ORAU TEAM
Dose Reconstruction Project for NIOSH

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03/17/2004	00	New Technical Information Bulletin in Support of INEEL Technical Basis Document Section 6: Reanalysis of Hankins MTR Bonner Sphere Surveys. First approved issue. Initiated by Norman D. Rohrig.
12/13/2006	01	Approved Revision 01 for biennial review. Adds Introduction with required language and a Purpose section. Per new document requirements, added a Table of Contents. Constitutes a total rewrite of document. Incorporates internal and NIOSH formal review comments. This revision results in no change to the assigned dose and no PER is required. Initiated by Norman D. Rohrig. Training required: As determined by the Task Manager. Initiated by Norman D. Rohrig.

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ACRONYMS AND ABBREVIATIONS

cm	centimeter
DE	dose equivalent
DECF	dose equivalent conversion factor
DOE	U.S. Department of Energy
EBR	Experimental Breeder Reactor
ETR	Engineering Test Reactor
eV	electron-volt
hr	hour
in.	inch
ICRP	International Commission on Radiological Protection
INEEL	Idaho National Engineering and Environmental Laboratory
IREP	Interactive RadioEpidemiological Program
keV	kiloelectron-volt, 1,000 electron-volts
MeV	megavolt-electron, 1 million electron-volts
mm	millimeter
mrem	millirem
MTR	Materials Test Reactor
NCRP	National Council on Radiological Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
nrem	nanorem
NTA	nuclear track emulsion, Type A
TIB	technical information bulletin
U.S.C.	United States Code
§	section or sections

1.0 INTRODUCTION

Technical information bulletins (TIBs) are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained. TIBs may be used to assist NIOSH staff in the completion of individual dose reconstructions.

In this document the word “facility” is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an “atomic weapons employer facility” or a “Department of Energy [DOE] facility” as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [42 U.S.C. § 7384l(5) and (12)].

2.0 PURPOSE

This TIB provides a reanalysis of early neutron measurements from the Materials Test Reactor (MTR) at the Idaho National Engineering and Environmental Laboratory (INEEL) using present-day results for detector sensitivity to provide neutron spectra results based on current knowledge. This TIB results in neutron spectra which then have a certain portion of dose equivalent with energy below the detection threshold for NTA film. The correction for undetected neutron dose is then applied to neutron dose both measured by NTA film badges and that which would be missed by the badges. For persons not exposed to neutrons, this TIB has no affect on their dose reconstruction.

3.0 REANALYSIS OF HANKINS MTR BONNER SPHERE SURVEYS

Dale Hankins made a series of neutron field measurements (Hankins 1961) with 2-, 3-, and 8-in.-diameter Bonner spheres (or balls) around the INEEL Materials Test Reactor (MTR). The balls were covered with a cadmium shield, which eliminates thermal neutrons below 0.41 eV. These 25 measurements were mostly around the MTR floor, but one was at Experimental Breeder Reactor (EBR)-I through 9 ft of concrete and three were at the Engineering Test Reactor (ETR). Six other measurements labeled A to F include a thermal neutron component determined from the difference between a bare and a cadmium covered detector.

Since then, significant improvements have been made to understanding the responses of these detectors to neutrons of all energies and, in particular, intermediate neutrons. The Hankins data have been reanalyzed using detector responses calculated by Hertel and Davidson (1985) for 171 energy groups from thermal to 17.3 MeV, as shown in Figure 3-1. This figure shows a higher sensitivity for the 2-in. and 3-in. detectors at low energies as compared to Figure 2 in Hankins (1961). These calculated response curves are more complete than the ones available in 1961, particularly below 100-keV neutron energy where monoenergetic neutron spectra are not available.

These calculated response matrices are for 4- by 4-mm lithium iodide detectors, whereas the Hankins data used 2- by 8-mm detectors. Hertel and Davidson (1985) also calculated responses for 0.5- by 0.5-in. detectors, which have a larger response by about a factor of the detector surface area. Because most reactions in the detector are on the detector surface, the calculated neutron fluences and resulting dose equivalents are reduced by roughly a factor of 2 for all detectors and energies to account for the different size detectors used by Hankins (1961).

