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SENSITIVITY OF NTA FILM TO NEUTRON SOURCES AT MOUND LABORATORY

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Record of Revisions

Revision Number	Effective Date	Description of Revision
0 (Draft)	05/24/2010	Initial issue—distributed on June 4, 2010, following DOE clearance
1 (Draft)	07/22/2010	Revised correction factors in table 3 and minor editorial changes and format corrections.

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SENSITIVITY OF NTA FILM TO NEUTRON SOURCES AT MOUND LABORATORY

SC&A has performed a set of analyses to determine the relationship between the doses inferred from NTA films at the Mound Laboratory and the actual doses to the monitored worker from external exposure to neutron radiation. These analyses were performed to resolve some questions that were raised at the meeting of the Advisory Board's Work Group on Mound on January 5, 2010, regarding the MCNP modeling of neutron spectra by Faust et al. (2009).

Background

Dosimeters containing Eastman nuclear track emulsion Type A (NTA) film were used to monitor external exposures to neutron radiation of Mound personnel from February 1949 through November 1977. Initially, the dental-type film packets were contained in a steel badge copied from a design used at ORNL in 1948. 'This . . . badge, consists of a small steel box measuring 5/16" x 1 3/8" x 1 7/8".' One-millimeter-thick cadmium shields covered one half of both the front and rear surfaces of the film packets, while the other half was unshielded. This configuration was used until September 1, 1968, when a new film badge dosimeter modeled after the one then used at the Nevada Test Site was introduced. This "NTS-type" badge used "a ten mil [0.25 mm] lead and a plastic insert over the [NTA] film." (Meyer 1994)

The energy response of the NTA film was long known to depend on the neutron spectra to which the badge was exposed. Mound therefore sought to calibrate the films using sources that were similar to the neutron emitters that were being processed on site. Initially, the calibration sources were ^{210}Po-Be. Effective January 1, 1963, NTA films of workers in the SM areas were assessed using a $^{238}PuF_4$ calibration source. Meyer (1994, p. 17)[1] states his belief that neutron exposures were underestimated since the start of operations in early 1962; however, there is no indication that these early doses were corrected. Around January 1963, the average neutron energy in the SM Building was measured to be 0.75 MeV. However, we calculated the average energy of a bare $^{238}PuF_4$ source to be 1.3 MeV,[2] while that of a ^{210}Po-Be source is 4.7 MeV. Consequently, both calibration sources lead to an underestimate of the actual neutron exposures of the workers in that location.

Subsequent to that date, film calibrated using ^{210}Po-Be sources was used as the reference for reading film badges at some work locations, notably the T and SW Buildings, while $^{238}PuF_4$ was used as the calibration standard for NTA film from other locations at Mound. Beginning on August 9, 1965, "all neutron exposures received in the plant [were to be] estimated on the basis of $^{238}PuF_4$ neutron calibrations." (Meyer 1994)

The assumed relationship between neutron flux and dose rate also varied over the years. Starting August 1, 1949, a flux of 150 n s^{-1} cm^{-2} was assumed to deliver a dose of 300 mrem per 40-h work week. The corresponding dose conversion factor is 1.39×10^{-5} mrem per n/cm^2. Over the next 20 years, the assumed DCF, used to convert the reading of the NTA film to doses to

[1] The pagination refers to the numbers that appear on the bottom of the pages in Meyer's report of March 1994. This report is dispersed throughout seven SRDB pdf files. The pages are not contiguous, and sometimes out of order.

[2] This is confirmed by measurements performed at Mound (Meyers 1994, Vol. 1, p. 302 of PDF file SRDB 3268).

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workers, was changed periodically, based on measurements of the average neutron energies in various locations in the plant. The date the change was implemented, the neutron flux corresponding to 7.5 mrem/h (i.e., 300 mrem per 40-h work week), and the resulting DCF, are listed in table 1.

