Document Title:	Document Number: ORAUT-OTIB-0051
Effect of Threshold Energy and Angular Response of NTA Film on Missed Neutron Dose at the Oak Ridge Y-12 Facility	Revision: 00 Effective Date: 05/15/2006 Type of Document: OTIB Supersedes: None

Subject Expert: George D. Kerr

Document Owner Approval:	Signature on File William E. Murray, TBD Team Leader	Approval Date:	05/03/2006
Approval:	Signature on File John M. Byrne, Task 3 Manager	Approval Date:	04/13/2006
Concurrence:	Signature on File Kate Kimpan, Project Director	Concurrence Date:	05/12/2006
Approval:	Signature on File James W. Neton, Associate Director for Science	Approval Date:	05/15/2006

☒ New ☐ Total Rewrite ☐ Revision ☐ Page Change

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PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
05/15/2006	00	New document to describe the effect of threshold energy and angular response of NTA film on missed neutron dose at the Oak Ridge Y-12 facility. First approved issue. Training required: As determined by the Task Manager. Initiated by George D. Kerr.

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ACRONYMS AND ABBREVIATIONS

CEF	Critical Experiments Facility
DOE	U.S. Department of Energy
E	neutron energy
eV	electron-volt
IAEA	International Atomic Energy Agency
ICRU	International Commission on Radiation Units and Measurements
ISO	International Organization for Standardization
keV	kiloelectron-volt, 1 thousand electron-volts
MDL	minimum detectable limit
MeV	megaelectron-volts, 1 million electron-volts
mm	millimeter
mrem	millirem
n	neutron
NCRP	National Council on Radiation Protection and Measurement
NIOSH	National Institute for Occupational Safety and Health
NTA	nuclear track emulsion, type A
p	proton
PMMA	polymethyl methacrylate
PNL	Pacific Northwest Laboratory
TIB	technical information bulletin
TRS	Technical Reports Series
U.S.C.	United States Code
Z	atomic number
α	alpha particle
§	section

1.0 INTRODUCTION

Technical information bulletins (TIBs) are general working documents that provide guidance concerning 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 the National Institute for Occupational Safety and Health (NIOSH) 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 [EEOICPA; 42 U.S.C. § 7384l(5) and (12)]. EEOICPA defines a DOE facility as “any building, structure, or premise, including the grounds upon which such building, structure, or premise is located … in which operations are, or have been, conducted by, or on behalf of, the Department of Energy (except for buildings, structures, premises, grounds, or operations … pertaining to the Naval Nuclear Propulsion Program)” [42 U.S.C. § 7384l(12)]. Accordingly, except for the exclusion for the Naval Nuclear Propulsion Program noted above, any facility that performs or performed DOE operations of any nature whatsoever is a DOE facility encompassed by EEOICPA.

For employees of DOE or its contractors with cancer, the DOE facility definition only determines eligibility for a dose reconstruction, which is a prerequisite to a compensation decision (except for members of the Special Exposure Cohort). The compensation decision for cancer claimants is based on a section of the statute entitled “Exposure in the Performance of Duty.” That provision [42 U.S.C. § 7384n(b)] says that an individual with cancer “shall be determined to have sustained that cancer in the performance of duty for purposes of the compensation program if, and only if, the cancer … was at least as likely as not related to employment at the facility [where the employee worked], as determined in accordance with the POC [probability of causation[1]] guidelines established under subsection (c) …” [42 U.S.C. § 7384n(b)]. Neither the statute nor the probability of causation guidelines (nor the dose reconstruction regulation) define “performance of duty” for DOE employees with a covered cancer or restrict the “duty” to nuclear weapons work.

As noted above, the statute includes a definition of a DOE facility that excludes “buildings, structures, premises, grounds, or operations covered by Executive Order No. 12344, dated February 1, 1982 (42 U.S.C. 7158 note), pertaining to the Naval Nuclear Propulsion Program” [42 U.S.C. § 7384l(12)]. While this definition contains an exclusion with respect to the Naval Nuclear Propulsion Program, the section of EEOICPA that deals with the compensation decision for covered employees with cancer [i.e., 42 U.S.C. § 7384n(b), entitled “Exposure in the Performance of Duty”] does not contain such an exclusion. Therefore, the statute requires NIOSH to include all occupationally derived radiation exposures at the facility in its dose reconstructions for employees at DOE facilities, including radiation exposures related to the Naval Nuclear Propulsion Program. As a result, all internal and external dosimetry monitoring results are considered valid for use in dose reconstruction. No efforts are made to determine the eligibility of any fraction of total measured exposure for inclusion in dose reconstruction. NIOSH, however, does not consider the following exposures to be occupationally derived:

- Radiation from naturally occurring radon present in conventional structures
- Radiation from diagnostic X-rays received in the treatment of work-related injuries

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

The purpose of this TIB is to provide definitive documentation of the effects of threshold energy and angular response of nuclear track emulsion, type A (NTA) film on missed neutron dose at the Oak Ridge Y-12 Plant.

2.0 SOURCES OF NEUTRON EXPOSURE TO WORKERS AT Y-12

Table 2-1 lists the most common sources of neutron exposure to Y-12 workers during the period of film badge monitoring (ORAUT 2004a, 2005a). With the exception of neutron fission sources at the Critical Experiments Facility (CEF), this analysis used two different approaches to calculate the effect of the threshold energy of NTA film on the dose measurements for fast neutrons (Sections 4.0 and 6.0). Information on the effect of threshold energy of NTA film on neutron exposure doses at the CEF was available from measurements at a number of locations outside and inside the facility during extended operations of critical assemblies at relatively high power (ORAUT 2005a). During one measurement collection session in January 1960, a critical volume of an enriched uranium solution in the West Assembly Room was operated in a steady-state mode to produce 7×10^{12} fissions/s. These 1960 measurements at six locations in the CEF suggested a range of missed neutron doses for NTA film ranging from 42% to 74% with a mean of 55% (ORAUT 2005a).

Table 2-1. Sources of neutron exposure at Y-12.[a]

Location	Building	Source
Assay Laboratory	9203 (Room 8), 9205	Ra–Be, Po–Be
Chemical Operations	9202, 9206, 9212	UF_4, UO_3
CEF	9213	Po–Be, Pu–Be
		Fission neutrons
Electromagnetic Research	9201-2, 9204-3	Po–Be
		86-Inch Cyclotron
Health Physics	9983 (Calibration Laboratory)	Po–Be, Am–Be
Instrument Department	9737	Po–Be
Nondestructive Assay Laboratory	9720-5	Cf–252 fission neutrons

a. Sources: ORAUT (2004a, 2005a,b).