Limited determination of the energy spectrum can be made from three different measurements of neutron response and the additional requirement that the number of neutrons in any energy region

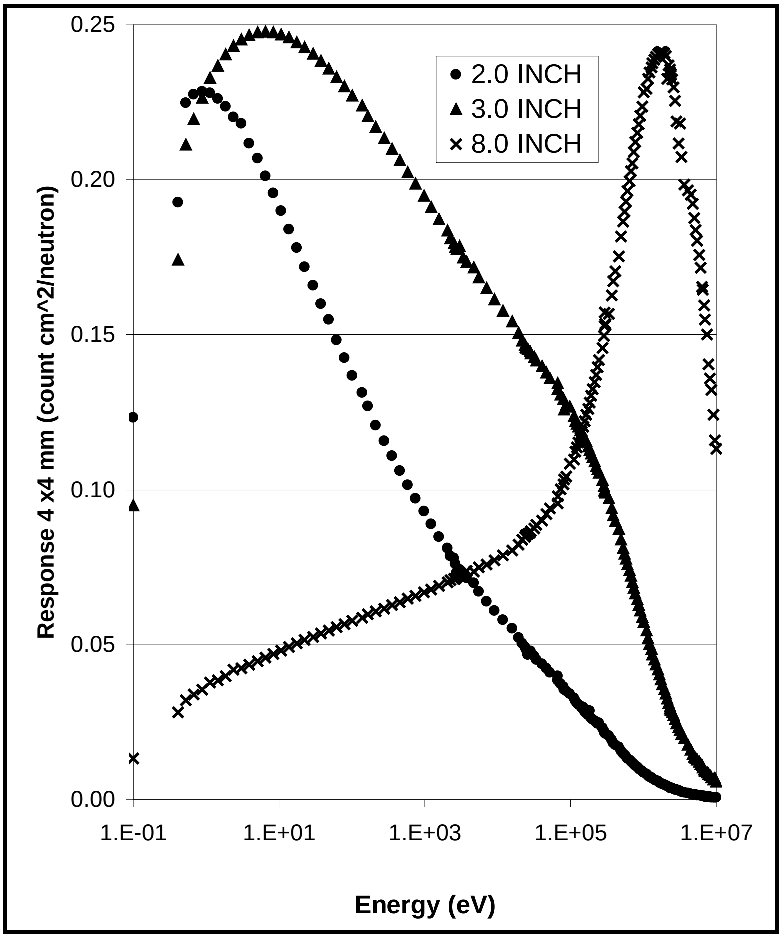

Figure 3-1. Energy response of Bonner spheres.

cannot be negative. Following Hankins (1961), the fraction of the summed response in each of the three balls (2-, 3-, and 8-in.) is calculated for a fission spectrum, and a 1/*E* slowing down spectrum; spectral components expected in the reactor. The 1/*E* spectrum was assumed to go up to 0.6 MeV and was divided into two sections at 10 keV. To fit the Hankins data, the fission spectrum of the form (Knoll, p 21) was used above 0.6 MeV.

$$\varphi(E) = \frac{1}{E^{1/2}} e^{-E/T} \tag{3-1}$$

For a typical fission spectrum, the characteristic temperature *T* is about 1.3 MeV, which was used in these calculations. The measured detector responses were expressed as a linear combination of the three spectra (1/*E*: 0.4 eV to 10 keV, 1/*E*: 10 to 600 keV, and fission) and solved.

To determine the dose equivalent, one must multiply the fluence at each energy by the dose equivalent conversion factor (DECF) for that energy and add them (i.e., integrate). The official tabulations provide conversion factors at limited energy values. Ing and Makra (1978) provide a parameterization for dose equivalent with energy that we use here. Figure 3-2 compares this parameterization to Monte Carlo calculations reported in National Council on Radiological Protection and Measurements (NCRP) Report 38 (NCRP 1971) and by Auxier et al. (1968).