Table 1. Neutron Dose Conversion Factor (DCF) Used to Calibrate NTA Film at Mound

Date[a]	Flux[b] ($n\ s^{-1}\ cm^{-2}$)	DCF (mrem per n/cm^2)
8/01/1949	150	1.39e-05
10/01/1951	75	2.78e-05
1/01/1955	35	5.95e-05
1/25/1956	30	6.94e-05
1/1/1959	55	3.79e-05
8/09/1963	70	2.98e-05
12/1/1969	55	3.79e-05
1/1/1970[c]	27.5	7.58e-05

Source: Meyer 1994

[a] Effective date of calibration factor

[b] Neutron flux corresponding to 300 mrem per 40-h work week

[c] All previously reported neutron doses for 1970–1976 were doubled according to directive of March 15, 1978

The NTA film calibrations were performed using bare sources. Meyer (1994) cites one instance in which a $^{238}PuF_4$ source was placed inside polyethylene spheres, but this appears to have been done for the measurement of neutron energy spectra. However, workers were exposed to neutron sources involving various amounts of Benelex shielding (a cellulose laminate). Cellulose, whose empirical formula is $C_6H_{10}O_5$, has the effect of reducing the neutron flux due to its high hydrogen content, but also of shifting the spectrum to lower energies. Since NTA film is less sensitive to lower-energy neutrons, the shielding could lead to an underestimate of neutron doses delivered to workers if these doses were assessed by comparing the films to films calibrated with a bare source.

After development, the NTA films were read under a microscope. Initially, the tracks in each of 10 static fields of vision were counted—the results were recorded as the average number of tracks per field. After March 10, 1967, the film was scanned, still under visual inspection, but allowing larger areas to be read. The tracks per field on the calibration film, combined with a knowledge of the neutron flux, the exposure duration, and the assumed DCF, were used to construct a calibration curve. The doses to individual workers were read from this calibration curve, based on the average tracks per field on the worker's NTA film.

Method of Analysis

We used MCNPX to simulate the energy-dependent neutron flux from the calibration sources used at Mound, as well as the flux at the location of a film badge worn by a worker exposed to neutron sources in various exposure geometries. Lehman (1961) proposed the concept of the track unit to quantify the response of NTA film packets to neutrons of various energies, and

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presented a model for calculating the response, based on the physical properties of the film packets.[3] We applied the Lehman model, incorporating updated neutron cross-sections of hydrogen, to compare the tracks per unit exposure observed on the films worn by workers in our model geometries to the tracks on the calibration films, and calculated correction factors for various combinations of calibration sources and postulated workplace exposures.

The exposures in our MCNP model were assumed to occur in a room in the shape of a hollow cylinder, with a radius of 5 m and a height of 3 m, dimensions which correspond to a typical industrial facility. The walls, floors, and ceiling were composed of concrete 1 ft (30.48 cm) thick. The source was located along the axis of the cylinder, 131 cm above the floor (a typical elevation of a film badge worn on the chest of a worker standing erect). The flux across the calibration film was calculated in air at the same elevation, 34.5 cm from the source. This distance was the radius of the film badge calibration rack (see "Neutron Film Calibration," Meyer 1994, Vol. 1, p. 255 of PDF file). The simulations included the two types of calibration sources used at Mound: ^{210}Po-Be and $^{238}PuF_4$.

The flux across the film badge worn by the worker was calculated at the same elevation. To include a realistic simulation of backscatter from the worker's body, the flux was calculated just in front of the chest of a human body. The body was represented by a mathematical phantom generated by BodyBuilder, a commercial computer program from White Rock Science (2004); this model is based on the description by Eckerman et al. (1996). The phantom was positioned facing the source, at a distance of either 60 or 240 cm from the source. To simulate the effect of various thicknesses of shielding, successive simulations modeled a bare source or a source surrounded by a spherical volume of water with a radius of 2 to 12 inches (5.08–30.48 cm), in 2-inch (5.08-cm) increments. The simulations modeled three sources—^{210}Po-Be, $^{238}PuO_2$, and $^{238}PuF_4$—which typify the sources of neutron exposures at Mound.

