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Correction Factors for Neutron Dose Measured with Nuclear Track Emulsion, Type A Film	ORAUT-OTIB-0092	Rev. 00
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☒ New ☐ Total Rewrite ☐ Revision

PUBLICATION RECORD

EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
02/22/2024	00	New document to describe a method for estimation of the amount of underreported neutron dose as measured by nuclear track emulsion, Type A film. Expanded Purpose section to better explain methodology and application, updated analyses to incorporate latest revision of ISO 8529-1, part 1, interpolated the film response and DE functions into the energy bin structure of TRS 403, and expanded discussion on benchmarking process. Incorporates formal internal and NIOSH review comments. Training required: As determined by the Objective Manager. Initiated by John M. Byrne and authored by Stephen T. Pittman.

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ACRONYMS AND ABBREVIATIONS

AmB	americium-boron (alloy)
AmBe	americium-beryllium (alloy)
AmLi	americium-lithium (alloy)
AWE	Atomic Weapons Employer
CERN	European Organization for Nuclear Research
cm	centimeter
CmBe	curium-beryllium (alloy)
D_2O	deuterium oxide, heavy water
DE	dose equivalent
DE SWR	dose equivalent spectrum-weighted response
DOE	U.S. Department of Energy
eV	electron-volt
GBq	gigabecquerel
IAEA	International Atomic Energy Agency
in.	inch
ISO	International Organization for Standardization
m	meter
meV	millielectron-volt, 0.001 electron-volt
MeV	megaelectron-volt, 1 million electron-volts
mrem	millirem
NaBe	sodium-beryllium (alloy)
NIOSH	National Institute for Occupational Safety and Health
NTA	nuclear track emulsion, Type A
ORAU	Oak Ridge Associated Universities
ORAUT	ORAU Team
PoBe	polonium-beryllium (alloy)
PuBe	plutonium-beryllium (alloy)
PuLi	plutonium-lithium (alloy)
RaBe	radium-beryllium (alloy)
SRDB Ref ID	Site Research Database Reference Identification (number)
Sv	sievert
SWDE	spectrum-weighted DE
SWR	spectrum-weighted response
TIB	technical information bulletin
TRS	Technical Reports Series
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 historical 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 about the affected site(s), such as changing scientific understanding of operations, processes, or procedures involving radioactive materials. TIBs may be used to assist NIOSH staff in the completion of individual dose reconstructions.

In this document the word “facility” is used to refer to an area, building, or group of buildings that served a specific purpose at a U.S. Department of Energy (DOE) or Atomic Weapons Employer (AWE) facility. It does not mean, nor should it be equated to, an “AWE facility” or a “DOE facility.” The terms AWE and DOE facility are defined in 42 *United States Code* (U.S.C.) § 7384l(5) and (12) of the Energy Employees Occupational Illness Compensation Program Act of 2000, respectively.

2.0 PURPOSE

This document describes a method the Oak Ridge Associated Universities (ORAU) Team (ORAUT) can use to estimate the potential under- or overreported neutron dose measured by Eastman Kodak nuclear track emulsion, Type A (NTA) film at DOE and AWE facilities. This is accomplished by comparing the dose equivalent (DE) spectrum-weighted response (SWR) of the film to the calibration source and to the source term at the facility, and such a comparison accounts for the difference in energy fluence between the two terms. This method can be used to estimate personnel neutron dose when detailed information about the facility is unavailable. It requires only three pieces of information: the type of detector worn, the calibration source, and the personnel exposure source. This information usually can be determined from site documents. Additional details about geometry, shielding, track fading, angular dependence, and other factors related to dose measurement can improve estimates but are not addressed in this TIB. This TIB is designed to estimate the dose when limited information is available.

The ORAU Team method is based on an International Atomic Energy Agency (IAEA) method for calculating a dosimeter’s SWR when exposed to various neutron sources, but it further develops that method to use tabulated dosimetric quantities for the neutron spectra as well. The IAEA SWR method is discussed in Technical Reports Series (TRS) No. 318, *Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes* [TRS 318; Griffith et al. 1990], and TRS No. 403, *Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes Supplement to Technical Reports Series No. 318* [TRS 403; IAEA 2001]. Dosimetric quantities are also found in these reports. Although this TIB discusses using this method for NTA film, this procedure can be used for any neutron detector with a known response function as long as that function has the same energy bin structure as the source spectrum it is folded into. This TIB was developed using the data in TRS 318 and TRS 403 with their respective bin structures.

3.0 HISTORY AND USE OF NUCLEAR TRACK EMULSION, TYPE A FILM

Eastman Kodak first produced NTA film in a dental packet size in 1947. By the early 1950s, many government research facilities had adopted it for personnel neutron dosimetry, and it remained in use at some locations well into the 1980s.

The NTA film neutron response function is energy dependent with a threshold estimated as low as 0.4 MeV dependent on site-specific background and dosimetry procedures [Lehman 1961]. Recoil tracks in the emulsion layer are not long enough to be distinguished from background tracks at lower energies. A thorough description of the NTA film dosimeter and its physics can be found in Lehman [1961].

Because the detector response is a function of energy, the response varies from one spectrum to the next. Therefore, many research facilities attempted to calibrate NTA film using neutron sources with spectra similar to those encountered by personnel during work activities. If the calibration source emitted a neutron energy spectrum dissimilar to neutron sources encountered during work and monitored by the film, then calibration did not allow an accurate reading of the measured dose on the film. To address this issue and more accurately determine the dose measured by NTA film, the ORAU Team proposes adopting a method similar to that described in TRS 318 using the NTA film SWR but also accounting for the variability in DE between different neutron spectra.

4.0 IAEA AND ORAU TEAM CALCULATIONS

4.1 CALCULATIONS WITH TRS 318 DATA

TRS 318 lists a collection of neutron spectra encountered in various occupational environments along with spectra of neutron calibration sources. It provides dose conversion factors as a function of neutron fluence and detector response functions for a variety of neutron dosimeters and survey instruments including NTA film. These dose conversion factors and response functions are then folded into each of the neutron spectra and summed to yield a calculated SWR value in units of track/neutron (for NTA film) and a spectrum-weighted DE (SWDE) value in units of Sv/1×10^{11} neutrons/cm^2, which is converted to rem/neutron/cm^2.

According to TRS 318 [p. 16], “spectrum weighted detector responses are presented in terms of response per unit neutron fluence,” except NTA film response, which is presented as “track/neutron” [TRS 318, p. 41]. The origin of this unit in TRS 318 can be traced back to Lehman [1961], who coined the term “track unit” for the unit of measure for NTA film tracks. One track unit is defined as the number of tracks/cm^2 of emulsion (normalized to the most common emulsion thickness) resulting from 1×10^4 neutrons/cm^2 incident normally on the back of the film packet [Lehman 1961]. Combining units for track density and neutron fluence gives NTA response in track/neutron on the order of 1×10^{-4}.

The NTA film SWR and the SWDE for a given neutron field can be found in TRS 318 or calculated as described in this document. Once those values are determined, this method builds on that information by calculating the DE SWR as the quotient of SWR and SWDE and then divides the calibration source DE SWR by the exposure source DE SWR to determine the full dose from the value reported by NTA film. Note that this method is based on the energy bin structures in those reports and calculates a dose correction factor to modify the original NTA dose measurement.

The following steps outline the procedure described in this document. Steps 1 and 2 are calculations from TRS 318 and TRS 403 for individual dosimeters and spectra. Steps 3 to 5 build on that principle:

1. Sum the product of the spectrum fluence and dosimeter response for each energy bin and normalize the result to calculate the SWRs (track/neutron) for the calibration and exposure sources:

$$SWR = \sum_{i=E_{\min}\ \text{bin}}^{E_{\max}\ \text{bin}} \left(\frac{\varphi_i \times R_i}{\sum_i \varphi_i} \right) \text{ (track/neutron)} \qquad (4\text{-}1)$$

where φ is the fluence (neutron/cm^2), R is the detector response (track/neutron) of energy bin i, and the summation is performed over all energy bins of the spectrum.

2. Sum the product of the spectrum fluence and DE for each energy bin and normalize the result to calculate the SWDE (rem/neutron/cm^2) for the calibration and exposure sources:

$$SWDE = \sum_{i=E_{\min}\text{ bin}}^{E_{\max}\text{ bin}} \left(\frac{\varphi_i \times DE_i}{\sum_i \varphi_i} \right) \text{(rem/neutron/cm}^2\text{)} \tag{4-2}$$

where φ is the fluence (neutron/cm^2), DE is the dose equivalent (rem/neutron/cm^2) of energy bin i, and the summation is performed over all energy bins of the spectrum.

3. Take the quotient of the SWR and SWDE to determine the DE SWR (tracks/cm^2/rem) for each source:

$$DE\ SWR \text{ (tracks/cm}^2\text{/rem)} = SWR \text{ (track/neutron)} \div SWDE \text{ (rem/neutron/cm}^2\text{)} \tag{4-3}$$

4. Take the quotient of the calibration and exposure source DE SWR values to determine the dose correction factor:

$$Dose\ correction\ factor = DE\ SWR_{\text{Calibration}} \text{ (tracks/cm}^2\text{/rem)} \div DE\ SWR_{\text{Exposure}} \text{ (tracks/cm}^2\text{/rem)} \tag{4-4}$$

5. Take the product of the dose correction factor and the dosimeter-recorded dose to determine the correct dose of exposure for personnel:

$$Correct\ dose = Dose_{\text{NTA}} \times Dose\ correction\ factor \tag{4-5}$$

TRS 318 presents tables of detector responses and neutron dose and source spectra for energies across 10 orders of magnitude spanning 0.188 to 4.35 × 10^8 eV. In addition, a thermal energy band encompasses neutrons with energies from 0.025 to less than 0.188 eV. Each order of magnitude is divided into 3 to 10 energy groups (or bins). TRS 403 presents these data across an energy range of 0.001 to 6.30 × 10^8 eV.