Table 3-1 lists measured values from Hankins (1961) and the resulting reanalyzed dose equivalents from the three energy groups and their sum. Table 3-2 provides the same information for the six

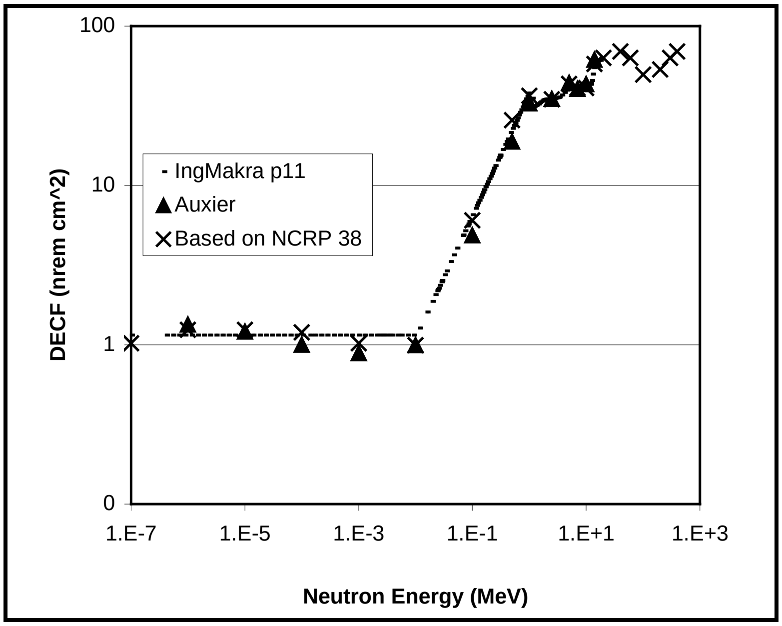

Figure 3-2. Neutron dose equivalent conversion factor (nrem/cm^2).

Table 3-1. Data from Hankins (1961) and reanalyzed doses.

Location[b]	**Total cpm**[a]	***% Total cpm***[a]			***Dose equivalent (mrem/hr)***			
		2 in.	***3 in.***	***8 in.***	***0.4 eV–10 keV***	***0.01–0.6 MeV***	***Fission***	***>0.4 eV***
EBR-I 1	2,935.6	31.3	49.9	18.8	0.208	0.337	0.300	0.845
2	491.7	30.7	49.5	19.8	0.034	0.064	0.066	0.163
3	2,854.1	31	49.4	19.6	0.200	0.304	0.462	0.966
4	2,966.2	30.6	49.1	20.3	0.204	0.340	0.556	1.100
5	2,315.2	29.8	49.1	21.1	0.152	0.375	0.350	0.876
6	1,698.5	29.9	48.9	21.2	0.113	0.247	0.314	0.674
7	611.1	29.6	48.4	22	0.040	0.084	0.149	0.273
8	981.9	29.5	48.3	22.2	0.064	0.136	0.250	0.450
9	5,539	28.9	48.2	22.9	0.350	0.933	1.338	2.621
10	662.9	29.1	48.1	22.8	0.042	0.100	0.176	0.319
11	5,700.6	29.5	48	22.5	0.376	0.699	1.699	2.773
12	7,603.3	28.7	47.9	23.3	0.477	1.257	2.056	3.789
13	6,185.1	29.3	47.8	23	0.404	0.763	2.005	3.172
14	2,694.6	29.6	47.6	22.8	0.180	0.258	0.973	1.411
15	3,116.3	28.9	47.5	23.6	0.200	0.412	1.071	1.683
16	8,877.1	28.5	47.4	24.1	0.556	1.337	3.021	4.913
17	2,083.4	29	47.3	23.7	0.135	0.241	0.787	1.163
18	2,581.4	28.4	47.3	24.3	0.161	0.391	0.904	1.456
19	1,627.8	28.1	47.3	24.6	0.099	0.275	0.548	0.923
20	4,848.1	28.2	46.8	25	0.302	0.665	2.008	2.975
ETR 21	111.3	27.7	46.5	25.8	0.007	0.017	0.048	0.072
22	1,494.8	28.2	46.2	25.6	0.094	0.158	0.750	1.003
23	4,427.9	26.5	45.6	28	0.252	0.774	2.295	3.321
ETR 24	199.2	26	44.7	29.3	0.011	0.032	0.124	0.166
ETR 25	210.9	25	44	31.1	0.011	0.038	0.144	0.193
				Total	4.672	10.236	22.393	37.300

