Draft

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National Institute for Occupational Safety and Health

A Review of ORAUT-OTIB-0092 Correction Factors for Neutron Dose Measured with Nuclear Track Emulsion, Type A Film

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Abbreviations and Acronyms

ABRWH	Advisory Board on Radiation and Worker Health
Be	beryllium
CF	correction factor
cm^2	centimeter squared
Δln	difference in natural logarithm
DE	dose equivalent
DE SWR	dose equivalent spectrum-weighted response
DOE	U.S. Department of Energy
DR	dose reconstruction
E	energy
eV	electron volt
IAEA	International Atomic Energy Agency
MeV	mega-electron volt
mrem	millirem
NA	not applicable
NIOSH	National Institute for Occupational Safety and Health
n,p	neutron-proton
NTA	nuclear track emulsion, Type A
ORAUT	Oak Ridge Associated Universities Team
Po	polonium
PoBe	polonium beryllium
Pu	plutonium
PuBe	plutonium beryllium
PuF4	plutonium-239 tetrafluoride
SRDB	Site Research Database
SWR	spectrum-weighted response
SWDE	spectrum-weighted dose equivalent
TRS	Technical Reports Series

1 Statement of Purpose

To support dose reconstruction (DR), the National Institute for Occupational Safety and Health (NIOSH) and the Oak Ridge Associated Universities Team (ORAUT) assembled a large body of guidance documents, workbooks, computer codes, and tools. One of those documents is ORAUT-OTIB-0092, revision 00, "Correction Factors for Neutron Dose Measured with Nuclear Track Emulsion, Type A Film" (ORAUT, 2024a; "OTIB-0092"), which provides information to allow ORAUT dose reconstructors to apply a neutron energy spectrum correction factor (CF) to recorded neutron doses measured using nuclear track emulsion, Type A (NTA) dosimetry film.

On November 8, 2024, SC&A was tasked by the Subcommittee for Procedure Reviews to review ORAUT-OTIB-0092, revision 00 (ORAUT, 2024a).

2 Use of NTA Film for Neutron Dosimetry

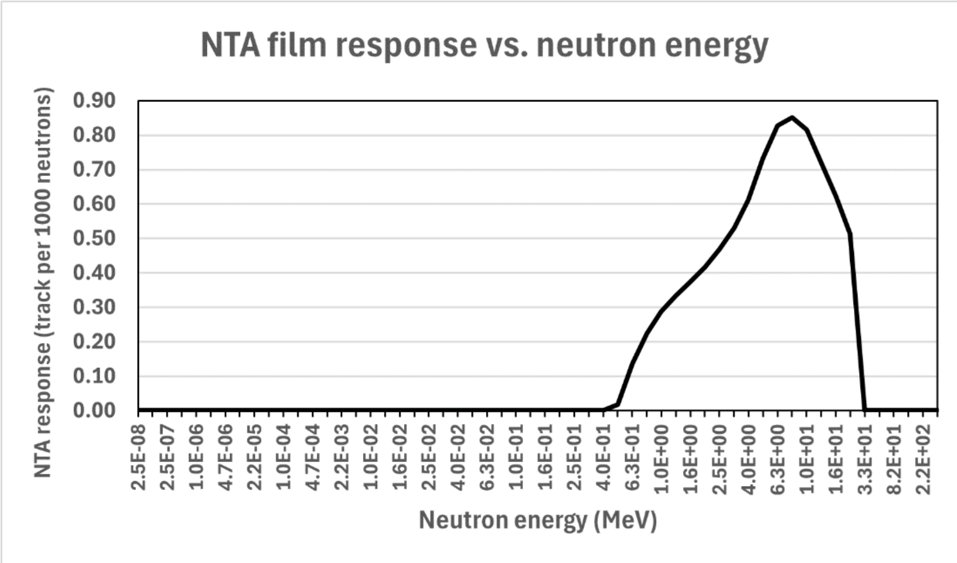
NTA film has been used to determine neutron exposure since 1944. In 1947, Eastman Kodak produced a special fine-grained film, type NTA, in dental packet size, for use as a personnel neutron monitor. The nuclear emulsion film is the portion of the packet that detects fast charged particles from neutron particle interactions. NTA film dosimetry detects the albedo neutrons reflected off the body into the back side a personnel monitoring badge, generally worn mid chest by the worker. According to Lehman (1961, PDF p. 8):

> Neutrons may be detected in the standard NTA packet by three mechanisms: (a) elastic collision with hydrogen nuclei, (b) the exoergic neutron-proton (n, p) reaction with nitrogen nuclei, and (c) inelastic interaction with any nucleus that results in a "star" [cluster of tracks]. In each case, high-energy charged particles are released. It is these charged particles that create a trail of developable grains of silver bromide in the emulsion.