The unattenuated neutron spectra generated by these three sources were calculated using the computer code Sources-4C (LANL 2002). The output of this code was entered into MCNPX. The neutron flux from the various simulations of ^{210}Po-Be and $^{238}PuO_2$ sources was tallied in 15-keV-wide bins, while the flux from $^{238}PuF_4$, spanning a much narrower energy range, was tallied in 5-keV-wide bins. The energy range began at 0.4 MeV, the threshold response of the NTA film according to the Lehman (1961) model. The upper end was the effective upper limit

[3] Lehman defines the track unit as "the number of tracks per cm^2 of emulsion (normalized to the most frequent emulsion thickness, 33 μm) resulting from 10,000 neutrons per cm^2 incident normally on the back of the film packet." It is not clear why the concept should be limited to neutron incident on the back of the film packet, since most neutrons would strike the film from the front. We have generalized the concept to include neutrons from all directions, and normalizing to 1 rather than 10,000 neutrons.

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of the spectrum calculated by Sources-4C: 10.87 MeV for ^{210}Po-Be, 11.245 MeV for $^{238}PuO_2$, and 3.745 MeV for $^{238}PuF_4$.[4]

According to Lehman (1961), the tracks produced by the hydrogen nuclei (i.e., protons) in the film emulsion, resulting from neutrons impinging on the emulsion, can be expressed as:

$$t_e = \rho_{H_e}\,\sigma_H(E)\,d\left(1 - \frac{E_m}{E}\right) \qquad (1)$$

t_e = track units originating in emulsion per incident neutron

ρ_{He} = atom density of hydrogen in emulsion
= 3.5×10^{22} atoms/cm^3

$\sigma_H(E)$ = elastic scattering cross-section for hydrogen for neutrons of energy E (barns) (NNDC n/d)

d = thickness of emulsion
= 0.0033 cm

E_m = threshold energy of neutron producing detectable track
= 0.4 MeV

E = energy of incident neutron (MeV)

In addition to tracks produced by neutrons colliding with hydrogen nuclei in the film emulsion, tracks are also produced by neutrons interacting with hydrogen in the film base and in the wrapper. Lehman models this phenomenon using the following equation, which he attributes to J. E. Cook:

$$t_r = \rho_{H_r}\,\sigma_H(E)\left[\frac{2}{2n+3}R(E) - \frac{2}{3}R(E_m)\left(\frac{E_m}{E}\right)^{\frac{3}{2}}\right] \qquad (2)$$

t_r = track units originating in radiator (film base + paper wrapper) per incident neutron

ρ_{Hr} = atom density of hydrogen in radiator (weighted combination of hydrogen densities in film base and paper wrapper)
= 3.8×10^{22} atoms/cm^3

[4] Our analyses assumed that the oxygen isotopes in the $^{238}PuO_2$ sources were present in their natural abundances. We later noted that, according to Faust et al. (2009), the Mound sources were enriched in ^{17}O and ^{18}O to enhance the neutron yield. Our subsequent analysis of the neutron spectrum of $^{238}PuO_2$ enriched in these isotopes showed that, although the absolute neutron yield was greatly increased, the energy distribution was little changed. The average energy of the neutrons from the isotopically enriched source is 2.374 MeV, compared to 2.329 MeV for the source with natural abundances. Since it is the relative rather than the absolute intensities of the neutrons in the spectrum that is relevant to our analysis, this difference would have little effect on our results.