a. cpm = counts per minute.
b. At MTR, unless otherwise noted.

locations where Hankins provided thermal measurements. The thermal values are as reported by Hankins. Figure 3-3 shows the resulting neutron spectra for locations 3 and 23, which have higher doses and nearly the maximum low energy and fission components, respectively.

Table 3-2. Data from Hankins (1961) with thermal neutron measurement and reanalyzed doses.

	cpm			Dose equivalent (mrem/hr)				
Location	**2 in.**	**3 in.**	**8 in.**	**Thermal**	**0.4 eV–10 keV**	**0.01–0.6 MeV**	**Fission**	**Neutron**
A	877	1,473	700	0.11	0.19	0.56	0.67	1.42
B	196	317	153	0.02	0.04	0.07	0.24	0.35
C	778	1,293	647	0.09	0.17	0.41	0.87	1.46
D	3,518	5,973	3,108	0.32	0.76	2.33	3.94	7.03
E	3,482	5,734	3,064	0.21	0.77	1.50	5.36	7.64
F	557	925	470	0.06	0.12	0.29	0.67	1.08

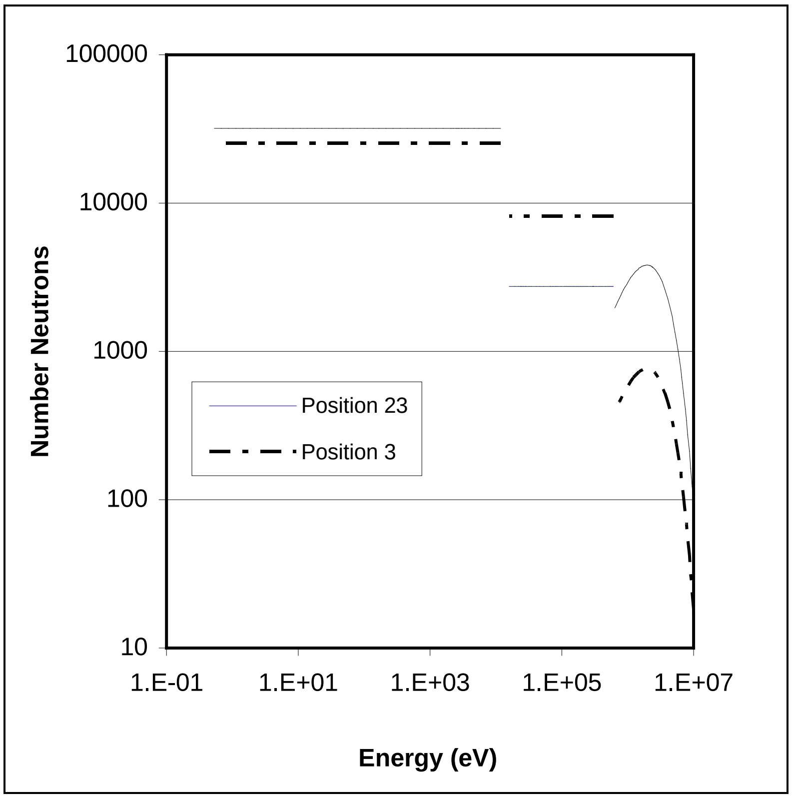

Figure 3-3. Sample MTR spectra from reanalyzing Hankins Bonner sphere measurements.