A common way to present neutron source spectra is to quantify the number of neutrons per energy bin, but source spectra in TRS 318 and TRS 403 are in a lethargy format. IAEA chose to present spectra as a function of lethargy (fluence per unit natural logarithmic energy; neutron/cm^2/Δln(E), where Δln(E) is the difference in natural logarithm of the upper and lower boundaries of the bin) to simplify the graphic presentation of the spectra. According to IAEA, “The lethargy unit is preferred because neutron spectra, when plotted as fluence per unit energy, often display a steep negative slope at lower energies because of a roughly inverse energy dependence, and require many decades on the fluence axis for presentation. This gives a false impression of the relative number of low-energy neutrons and their contribution to total dose or dose equivalent” [TRS 318, p. 19]. Using this format, the tabulated value in TRS 318 for energy bin i is the value at the upper boundary of that bin E_i with the lower boundary E_{i-1} defined by the preceding energy in the row of the table above it. The opposite is true for tabulated lethargy values in TRS 403 where the bin value is given for the lower boundary of the bin E_i with the upper boundary E_{i+1} defined by the energy in the row of the table below it. Once converted to the lethargy format, spectra were normalized to 1 neutron/cm^2. Values in the reports are presented in units of neutron/cm^2/Δln(E).

Table 4-1 is a subset of data from TRS 318 that presents the NTA film response and the neutron spectrum for an unmoderated PoBe source.

Table 4-1. TRS 318 and ORAU Team SWR calculations for an unmoderated PoBe source.

Neutron energy (eV)	**NTA film response (track/neutron)[a]**	**PoBe source [neutron/cm^2/Δln(*E*)][b]**	**Spectrum × lethargy (neutron/cm^2)**	**Detector-weighted response (track/cm^2)**
Thermal[c]	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.88E−01	Not available	Not available	Not available	Not available
2.50E−01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5.00E−01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.65E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.65E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.65E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E+03	0.00E+00	1.68E−03	1.29E−03	0.00E+00
4.65E+03	0.00E+00	4.03E−03	3.11E−03	0.00E+00
1.00E+04	0.00E+00	6.04E−03	4.62E−03	0.00E+00
1.26E+04	0.00E+00	7.47E−03	1.73E−03	0.00E+00
1.58E+04	0.00E+00	8.41E−03	1.90E−03	0.00E+00
2.00E+04	0.00E+00	1.00E−02	2.36E−03	0.00E+00
2.51E+04	0.00E+00	1.05E−02	2.38E−03	0.00E+00
3.16E+04	0.00E+00	1.19E−02	2.74E−03	0.00E+00
3.98E+04	0.00E+00	1.21E−02	2.79E−03	0.00E+00
5.01E+04	0.00E+00	1.20E−02	2.76E−03	0.00E+00
6.31E+04	0.00E+00	1.26E−02	2.91E−03	0.00E+00
7.94E+04	0.00E+00	1.32E−02	3.03E−03	0.00E+00
1.00E+05	0.00E+00	1.42E−02	3.28E−03	0.00E+00
1.26E+05	0.00E+00	1.50E−02	3.47E−03	0.00E+00
1.58E+05	0.00E+00	1.63E−02	3.69E−03	0.00E+00
2.00E+05	0.00E+00	1.76E−02	4.15E−03	0.00E+00
2.51E+05	0.00E+00	1.92E−02	4.36E−03	0.00E+00
3.16E+05	0.00E+00	2.38E−02	5.48E−03	0.00E+00
3.98E+05	0.00E+00	2.96E−02	6.83E−03	0.00E+00
5.01E+05[d]	1.76E−05	3.75E−02	8.63E−03	1.52E−07
6.31E+05	1.37E−04	4.72E−02	1.09E−02	1.49E−06
7.94E+05	2.25E−04	5.95E−02	1.37E−02	3.08E−06
1.00E+06	2.87E−04	7.01E−02	1.62E−02	4.64E−06
1.26E+06	3.34E−04	6.54E−02	1.51E−02	5.05E−06
1.58E+06	3.74E−04	5.64E−02	1.28E−02	4.77E−06
2.00E+06	4.17E−04	6.12E−02	1.44E−02	6.02E−06
2.51E+06	4.70E−04	6.79E−02	1.54E−02	7.25E−06
3.16E+06	5.30E−04	7.42E−02	1.71E−02	9.06E−06
3.98E+06	6.12E−04	7.24E−02	1.67E−02	1.02E−05
5.01E+06	7.33E−04	6.87E−02	1.58E−02	1.16E−05
6.31E+06	8.28E−04	5.48E−02	1.26E−02	1.05E−05
7.94E+06	8.52E−04	1.74E−02	4.00E−03	3.41E−06
1.00E+07	8.15E−04	1.74E−03	4.01E−04	3.27E−07
1.26E+07	7.18E−04	0.00E+00	0.00E+00	0.00E+00
1.58E+07	6.22E−04	0.00E+00	0.00E+00	0.00E+00
2.00E+07	5.14E−04	0.00E+00	0.00E+00	0.00E+00
3.30E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Neutron energy (eV)	NTA film response (track/neutron)[a]	PoBe source [neutron/cm²/Δln(*E*)][b]	Spectrum × lethargy (neutron/cm²)	Detector-weighted response (track/cm²)
5.90E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.23E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.60E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.23E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.35E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00

a. Source: TRS 318, Table 3-IX.
b. Source: TRS 318, Table 4-X; Δln(*E*) is the difference in natural logarithm of the boundaries of the bin.
c. Thermal = 2.5E−02 to less than 1.88E−01 eV.
d. Values in this bin are highlighted in Table 4-2 and calculated with Equations 4-6 and 4-7.

Table 4-2 below illustrates the lowest energy bin of the NTA film response in Table 4-1 (footnote d), and the following equations demonstrate how values are determined for that bin.

Step 1 calculates the detector SWR (track/neutron) for the calibration source using Equation 4-1 above. Before the NTA SWR can be calculated with Equation 4-1, the lethargy format for fluence, which is used in the compendia (column 3), needs to be converted to fluence in units of neutron/cm² (column 4) with the multiplication of the difference in natural logarithm of the upper and lower boundaries of the energy bin (column 1). This is demonstrated in Equation 4-6:

$$3.75\times10^{-2}\left[\ln\left(5.01\times10^{5}\right)-\ln\left(3.98\times10^{5}\right)\right]=8.63\times10^{-3}\ \text{(neutron/cm}^2\text{)} \quad (4\text{-}6)$$

(fluence)

Then the fluence for each energy bin (column 4) is multiplied by the detector response (track/neutron value) for that bin (column 2) to determine the detector-weighted response (column 5) for that bin. This is demonstrated in Equation 4-7:

$$\left(8.63\times10^{-3}\ [\text{neutron/cm}^2]\right)\left(1.76\times10^{-5}\ [\text{track/neutron}]\right)=1.52\times10^{-7}\ \text{(track/cm}^2\text{)} \quad (4\text{-}7)$$

(detector-weighted response)

Table 4-2. Example from the lowest energy bin of the NTA film response in Table 4-1.

Neutron energy (eV)	NTA film response (track/neutron)[a]	PoBe source [neutron/cm²/Δln(*E*)][b]	Spectrum × lethargy (neutron/cm²)	Detector-weighted response (track/cm²)
3.98E+05	0.00E+00	2.96E−02	6.83E−03	0.00E+00
5.01E+05	1.76E−05	3.75E−02	8.63E−03[c]	1.52E−07[c]
6.31E+05	1.37E−04	4.72E−02	1.09E−03	1.49E−06

a. Source: TRS 318, Table 3-IX.
b. Source: TRS 318, Table 4-X; Δln(*E*) is the difference in natural logarithm of the boundaries of the bin.
c. See Equations 4-6 and 4-7; calculations in this bin pertain to footnote d in Table 4-1.

Once the detector-weighted response is calculated for each bin, summing the detector-weighted response values and dividing by the sum of the Spectrum × lethargy values to normalize the fluence to 1 neutron/cm² determines the SWR (Equation 4-1).

For NTA film exposed to a PoBe neutron source, the SWR is 3.28×10^{-4} track/neutron.

Step 2 calculates the SWDE for the calibration source. Table 4-3 lists the values used in these calculations for the PoBe spectrum above. TRS 318 tabulates DE (in units of Sv/1E+11 neutrons/cm²) as a function of energy. To proceed with step 2, this must be converted to rem/neutron/cm² before folding into the PoBe spectrum (in the same manner as the NTA film response function in step 1). The dose-weighted response values are then summed and divided by the sum of the Spectrum × lethargy values to generate the SWDE value using Equation 4-2. For the PoBe spectrum here, the SWDE is 2.73×10^{-8} rem/neutron/cm^2.

Table 4-3. TRS 318 data and ORAU Team SWDE calculations for an unmoderated PoBe source.