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n = 1.63 $(0.4 < E < 2)$
= 1.77 $(2 < E < 10)$
= 1.81 $(E > 10)$

$R(E)$ = range of recoil protons
= aE^n
a = 0.00177 $(0.4 < E < 2)$
= 0.0016 $(2 < E < 10)$
= 0.00146 $(E > 10)$

The total film response can be expressed by the quantity $t_u = t_e + t_r$, as given by equations 1 and 2. Lehman further notes that equation 2 is strictly valid only if the range of the recoil proton does not exceed the thickness of the radiator. According to Meyer (1994), the NTA film packet was inserted into the badge behind the film used to detect photon radiation. We will assume that the photon film packet was made of similar materials as the NTA packet, except that, as reported by Meyer, it contained two films: a sensitive and an insensitive film. The total thickness of the radiator in front of the NTA emulsion, comprising the photon film packet and the front wrappers of the NTA packet, is estimated to be 0.0751 cm, which corresponds to the maximum range of a proton with an energy of 8.8 MeV. The maximum energy of a recoil proton is approximately equal to that of the incident neutron. Ninety percent of the unattenuated neutron spectrum of the ^{210}Po-Be source lies below this energy, as does 99.97% of the $^{238}PuO_2$ spectrum and all of the $^{238}PuF_4$ spectrum. The two equations can therefore be used to estimate the track units registered by the NTA film.

The ambient dose equivalent at a depth of 10 mm, H*(10), per source neutron was calculated at the receptor location for each exposure scenario, comprising two distances, seven source geometries, and three neutron sources. The doses were calculated by applying the ambient dose equivalent per unit neutron fluence, listed by ICRP (1996, Table A.42), to the neutron fluence in air computed by MCNPX. (Since the Mound calibration procedures for NTA film were performed in air, the phantom was omitted from these simulations.)

The next step in deriving correction factors for the NTA film readings was to calculate an NTA film calibration factor for each combination of source, shield, and position, based on the MCNP simulations of the respective exposure geometries and using the track units calculated using the Lehman model as a surrogate for the actual track counts. Such a calibration factor is given by the following expression:

$$f_{ijk} = \frac{d_{ijk}}{t_{ijk}} \quad \textbf{(3)}$$

f_{ijk} = calibration factor for neutrons from source i, attenuated by shield thickness j, at position k (mrem per track unit)

d_{ijk} = dose per neutron from source i, attenuated by shield thickness j, at position k, as calculated by MCNP (mrem/n)

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t_{ijk} = track unit per neutron from source *i*, attenuated by shield thickness *j*, at position *k*, as calculated by equations 1 and 2, utilizing the results of MCNP simulations

Next we needed to derive a surrogate for the calibration factors used at Mound, based on the Mound calibration procedures and the MCNP-calculated track units to represent the actual track counts.

$$F_{mnr} = \frac{c_r D'}{k_t t'_{mr} \Phi'_n} \quad \textbf{(4)}$$

F_{mnr} = derived Mound calibration factor for source *m*, based on dose conversion factor corresponding to flux *n*, using a calibration rack of radius *r*

c_r = geometrical factor used to calculate neutron flux at radius *r* from point source at center

$$= \frac{1}{4 \pi r^2}$$

r = 34.5 cm (Meyer 1994)

D' = "tolerance" dose
= 300 mrem per 40-h week

k_t = factor to convert mrem per 40-h week to mrem/s
= 40 × 3600 = 144,000 s per work-week

t_m' = track units in calibration film from source *m* at distance *r*

ϕ_n' = neutron flux *n* assumed to correspond to "tolerance" dose D' (see table 1)

The correction factors that should be applied to each NTA film for each neutron source in the workplace, calibrated against one of two neutron calibration sources used at Mound, assuming two locations with reference to the source and various shield thicknesses, are given by the following expression:

$$C_{ijkmnr} = \frac{f_{ijk}}{F_{mnr}} \quad \textbf{(5)}$$

C_{ijkmnr} = correction factor for NTA film exposed to neutrons from source *i*, attenuated by shield thickness *j*, at position *k*, which had been assessed by reference to calibration film exposed to source *m* in a rack with radius *r*, using a dose conversion factor based on neutron flux *n*.