Most of the neutron sources at Y-12 were small and produced neutrons by alpha particle reactions in beryllium. These neutron sources were used in basic research (Buildings 9201-2 and 9204-3), critical assembly and reactor research (Building 9213), calibration of radiation detection instruments and dosimeters (Buildings 9737 and 9983), and material assay (Buildings 9203 and 9205). The neutron energy spectra from all radionuclide sources using the (α, n) reaction in beryllium are similar, and the average energy of the neutrons is about 4 MeV (Nachtigall 1967; Kerr, Jones, and Hwang 1978). Figure 2-1 shows the neutron energy spectrum used in the calculations of this study for an unshielded ^{241}Am–Be source from Kluge and Weise (1981; also see Table 4 of IAEA 1990) as fluence per unit lethargy. Thus, the area under the curve in any energy range corresponds to the neutron fluence in that energy range.

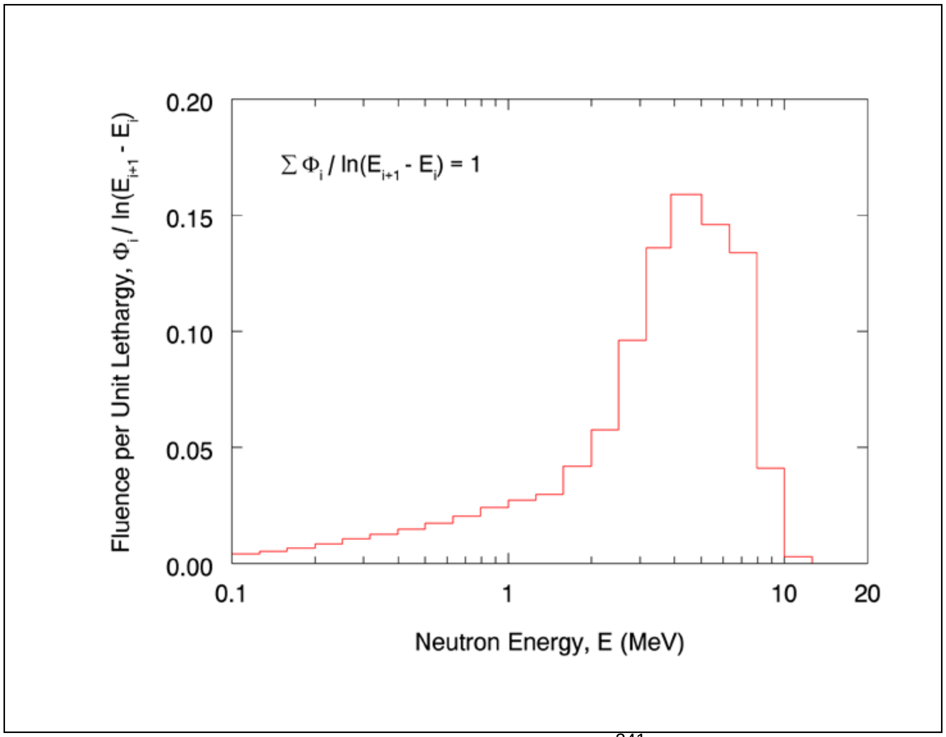

Figure 2-1. Neutron energy spectrum for a ^{241}Am–Be source (Kluge and Weise 1981).

Several other neutron spectra used in the calculations for this study are from spectral measurements made by Pacific Northwest Laboratory (PNL 1990; McMahan 1991; BWXT 2001). These spectra are from measurements made near an unshielded ^{252}Cf fission neutron source, storage containers of UF_4 and UO_3 containing highly enriched uranium as feed material for the manufacture of nuclear weapon parts, and the storage vault in the calibration laboratory that contained radionuclide sources. These spectra simulated neutron exposures to Y-12 workers in the Nondestructive Assay Laboratory (Building 9720-5), various chemical operations areas throughout the Y-12 facility (Buildings 9202, 9206, and 9212), and shielded radionuclide sources in the storage vault of the Health Physics Calibration Laboratory (Building 9983). Figure 2-2 shows the neutron energy spectra for the above PNL measurements (PNL 1990; McMahan 1991; BWXT 2001) as fluence per unit lethargy.

The final spectrum used in the calculations of this study was an empirical neutron spectrum that was used to simulate exposures to Y-12 workers from stray neutron radiation at the Oak Ridge 86-Inch Cyclotron (Building 9201-2). This study used an empirical neutron spectrum because the neutron energy spectra in work areas near the cyclotron, like those near other early proton accelerators, are not well known. The empirical neutron spectrum used a Maxwellian thermal neutron spectrum at energies less than 0.125 eV and a 1/E slowing-down spectrum of neutrons at energies from 0.125 eV to 20 MeV, where E is neutron energy. This empirical neutron spectrum appears to give results that are consistent with observations by others (IAEA 1988). For example, it was found that most of the neutron dose at early accelerators came from neutrons with energies between 0.1 and 10 MeV, and our calculations using the above empirical neutron spectrum suggest that almost 80% of the total neutron dose in the stray radiation fields of the Oak Ridge 86-Inch Cyclotron was from neutrons with energies of more than 0.1 MeV and less than 10 MeV. ORAUT (2005a) contains a detailed discussion of the Oak Ridge 86-Inch Cyclotron and its operation.