Neutron energy (eV)	DE (Sv/1E+11 neutrons/cm^2)[a]	Dose conversion factor (rem/neutron/cm^2)	Po-Be source [neutron/cm^2/Δln(E)][b]	Spectrum × lethargy (neutron/cm^2)	Dose-weighted response (rem)
Thermal[c]	1.07E+00	1.07E−09	0.00E+00	0.00E+00	0.00E+00
1.88E−01	Not available	Not available	Not available	Not available	Not available
2.50E−01	1.19E+00	1.19E−09	0.00E+00	0.00E+00	0.00E+00
5.00E−01	1.21E+00	1.21E−09	0.00E+00	0.00E+00	0.00E+00
1.00E+00	1.25E+00	1.25E−09	0.00E+00	0.00E+00	0.00E+00
2.15E+00	1.25E+00	1.25E−09	0.00E+00	0.00E+00	0.00E+00
4.65E+00	1.24E+00	1.24E−09	0.00E+00	0.00E+00	0.00E+00
1.00E+01	1.22E+00	1.22E−09	0.00E+00	0.00E+00	0.00E+00
2.15E+01	1.20E+00	1.20E−09	0.00E+00	0.00E+00	0.00E+00
4.65E+01	1.18E+00	1.18E−09	0.00E+00	0.00E+00	0.00E+00
1.00E+02	1.17E+00	1.17E−09	0.00E+00	0.00E+00	0.00E+00
2.15E+02	1.13E+00	1.13E−09	0.00E+00	0.00E+00	0.00E+00
4.65E+02	1.09E+00	1.09E−09	0.00E+00	0.00E+00	0.00E+00
1.00E+03	1.05E+00	1.05E−09	0.00E+00	0.00E+00	0.00E+00
2.15E+03	1.02E+00	1.02E−09	1.68E−03	1.29E−03	1.31E−12
4.65E+03	1.01E+00	1.01E−09	4.03E−03	3.11E−03	3.14E−12
1.00E+04	9.98E−01	9.98E−10	6.04E−03	4.62E−03	4.62E−12
1.26E+04	1.08E+00	1.08E−09	7.47E−03	1.73E−03	1.86E−12
1.58E+04	1.29E+00	1.29E−09	8.41E−03	1.90E−03	2.46E−12
2.00E+04	1.54E+00	1.54E−09	1.00E−02	2.36E−03	3.63E−12
2.51E+04	1.84E+00	1.84E−09	1.05E−02	2.38E−03	4.39E−12
3.16E+04	2.19E+00	2.19E−09	1.19E−02	2.74E−03	6.00E−12
3.98E+04	2.63E+00	2.63E−09	1.21E−02	2.79E−03	7.34E−12
5.01E+04	3.12E+00	3.12E−09	1.20E−02	2.76E−03	8.62E−12
6.31E+04	3.72E+00	3.72E−09	1.26E−02	2.91E−03	1.08E−11
7.94E+04	4.44E+00	4.44E−09	1.32E−02	3.03E−03	1.35E−11
1.00E+05	5.30E+00	5.30E−09	1.42E−02	3.28E−03	1.74E−11
1.26E+05	6.32E+00	6.32E−09	1.50E−02	3.47E−03	2.19E−11
1.58E+05	7.54E+00	7.54E−09	1.63E−02	3.69E−03	2.78E−11
2.00E+05	8.99E+00	8.99E−09	1.76E−02	4.15E−03	3.73E−11
2.51E+05	1.07E+01	1.07E−08	1.92E−02	4.36E−03	4.67E−11
3.16E+05	1.28E+01	1.28E−08	2.38E−02	5.48E−03	7.02E−11
3.98E+05	1.53E+01	1.53E−08	2.96E−02	6.83E−03	1.04E−10
5.01E+05[d]	1.82E+01	1.82E−08	3.75E−02	8.63E−03	1.57E−10
6.31E+05	2.16E+01	2.16E−08	4.72E−02	1.09E−02	2.35E−10
7.94E+05	2.55E+01	2.55E−08	5.95E−02	1.37E−02	3.49E−10
1.00E+06	3.01E+01	3.01E−08	7.01E−02	1.62E−02	4.87E−10
1.26E+06	3.38E+01	3.38E−08	6.54E−02	1.51E−02	5.11E−10
1.58E+06	3.60E+01	3.60E−08	5.64E−02	1.28E−02	4.60E−10
2.00E+06	3.84E+01	3.84E−08	6.12E−02	1.44E−02	5.54E−10
2.51E+06	3.98E+01	3.98E−08	6.79E−02	1.54E−02	6.14E−10
3.16E+06	4.01E+01	4.01E−08	7.42E−02	1.71E−02	6.85E−10
3.98E+06	4.04E+01	4.04E−08	7.24E−02	1.67E−02	6.75E−10
5.01E+06	4.07E+01	4.07E−08	6.87E−02	1.58E−02	6.44E−10
6.31E+06	4.09E+01	4.09E−08	5.48E−02	1.26E−02	5.17E−10

Neutron energy (eV)	DE (Sv/1E+11 neutrons/cm^2)[a]	Dose conversion factor (rem/neutron/cm^2)	Po-Be source [neutron/cm^2/Δln(*E*)][b]	Spectrum × lethargy (neutron/cm^2)	Dose-weighted response (rem)
7.94E+06	4.09E+01	4.09E−08	1.74E−02	4.00E−03	1.64E−10
1.00E+07	4.09E+01	4.09E−08	1.74E−03	4.01E−04	1.64E−11
1.26E+07	4.12E+01	4.12E−08	0.00E+00	0.00E+00	0.00E+00
1.58E+07	4.18E+01	4.18E−08	0.00E+00	0.00E+00	0.00E+00
2.00E+07	4.24E+01	4.24E−08	0.00E+00	0.00E+00	0.00E+00
3.30E+07	4.35E+01	4.35E−08	0.00E+00	0.00E+00	0.00E+00
5.90E+07	4.49E+01	4.49E−08	0.00E+00	0.00E+00	0.00E+00
8.23E+07	4.74E+01	4.74E−08	0.00E+00	0.00E+00	0.00E+00
1.60E+08	5.05E+01	5.05E−08	0.00E+00	0.00E+00	0.00E+00
2.23E+08	5.41E+01	5.41E−08	0.00E+00	0.00E+00	0.00E+00
4.35E+08	6.45E+01	6.45E−08	0.00E+00	0.00E+00	0.00E+00

a. Source: TRS 318, Table 2-II.
b. Source: TRS 318, Table 4-X; Δln(*E*) is the difference in natural logarithm of the boundaries of the bin.
c. Thermal = 2.5E−02 to less than 1.88E−01 eV.
d. Energy bin highlighted in Table 4-2.

Once the NTA SWR and SWDE are calculated for the calibration source, steps 1 and 2 are repeated to obtain the SWR and SWDE for the occupational neutron spectra encountered by the worker's NTA dosimeter.

In step 3, the quotient of the SWR (step 1) and SWDE (step 2) is calculated for each spectrum to determine the expected DE SWR in tracks/cm^2/rem for NTA film exposed to each spectrum using Equation 4-3.

In step 4, the DE SWR for the calibration source (step 3) is divided by the DE SWR for the occupational source (step 3) to determine the dose correction factor as shown in by Equation 4-4.

Finally, step 5 uses the dose correction factor from step 4 to adjust the individual's original NTA dose of record to account for film spectrum response differences as shown in Equation 4-5. The original NTA dose of record must be void of other dose correction factors implemented by the site.

As an example, if a worker was exposed to the Lawrence Berkeley Laboratory Bevatron spectrum, the NTA film SWR would be 1.53×10^{-4} track/neutron according to TRS 318. Calculations determine that the SWDE is 2.25×10^{-8} rem/neutron/cm^2; therefore, the DE SWR is 6.80×10^3 tracks/cm^2/rem for NTA film exposed to this source. NTA film calibrated with the PoBe neutron source in the example above has a DE SWR of 1.20×10^4 tracks/cm^2/rem.

The ratio of the DE SWR calibration value to the exposure value determines the correction factor for the dose that was under- or overreported by NTA film in that environment. In this case, the correction factor for NTA film calibrated with a PoBe source and exposed to Bevatron neutrons is 1.76 ($1.20 \times 10^4 \div 6.80 \times 10^3$). This means the reported dose calculated from the worker's NTA film was underreported. To correct for this underresponse, the dose reported by the worker's NTA film should be multiplied by a factor 1.76. Had the ratio of calibration-to-exposure been less than 1, it would indicate that occupational exposure resulted in an overresponse of NTA film for personnel dose, and the actual DE would be lower after applying the correction factor.

Additional examples can be found in Attachment A, where two of the most common calibration source exposure scenarios are analyzed. Further benchmarking with published literature is discussed in Attachment B, and Attachment C presents a summary table of SWR (track/neutron), SWDE (rem/neutron/cm^2), and DE SWR (tracks/cm^2/rem) values for a variety of neutron source spectra in TRS 318. These calculations are provided in ORAUT [2024].

4.2 CALCULATIONS WITH TRS 403 DATA

The procedure above describes how to perform calculations with spectra in the format of TRS 318. If spectra are in a different format, additional steps need to be performed to use this procedure. TRS 318 tabulates values for the energy bin *i*–1 to *i*, and TRS 403 tabulates values for the bin *i* to *i*+1. Further, some bin boundary values differ slightly between the two documents, and TRS 403 has fewer bins in the energy range of NTA film response. However, the most significant difference between the two documents is TRS 403 does not provide NTA film response and neutron DE values for its energy bins. To avoid the errors introduced by these differences in calculations with TRS 403 spectral data, the ORAU Team has interpolated the NTA film response and DE values for the TRS 403 energy bins [ORAUT 2024].

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 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 provide the energies, response function, and DE function used in calculations with TRS 318 and TRS 403 source spectra data, respectively.

Table 4-4. TRS 318 DE and SWR functions.