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Results of MCNP Analysis

Table 2 lists the correction factors to the NTA films that were evaluated using a calibration curve based on a ^{210}Po-Be source, calculated using the methodology described above. The correction factors depend on the assumed neutron flux that corresponds to 300 mrem per 40-h work week, as listed in Table 1. The factors also depend on the actual neutron source to which the worker was exposed, and the amount of hydrogenous material shielding that source (expressed as inches of water). The dates span the period from the beginning of neutron dosimetry at Mound until the date when NTA films were calibrated exclusively with $^{238}PuF_4$ sources. Plutonium-239 was first present at Mound in 1956, while both ^{238}Pu and ^{239}Pu were used in 1959 and later years.[5] Consequently, the correction factors for $^{238}PuO_2$ and $^{238}PuF_4$ for time periods prior to 1956 are displayed with a shaded background—they are included for reference and completeness, but do not play a significant role in the dose assessments. Table 3 lists the correction factors to the NTA films that were evaluated using a calibration curve based on a $^{238}PuF_4$ source. The dates span the period from the earliest date that $^{238}PuF_4$ calibration sources were used at Mound until the time that the NTA films were replaced with TLDs.

These correction factors do not account for the fading of the latent images on the NTA film between the time of exposure and development, which is discussed in a later section of this report, nor for the angle of incidence, also discussed later.

Track Fading

Another factor compromising neutron exposure assessment using NTA film is proton track fading. Track fading—the fading of the latent image between the time of exposure and the development of the film—depends on both the elapsed time between exposure and development and on the energy imparted by the incident neutron to the proton: the lower-energy tracks, comprising fewer dots, disappear faster than the higher-energy tracks. Mound dosimetry personnel became aware of this phenomenon in 1967. A study of track fading in NTA film exposed to a $^{238}PuF_4$ source, performed in the summer of 1967 and issued as a formal Mound report on July 1, 1968, concluded that 33% of the tracks faded after 1 week and 56% after 2 weeks. We independently analyzed the data presented in that report and derived the following expression:

$$n(t) = n_0 e^{-\lambda t} \quad \textbf{(6)}$$

$n(t)$ = number of tracks after time t (d)

n_0 = number of tracks at $t = 0$

λ = track fading decay constant
= 0.059888/d

[5] We did not perform an explicit analysis of ^{239}Pu, inasmuch as most references in Meyer 1994 are either to unspecified Pu or to ^{238}Pu. However, we did calculate the neutron spectrum from $^{239}PuF_4$ and found that its average energy is 1.24 MeV, about 5% less than that of $^{238}PuF_4$. Thus, the correction factors for ^{239}Pu sources might be somewhat greater than for ^{238}Pu.

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Table 2. Correction Factors to NTA Film Calibrated with ^{210}Po-Be Sources at Mound