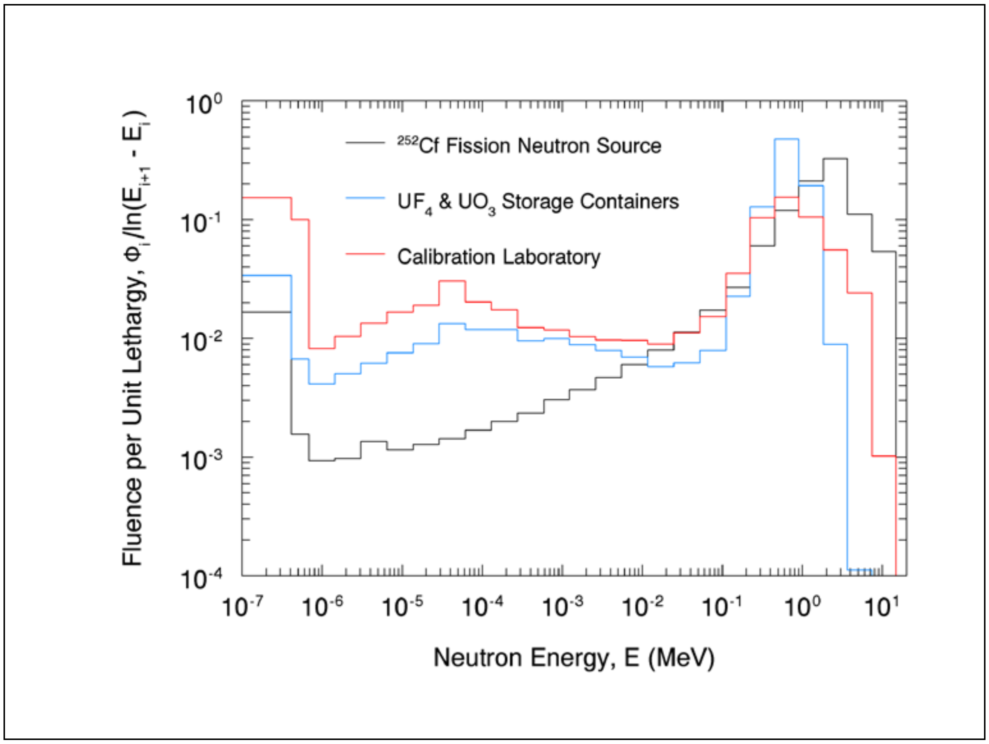

Figure 2-2. Neutron energy spectra for various Y-12 sources (PNL 1990; McMahan 1991; BWXT 2001).

3.0 THRESHOLD ENERGY FOR DETECTION OF FAST NEUTRONS BY NTA FILM

Track counting of fast neutrons in NTA film depends on the hydrogen content of the emulsion and surrounding materials of the film packet (Lehman 1961; Moe 1992). Elastic scattering of fast neutrons by hydrogen produces proton recoil ions. These recoil ions lose energy to the silver grains in the NTA film, which are much finer than those in photographic films used in photon and beta particle dosimetry. However, the NTA film contains more of these silver grains than the photon and beta particle films. The latent images formed in the NTA film consist of a number of individual silver grains along the path of the recoil proton ion. In addition, there is a thermal neutron response, derived from the nitrogen content of the NTA film, via the $^{14}N(n,p)^{14}C$ capture reaction (Tanner et al. 2001). This part of the response was suppressed in the Y-12 film dosimeter by track counting in the portion of the NTA film that was covered by a cadmium filter with a thickness of approximately 1 mm. The film badge dosimeters used at Y-12 from 1950 to 1980 are discussed in more detail in two ORAUT reports (2005a,c).

The limitations of the NTA films in neutron dosimetry derive from problems of track identification by a reader (Lehman 1961; Tanner et al. 2001). At least 100 keV must be deposited to form a silver grain in the emulsion and at least three or four grains are required to define a track because photons produce shorter tracks. The problem of track identification becomes even more difficult when the background of shorter tracks caused by the photons is intense in comparison to that caused by neutrons (Tanner et al. 2001). As a consequence, NTA films have a fast neutron detection threshold in the region of approximately 400 keV and an energy-dependent response that rises rapidly from that energy. Figure 3-1 shows the energy-dependent response of NTA film exposed on an anthropomorphic phantom (Sayed and Piesh 1974; also see Table 3 of IAEA 1990), and Table 3-1 lists examples of the widely variant values quoted for the fast neutron threshold of NTA films. The fast neutron threshold of 1,000 keV in Table 3.1 is an unrealistically high value from a very early study. It is often cited, however, as a reason for dismissing neutron dose measurements made with NTA films. Sections 4.0 and 6.0 discuss the effects of the fast neutron threshold of NTA films on missed neutron dose by film badge dosimeters used at Y-12.

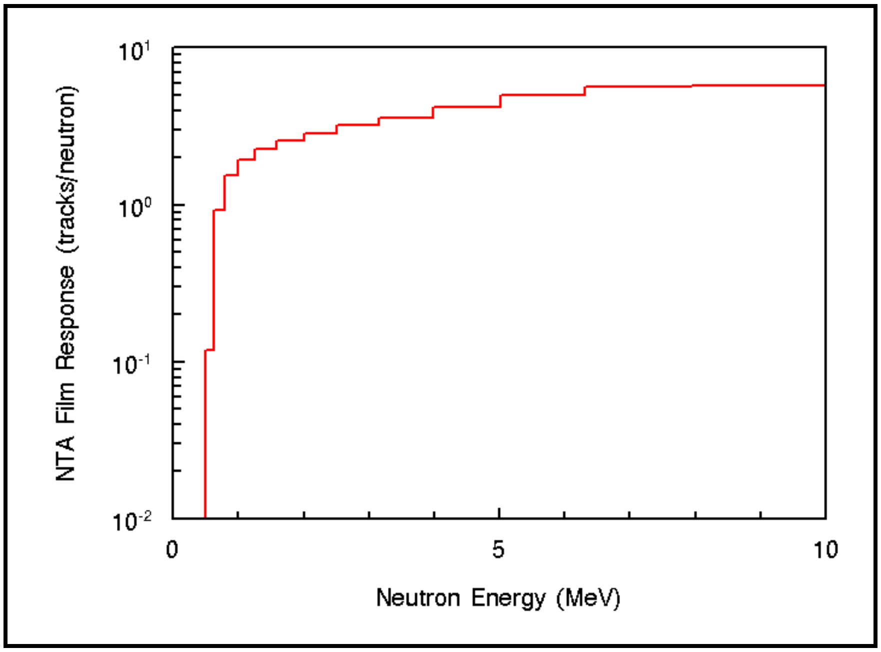

Figure 3-1. Energy response of NTA film exposed on an anthropomorphic phantom to fast neutrons (Sayed and Piesh 1974; IAEA 1990).

Table 3-1. Literature values of threshold energy for detection of fast neutrons by NTA film.