The nitrogen (n, p) reaction is important only at neutron energies below approximately 10 electron volts (eV), since at greater energies the reaction probability drops, so that the sensitivity of the emulsion as a personnel neutron monitor is impractically low. "Elastic collision with hydrogen is important only at neutron energies above about 0.4 MeV; at energies below this, the proton recoil tracks are in practice too short to be observed" (Lehman, 1961, PDF p. 8). Tracks from inelastic interactions with a nucleus are only detectable for neutrons of energy above about 20 mega-electron volts (MeV), which are not generally used for NTA film analysis and not usually present in a worker's exposure environment. Standard practice in the use of NTA film is to report the response of the film packet in terms of tracks per unit area, i.e., tracks per square centimeter (cm^2) as seen through a microscope (Lehman, 1961, PDF p. 8). NTA film was used to monitor personnel and determine area neutron exposures up to the 1980s when thermoluminescent dosimetry came into use, which provided for automated chip reading and more accurate and reproducible results compared to the manual reading of tracks in NTA film.

Figure 1 shows NTA film response as a function of neutron energy. Note the sharp cutoff in response when the neutron energy is below 0.5 MeV and greater than 20 MeV.

Figure 1. NTA film response as a function of neutron energy

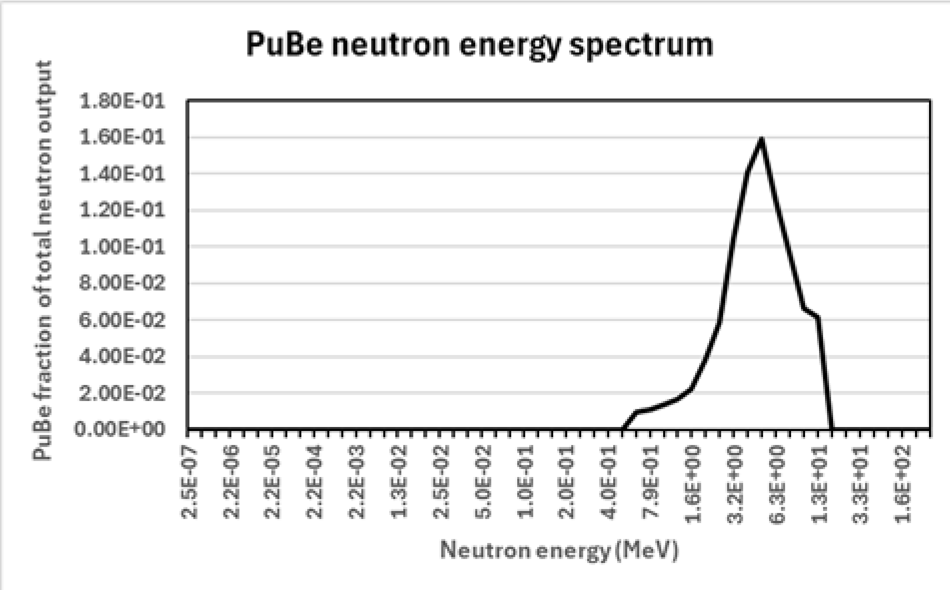


Source: Data from IAEA (1990), table 3-IX.

Since the response of NTA film varies with neutron energy, the NTA film used at a facility is usually calibrated using a known neutron standard that as closely as possible matches the neutron energy spectrum of the workers' exposure conditions at the facility. However, this is not always possible when there are potentially multiple exposure sources, the neutron energy spectrum of the exposure is uncertain, or the neutron energy spectrum is determined after the NTA film results are recorded.

Figure 2 shows a typical plutonium (Pu)-239 beryllium (Be), i.e., PuBe, neutron energy spectrum.

Figure 2. Typical PuBe neutron energy spectrum



Source: Data from IAEA (1990), table 4-X.

The NTA film results recorded for workers' neutron exposures at U.S. Department of Energy (DOE) facilities are generally recorded in units of rem determined at the time of processing and analysis of the NTA film. During the processing of a claim, NIOSH may apply CFs that have been determined after the results were recorded to provide a better estimate of the neutron dose received. Examples of possible CFs that have been applied as needed in DR are for geometry, fading, threshold energy, etc. OTIB-0092 is a recent technical information bulletin that can enable the dose reconstructor to apply a neutron energy spectrum CF to recorded NTA film dose to correct for differences in the neutron energy spectrum of the calibration standard that NTA films were exposed to compared to the potential neutron energy spectrum the worker was exposed to.