Neutron energy (eV)	DE (Sv/1E+11 neutrons/cm^2)[a]	Dose conversion factor (rem/neutron/cm^2)	NTA film response (track/neutron)[b]
Thermal[c]	1.07E+00	1.07E−09	0.00E+00
1.88E−01	Not available	Not available	Not available
2.50E−01	1.19E+00	1.19E−09	0.00E+00
5.00E−01	1.21E+00	1.21E−09	0.00E+00
1.00E+00	1.25E+00	1.25E−09	0.00E+00
2.15E+00	1.25E+00	1.25E−09	0.00E+00
4.65E+00	1.24E+00	1.24E−09	0.00E+00
1.00E+01	1.22E+00	1.22E−09	0.00E+00
2.15E+01	1.20E+00	1.20E−09	0.00E+00
4.65E+01	1.18E+00	1.18E−09	0.00E+00
1.00E+02	1.17E+00	1.17E−09	0.00E+00
2.15E+02	1.13E+00	1.13E−09	0.00E+00
4.65E+02	1.09E+00	1.09E−09	0.00E+00
1.00E+03	1.05E+00	1.05E−09	0.00E+00
2.15E+03	1.02E+00	1.02E−09	0.00E+00
4.65E+03	1.01E+00	1.01E−09	0.00E+00
1.00E+04	9.98E−01	9.98E−10	0.00E+00
1.26E+04	1.08E+00	1.08E−09	0.00E+00
1.58E+04	1.29E+00	1.29E−09	0.00E+00
2.00E+04	1.54E+00	1.54E−09	0.00E+00
2.51E+04	1.84E+00	1.84E−09	0.00E+00
3.16E+04	2.19E+00	2.19E−09	0.00E+00
3.98E+04	2.63E+00	2.63E−09	0.00E+00
5.01E+04	3.12E+00	3.12E−09	0.00E+00
6.31E+04	3.72E+00	3.72E−09	0.00E+00
7.94E+04	4.44E+00	4.44E−09	0.00E+00
1.00E+05	5.30E+00	5.30E−09	0.00E+00

Neutron energy (eV)	DE (Sv/1E+11 neutrons/cm^2)[a]	Dose conversion factor (rem/neutron/cm^2)	NTA film response (track/neutron)[b]
1.26E+05	6.32E+00	6.32E−09	0.00E+00
1.58E+05	7.54E+00	7.54E−09	0.00E+00
2.00E+05	8.99E+00	8.99E−09	0.00E+00
2.51E+05	1.07E+01	1.07E−08	0.00E+00
3.16E+05	1.28E+01	1.28E−08	0.00E+00
3.98E+05	1.53E+01	1.53E−08	0.00E+00
5.01E+05	1.82E+01	1.82E−08	1.76E−05
6.31E+05	2.16E+01	2.16E−08	1.37E−04
7.94E+05	2.55E+01	2.55E−08	2.25E−04
1.00E+06	3.01E+01	3.01E−08	2.87E−04
1.26E+06	3.38E+01	3.38E−08	3.34E−04
1.58E+06	3.60E+01	3.60E−08	3.74E−04
2.00E+06	3.84E+01	3.84E−08	4.17E−04
2.51E+06	3.98E+01	3.98E−08	4.70E−04
3.16E+06	4.01E+01	4.01E−08	5.30E−04
3.98E+06	4.04E+01	4.04E−08	6.12E−04
5.01E+06	4.07E+01	4.07E−08	7.33E−04
6.31E+06	4.09E+01	4.09E−08	8.28E−04
7.94E+06	4.09E+01	4.09E−08	8.52E−04
1.00E+07	4.09E+01	4.09E−08	8.15E−04
1.26E+07	4.12E+01	4.12E−08	7.18E−04
1.58E+07	4.18E+01	4.18E−08	6.22E−04
2.00E+07	4.24E+01	4.24E−08	5.14E−04
3.30E+07	4.35E+01	4.35E−08	0.00E+00
5.90E+07	4.49E+01	4.49E−08	0.00E+00
8.23E+07	4.74E+01	4.74E−08	0.00E+00
1.60E+08	5.05E+01	5.05E−08	0.00E+00
2.23E+08	5.41E+01	5.41E−08	0.00E+00
4.35E+08	6.45E+01	6.45E−08	0.00E+00

a. Source: TRS 318, Table 2-II.
b. Source: TRS 318, Table 3-IX.
c. Thermal = 2.5E−02 to less than 1.88E−01 eV.

Table 4-5. Interpolated TRS 403 DE and SWR functions.

Neutron energy (eV)	DE (Sv/1E+11 neutrons/cm^2)[a]	Dose conversion factor (rem/neutron/cm^2)	NTA film response (track/neutron)[b]
1.00E−03	8.97E−01	8.97E−10	0.00E+00
2.15E−03	9.01E−01	9.01E−10	0.00E+00
4.64E−03	9.09E−01	9.09E−10	0.00E+00
1.00E−02	9.25E−01	9.25E−10	0.00E+00
2.15E−02	9.59E−01	9.59E−10	0.00E+00
4.64E−02	1.03E+00	1.03E−09	0.00E+00
1.00E−01	1.14E+00	1.14E−09	0.00E+00
2.15E−01	1.21E+00	1.21E−09	0.00E+00
4.64E−01	1.25E+00	1.25E−09	0.00E+00
1.00E+00	1.25E+00	1.25E−09	0.00E+00
2.15E+00	1.24E+00	1.24E−09	0.00E+00
4.64E+00	1.22E+00	1.22E−09	0.00E+00
1.00E+01	1.20E+00	1.20E−09	0.00E+00
2.15E+01	1.18E+00	1.18E−09	0.00E+00
4.64E+01	1.17E+00	1.17E−09	0.00E+00
1.00E+02	1.13E+00	1.13E−09	0.00E+00

Neutron energy (eV)	DE (Sv/1E+11 neutrons/cm²)[a]	Dose conversion factor (rem/neutron/cm²)	NTA film response (track/neutron)[b]
2.15E+02	1.09E+00	1.09E−09	0.00E+00
4.64E+02	1.05E+00	1.05E−09	0.00E+00
1.00E+03	1.02E+00	1.02E−09	0.00E+00
2.15E+03	1.01E+00	1.01E−09	0.00E+00
4.64E+03	9.98E−01	9.98E−10	0.00E+00
1.00E+04	1.08E+00	1.08E−09	0.00E+00
1.25E+04	1.29E+00	1.29E−09	0.00E+00
1.58E+04	1.54E+00	1.54E−09	0.00E+00
1.99E+04	1.84E+00	1.84E−09	0.00E+00
2.51E+04	2.19E+00	2.19E−09	0.00E+00
3.16E+04	2.63E+00	2.63E−09	0.00E+00
3.98E+04	3.12E+00	3.12E−09	0.00E+00
5.01E+04	3.72E+00	3.72E−09	0.00E+00
6.30E+04	4.44E+00	4.44E−09	0.00E+00
7.94E+04	5.30E+00	5.30E−09	0.00E+00
1.00E+05	6.30E+00	6.30E−09	0.00E+00
1.25E+05	7.52E+00	7.52E−09	0.00E+00
1.58E+05	8.97E+00	8.97E−09	0.00E+00
1.99E+05	1.07E+01	1.07E−08	0.00E+00
2.51E+05	1.28E+01	1.28E−08	0.00E+00
3.16E+05	1.53E+01	1.53E−08	0.00E+00
3.98E+05	1.82E+01	1.82E−08	1.76E−05
5.01E+05	2.16E+01	2.16E−08	1.37E−04
6.30E+05	2.55E+01	2.55E−08	2.25E−04
7.94E+05	3.01E+01	3.01E−08	2.87E−04
1.00E+06	3.38E+01	3.38E−08	3.33E−04
1.25E+06	3.60E+01	3.60E−08	3.73E−04
1.58E+06	3.84E+01	3.84E−08	4.16E−04
1.99E+06	3.98E+01	3.98E−08	4.69E−04
2.51E+06	4.01E+01	4.01E−08	5.30E−04
3.16E+06	4.04E+01	4.04E−08	6.12E−04
3.98E+06	4.07E+01	4.07E−08	7.33E−04
5.01E+06	4.09E+01	4.09E−08	8.28E−04
6.30E+06	4.09E+01	4.09E−08	8.52E−04
7.94E+06	4.09E+01	4.09E−08	8.15E−04
1.00E+07	4.15E+01	4.15E−08	6.65E−04
1.58E+07	4.28E+01	4.28E−08	2.32E−04
2.51E+07	4.40E+01	4.40E−08	0.00E+00
3.98E+07	4.54E+01	4.54E−08	0.00E+00
6.30E+07	4.82E+01	4.82E−08	0.00E+00
1.00E+08	5.09E+01	5.09E−08	0.00E+00
1.58E+08	5.49E+01	5.49E−08	0.00E+00
2.51E+08	6.39E+01	6.39E−08	0.00E+00
3.98E+08	8.44E+01	8.44E−08	0.00E+00
6.30E+08	Not available	Not available	Not available

a. Interpolated from source: TRS 318, Table 2-II.
b. Interpolated from source: TRS 318, Table 3-IX.

4.3 ADDITIONAL OBSERVATIONS

The IAEA compendia consist of hundreds of neutron spectra. If the site being considered has neutron spectra similar to those in TRS 318 and TRS 403, development of site-specific SWRs might not be necessary. The SWR can be found in these compendia if the dosimeter of choice has been evaluated there. However, site-specific spectra should be used when available because the calculations will yield more accurate results tailored to that site.