Dates:	8/49-9/51	10/51-12/54	1/55-1/24/56	1/25/56-12/58	1/59-8/8/63	8/9/63-8/8/65
Flux (n s^{-1} cm^{-2})[a]:	150	75	35	30	55	70
^{210}Po-Be						
H_2O shield (in)	Worker position: 60 cm					
0	2.8	1.4	0.7	0.6	1.0	1.3
2	3.2	1.6	0.8	0.6	1.2	1.5
4	3.4	1.7	0.8	0.7	1.2	1.6
6	3.4	1.7	0.8	0.7	1.2	1.6
8	3.4	1.7	0.8	0.7	1.2	1.6
10	3.4	1.7	0.8	0.7	1.2	1.6
12	3.3	1.7	0.8	0.7	1.2	1.5
	Observer position: 240 cm					
0	3.7	1.8	0.9	0.7	1.3	1.7
2	4.2	2.1	1.0	0.8	1.5	2.0
4	4.4	2.2	1.0	0.9	1.6	2.1
6	4.4	2.2	1.0	0.9	1.6	2.1
8	4.5	2.2	1.0	0.9	1.6	2.1
10	4.4	2.2	1.0	0.9	1.6	2.1
12	4.5	2.3	1.1	0.9	1.7	2.1
$^{238}PuO_2$						
	Worker position: 60 cm					
0	4.2	2.1	1.0	0.8	1.6	2.0
2	4.9	2.5	1.1	1.0	1.8	2.3
4	5.1	2.5	1.2	1.0	1.9	2.4
6	5.1	2.6	1.2	1.0	1.9	2.4
8	5.2	2.6	1.2	1.1	1.9	2.4
10	5.3	2.6	1.2	1.1	1.9	2.5
12	5.2	2.6	1.2	1.0	1.9	2.4
	Observer position: 240 cm					
0	5.3	2.7	1.2	1.1	1.9	2.5
2	6.4	3.2	1.5	1.3	2.3	3.0
4	6.7	3.3	1.6	1.3	2.4	3.1
6	6.6	3.3	1.5	1.3	2.4	3.1
8	6.9	3.4	1.6	1.4	2.5	3.2
10	6.7	3.4	1.6	1.3	2.5	3.1
12	5.8	2.9	1.3	1.2	2.1	2.7
$^{238}PuF_4$						
	Worker position: 60 cm					
0	5.7	2.8	1.3	1.1	2.1	2.6
2	6.6	3.3	1.5	1.3	2.4	3.1
4	6.9	3.5	1.6	1.4	2.5	3.2
6	6.8	3.4	1.6	1.4	2.5	3.2
8	6.8	3.4	1.6	1.4	2.5	3.2
10	6.5	3.3	1.5	1.3	2.4	3.0
12	6.2	3.1	1.4	1.2	2.3	2.9
	Observer position: 240 cm					
0	7.2	3.6	1.7	1.4	2.7	3.4
2	8.6	4.3	2.0	1.7	3.1	4.0
4	9.4	4.7	2.2	1.9	3.5	4.4
6	9.4	4.7	2.2	1.9	3.4	4.4
8	10.1	5.0	2.4	2.0	3.7	4.7
10	9.6	4.8	2.2	1.9	3.5	4.5
12	8.5	4.2	2.0	1.7	3.1	3.9

[a] Neutron flux equal to 300 mrem per 40-h work week

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Table 3. Correction Factors to NTA Film Calibrated with $^{238}PuF_4$ Sources at Mound

Dates:	1/63–8/8/63	8/9/63–11/30/68	12/1/68–12-31-69	1970-77
Flux (n s^{-1} cm^{-2})[a]:	55	70	55	27.5
$^{238}PuO_2$				
H_2O shield (in)	Worker position: 60 cm			
0	0.8	1.0	0.8	0.4
2	0.9	1.1	0.9	0.4
4	0.9	1.1	0.9	0.5
6	0.9	1.2	0.9	0.5
8	0.9	1.2	0.9	0.5
10	0.9	1.2	0.9	0.5
12	0.9	1.2	0.9	0.5
	Observer position: 240 cm			
0	0.9	1.2	0.9	0.5
2	1.1	1.4	1.1	0.6
4	1.2	1.5	1.2	0.6
6	1.2	1.5	1.2	0.6
8	1.2	1.5	1.2	0.6
10	1.2	1.5	1.2	0.6
12	1.0	1.3	1.0	0.5
$^{238}PuF_4$				
	Worker position: 60 cm			
0	1.0	1.3	1.0	0.5
2	1.2	1.5	1.2	0.6
4	1.2	1.6	1.2	0.6
6	1.2	1.5	1.2	0.6
8	1.2	1.5	1.2	0.6
10	1.2	1.5	1.2	0.6
12	1.1	1.4	1.1	0.5
	Observer position: 240 cm			
0	1.3	1.6	1.3	0.6
2	1.5	1.9	1.5	0.8
4	1.7	2.1	1.7	0.8
6	1.7	2.1	1.7	0.8
8	1.7	2.2	1.7	0.9
10	1.7	2.2	1.7	0.8
12	1.5	1.9	1.5	0.7

[a] Neutron flux equal to 300 mrem per 40-h work week.