3 ORAUT-OTIB-0092 Approach to Neutron Energy Spectra Correction Factor

OTIB-0092 covers the following major topics:

- Section 3.0: A brief history of the use of NTA film
- Section 4.1: Methods for calculating spectrum-weighted response (SWR), spectrum-weighted dose equivalent (SWDE), dose equivalent spectrum-weighted response (DE SWR), and CF using International Atomic Energy Agency (IAEA) Technical Reports Series (TRS) 318 data (IAEA, 1990)
- Section 4.2: Calculations of SWR and SWDE using IAEA TRS 403 data (IAEA, 2001) and comparison to data obtained using TRS 318 data as described in section 4.1
- Attachment A: Two examples of common calibration exposure scenarios

- Attachment B: Comparison of OTIB-0092 derived parameters for determining CFs to values in published literature

- Attachment C: A table of SWR, SWDE, and DE SWR values for various common neutron sources, which contains the information that will be directly applicable to DRs

The following sections expand on some of the major topics contained in OTIB-0092.

3.1 Determining NTA film energy bins in TRS 318 and TRS 403

The usual method of presenting a neutron energy spectrum is to quantify the number of neutrons per energy bin, which are uniform intervals (e.g., 0.5 MeV to 1.0 MeV, 1.0 MeV to 1.5 MeV, etc.). However, neutron energy spectra in TRS 318 and TRS 403 are in a lethargy format. IAEA chose to present neutron energy spectrum as a function of lethargy, i.e., fluence (neutron per cm^2) per unit natural logarithmic (Δln) of energy (E), resulting in the units of neutron/cm^2/Δln(E), where Δln(E) is the difference in natural logarithm of the upper and lower boundaries of the bin. This method simplifies the graphic presentation of the spectrum. However, TRS 318 and TRS 403 use slightly different methods to determine the energy bins and energy values.

- TRS 318 (IAEA, 1990) covers a neutron energy range of 0.025 eV to 435 MeV and uses the energy value below the energy of interest as the lower energy of the bin (e.g., 0.794 MeV to 1.0 MeV for the 1.0 MeV energy bin).

- TRS 403 (IAEA, 2001) covers a neutron energy range of 0.001 eV to 630 MeV and uses the energy value above the energy of interest as the upper energy of the bin (e.g., 1.0 MeV to 1.25 MeV for the 1.0 MeV energy bin).

Additionally, for some energy bins, TRS 403 uses different energy values compared to TRS 318, as shown in table 1; column 1 shows TRS 318 values and column 2 shows TRS 403 values.

Table 1. TRS 318 and TRS 403 neutron energy bins

TRS 318 neutron energies (ev)	TRS 403 neutron energies (ev)
NA	1.00E-03
NA	2.15E-03
NA	4.64E-03
NA	1.00E-02
NA	2.15E-02
2.5E-02	4.64E-02
1.88E-01	1.00E-01
2.50E-01	2.15E-01
5.00E-01	4.64E-01
1.00E+00	1.00E+00
2.15E+00	2.15E+00
4.65E+00	4.64E+00
1.00E+01	1.00E+01
2.15E+01	2.15E+01
4.65E+01	4.64E+01
1.00E+02	1.00E+02

TRS 318 neutron energies (ev)	TRS 403 neutron energies (ev)
2.15E+02	2.15E+02
4.65E+02	4.64E+02
1.00E+03	1.00E+03
2.15E+03	2.15E+03
4.65E+03	4.64E+03
1.00E+04	1.00E+04
1.26E+04	1.25E+04
1.58E+04	1.58E+04
2.00E+04	1.99E+04
2.51E+04	2.51E+04
3.16E+04	3.16E+04
3.98E+04	3.98E+04
5.01E+04	5.01E+04
6.31E+04	6.30E+04
7.94E+04	7.94E+04
1.00E+05	1.00E+05
1.26E+05	1.25E+05
1.58E+05	1.58E+05
2.00E+05	1.99E+05
2.51E+05	2.51E+05
3.16E+05	3.16E+05
3.98E+05	3.98E+05
5.01E+05d	5.01E+05
6.31E+05	6.30E+05
7.94E+05	7.94E+05
1.00E+06	1.00E+06
1.26E+06	1.25E+06
1.58E+06	1.58E+06
2.00E+06	1.99E+06
2.51E+06	2.51E+06
3.16E+06	3.16E+06
3.98E+06	3.98E+06
5.01E+06	5.01E+06
6.31E+06	6.30E+06
7.94E+06	7.94E+06
1.00E+07	1.00E+07
1.26E+07	1.58E+07
1.58E+07	2.51E+07
2.00E+07	3.98E+07
3.30E+07	6.30E+07
5.90E+07	1.00E+08
8.23E+07	1.58E+08
1.60E+08	2.51E+08
2.23E+08	3.98E+08
4.35E+08	6.30E+08