Attachment B compares calculations from this procedure to measured values in peer-reviewed literature and shows a percent error that ranges from 59% lower to 137% higher than published values. This range can be attributed to uncertainties in time, distance, shielding, and orientation between measured values and spectra available for the comparison. Therefore, if detector type and source terms at the site can be determined from site documentation but no additional information (e.g., time, distance, shielding, and orientation) is available, based upon comparisons with published values indicating an accuracy better than ±200%, this procedure is considered an acceptable approach for estimating correction factors for NTA film.

Understanding the format of the neutron spectra is critical. IAEA presented its spectra in lethargy format, which had to be multiplied by the difference of the natural logarithm of the upper and lower boundaries of the energy bins to attain a format useful for the SWR calculations shown in this TIB. If the spectra are not presented in this format, that multiplication is unnecessary, but other calculations might be necessary before this procedure can be used because it has been designed based on calculations in TRS 318 and its energy bin structure. In the case of TRS 403 spectra, the decision was made to interpolate the TRS 318 film response and DE functions into the energy bin structure of TRS 403, rather than interpolating individual spectra from TRS 403 into TRS 318 energy bins, so all spectra from TRS 403 could easily be used with this procedure.

5.0 THE CUTOFF CAVEAT

The ORAU Team initially had difficulty in precisely reproducing SWR values in TRS 318. TRS 318 does not describe an energy bin cutoff for its summations. However, TRS 403 does describe an energy bin cutoff caveat in its text: “Any bin is described by its lower boundary, E_i, and its upper boundary, E_{i+1}. Sixty energy bins are used with E_1 = 1 meV and E_{61} = 630 MeV” [IAEA 2001, p. 19]. Therefore, the team assessed the possibility that TRS 318 also used an energy bin cutoff.

The ORAU Team calculated the NTA film SWR and the SWDE for 56 randomly selected neutron spectra in TRS 318 and compared these values to those in the report. The Team’s calculations matched IAEA calculations when 0.5 eV was set as the cutoff energy for the lowest neutron energy bin of the SWR and SWDE summations. Setting a 0.5-eV cutoff energy, the ratios of the ORAU Team to IAEA SWR values were 1.01 for 3 spectra, 1.02 for 2 spectra, and 1.00 for 51 spectra. The ratios of the ORAU Team to IAEA SWDE values were 0.99 for 1 spectrum and 1.00 for 55 spectra.

Calculations were also performed for 17 randomly selected detectors and neutron spectra in TRS 403, and the results were compared to tabulated SWR and effective dose-weighted values to determine a cutoff energy for calculations. ORAU Team calculations with TRS 403 data perfectly matched tabulated values when all energy bins were used in the calculations. That is, the cutoff energy is established by the lowest energy bin in the tables of the report.

Therefore, the ORAU Team recommends applying a 0.5-eV energy bin cutoff for SWR and SWDE calculations using TRS 318 neutron spectra data and the tabulated 1-meV energy bin cutoff for SWR and SWDE calculations using TRS 403 neutron spectra data.

6.0 SUMMARY

NTA film dose correction factors can be calculated to determine how well film responds to exposure from a neutron source different from that used to calibrate the film. This method uses detector-weighted dosimetric quantities from TRS 318 and TRS 403 along with published neutron source spectra. If site-specific source spectra are not known, a general estimate can be made using spectra in the IAEA reports. ORAU Team benchmarking of this method against published values indicates that an estimate of dose using this procedure resulted in predicted doses within a factor of less than ±200%.

The purpose of benchmarking this procedure against published values was to determine the accuracy of this procedure for predicting dose. During this process, published values in the benchmarking references were considered the "true" dose. Had published values not been available, there would have been no data to compare. That is the expected scenario when choosing to use this procedure. This procedure offers a method to estimate neutron dose when little detailed information is available, including the "true" dose. There is no value beyond which this procedure should be discarded. This procedure estimates a dose when there is no other means to do so. Benchmarking suggests this method will estimate a dose within ±200% of the unknown "true" dose. If additional information is available for estimating the dose, another method should be used.

The following steps summarize the approach in this TIB for NTA film calibrated with source A but used to estimate a worker's exposure to source B:

1. Calculate the SWR (track/neutron) values for source A and source B:

$$SWR = \sum_{i=E_{\min}\text{ bin}}^{E_{\max}\text{ bin}} \left(\frac{\varphi_i \times R_i}{\sum_i \varphi_i} \right) \text{(track/neutron)} \quad (6\text{-}1)$$

2. Calculate the SWDE (rem/neutron/cm^2) values for source A and source B:

$$SWDE = \sum_{i=E_{\min}\text{ bin}}^{E_{\max}\text{ bin}} \left(\frac{\varphi_i \times DE_i}{\sum_i \varphi_i} \right) \text{(rem/neutron/cm}^2\text{)} \quad (6\text{-}2)$$

3. Calculate the DE SWR (tracks/cm^2/rem) values for source A and source B:

$$DE\ SWR\ \text{(tracks/cm}^2\text{/rem)} = SWR\ \text{(track/neutron)} \div SWDE\ \text{(rem/neutron/cm}^2\text{)} \quad (6\text{-}3)$$

4. Calculate the dose correction factor:

$$Dose\ correction\ factor = (tracks/\text{cm}^2/rem)_\text{A} \div (tracks/\text{cm}^2/rem)_\text{B} \quad (6\text{-}4)$$

5. Correct the dose:

$$Correct\ dose = Dose_\text{NTA} \times Dose\ correction\ factor \quad (6\text{-}5)$$

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ATTACHMENT A
COMMON CALIBRATION EXPOSURE SCENARIOS

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LIST OF TABLES

ATTACHMENT A
COMMON CALIBRATION EXPOSURE SCENARIOS (continued)

A.1 PLUTONIUM-BERYLLIUM CALIBRATION SOURCE WITH A PLUTONIUM TETRAFLUORIDE EXPOSURE SCENARIO

Using spectra in the TRS 318 compendium, Tables A-1 to A-4 list the values for the calculation of the DE correction factor for NTA film calibrated with a ^{239}PuBe source and exposed to $^{239}PuF_4$ in the work environment.

To summarize the results of the calculations from the data in each table:

- The calibration source SWR equals 6.56 × 10^{-4} track/neutron (Table A-1),
- The calibration source SWDE equals 3.95 × 10^{-8} rem/neutron/cm^2 (Table A-2),
- Therefore, the calibration source DE SWR equals 1.66 × 10^4 tracks/cm^2/rem.
- The exposure source SWR equals 2.86 × 10^{-4} track/neutron (Table A-3).
- The exposure source SWDE equals 3.02 × 10^{-8} rem/neutron/cm^2 (Table A-4),
- Therefore, the exposure source DE SWR equals 9.48 × 10^3 tracks/cm^2/rem.

The DE correction factor equals the tracks/cm^2/rem for calibration divided by the tracks/cm^2/rem for exposure, and this ratio is 1.75.

Therefore, based on the spectra analyzed in TRS 318, NTA film calibrated with a PuBe source (^{239}Pu) and exposed to PuF_4 (^{239}Pu) requires a DE correction factor of 1.75 to account for missed dose in the NTA film. The dose of record under these conditions must be multiplied by this factor to determine the best estimate of the true DE.

However, knowledge of the site spectra is essential for an accurate assessment. For example, if the PuBe calibration source contains ^{238}Pu rather than ^{239}Pu, TRS 403 indicates a dose correction factor of 1.06 for a bare source with room scatter. Another example is the spectrum in TRS 403 for a European Organization for Nuclear Research (CERN) ^{238}PuBe calibration source at 1 m, which yields a dose correction factor of 1.12.

Table A-1. ^{239}PuBe calibration SWR.

Neutron energy (eV)	NTA film response (track/neutron)	^{239}PuBe source [neutron/cm^2/Δln(E)][a]	Spectrum × lethargy (neutron/cm^2)	Detector-weighted response (track/cm^2)
Thermal[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.88E−01	Not available	Not available	Not available	Not available
2.50E−01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5.00E−01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.65E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.65E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00

ATTACHMENT A
COMMON CALIBRATION EXPOSURE SCENARIOS (continued)

Neutron energy (eV)	NTA film response (track/neutron)	^{239}PuBe source [neutron/cm^2/Δln(*E*)][a]	Spectrum × lethargy (neutron/cm^2)	Detector-weighted response (track/cm^2)
2.15E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.65E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.65E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.26E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.58E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.00E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.51E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.16E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.98E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5.01E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.31E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7.94E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.26E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.58E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.00E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.51E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.16E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.98E+05	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5.01E+05	1.76E−05	0.00E+00	0.00E+00	0.00E+00
6.31E+05	1.37E−04	9.39E−03	2.17E−03	2.97E−07
7.94E+05	2.25E−04	1.13E−02	2.60E−03	5.84E−07
1.00E+06	2.87E−04	4.26E−02	9.83E−03	2.82E−06
1.26E+06	3.34E−04	1.69E−02	3.91E−03	1.30E−06
1.58E+06	3.74E−04	2.20E−02	4.98E−03	1.86E−06
2.00E+06	4.17E−04	3.85E−02	9.08E−03	3.78E−06
2.51E+06	4.70E−04	5.88E−02	1.34E−02	6.28E−06
3.16E+06	5.30E−04	1.04E−01	2.40E−02	1.27E−05
3.98E+06	6.12E−04	1.41E−01	3.25E−02	1.99E−05
5.01E+06	7.33E−04	1.59E−01	3.66E−02	2.68E−05
6.31E+06	8.28E−04	1.25E−01	2.88E−02	2.39E−05
7.94E+06	8.52E−04	1.45E−01	3.33E−02	2.84E−05
1.00E+07	8.15E−04	6.63E−02	1.53E−02	1.25E−05
1.26E+07	7.18E−04	6.12E−02	1.41E−02	1.02E−05
1.58E+07	6.22E−04	0.00E+00	0.00E+00	0.00E+00
2.00E+07	5.14E−04	0.00E+00	0.00E+00	0.00E+00
3.30E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5.90E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.23E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.60E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.23E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.35E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00

a. Source: TRS 318, Table 4-X; Δln(*E*) is the difference in natural logarithm of the boundaries of the bin.
b. Thermal = 2.5E−2 to less than 1.88E−1 eV.