Threshold energy (keV)	Reference
400	Lehman 1961, p. 6
400	IAEA 1970, p. 34
400	Gupton 1978, p. 9
400	Tanner et al. 2001, p. 10
500	Kathren, Prevo, and Block 1965
500	Becker 1966
500	Oshion 1973
500	Griffith et al. 1979
500	Parrish 1979, p. 85
500	Moe 1992, pp. 13–14
500	NIOSH 2002, pp. 26–28
500-600	Drew and Thomas 1998, p. 35
700	IAEA 1985, p. 64
700-800	Wilson 1987, p. 2.21
800	Wilson et al. 1990, pp. 3.1–3.2
1,000	Bemis 1956, p. 489

4.0 MISSED DOSE CALCULATIONS ASSUMING A FIXED THRESHOLD ENERGY

Figures 4-1 to 4-5 show the results of missed neutron dose calculations using fixed threshold energies for the NTA film of 400, 500, 600, 700, 800, 900, and 1,000 keV. The calculations used Monte Carlo sampling and scoring routines from the MCNP computer program (Briesmeister 2000), the energy spectra for the neutron sources discussed in Section 2.0, and dose equivalent coefficients from Report 38 of the National Commission on Radiation Protection and Measurements (NCRP 1971; also see Table 2 of IAEA 1990). The missed dose varies significantly with the assumed value for the threshold energy of the NTA film, and there is a strong correlation of the missed dose with the mean energy of the neutron spectra from the sources as shown in Figure 4-6 for a 700-keV threshold energy for the NTA film. The calculated mean energies of the neutron spectra were 525 keV at the Calibration Laboratory, 636 keV for the highly enriched UF_4 and UO_3 storage containers, 1.05 MeV for the 86-Inch Cyclotron, 2.48 MeV for the unshielded ^{252}Cf fission neutron source, and 4 MeV for the ^{241}Am–Be neutron source. Figure 4-6 suggests a mean neutron energy of about 300 to 400 keV for neutron spectra at measurement points inside the CEF based on a measured missed neutron dose of approximately 55% (see Section 2.0). The data shown in Figures 4-1 to 4-5 can be used to evaluate the missed dose for threshold energies other than 700 keV. However, a threshold energy of 700 keV appears to give a conservative estimate of the missed dose from NTA film measurements at most facilities (see Table 3-1 and Figure 6-1).

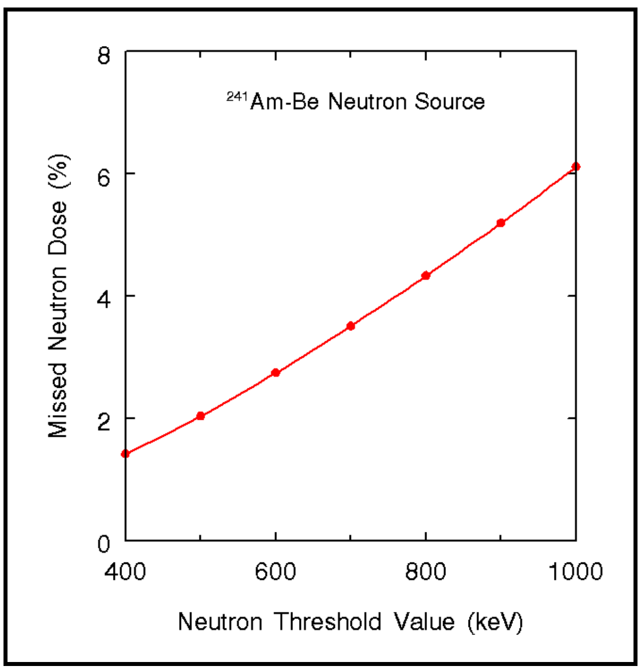

Figure 4-1. Missed neutron dose from radionuclide sources using (α,n) reaction in beryllium calculated as a function of threshold energy of NTA film. (The results are from calculations for a ^{241}Am–Be source but they are applicable to ^{210}Po–Be and ^{239}Pu–Be neutron sources.)

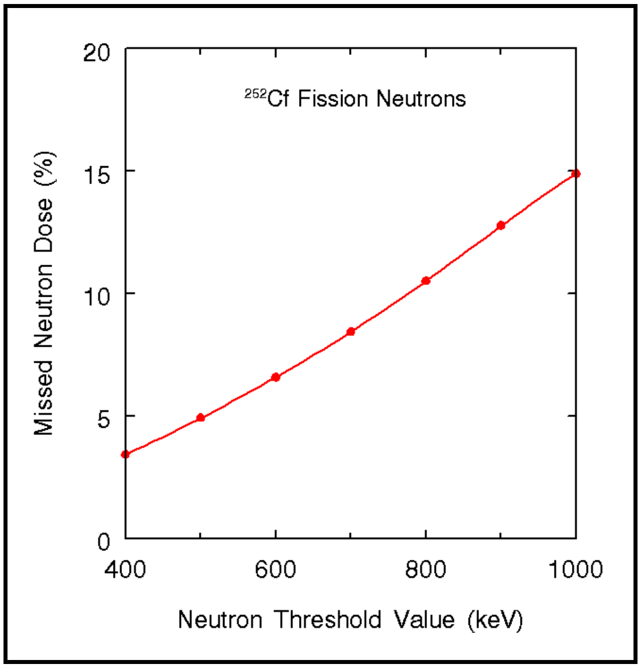

Figure 4-2. Missed neutron dose from unshielded ^{252}Cf fission neutron source calculated as a function of threshold energy of NTA film.

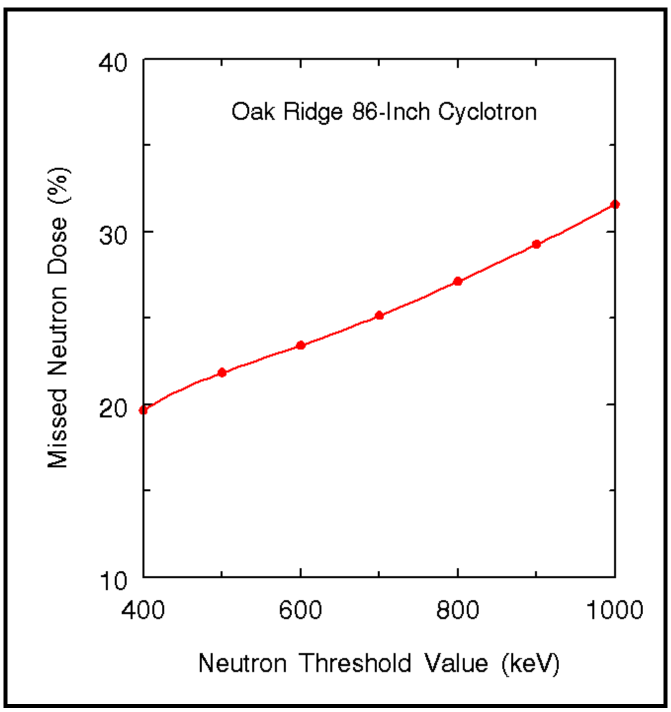

Figure 4-3. Missed neutron dose at 86-Inch Cyclotron calculated as a function of threshold energy of NTA film.

