studies in calibration laboratories had shown a much better correspondence between the results generated by the two instruments. The TEPC values are always lower than the multisphere values, supporting the conclusion that multisphere measurements do not underestimate the true value of $H_p(10)_n$.

The $H_p(10)$ values determined by the multisphere were all higher than the corresponding E_{ROT} and the E_{AP} values. This demonstrates that the operational quantities are conservative compared to the protection quantities recommended by ICRP 60 and recently adopted by DOE (DOE 2007).

Comparing the E_{ROT} values calculated from the multisphere measurements to the $H_p(10)_n$ values reported by dosimeters exposed on the rotating phantom is a technique for testing the performance of the dosimeters. The multisphere determines the neutron energy distribution, and this distribution is converted to effective dose assuming a rotational exposure geometry. The dosimeter reported neutron dose is based on calibration of the dosimeter to $H_p(10)_n$ in parallel beam AP exposure geometry. The $H_p(10)$ values reported by the 8816 are all higher than the corresponding E_{ROT} values, which demonstrates that the value reported by the dosimeter is conservative compared to the protection quantity for the work locations measured.

For the HSD dosimeters exposed on rotating phantoms, reported $H_p(10)$ values were significantly higher than those reported by the 8816s, and these values were substantially higher than the E_{ROT} values at the same locations. The HSD reported $H_p(10)_n$ values are based on a dosimeter neutron calibration factor derived from calibration of the dosimeter to bare ^{252}Cf in parallel beam AP exposure geometry under laboratory conditions. For workplace spectra with average neutron energies substantially less than bare ^{252}Cf (2.2 MeV average energy for the emission spectrum), a significant over-response is to be expected.

Comparing E_{AP} values to the reported $H_p(10)$ values for dosimeters exposed on slab phantoms is also an indicator of dosimeter performance. The unscattered neutrons emitted from the glovebox that strike the face of the phantom would approximate an A-P beam, and this component of the neutron field would dominate the total dose equivalent. The dosimeter reported dose is based on calibration of the dosimeter to $H_p(10)_n$ in parallel beam AP geometry, which over estimates effective dose in AP exposures, for neutron energies between 100 keV and a few MeV (see Figure 57 in ICRP 74). The $H_p(10)$ values reported by 8816's are all higher than the corresponding E_{AP} values, demonstrating conservatism. HSD values are substantially higher than 8816 values, as observed on the rotating phantoms.

In general, the effective dose values derived from the multisphere measurements should be reliable estimates of the effective dose that would be encountered by workers in this room. PNNL believes that the estimates of neutron energy distribution could be improved with new multisphere response functions (Scherpelz and Conrady 2008), but the current performance of the instrument is adequate for evaluating the performance of the dosimeters. The TEPC measurements generally confirmed the $H_p(10)_n$ values from the multispheres, further confirming the effective dose evaluations of the multispheres.

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