Another survey at the MTR measured the fast neutron field (Sommers 1959a) using a Rudolf counter described as “a dose rate instrument, sensitive to neutrons in the range of 0.2 to above 10 MeV” (Sommers 1959b). This has been remembered as a detector about the size of a soda can with the end painted red. The Dennis and Loosemore (1961) detector shown in Figure 3-4 is believed to be what was known as the Rudolf counter at the INEEL. It detects hydrogen recoils and has a threshold energy of about 0.2 MeV. Using 0.2 MeV as the division line between fast and intermediate neutrons to correspond to that for this instrument, Figure 3-5 shows the correlation of the recalculated 0.4-eV to 10-keV and 10- to 200-keV neutron dose equivalent rates with the recalculated fast neutron dose equivalent rates along with the correlation of the Hankins analysis intermediate to fast neutron dose equivalents. Also shown are the Hankins thermal dose equivalent rates compared to the recalculated fast neutron dose equivalent rate.

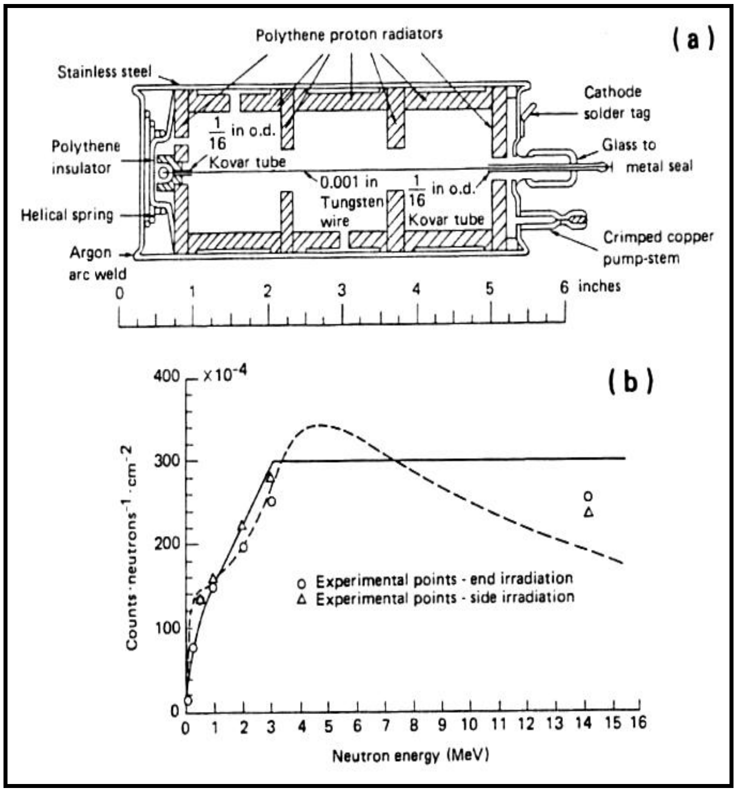

Figure 3-4. Dennis and Loosemore detector known as the Rudolf at the INEEL with its energy response curve.