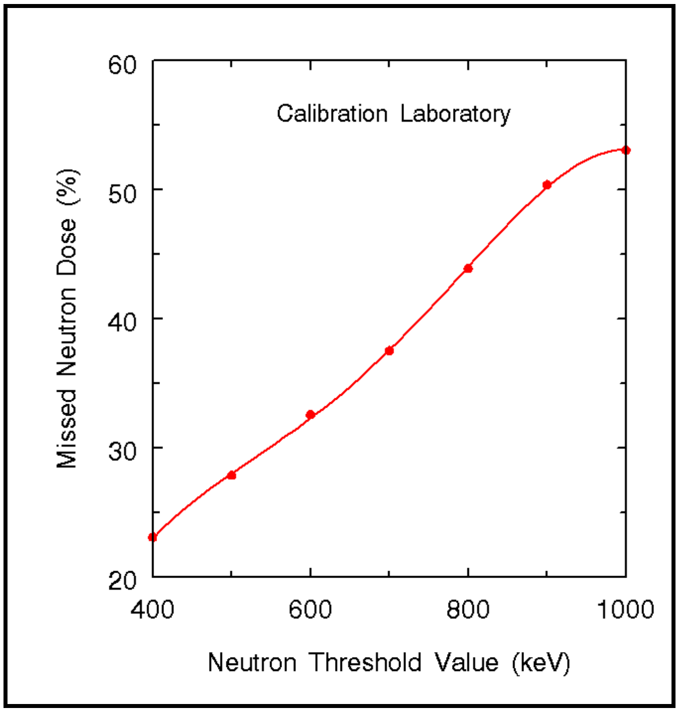

Figure 4-4. Missed neutron dose from shielded radionuclide sources at Health Physics Calibration Laboratory calculated as a function of threshold energy of NTA film.

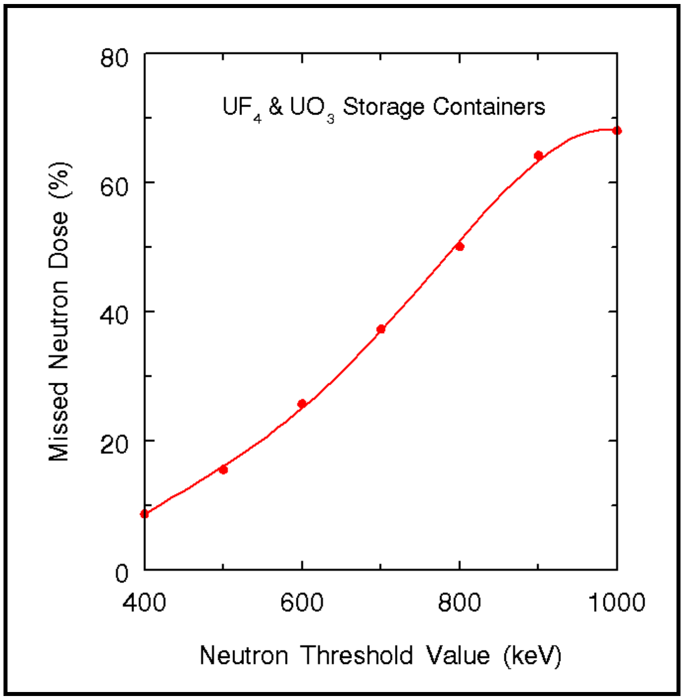

Figure 4-5. Missed neutron dose from neutrons emitted by storage containers of highly enriched UF_4 and UO_3 calculated as a function of threshold energy of NTA film.

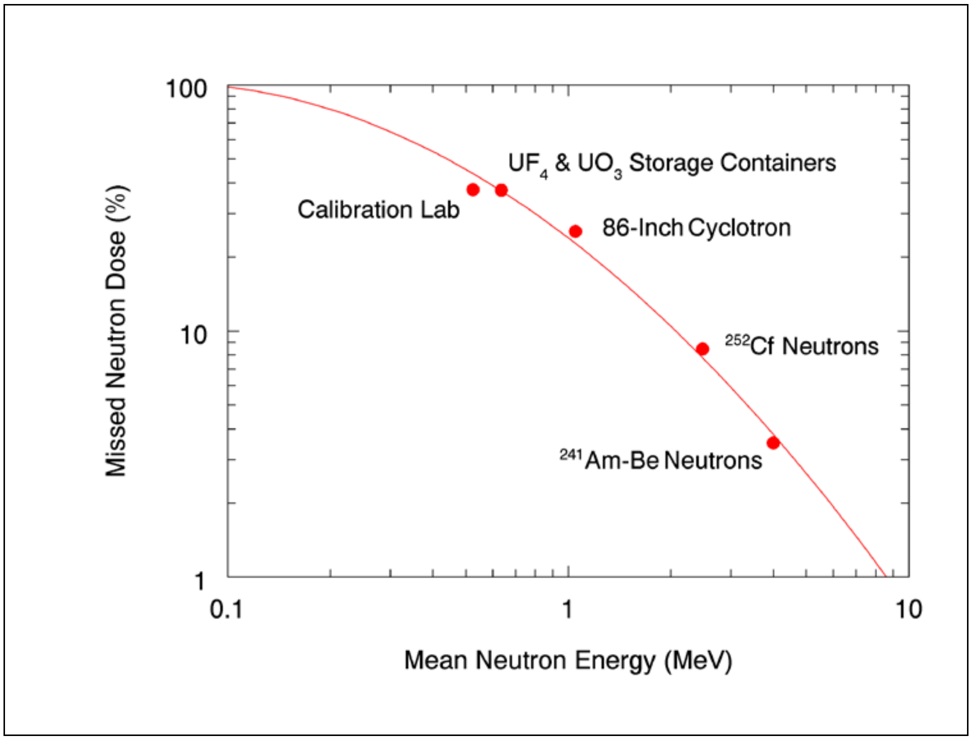

Figure 4-6. Missed neutron dose versus mean energy of a broad spectrum of neutron energies for assumed threshold energy of 700 keV for NTA film.