Based on this derivation, we predict fading of 34% after 1 week and 87% after 2 weeks, a minor discrepancy with the Mound report. The square of the product-moment (Pearson) correlation coefficient derived from our analysis, $R^2 = 0.985$, indicates an excellent fit of equation 6 to the 11 data points.

No action was taken on this finding by Mound until July 15, 1968, when the dosimetry supervisor directed that all weekly and visitor neutron film badges processed after that date were to be corrected for 33% fading, and 2-week badges for 56% fading. Based on an earlier track

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fading study, which is not further documented, 4-week badges were also to be corrected for 56% fading.

During the summer of 1968, a second study was performed of track fading in NTA film exposed to an attenuated $^{238}PuO_2$ source. The aim of this study was to determine an energy dependence of track fading. That study, which was never issued as a formal Mound report, produced inconclusive results.

An undated, unsigned document included in Meyer 1994, and assumed by Meyer to postdate the studies discussed above, reports another study of track fading in NTA film exposed to a $^{238}PuF_4$ source. In this study, the films were exposed on a daily basis on each weekday for periods of 1, 2, 3, or 4 weeks, and processed the following Monday. Such an experiment more closely simulated the actual exposures of films worn by workers than the study in the July 1, 1968, report, in which each film was subjected to a single exposure. The report concludes that, on the basis of five data points—the baseline exposure with no delay from the exposure time to development plus the four points corresponding to delays of 1–4 weeks—the films faded an average of 9% per week. Our independent analysis of the data presented in this report yields a fading rate of 9.55%, a minor discrepancy.

In order to make a meaningful comparison with the July 1, 1968, report, we used the results of our analysis of the data in the latter report to simulate the fading of films worn by workers during the normal work-week. We assumed that the films were exposed to a uniform neutron flux for 8 hours, Monday–Friday, during the day shift, for either 1, 2, or 4 weeks, and that they were developed on the Monday following the monitoring period at the start of the same shift. This is consistent with the film badge monitoring procedures described in Meyer (1994, Vol. 1). The fading of the films was calculated from the following expression:

$$f(\tau) = 1 - \frac{1}{n} \sum_{i=1}^{n} 3 \int_{t_i - \frac{1}{3}}^{t_i} e^{-\lambda t}\, dt \qquad (7)$$

$f(\tau)$ = fraction of tracks faded during monitoring period τ

n = number of shifts during monitoring period τ

t_i = time from beginning of i-th shift until film is processed

t_i-⅓ = time from end of i-th shift until film is processed

The factor 3 accounts for the length of the shift as a fraction of a 24-h day. The decay constant λ is derived in equation 6. Applying equation 7, we derived fading fractions of 25% for 1-week films, 38% for 2-week films, and 55% for 4-week films. This is far higher than the fading measured in the later study.

In November 1968, Mound began to expose calibration films daily over 1–4-week periods and used these films to calibrate personnel dosimeters worn during corresponding monitoring periods in order to correct for the fading of the films worn by the workers.

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Angular Dependence

Kathren (1965) discusses the angular dependence of NTA film, and concludes that the number of tracks in the film exposed to a calibration source should be multiplied by 0.75 to account for the random angles of incidence on the film worn by the monitored personnel for neutrons of energy above 3.0 MeV, which would lead to an overestimate of the doses from neutrons, $E_n < 3$ MeV. Such a correction would thus produce a claimant-favorable dose estimate.