ATTACHMENT A
COMMON CALIBRATION EXPOSURE SCENARIOS (continued)

Table A-2. ^{239}PuBe calibration SWDE.[a]

Neutron energy (eV)	DE (Sv/1E+11 neutrons/cm^2)	Dose conversion factor (rem/neutron/cm^2)	Spectrum × lethargy (neutron/cm^2)	Dose-weighted response (rem)
Thermal[b]	1.07E+00	1.07E−09	0.00E+00	0.00E+00
1.88E−01	Not available	Not available	Not available	Not available
2.50E−01	1.19E+00	1.19E−09	0.00E+00	0.00E+00
5.00E−01	1.21E+00	1.21E−09	0.00E+00	0.00E+00
1.00E+00	1.25E+00	1.25E−09	0.00E+00	0.00E+00
2.15E+00	1.25E+00	1.25E−09	0.00E+00	0.00E+00
4.65E+00	1.24E+00	1.24E−09	0.00E+00	0.00E+00
1.00E+01	1.22E+00	1.22E−09	0.00E+00	0.00E+00
2.15E+01	1.20E+00	1.20E−09	0.00E+00	0.00E+00
4.65E+01	1.18E+00	1.18E−09	0.00E+00	0.00E+00
1.00E+02	1.17E+00	1.17E−09	0.00E+00	0.00E+00
2.15E+02	1.13E+00	1.13E−09	0.00E+00	0.00E+00
4.65E+02	1.09E+00	1.09E−09	0.00E+00	0.00E+00
1.00E+03	1.05E+00	1.05E−09	0.00E+00	0.00E+00
2.15E+03	1.02E+00	1.02E−09	0.00E+00	0.00E+00
4.65E+03	1.01E+00	1.01E−09	0.00E+00	0.00E+00
1.00E+04	9.98E−01	9.98E−10	0.00E+00	0.00E+00
1.26E+04	1.08E+00	1.08E−09	0.00E+00	0.00E+00
1.58E+04	1.29E+00	1.29E−09	0.00E+00	0.00E+00
2.00E+04	1.54E+00	1.54E−09	0.00E+00	0.00E+00
2.51E+04	1.84E+00	1.84E−09	0.00E+00	0.00E+00
3.16E+04	2.19E+00	2.19E−09	0.00E+00	0.00E+00
3.98E+04	2.63E+00	2.63E−09	0.00E+00	0.00E+00
5.01E+04	3.12E+00	3.12E−09	0.00E+00	0.00E+00
6.31E+04	3.72E+00	3.72E−09	0.00E+00	0.00E+00
7.94E+04	4.44E+00	4.44E−09	0.00E+00	0.00E+00
1.00E+05	5.30E+00	5.30E−09	0.00E+00	0.00E+00
1.26E+05	6.32E+00	6.32E−09	0.00E+00	0.00E+00
1.58E+05	7.54E+00	7.54E−09	0.00E+00	0.00E+00
2.00E+05	8.99E+00	8.99E−09	0.00E+00	0.00E+00
2.51E+05	1.07E+01	1.07E−08	0.00E+00	0.00E+00
3.16E+05	1.28E+01	1.28E−08	0.00E+00	0.00E+00
3.98E+05	1.53E+01	1.53E−08	0.00E+00	0.00E+00
5.01E+05	1.82E+01	1.82E−08	0.00E+00	0.00E+00
6.31E+05	2.16E+01	2.16E−08	2.17E−03	4.68E−11
7.94E+05	2.55E+01	2.55E−08	2.60E−03	6.62E−11
1.00E+06	3.01E+01	3.01E−08	9.83E−03	2.96E−10
1.26E+06	3.38E+01	3.38E−08	3.91E−03	1.32E−10
1.58E+06	3.60E+01	3.60E−08	4.98E−03	1.79E−10
2.00E+06	3.84E+01	3.84E−08	9.08E−03	3.48E−10
2.51E+06	3.98E+01	3.98E−08	1.34E−02	5.32E−10
3.16E+06	4.01E+01	4.01E−08	2.40E−02	9.60E−10
3.98E+06	4.04E+01	4.04E−08	3.25E−02	1.31E−09
5.01E+06	4.07E+01	4.07E−08	3.66E−02	1.49E−09
6.31E+06	4.09E+01	4.09E−08	2.88E−02	1.18E−09
7.94E+06	4.09E+01	4.09E−08	3.33E−02	1.36E−09
1.00E+07	4.09E+01	4.09E−08	1.53E−02	6.26E−10
1.26E+07	4.12E+01	4.12E−08	1.41E−02	5.83E−10

ATTACHMENT A
COMMON CALIBRATION EXPOSURE SCENARIOS (continued)

Neutron energy (eV)	DE (Sv/1E+11 neutrons/cm²)	Dose conversion factor (rem/neutron/cm²)	Spectrum × lethargy (neutron/cm²)	Dose-weighted response (rem)
1.58E+07	4.18E+01	4.18E−08	0.00E+00	0.00E+00
2.00E+07	4.24E+01	4.24E−08	0.00E+00	0.00E+00
3.30E+07	4.35E+01	4.35E−08	0.00E+00	0.00E+00
5.90E+07	4.49E+01	4.49E−08	0.00E+00	0.00E+00
8.23E+07	4.74E+01	4.74E−08	0.00E+00	0.00E+00
1.60E+08	5.05E+01	5.05E−08	0.00E+00	0.00E+00
2.23E+08	5.41E+01	5.41E−08	0.00E+00	0.00E+00
4.35E+08	6.45E+01	6.45E−08	0.00E+00	0.00E+00

a. Source: TRS 318, Table 4-X.
b. Thermal = 2.5E−2 to less than 1.88E−1 eV.

Table A-3. $^{239}PuF_4$ exposure SWR.

Neutron energy (eV)	NTA film response (track/neutron)	$^{239}PuF_4$ source [neutron/cm²/Δln(*E*)][a]	Spectrum × lethargy (neutron/cm²)	Detector-weighted response (track/cm²)
Thermal[b]	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.88E−01	Not available	Not available	Not available	Not available
2.50E−01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5.00E−01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.65E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.65E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.65E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.65E+03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.26E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.58E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.00E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.51E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.16E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.98E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5.01E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.31E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
7.94E+04	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+05	0.00E+00	1.08E−02	2.49E−03	0.00E+00
1.26E+05	0.00E+00	1.29E−02	2.98E−03	0.00E+00
1.58E+05	0.00E+00	1.55E−02	3.51E−03	0.00E+00
2.00E+05	0.00E+00	1.84E−02	4.34E−03	0.00E+00
2.51E+05	0.00E+00	1.86E−02	4.22E−03	0.00E+00
3.16E+05	0.00E+00	2.36E−02	5.43E−03	0.00E+00
3.98E+05	0.00E+00	2.81E−02	6.48E−03	0.00E+00

ATTACHMENT A
COMMON CALIBRATION EXPOSURE SCENARIOS (continued)

Neutron energy (eV)	NTA film response (track/neutron)	$^{239}PuF_4$ source [neutron/cm²/Δln(*E*)][a]	Spectrum × lethargy (neutron/cm²)	Detector-weighted response (track/cm²)
5.01E+05	1.76E−05	3.63E−02	8.35E−03	1.47E−07
6.31E+05	1.37E−04	4.58E−02	1.06E−02	1.45E−06
7.94E+05	2.25E−04	6.69E−02	1.54E−02	3.46E−06
1.00E+06	2.87E−04	1.29E−01	2.98E−02	8.54E−06
1.26E+06	3.34E−04	1.77E−01	4.09E−02	1.37E−05
1.58E+06	3.74E−04	2.12E−01	4.80E−02	1.79E−05
2.00E+06	4.17E−04	1.50E−01	3.54E−02	1.47E−05
2.51E+06	4.70E−04	5.37E−02	1.22E−02	5.73E−06
3.16E+06	5.30E−04	1.82E−03	4.19E−04	2.22E−07
3.98E+06	6.12E−04	0.00E+00	0.00E+00	0.00E+00
5.01E+06	7.33E−04	0.00E+00	0.00E+00	0.00E+00
6.31E+06	8.28E−04	0.00E+00	0.00E+00	0.00E+00
7.94E+06	8.52E−04	0.00E+00	0.00E+00	0.00E+00
1.00E+07	8.15E−04	0.00E+00	0.00E+00	0.00E+00
1.26E+07	7.18E−04	0.00E+00	0.00E+00	0.00E+00
1.58E+07	6.22E−04	0.00E+00	0.00E+00	0.00E+00
2.00E+07	5.14E−04	0.00E+00	0.00E+00	0.00E+00
3.30E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5.90E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8.23E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.60E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.23E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.35E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00

a. Source: TRS 318, Table 5-XXXI; Δln(*E*) is the difference in natural logarithm of the boundaries of the bin.
b. Thermal = 2.5E−2 to less than 1.88E−1 eV.