5.0 CALIBRATION OF FAST NEUTRON DOSIMETERS CONTAINING NTA FILMS

The NTA films were first calibrated at Y-12 using a Po–Be neutron source (Struxness 1949, 1952) and later an Am–Be neutron source (McLendon 1963; McRee, West, and McLendon 1965). The dosimeters containing the NTA films were exposed free in air (no phantom) to neutrons from the Po–Be and Am–Be sources for pre-selected times to produce a range of neutron doses similar to those normally encountered in the workplace. There have been questions about the validity of calibrations using a first collision dose that assumes that the NTA film measures the incident neutron dose on an anthropomorphic phantom and the reflected neutron dose from the phantom with equal efficiency (Budd 1963; ORAUT 2004b). This assumption is questionable because of the poor response of NTA films at energies less than approximately 0.7 MeV (see Figure 3-1) and the lower energies of the reflected neutrons from the calibration source.

A calibration study using NTA film badge dosimeters exposed to identical fast neutron fluences (1) free in air (no phantom) and (2) with the badges on a moderating phantom was made by Budd (1963) to determine the increase in tracks, if any, produced by the reflected neutrons from a Pu–Be source with an average neutron energy of about 3.9 MeV and a PuF_4 source with an average neutron energy of about 1.2 MeV. With the Pu–Be source, there was a 15% increase in track density when the dosimeters were exposed on the moderating phantom. With the PuF_4 source, which produced tracks in the NTA film with an average length that was more similar to those observed in Hanford dosimeters, no difference was observed when the dosimeters were backed with the moderator (Budd 1963; ORAUT 2004b).

A number of other studies using a variety of phantoms and neutron sources have been published with results for the increase of track density in NTA film from reflected neutrons ranging from a low of zero to a high of 33% (Thomas et al. 1997). To better define the effect of reflected neutrons on track density in NTA films exposed on a phantom, the National Physical Laboratory in England made a study using two different phantoms [the International Organization for Standardization (ISO) water phantom and the International Commission on Radiological Units and Measurements (ICRU) polymethyl methacrylate (PMMA) phantom], two different neutron sources (^{252}Cf and Am–Be), and two different track readers (Thomas et al. 1997). There was a systematic difference between the two track readers of about 10%; however, this difference was roughly the same for all irradiation conditions and the ratios determined by the two readers typically agreed to within about 3%. The subjectivity introduced by manual evaluation of the tracks is part of the dosimeter reading process, and the final mean ratios included all data from the two readers (Thomas et al. 1997). The final mean ratios suggested that the reflected neutrons add about 5% on average to the track reading of the NTA film and that there were no statistically significant differences for NTA film between the responses for either the two sources (^{252}Cf and Am–Be) or the two phantoms (ISO or ICRU). The characteristics of the ISO water phantom and ICRU PMMA phantom are discussed in ISO (1998) and ICRU (1992), respectively.

For calibrations made without a phantom, one would typically use a first collision dose such as that shown by the red circles and red fitted curve in Figure 5-1. This curve was obtained by multiplying the first collision absorbed dose data in National Bureau of Standards Handbook 75 (NBS 1961) by a relative biological effectiveness (or quality factor) of 10 for fast neutrons with energies higher than approximately 100 keV. For calibrations made on a phantom, one would typically use the point-wise multicollision dose equivalent data from National Council on Radiation Protection and Measurements Report 38 (NCRP 1971) shown by the blue circles in Figure 5-1 or the continuous group data for the multicollision dose equivalent from Table 2 of the International Atomic Energy Agency's Technical Reports Series (TRS) No. 318 (IAEA 1990) shown by the blue line in Figure 5-1. The study by Budd (1963) resulted in a change at the Hanford facility from NTA film calibration using a first collision dose (no phantom) to NTA film calibration using a multicollision dose and a phantom. A PuF_4 neutron source was used in the NTA film calibrations because this best matched the neutron spectra found in the workplace at the Hanford facility. This change in the calibration procedure was found to increase all fast neutron measurements with NTA films at the Hanford facility by about 38% (Budd 1963) due to differences between the first collision and multicollision dose around the 1.2-MeV mean energy of the neutrons from the PuF_4 source (see Figure 5-1).

It was surprising to find in this study that calibration of NTA film with a Po–Be or Am–Be neutron source using a first collision dose and no phantom or a multicollision dose and a phantom would only make a difference of a few percent in the calibration factor for the NTA film (i.e., the dose equivalent per unit track density in the film) or the recorded neutron dose equivalent to a worker at Y-12. This surprising observation resulted from the fact that the first collision and multicollision doses in rem are essentially the same due to the cross over of the first collision dose and the multicollision dose near the 4-MeV mean energy of the neutrons from either a Po–Be or Am–Be neutron source (see Figure 5-1) and that the number of tracks in the NTA film from exposure either with or without a phantom vary by only 5% (Thomas et al. 1997). Therefore, it is possible to use the energy response of NTA film exposed to fast neutrons on a phantom to make a reliable estimate of the missed dose for various neutron energy spectra at Y-12. Neutrons from a Po–Be or Am–Be source were used in the calibration of NTA film dosimeters at Y-12 because these sources were considered to provide a good match to neutron spectra found in the workplace at that facility, particularly the stray neutron field about the Oak Ridge 86-Inch Cyclotron (see Section 2.0). The Oak Ridge 86-Inch Cyclotron was the primary source for neutron exposure to Y-12 workers during the 1950s and early 1960s (ORAUT 2005a).