Unfortunately, TRS 318 contains NTA film response (table 3-IX) but TRS 403 does not, and TRS 403 contains some updated and additional neutron energy spectra data that are not included in TRS 318. Therefore, ORAUT interpolated the NTA film response and dose equivalent (DE) values from TRS 318 to the TRS 403 energy bins to enable the data available in TRS 403 to be useful. Details of the analysis is contained in a support zip file, "otib92_energy_bins_with_ISO_benchmark" (ORAUT 2024b). This analysis is summarized in OTIB-0092 as follows:

> To interpolate the film response and DE functions into the energy bin structure of TRS 403, it was assumed that these functions are continuous and that the bin values represent the average value of the function between the endpoints of the bin. For each set of data, the value of the cumulative function was calculated at each bin endpoint of TRS 318 and a monotone cubic spline[1] was fit to the cumulative function at the bin endpoints. The derivative of the cubic spline was calculated to obtain an estimate of the underlying function of interest for the binned data, and this function was integrated over the new bin endpoints of TRS 403 and divided by the width of each bin to calculate the new bin values. In this way, the interpolation ensured the area under the curves in each of the energy bins of TRS 318 is preserved. Tables 4-4 and 4-5 [of OTIB-0092] provide the energies, response function, and DE function used in calculations with TRS 318 and TRS 403 source spectra data, respectively. [ORAUT, 2024a, p. 12]

3.2 Determining NTA film energy correction factors using TRS 318 data

Section 4.1 of OTIB-0092 presents a method using the data in TRS 318 (IAEA, 1990) for determining NTA film DE SWR value for a given neutron source (e.g., polonium (Po)-210-Be, i.e., PoBe) by calculating the value of:

1. SWR, i.e., the response (sum of the tracks per neutron) in the NTA film
2. SWDE, i.e., the dose equivalent (rem) per neutron per cm^2
3. DE SWR, i.e., the dose equivalent (track per cm^2 per rem) derived by dividing SWR by SWDE

The DE SWR calibration value is derived for the source that the NTA film was calibrated with, and the DE SWR exposure value is derived for the neutron energy spectrum the worker was potentially exposed to. Then the NTA film CF is determined by dividing the DE SWR calibration value by the DE SWR exposure value. The recorded neutron dose is then adjusted by this CF, which can be equal to, less than, or greater than 1.0.

For example, if the NTA film was calibrated using a PoBe standard, with a DE SWR of 1.20E4 tracks per cm^2 per rem (per table C-1 of OTIB-0092), and the worker was potentially exposed to a PuBe neutron field, with a DE SWR of 1.66E4 tracks per cm^2 per rem (per table C-1 of OTIB-0092), the CF would be 1.20E4 divided by 1.66E4, which equals a CF of 0.72. If the worker's recorded dose was 500 millirem (mrem) of neutron dose, the corrected dose would be 500 mrem times 0.72, which equals 361 mrem. If the neutron calibration source and the neutron exposure field were reversed, then the worker's recorded dose of 500 mrem would be multiplied by 1.66E4 divided by 1.20E4 (equals 1.38), which results in a corrected dose 692 mrem.

[1] Monotone cubic spline fit is a statistical method used to provide a smooth fit to discrete data points.

Attachment A of OTIB-0092 gives two detailed examples of the derivation of SWRs, SWDEs, DE SWRs, and CFs for calibration and exposure scenarios involving (1) PuBe and Pu-239-tetrafluoride (PuF_4) in example A.1 and (2) PuF_4 and plutonium metal in example A.2. Example A.1 uses TRS 318 data for deriving the CF. Example A.2 uses both TRS 318 (NTA film response) and TRS 403 data for the plutonium metal neutron energy spectrum in deriving the CF.

4 SC&A's Review of ORAUT-OTIB-0092

The following is a summary of SC&A's review of each technical section in OTIB-0092.