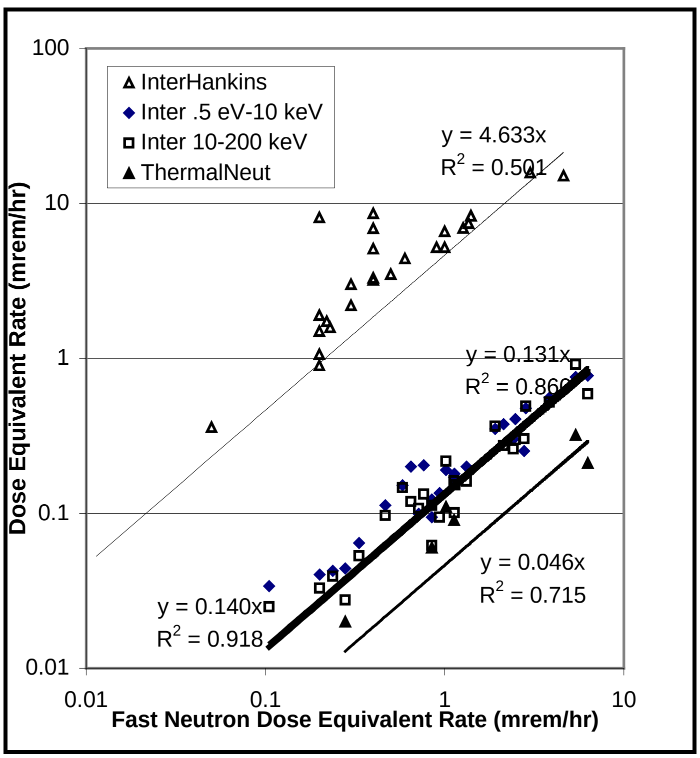

Figure 3-5. MTR neutron field components.

The R^2 values shown on the trend lines are the fractions of the variance, which is explained by the lines. For the reanalyzed data the R^2 values are 92% and 86% compared to only 50% for the original Hankins analysis, demonstrating that the reanalysis is a better fit. The slope of the trend lines is a dose weighted average of the ratios for the various data points. Table 3-3 provides comparisons of the different components of the neutron dose equivalent rate.

Table 3-3. Ratio of neutron dose equivalent rates at MTR.

	Thermal fast	**0.4 eV–10 keV fast**	**10–200 keV fast**	**Total fast**
Trend line	0.046	0.140	0.131	
Average	0.071	0.175	0.147	1.393
Minimum	0.033	0.066	0.073	1.226
Maximum	0.108	0.408	0.259	1.738
St dev	0.025	0.074	0.050	0.121

The Interactive RadioEpidemiological Program (IREP), which calculates the probability of causation[1], uses certain neutron energy groups. The dose equivalent rate and the fraction of the dose equivalent in each of these regions are listed in Table 3-4. For the numbered locations where no thermal neutron value is available, the average value for the ratio of thermal to fast of 0.71 from Table 3-3 is assumed.

The nuclear track emulsion, Type A (NTA) neutron dosimeters in use when the MTR was operating at the INEEL respond only to neutrons above 0.5 to 0.8 MeV. For the MTR spectra, Table 3-4 lists the fraction of neutron dose equivalent above 0.8 MeV, which would be picked up by the NTA film and which varies from 35% to 66%, depending on the location, with a mean of 0.52 and a standard deviation of 0.08. The remainder of these low-energy neutron fields would probably not be detected by the NTA film because of its 0.8-MeV threshold. To correct for missed dose on the MTR experiment floor, the NTA results from MTR should be multiplied by 2 ± 0.3 (1/0.52, $0.08/0.52^2$) for a Monte Carlo dose reconstruction.

Sommers (1962) reported thermal and fast neutron dose equivalent rates and gamma dose rates around the MTR beam lines. The thermal measurements near beams are believed to not be representative of the workplace. Figure 3-6 shows the correlation of fast neutron dose equivalent to the gamma dose for these measurements. The fast neutron component was insignificant for several of the measurements. These points are shown by the triangles at 0.5 mrem/hr, which is one-half of the smallest measured value. Including all the data in a Shapiro and Wilk W test for normality (Gilbert 1987) gives a slightly better result for a normal distribution rather than a lognormal distribution. The fast neutron dose is 0.419 ±0.347 times the gamma dose. Combining these results with those of Table 3-3, one can conclude that the ratio of total neutron dose equivalent to gamma dose is 0.58 ±0.48 at the 1-sigma level. The variation on the relative neutron components are buried by the fast neutron to gamma variation.