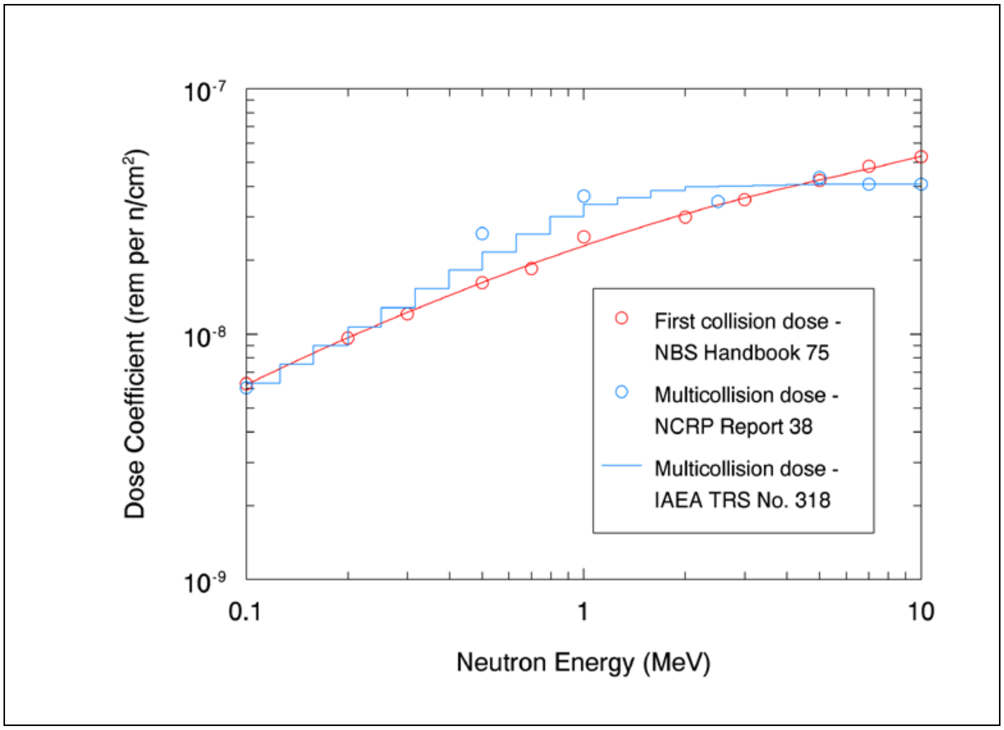

Figure 5-1. Comparison of first collision dose coefficients from NBS Handbook 75 (NBS 1961) and multicollision dose coefficients from NCRP Report 38 (NCRP 1971) and IAEA TRS No. 318 (IAEA 1990).

6.0 MISSED DOSE CALCULATIONS WITHOUT ASSUMING A FIXED THRESHOLD ENERGY

Calculations of the missed neutron dose without assuming a fixed threshold energy for NTA films were made using the following equation:

$$\text{Missed Dose } (S_X) = \text{Dose Equivalent } (S_X) - \text{NTA Tracks } (S_X) \frac{\text{Dose Equivalent } (S_C)}{\text{NTA Tracks } (S_C)}$$

where S_x designates calculations using the neutron spectra for the source of interest and S_c designates calculations using the neutron spectra for the source used to calibrate the NTA film (typically ^{210}Po–Be or ^{241}Am–Be). The NTA films were usually calibrated in air (no phantom), but the results of this study show that there is no significant statistical difference in response between NTA film calibrated in air or on a phantom using either a ^{210}Po–Be or ^{241}Am–Be source (see Section 5.0). Therefore, it is possible to calculate both “Dose Equivalent” terms using the dose coefficients from NCRP Report 38 (NCRP 1971; also see Table 2 of IAEA 1990) and both NTA Tracks terms in the above equation using the NTA response coefficients from Sayed and Piesch (1974; also see Table 3 of IAEA 1990).

The Missed Dose (S_x) in percent was calculated using the following equation:

$$\text{Percent Missed Dose } (S_X) = 100\left[1 - \frac{\text{NTA Tracks } (S_X)}{\text{Dose Equivalent } (S_X)} \frac{\text{Dose Equivalent } (S_C)}{\text{NTA Tracks } (S_C)}\right]$$

Figure 6-1 shows the results of MCNP calculations for the sources discussed in Section 2.0 without assuming a fixed threshold energy for the NTA films. This figure suggests a mean neutron energy of about 400 keV for the neutron spectra at measurement points inside the CEF based on a measured missed neutron dose of approximately 55% (see Section 2.0). Figures 4-6 and 6-1 show the results of the calculations, which suggest that it is possible to make reliable estimates of neutron dose to Y-12 workers by adjusting their recorded neutron doses using the missed dose values in this document. The missed dose values in Figure 6-1 are recommended for use in neutron dose reconstruction for Y-12 workers during the film badge dosimetry period starting in 1950 and ending in 1979 (ORAUT 2005a,b,c). These missed dose values are as follows: 21% for the unshielded ^{252}Cf fission neutron source, 28% for the 86-Inch Cyclotron, 51% for the shielded radionuclide sources at the Health Physics Calibration Laboratory, and 54% for the highly enriched UF_4 and UO_3 storage containers. Based on these data, dose reconstructors should apply a correction of [100/(100 – Percent Missed Dose)] to all recorded NTA film dosimeter results for Y-12 workers.

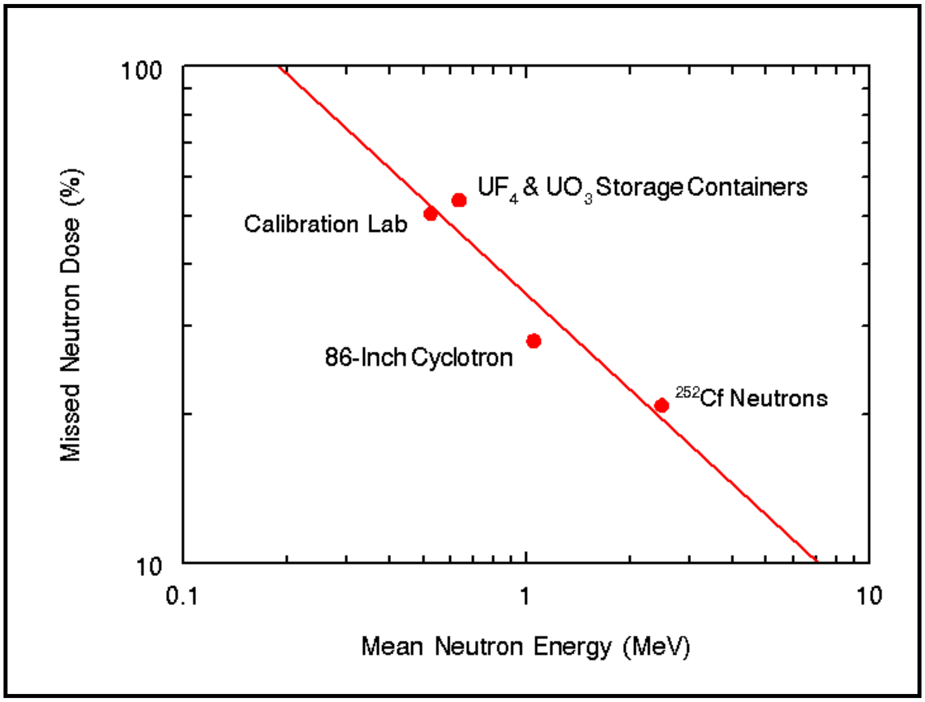

Figure 6-1. Missed neutron dose calculated without assuming a fixed threshold energy for NTA film.