Table A-4. $^{239}PuF_4$ exposure SWDE.[a]

Neutron energy (eV)	DE (Sv/1E+11 neutrons/cm²)	Dose conversion factor (rem/neutron/cm²)	Spectrum × lethargy (neutron/cm²)	Dose-weighted response (rem)
Thermal[b]	1.07E+00	1.07E−09	0.00E+00	0.00E+00
1.88E−01	Not available	Not available	Not available	Not available
2.50E−01	1.19E+00	1.19E−09	0.00E+00	0.00E+00
5.00E−01	1.21E+00	1.21E−09	0.00E+00	0.00E+00
1.00E+00	1.25E+00	1.25E−09	0.00E+00	0.00E+00
2.15E+00	1.25E+00	1.25E−09	0.00E+00	0.00E+00
4.65E+00	1.24E+00	1.24E−09	0.00E+00	0.00E+00
1.00E+01	1.22E+00	1.22E−09	0.00E+00	0.00E+00
2.15E+01	1.20E+00	1.20E−09	0.00E+00	0.00E+00
4.65E+01	1.18E+00	1.18E−09	0.00E+00	0.00E+00
1.00E+02	1.17E+00	1.17E−09	0.00E+00	0.00E+00
2.15E+02	1.13E+00	1.13E−09	0.00E+00	0.00E+00
4.65E+02	1.09E+00	1.09E−09	0.00E+00	0.00E+00
1.00E+03	1.05E+00	1.05E−09	0.00E+00	0.00E+00
2.15E+03	1.02E+00	1.02E−09	0.00E+00	0.00E+00
4.65E+03	1.01E+00	1.01E−09	0.00E+00	0.00E+00
1.00E+04	9.98E−01	9.98E−10	0.00E+00	0.00E+00
1.26E+04	1.08E+00	1.08E−09	0.00E+00	0.00E+00

ATTACHMENT A
COMMON CALIBRATION EXPOSURE SCENARIOS (continued)

Neutron energy (eV)	DE (Sv/1E+11 neutrons/cm^2)	Dose conversion factor (rem/neutron/cm^2)	Spectrum × lethargy (neutron/cm^2)	Dose-weighted response (rem)
1.58E+04	1.29E+00	1.29E−09	0.00E+00	0.00E+00
2.00E+04	1.54E+00	1.54E−09	0.00E+00	0.00E+00
2.51E+04	1.84E+00	1.84E−09	0.00E+00	0.00E+00
3.16E+04	2.19E+00	2.19E−09	0.00E+00	0.00E+00
3.98E+04	2.63E+00	2.63E−09	0.00E+00	0.00E+00
5.01E+04	3.12E+00	3.12E−09	0.00E+00	0.00E+00
6.31E+04	3.72E+00	3.72E−09	0.00E+00	0.00E+00
7.94E+04	4.44E+00	4.44E−09	0.00E+00	0.00E+00
1.00E+05	5.30E+00	5.30E−09	2.49E−03	1.32E−11
1.26E+05	6.32E+00	6.32E−09	2.98E−03	1.88E−11
1.58E+05	7.54E+00	7.54E−09	3.51E−03	2.64E−11
2.00E+05	8.99E+00	8.99E−09	4.34E−03	3.90E−11
2.51E+05	1.07E+01	1.07E−08	4.22E−03	4.52E−11
3.16E+05	1.28E+01	1.28E−08	5.43E−03	6.96E−11
3.98E+05	1.53E+01	1.53E−08	6.48E−03	9.92E−11
5.01E+05	1.82E+01	1.82E−08	8.35E−03	1.52E−10
6.31E+05	2.16E+01	2.16E−08	1.06E−02	2.28E−10
7.94E+05	2.55E+01	2.55E−08	1.54E−02	3.92E−10
1.00E+06	3.01E+01	3.01E−08	2.98E−02	8.96E−10
1.26E+06	3.38E+01	3.38E−08	4.09E−02	1.38E−09
1.58E+06	3.60E+01	3.60E−08	4.80E−02	1.73E−09
2.00E+06	3.84E+01	3.84E−08	3.54E−02	1.36E−09
2.51E+06	3.98E+01	3.98E−08	1.22E−02	4.85E−10
3.16E+06	4.01E+01	4.01E−08	4.19E−04	1.68E−11
3.98E+06	4.04E+01	4.04E−08	0.00E+00	0.00E+00
5.01E+06	4.07E+01	4.07E−08	0.00E+00	0.00E+00
6.31E+06	4.09E+01	4.09E−08	0.00E+00	0.00E+00
7.94E+06	4.09E+01	4.09E−08	0.00E+00	0.00E+00
1.00E+07	4.09E+01	4.09E−08	0.00E+00	0.00E+00
1.26E+07	4.12E+01	4.12E−08	0.00E+00	0.00E+00
1.58E+07	4.18E+01	4.18E−08	0.00E+00	0.00E+00
2.00E+07	4.24E+01	4.24E−08	0.00E+00	0.00E+00
3.30E+07	4.35E+01	4.35E−08	0.00E+00	0.00E+00
5.90E+07	4.49E+01	4.49E−08	0.00E+00	0.00E+00
8.23E+07	4.74E+01	4.74E−08	0.00E+00	0.00E+00
1.60E+08	5.05E+01	5.05E−08	0.00E+00	0.00E+00
2.23E+08	5.41E+01	5.41E−08	0.00E+00	0.00E+00
4.35E+08	6.45E+01	6.45E−08	0.00E+00	0.00E+00

a. Source: TRS 318, Table 5-XXXI.
b. Thermal = 2.5E−02 to less than 1.88E−01 eV.

A.2 PLUTONIUM TETRAFLUORIDE CALIBRATION SOURCE WITH A BARE PLUTONIUM METAL EXPOSURE SCENARIO

Spectra from the TRS 318 and TRS 403 compendia can be used to calculate the DE correction factor for NTA film calibrated with a $^{239}PuF_4$ source and exposed to bare plutonium metal in the work environment. Tables A-3 and A-4 in Section A.1 list the values for the calculation of the SWR and SWDE for NTA film calibrated with a $^{239}PuF_4$ source. There are no spectra in TRS 318 for bare

ATTACHMENT A
COMMON CALIBRATION EXPOSURE SCENARIOS (continued)

plutonium metal, but Table 4.XI of TRS 403 does tabulate a spectrum for bare plutonium metal at 0.5 m distance. Tables A-5 and A-6 list the values for the calculation of the SWR and SWDE for NTA film exposed to bare plutonium metal in the work environment. The reference for the bare plutonium metal source spectrum is incorrect in TRS 403, and the isotopic composition of this source could not be determined. If this procedure is used to calculate a dose correction factor for a particular site, the source spectrum chosen for analysis must be similar to that encountered at the site. The composition of this source is not important here, where the source spectrum is chosen simply to demonstrate the calculations performed in the procedure.

To summarize the results of the calculations from the data in each table:

- The calibration source SWR equals 2.86×10^{-4} track/neutron (Table A-3 above),
- The calibration source SWDE equals 3.02×10^{-8} rem/neutron/cm^2 (Table A-4 above),
- Therefore, the calibration source DE SWR equals 9.48×10^{3} tracks/cm^2/rem.
- The exposure source SWR equals 2.99×10^{-4} track/neutron (Table A-5 below),
- The exposure source SWDE equals 2.67×10^{-8} rem/neutron/cm^2 (Table A-6 below).
- Therefore, the exposure source DE SWR equals 1.12×10^{4} tracks/cm^2/rem.

The DE correction factor equals the tracks/cm^2/rem for calibration divided by the tracks/cm^2/rem for exposure, and this ratio equals 0.85.

Therefore, using the $^{239}PuF_4$ spectrum from TRS 318 and a spectrum for bare plutonium metal (unknown composition) at 0.5 m in TRS 403 yields a dose correction factor of 0.85 for neutron dose in NTA film. The dose of record under these conditions must be multiplied by this factor to determine the best estimate of the true DE.

Table A-5. Bare plutonium metal at 0.5-m exposure SWR.

TRS 403 neutron energy (eV)	TRS 403 NTA film response (track/neutron)	Bare Pu metal at 0.5 m [neutron/cm^2/Δln(*E*)][a]	Spectrum × lethargy (neutron/cm^2)	Detector-weighted response (track/cm^2)
1.00E−03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E−03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.64E−03	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E−02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.15E−02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4.64E−02	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E−01	0.00E+00	8.81E−02	6.74E−02	0.00E+00
2.15E−01	0.00E+00	7.04E−02	5.42E−02	0.00E+00
4.64E−01	0.00E+00	4.40E−02	3.38E−02	0.00E+00
1.00E+00	0.00E+00	2.44E−02	1.87E−02	0.00E+00
2.15E+00	0.00E+00	1.56E−02	1.20E−02	0.00E+00
4.64E+00	0.00E+00	1.13E−02	8.68E−03	0.00E+00
1.00E+01	0.00E+00	4.99E−03	3.82E−03	0.00E+00
2.15E+01	0.00E+00	2.13E−03	1.64E−03	0.00E+00
4.64E+01	0.00E+00	8.90E−04	6.83E−04	0.00E+00

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COMMON CALIBRATION EXPOSURE SCENARIOS (continued)