4.1 SC&A's review of section 4.1: Calculations with TRS 318 data

SC&A reviewed the methods used in OTIB-0092, section 4.1, and evaluated the data and derivation of the SWR, SWDE, DE SWR, and CF values:

- To verify the SWR values for NTA film exposure to a PoBe neutron source in table 4-1, column 5 (Detector-weighted response), and table 4-2, column 5, of OTIB-0092, SC&A used the data in TRS 318, table 3-IX, column 2, for NTA film response and in table 4-X, column 3, for PoBe spectrum, and the appropriate calculations presented in OTIB-0092.

- To verify the SWDE values for an NTA film exposed to a PoBe neutron source in table 4-3, column 6 (Dose-weighted response), of OTIB-0092, SC&A used the data in TRS 318, table 2-II, column 5, for dose equivalent values and in table 4-X, column 3, for PoBe spectrum, and the appropriate calculations presented in OTIB-0092.

SC&A concurs with the methods and results in section 4.1 of OTIB-0092 and did not identify any findings or observations.

4.2 SC&A's review of section 4.2: Calculations with TRS 403 data

SC&A reviewed the methods used in OTIB-0092, section 4.2, and evaluated the data and derivation of the values in table 4-4 and table 4-5. SC&A used the data in TRS 318, table 2-II, column 5, for dose equivalent values, and in table 3-IX, column 2, for NTA film response, to verify the corresponding values in table 4-4, columns 2 and 4 respectively, of OTIB-0092, according to the neutron energy bins used in TRS 318, which is listed in column 1 of table 4-4.

As described in section 3.1 of this report and page 12 of OTIB-0092, TRS 318 and TRS 403 use slightly different neutron energy intervals for some of the energy bins, and TRS 318 contains NTA film response that are not included in TRS 403. Also, TRS 403 contains some neutron energy spectra not contained in TRS 318. Therefore, NIOSH derived a method to interpolate the data between the two documents for use in DR when appropriate. NIOSH addressed two situations:

1. If the neutron energy interval was the same in TRS 318 and TRS 403, then the NTA film response and DE functions from TRS 318 were ratcheted one notch to a lower energy interval (i.e., one energy interval). For example, if TRS 318 listed the NTA film response function as 2.87E-4 tracks per neutron at 1.0 MeV (for the neutron energy interval of

0.794 MeV to 1.0 MeV), then the corresponding TRS 403 NTA film response function at 0.794 MeV would be 2.87E-4 tracks per neutron (for the neutron energy interval of 0.794 MeV to 1.0 MeV). The same method was applied to the DE function.

2. If the neutron energy interval was different in TRS 318 compared to TRS 403, then the NTA film response and DE functions from TRS 318 were interpolated from TRS 318 to match the corresponding energy interval in TRS 403. This interpolation process is outlined in section 4.2, second paragraph, on page 12 of OTIB-0092 and detailed in the spreadsheets (ORAUT, 2024b). Briefly, the process was to calculate the value of the cumulative function at each bin endpoint of TRS 318 and fit a monotone cubic spline to the cumulative function at the bin endpoints. The derivative of the cubic spline was calculated to obtain an estimate of the underlining function of the data in the energy bin, and then the function was integrated over the new energy bin interval and divided by the width of the new energy bin (i.e., the energy bin used in TRS 403). For example, if TRS 318 listed the DE function as 4.09E-8 rem per neutron per cm^2 at 10.0 MeV (for the neutron energy interval of 7.94 MeV to 10.0 MeV), then the corresponding interpolated value for the TRS 403 DE function at 10.0 MeV was calculated to be 4.15E-8 rem per neutron per cm^2 (for the neutron energy interval of 10.0 MeV to 15.8 MeV).

SC&A reviewed the NTA film response and DE function fitted spline plots in the spreadsheets (ORAUT, 2024b) and found that the interpolations fitted well with the data and did not show large deviations from the normal.

SC&A concurs with the methods and results in section 4.2 of OTIB-0092 and did not identify any findings or observations.

4.3 SC&A's review of section 6.0: Summary

SC&A reviewed the technical summary in section 6.0 and found that it gives an accurate overview of the previous sections of OTIB-0092. SC&A had no findings or observations.

4.4 SC&A's review of attachment A: Common calibration exposure scenarios

SC&A thoroughly evaluated the two examples in attachment A of OTIB-0092 and found them very valuable in illustrating the use of the data presented in OTIB-0092. SC&A evaluated the technical aspect and results of the two example as follows.