7.0 ANGULAR RESPONSE OF NTA FILM

NTA film response is dependent on the angle of incidence of the neutrons (IAEA 1970). The angular dependence is due to several factors including the backscattering of neutrons from the body of the worker wearing the dosimeter, the geometry of the film, and that the proton recoil ions generated in the hydrogen rich material surrounding the film produce a large portion of the tracks in the film. The geometry of the film suggests that an angular dependence would be likely (i.e., the response of the film would vary for different angles of incidence in relation to the plane of the film). Neutrons at nearly parallel incidence on the NTA film pack produce proton recoil ions that have a greater probability of escape from the film emulsion before producing observable tracks than do proton recoil ions from neutrons at nearly normal incidence on the film pack. The problem of angular dependence is further complicated because a large fraction of the proton tracks in the emulsion are produced by proton recoil ions generated in the hydrogenous material of the wrapper for the NTA film pack.

The angular dependence of NTA film has been studied experimentally by Cheka (1954), Lehman (1961), Piesch (1963; also see Figure 3.8 in IAEA 1970) and Kathren, Prevo, and Block (1965). In most workplace environments, neutrons will be incident on the NTA film dosimeter at widely variant angles, and dose reconstructors will underestimate a worker's neutron dose if the neutrons from a calibration source were perpendicularly incident on the NTA film dosimeter (i.e., the normal practice for calibration of NTA film dosimeters). Therefore, Kathren, Prevo, and Block (1965) suggested that multiplication of tracks produced by perpendicularly incident neutrons from a calibration source by a factor 0.75 would eliminate the underestimation of the dose equivalent to workers in such an environment. This is equivalent to multiplying the recorded dose equivalent from a worker's NTA film dosimeter by a factor of 1.3. Dose reconstructors should apply this correction to all recorded NTA film dosimeter results for Y-12 workers.

8.0 DISCUSSION

Table 8-1 summarizes correction factors for missed neutron dose due to the threshold energy and angular response of the NTA film dosimeters used at Y-12. Dose reconstructors should apply these factors to all recorded quarterly NTA film results for Y-12 workers to ensure that the estimated neutron doses are claimant-favorable. These factors should also be applied to missed neutron dose from recording a zero for a worker when the NTA film dosimeter indicated a quarterly neutron exposure less than the minimum detectable limit (MDL) of approximately 50 mrem (ORAUT 2005a,b). To assign missed neutron dose for measurements below the MDL for the NTA film dosimeters, the dose reconstructor must first determine if a person worked near neutrons and the relevant category of neutrons (see Table 8-1). The best approach is to look for the work location and whether the worker or others in the badge reporting group (or department) were assigned any neutron dose equivalent. If no neutron dose was assigned to the worker or to coworkers for several quarters, the dose reconstructor should assume that the worker was not exposed to neutrons, so there would be no missed neutron dose.

Table 8-1. Recommended correction for missed neutron dose due to threshold energy and angular response of NTA film.

Neutron source[a]	Correction factor for threshold energy	Correction factor for angular response	Total correction factor
Unshielded radionuclide sources	1.0	1.3	1.3
Cf-252 fission neutron source	1.3	1.3	1.7
86-Inch Cyclotron	1.4	1.3	1.8
Shielded radionuclide sources[b]	2.0	1.3	2.7
Enriched uranium storage containers	2.2	1.3	2.9
CEF[c]	2.2	1.3	2.9

a. See Section 2.0 and Table 2-1.
b. Health Physics Calibration Laboratory.
c. Normally inhabited locations inside CEF.

If a worker was exposed in an area with a highly degraded energy spectrum, most of the neutron dose might not be detected by the NTA film. However, exposure to highly degraded spectra of neutrons at Y-12 was the exception rather than the rule, and missed neutron dose is limited because of a very low potential for neutron exposure at Y-12. For example, the interaction of alpha particles from uranium with the nuclei of fluorine or other low-atomic number (Z) atoms generates neutrons with energies of approximately 2 MeV (DOE 2004). The potential for neutron exposure depends on both the total activity of the uranium (which is a function of enrichment) and the chemical compound in question (the mixing of uranium and fluorine or other low-Z atoms). In general, the exposure potential of workers to neutrons generated by (α, n) reactions is low unless their work assignments require them to spend significant time near storage or process areas for large quantities of highly enriched uranium compounds (DOE 2004). Therefore, the neutron fields of concern in chemical processing areas at Y-12 were not highly degraded in energy and are adequately defined by the PNL measurements near UF_4 and UO_3 storage containers at Y-12 (see Figure 2-2).

The techniques used here to investigate missed neutron dose due to the threshold energy and angular response of NTA film dosimeters were applied to neutron sources in use at Y-12 during the film badge dosimetry period from 1948 to 1980. These techniques appear to have useful application in investigations of the missed dose from neutron sources at other U.S. Department of Energy (DOE) sites of interest. However, the application of techniques used here to investigate missed neutron dose might not be useful at some facilities, particularly exposures of a worker to a highly moderated neutron fission spectra from nuclear reactors. For example, a PNL measurement near a K-reactor at the Savannah Ridge Site indicated a neutron energy spectrum with a mean energy of only 170 keV (ORAUT 2005d). Based on the data in Figure 4-6, approximately 85% of the neutron dose would have been missed by a dosimeter containing NTA film. Based on the data in Figure 6-1, an NTA film dosimeter calibrated with a Pu–Be or Am–Be source would have missed essentially 100% of the neutron dose from the K-reactor. In such cases the dose reconstructor should rely on an alternative technique such as the use of a neutron-to-gamma dose ratio for exposures at that DOE facility and a film badge estimate of the worker’s dose from gamma rays to make a reliable estimate of the worker’s dose from neutrons (ORAUT 2005d).

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