The IREP program uses equivalent dose as defined in International Commission on Radiological Protection (ICRP) Publication 60 (ICRP 1991) using the radiation weighting factor w_R defined in Table 1 of Publication 60. The NIOSH External Dose Implementation Guide (NIOSH 2002) provides conversion factors from ambient dose equivalent H^*_{10} to the organ equivalent dose, and ICRP Publication 74 (ICRP 1996) provides a calculation of the ambient dose equivalent as shown in Figure 3-7 so we can construct the ambient dose equivalent for these spectra. The ratios of the

[1] The U.S. Department of Labor is ultimately responsible under the EEOICPA for determining the POC.

neutron ambient dose equivalent from Publication 74 and the neutron dose equivalent from NCRP Report 38 (NCRP 1971) are shown in Table 3-4. For the 10- to 100-keV energy group, the ratio of the ambient dose equivalent to the neutron dose equivalent is 1.08, while for the above 2-MeV energy group, it is 1.121. For the groups where the spectra are not simple multiples of each other there is some variation with location.

Table 3-4. Distribution of MTR neutron dose equivalent among IREP energy groups, NTA response, and ratio of equivalent dose to dose equivalent.

	Dose equivalent fraction				IREP energy interval Ambient dose equivalent			Fractional NTA sensitivity >0.8 MeV
Location*	**<10 keV**	**10 keV–100 keV**	**100 keV–2 MeV**	**2M-20M**	**<10 keV**	**100 keV–2 MeV**	**Spectrum**	
EBR-I 1	0.28	0.079	0.47	0.17	0.89	1.38	1.14	0.32
2	0.24	0.077	0.49	0.19	0.88	1.37	1.14	0.36
3	0.24	0.062	0.47	0.23	0.87	1.35	1.13	0.42
4	0.22	0.061	0.47	0.24	0.87	1.35	1.13	0.45
5	0.21	0.084	0.51	0.19	0.88	1.37	1.16	0.35
6	0.21	0.072	0.50	0.22	0.87	1.36	1.15	0.41
7	0.19	0.060	0.49	0.26	0.86	1.34	1.14	0.48
8	0.19	0.059	0.49	0.26	0.85	1.34	1.14	0.49
9	0.18	0.070	0.51	0.24	0.86	1.35	1.15	0.45
10	0.18	0.062	0.50	0.26	0.85	1.34	1.14	0.49
11	0.18	0.049	0.48	0.29	0.84	1.33	1.13	0.54
12	0.17	0.065	0.51	0.26	0.85	1.35	1.15	0.48
13	0.17	0.047	0.48	0.30	0.84	1.32	1.13	0.56
14	0.17	0.036	0.46	0.33	0.83	1.31	1.12	0.61
15	0.17	0.048	0.49	0.30	0.83	1.32	1.13	0.56
16	0.16	0.053	0.50	0.29	0.83	1.33	1.14	0.54
17	0.16	0.040	0.48	0.32	0.82	1.31	1.12	0.60
18	0.16	0.052	0.50	0.29	0.83	1.33	1.14	0.55
19	0.15	0.058	0.51	0.28	0.84	1.34	1.14	0.52
20	0.15	0.044	0.49	0.32	0.82	1.32	1.13	0.59
22	0.15	0.031	0.47	0.35	0.80	1.30	1.12	0.66
23	0.13	0.045	0.50	0.33	0.80	1.32	1.14	0.61
A	0.20	0.075	0.51	0.22	0.92	1.36	1.20	0.41
B	0.17	0.039	0.47	0.32	0.92	1.31	1.17	0.59
C	0.17	0.055	0.49	0.28	0.92	1.33	1.19	0.52
D	0.15	0.065	0.52	0.27	0.92	1.34	1.20	0.50
E	0.13	0.039	0.49	0.34	0.91	1.31	1.18	0.64
F	0.16	0.052	0.49	0.29	0.92	1.33	1.19	0.55
ETR 21	0.14	0.046	0.49	0.32	0.81	1.32	1.13	0.59
ETR 24	0.12	0.037	0.49	0.35	0.78	1.30	1.13	0.65
ETR 25	0.11	0.038	0.50	0.35	0.77	1.30	1.13	0.65
Average	0.18	0.056	0.49	0.28	0.86	1.33	1.15	0.52
Minimum	0.13	0.031	0.46	0.19	0.80	1.30	1.12	0.35
Maximum	0.24	0.084	0.52	0.35	0.92	1.37	1.20	0.66
St Dev	0.030	0.013	0.015	0.043	0.037	0.020	0.026	0.08

* At MTR unless otherwise noted.