4.4.1 Section A.1: Plutonium-beryllium calibration source with a plutonium tetrafluoride exposure scenario

SC&A reviewed the data from TRS 318 and methods used to derive the entries in tables A-1 through A-4 for determining the CF from using a PuBe neutron calibration source and a neutron exposure spectrum from PuF_4 for NTA film. SC&A derived a neutron dose CF of 1.75, which matched the ratio calculated by NIOSH, as indicated on page 19 of OTIB-0092.

4.4.2 Section A.2: Plutonium tetrafluoride calibration source with a bare plutonium metal exposure scenario

SC&A reviewed the interpolated data from TRS 403 and methods used to derive the entries in tables A-5 and A-6 for determining the CF from using a PuF_4 neutron calibration source and a neutron exposure spectrum from bare plutonium metal for NTA film. SC&A derived a neutron dose CF of 0.85, which matched the ratio calculated by NIOSH, as indicated on page 25 of OTIB-0092.

SC&A concurs with the methods and results in attachment A of OTIB-0092 and did not identify any findings or observations.

4.5 SC&A's review of attachment B: Benchmarking the spectrum-weighted response method with published literature

Attachment B of OTIB-0092 presents ORAUT's comparison of several published documents analyzing NTA film response to various neutron energy spectra. These benchmarks indicate that an estimate of dose using the procedure in OTIB-0092 resulted in predicted doses within a factor of less than ±200 percent (i.e., a factor of 0.5 to 2.0). SC&A reviewed attachment B and concurs that the method used in OTIB-0092 produces results comparable to those in the cited literature.

4.6 SC&A's review of attachment C: A summary of various spectrum-weighted response and spectrum-weighted dose equivalent values

Table C-1 provides the most important part of OTIB-0092 for the dose reconstructor. It summarizes the SWR, SWDE, and DE SWR values for use in calculating the CF for a given calibration and exposure scenario that may be encountered in the DR process. SC&A verified a sample of the recommended SWR, SWDE, and DE SWR values and found them correct. SC&A had no findings or observations.

5 Conclusions

SC&A reviewed the methods used in OTIB-0092; reviewed the relevant data in TRS 318 and TRS 403; evaluated the derivation of SWRs, SWDEs, DE SWRs, and CFs values; and verified the various numerical values presented in tables 4-1 through C-1. SC&A did note that to copy and use the numerical values from the spreadsheets (ORAUT, 2024b) for analysis, all the "E‒xx" values had to be converted to "E-xx", i.e., dash changed to minus sign. SC&A finds that this is worth pointing out because it could prevent incorrect data entries and problems in future analysis of data by NIOSH or SC&A. SC&A found that OTIB-0092 used technically sound methods and presented a very complex subject in a concise but illustrative manner. OTIB-0092 also presents useful and applicable data for purposes of DR, summarized in table C-1, for use by the dose reconstructor.

However, SC&A did have the following observation.

Observation 1: Limited applicability of NTA film correction factor

Table C-1 provides a wide array of neutron exposures that potentially could be present at DOE facilities, along with the associated SWR, SWDE, and DE SWR values to determine an NTA film correction factor. Usually, the neutron energy spectrum of the source used to calibrate neutron detectors at a facility is known with a reasonable degree of accuracy. However, in many cases, the neutron energy spectrum of the exposure in the field will vary. Even if the neutron energy spectrum is measured at several locations in the field, the actual neutron exposure spectrum to the worker can vary, influenced by such factors as:

- neutron source (especially for changes in voltage and target materials at accelerators)
- shielding materials, thickness, layering, and angle neutrons transverse the shielding
- access ports, seams, and voids in the shielding
- sky shine (reflection of neutrons back down from the atmosphere)
- ground shine (reflection of neutrons up from the ground at an angle from the source)
- backscattered neutrons from material behind the worker

These parameters could change significantly as a worker moves around an area. This is further complicated when attempting to determine neutron dose from exposure situations that took place over 40 years ago, when NTA film was used. Some of the parameters for deriving the neutron dose CFs have been determined with much greater accuracy than most neutron exposure spectrum can be known. The neutron dose CF should be used with caution because it could lead to a false sense of being able to derive and assign neutron doses with a much greater degree of accuracy than is warranted. Therefore, SC&A recommends that given such uncertainties, only a spectrum CF of equal to or greater than 1 be applied to a worker's recorded neutron dose, unless the previously listed uncertainties are well documented.

6 References

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