Conclusions and Recommendations

The results of the MCNP analysis show that correction factors due to the differences between the neutron spectra experienced by the workers and the spectra used to calibrate the film, as well as the varying neutron flux DCFs employed at Mound during different periods of operation, span a range of 0.6–4.7. Since one cannot know the neutron spectrum to which a worker was exposed, we recommend that the highest correction factors for each time period be applied. For periods from August 1949 until January 24, 1956, the correction factors listed in Table 2 for the "observer" exposed to ^{210}Po-Be shielded by 8 inches of water should be applied to neutron doses during each period listed at the top of this table. From January 24, 1956, until August 8, 1965, the correction factors listed in Table 2 for the "observer" exposed to $^{238}PuF_4$ shielded by 8 inches of water should be used. From August 8, 1965, until the end of 1977, the correction factors listed in Table 3 for the "observer" exposed to $^{238}PuF_4$ shielded by 8 inches of water should be applied to neutron doses during each period listed at the top of this table.

Given the range of results of the track fading studies and our subsequent analysis, we recommend that the most claimant-favorable correction factors be applied to the neutron doses prior to July 15, 1968. The Mound procedure to correct *future* NTA film reports—applying a correction of 33% to 1-week films, and 56% to 2-week and 4-week films—is consistent with the assumption that the entire dose is received at the beginning of the 1-week or 2-week monitoring periods, but that it is delivered uniformly during each workday to workers on a 4-week monitoring schedule. This suggests that the study cited in the dosimetry supervisor's July 15, 1968, memo may have involved exposing films daily for a 4-week period, with results that were in complete agreement with our analysis of the July 1, 1968, report. The corrections that were applied by Mound following July 15, 1968, should be applied retrospectively to earlier neutron doses measured at Mound. These corrections are in addition to the correction factors derived from Tables 2 and 3.

The track fading study which forms the basis of the correction factors used a bare $^{238}PuF_4$ source, with neutrons normally incident on the film. The average neutron energy of this source is 1.3 MeV. As noted by Cusimano (1963), fading depends on the track length. A high-energy neutron produces a longer track than a neutron of lower energy. Since tracks of fewer than four grains are attributable to background and are not counted, a high-energy track can lose a larger fraction of its grains due to fading and still be counted, while if a four-grain track loses only one grain, it will not be counted. Measurements of neutron energies in radiation controlled areas at Mound were performed at various times. In January 1963, the time that a $^{238}PuF_4$ source was first used for film calibration, the average neutron energy in the SM Building was measured to be 0.75 MeV. According to an unsigned memo dated 11/26/69: Repeated energy evaluations in radiation control areas have indicated that personnel are subject to exposure to neutrons with an

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average energy of approximately 0.9 MeV (Meyer 1994, Vol. 8, p. 10). In January 1974, measurements in the R Building showed an average neutron energy range of 0.72–2.4 MeV, with a building average of 1.01 MeV. In February 1974, measurements in the PP Building showed an average neutron energy range of 0.5–1.2 MeV, with a building average of 0.8 MeV. Thus, the fading corrections, which are based on a 1.3 MeV spectrum, could underestimate the neutron doses to most workers in areas with lower-energy spectra. We have no sound basis for determining a fading correction under these circumstances.

The practice of exposing calibration films over the same time periods that the workers were monitored would have been an accurate means of correcting for track fading, provided:

(1) Personnel exposures were uniform during each workday during the monitoring period.

(2) Neutron spectra in the workplace were the same as the spectrum of the calibration sources.

We do not know if item 1 constitutes a valid assumption. It can be argued that, on average, the exposures over a period of one year would be uniformly distributed over the film badge monitoring period, provided that there were no systematic deviations: e.g., certain duties involving higher-than-normal exposures were always performed at the beginning of the week. With regard to item 2, the average energies of neutrons in the workplace during this period were definitely lower than that of the calibration source, so the tracks on the personnel badge might have faded faster than those on the calibration sources.

In summary, we believe that the NTA film badge records can be used to reconstruct doses to workers who wore these badges, provided that appropriate correction factors are applied. We have some remaining concerns over the fading of films exposed to low-energy neutrons and believe that this issue merits further study.

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