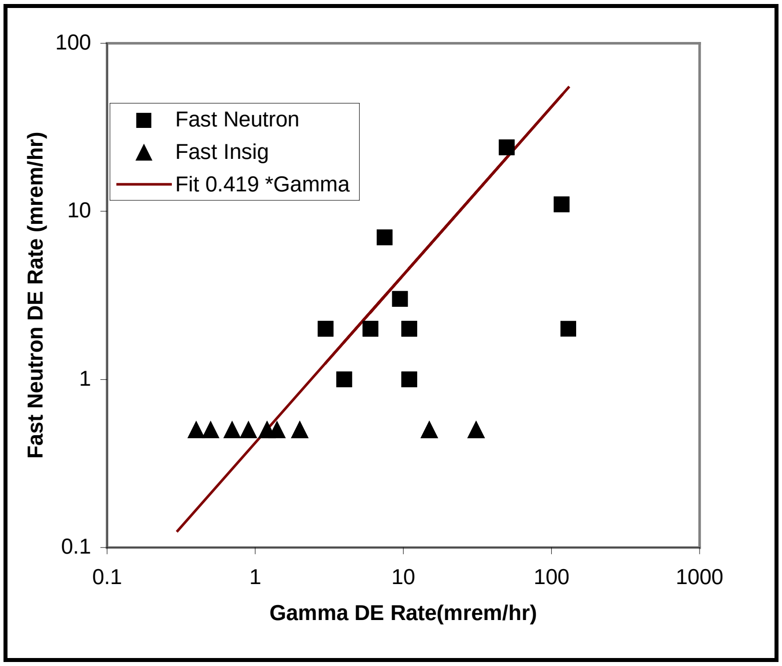

Figure 3-6. Correlation of fast neutron dose equivalent to gamma dose at MTR.

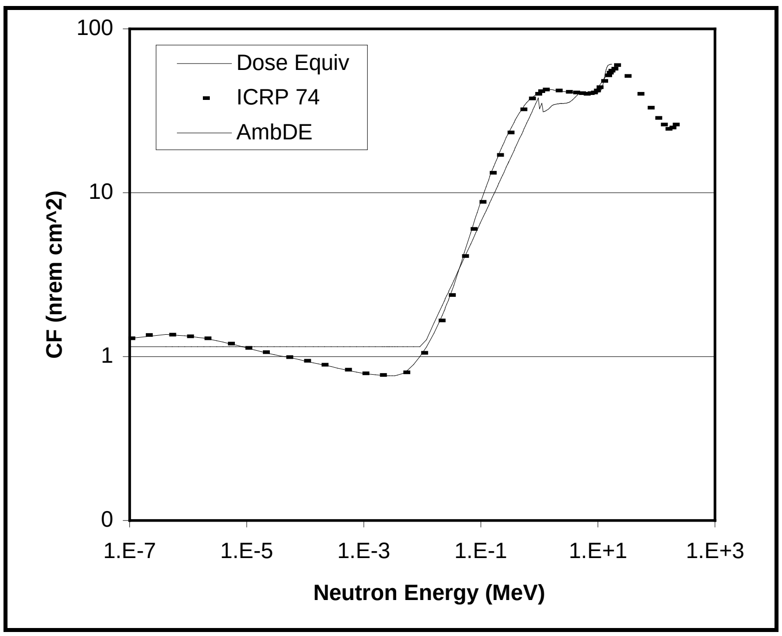

Figure 3-7. ICRP 74 ambient dose equivalent conversion factor.

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