TRS 403 neutron energy (eV)	TRS 403 NTA film response (track/neutron)	Bare Pu metal at 0.5 m [neutron/cm²/Δln(*E*)][a]	Spectrum × lethargy (neutron/cm²)	Detector-weighted response (track/cm²)
1.00E+02	0.00E+00	4.10E−04	3.14E−04	0.00E+00
2.15E+02	0.00E+00	9.15E−05	7.04E−05	0.00E+00
4.64E+02	0.00E+00	2.99E−05	2.30E−05	0.00E+00
1.00E+03	0.00E+00	9.49E−06	7.26E−06	0.00E+00
2.15E+03	0.00E+00	5.49E−06	4.22E−06	0.00E+00
4.64E+03	0.00E+00	4.75E−06	3.65E−06	0.00E+00
1.00E+04	0.00E+00	5.82E−06	1.30E−06	0.00E+00
1.25E+04	0.00E+00	7.58E−06	1.78E−06	0.00E+00
1.58E+04	0.00E+00	9.91E−06	2.29E−06	0.00E+00
1.99E+04	0.00E+00	1.38E−05	3.20E−06	0.00E+00
2.51E+04	0.00E+00	1.98E−05	4.56E−06	0.00E+00
3.16E+04	0.00E+00	2.94E−05	6.78E−06	0.00E+00
3.98E+04	0.00E+00	4.68E−05	1.08E−05	0.00E+00
5.01E+04	0.00E+00	8.12E−05	1.86E−05	0.00E+00
6.30E+04	0.00E+00	1.49E−04	3.45E−05	0.00E+00
7.94E+04	0.00E+00	3.11E−04	7.17E−05	0.00E+00
1.00E+05	0.00E+00	7.66E−04	1.71E−04	0.00E+00
1.25E+05	0.00E+00	1.85E−03	4.33E−04	0.00E+00
1.58E+05	0.00E+00	4.64E−03	1.07E−03	0.00E+00
1.99E+05	0.00E+00	1.30E−02	3.02E−03	0.00E+00
2.51E+05	0.00E+00	3.37E−02	7.76E−03	0.00E+00
3.16E+05	0.00E+00	7.69E−02	1.77E−02	0.00E+00
3.98E+05	1.76E−05	1.33E−01	3.06E−02	5.39E−07
5.01E+05	1.37E−04	2.13E−01	4.88E−02	6.67E−06
6.30E+05	2.25E−04	3.10E−01	7.17E−02	1.61E−05
7.94E+05	2.87E−04	4.22E−01	9.73E−02	2.79E−05
1.00E+06	3.33E−04	4.94E−01	1.10E−01	3.67E−05
1.25E+06	3.73E−04	4.07E−01	9.54E−02	3.56E−05
1.58E+06	4.16E−04	3.51E−01	8.10E−02	3.37E−05
1.99E+06	4.69E−04	2.44E−01	5.66E−02	2.66E−05
2.51E+06	5.30E−04	1.47E−01	3.39E−02	1.79E−05
3.16E+06	6.12E−04	1.26E−01	2.91E−02	1.78E−05
3.98E+06	7.33E−04	8.65E−02	1.99E−02	1.46E−05
5.01E+06	8.28E−04	7.61E−02	1.74E−02	1.44E−05
6.30E+06	8.52E−04	8.06E−02	1.86E−02	1.59E−05
7.94E+06	8.15E−04	1.13E−01	2.61E−02	2.12E−05
1.00E+07	6.65E−04	2.76E−02	1.26E−02	8.40E−06
1.58E+07	2.32E−04	3.76E−02	1.74E−02	4.04E−06
2.51E+07	0.00E+00	1.91E−04	8.81E−05	0.00E+00
3.98E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.30E+07	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.00E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
1.58E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2.51E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3.98E+08	0.00E+00	0.00E+00	0.00E+00	0.00E+00
6.30E+08	Not available	Not available	Not available	Not available

a. Source: TRS 403, Table 4.XI; Δln(*E*) is the difference in natural logarithm of the boundaries of the bin.

ATTACHMENT A
COMMON CALIBRATION EXPOSURE SCENARIOS (continued)

Table A-6. Bare plutonium metal at 0.5-m exposure SWDE.[a]

TRS 403 neutron energy (eV)	TRS 403 DE (Sv/1E+11 neutrons/cm²)	TRS 403 dose conversion factor (rem/neutron/cm²)	Spectrum × lethargy (neutron/cm²)	Dose-weighted response (rem)
1.00E−03	8.97E−01	8.97E−10	0.00E+00	0.00E+00
2.15E−03	9.01E−01	9.01E−10	0.00E+00	0.00E+00
4.64E−03	9.09E−01	9.09E−10	0.00E+00	0.00E+00
1.00E−02	9.25E−01	9.25E−10	0.00E+00	0.00E+00
2.15E−02	9.59E−01	9.59E−10	0.00E+00	0.00E+00
4.64E−02	1.03E+00	1.03E−09	0.00E+00	0.00E+00
1.00E−01	1.14E+00	1.14E−09	6.74E−02	7.66E−11
2.15E−01	1.21E+00	1.21E−09	5.42E−02	6.53E−11
4.64E−01	1.25E+00	1.25E−09	3.38E−02	4.22E−11
1.00E+00	1.25E+00	1.25E−09	1.87E−02	2.33E−11
2.15E+00	1.24E+00	1.24E−09	1.20E−02	1.49E−11
4.64E+00	1.22E+00	1.22E−09	8.68E−03	1.06E−11
1.00E+01	1.20E+00	1.20E−09	3.82E−03	4.58E−12
2.15E+01	1.18E+00	1.18E−09	1.64E−03	1.93E−12
4.64E+01	1.17E+00	1.17E−09	6.83E−04	8.00E−13
1.00E+02	1.13E+00	1.13E−09	3.14E−04	3.55E−13
2.15E+02	1.09E+00	1.09E−09	7.04E−05	7.67E−14
4.64E+02	1.05E+00	1.05E−09	2.30E−05	2.41E−14
1.00E+03	1.02E+00	1.02E−09	7.26E−06	7.41E−15
2.15E+03	1.01E+00	1.01E−09	4.22E−06	4.27E−15
4.64E+03	9.98E−01	9.98E−10	3.65E−06	3.64E−15
1.00E+04	1.08E+00	1.08E−09	1.30E−06	1.40E−15
1.25E+04	1.29E+00	1.29E−09	1.78E−06	2.28E−15
1.58E+04	1.54E+00	1.54E−09	2.29E−06	3.51E−15
1.99E+04	1.84E+00	1.84E−09	3.20E−06	5.88E−15
2.51E+04	2.19E+00	2.19E−09	4.56E−06	9.99E−15
3.16E+04	2.63E+00	2.63E−09	6.78E−06	1.78E−14
3.98E+04	3.12E+00	3.12E−09	1.08E−05	3.36E−14
5.01E+04	3.72E+00	3.72E−09	1.86E−05	6.92E−14
6.30E+04	4.44E+00	4.44E−09	3.45E−05	1.53E−13
7.94E+04	5.30E+00	5.30E−09	7.17E−05	3.80E−13
1.00E+05	6.30E+00	6.30E−09	1.71E−04	1.08E−12
1.25E+05	7.52E+00	7.52E−09	4.33E−04	3.26E−12
1.58E+05	8.97E+00	8.97E−09	1.07E−03	9.60E−12
1.99E+05	1.07E+01	1.07E−08	3.02E−03	3.22E−11
2.51E+05	1.28E+01	1.28E−08	7.76E−03	9.93E−11
3.16E+05	1.53E+01	1.53E−08	1.77E−02	2.71E−10
3.98E+05	1.82E+01	1.82E−08	3.06E−02	5.57E−10
5.01E+05	2.16E+01	2.16E−08	4.88E−02	1.05E−09
6.30E+05	2.55E+01	2.55E−08	7.17E−02	1.83E−09
7.94E+05	3.01E+01	3.01E−08	9.73E−02	2.93E−09
1.00E+06	3.38E+01	3.38E−08	1.10E−01	3.72E−09
1.25E+06	3.60E+01	3.60E−08	9.54E−02	3.43E−09
1.58E+06	3.84E+01	3.84E−08	8.10E−02	3.11E−09
1.99E+06	3.98E+01	3.98E−08	5.66E−02	2.25E−09
2.51E+06	4.01E+01	4.01E−08	3.39E−02	1.36E−09
3.16E+06	4.04E+01	4.04E−08	2.91E−02	1.17E−09
3.98E+06	4.07E+01	4.07E−08	1.99E−02	8.10E−10

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COMMON CALIBRATION EXPOSURE SCENARIOS (continued)

TRS 403 neutron energy (eV)	TRS 403 DE (Sv/1E+11 neutrons/cm^2)	TRS 403 dose conversion factor (rem/neutron/cm^2)	Spectrum × lethargy (neutron/cm^2)	Dose-weighted response (rem)
5.01E+06	4.09E+01	4.09E−08	1.74E−02	7.13E−10
6.30E+06	4.09E+01	4.09E−08	1.86E−02	7.63E−10
7.94E+06	4.09E+01	4.09E−08	2.61E−02	1.07E−09
1.00E+07	4.15E+01	4.15E−08	1.26E−02	5.24E−10
1.58E+07	4.28E+01	4.28E−08	1.74E−02	7.45E−10
2.51E+07	4.40E+01	4.40E−08	8.81E−05	3.87E−12
3.98E+07	4.54E+01	4.54E−08	0.00E+00	0.00E+00
6.30E+07	4.82E+01	4.82E−08	0.00E+00	0.00E+00
1.00E+08	5.09E+01	5.09E−08	0.00E+00	0.00E+00
1.58E+08	5.49E+01	5.49E−08	0.00E+00	0.00E+00
2.51E+08	6.39E+01	6.39E−08	0.00E+00	0.00E+00
3.98E+08	8.44E+01	8.44E−08	0.00E+00	0.00E+00
6.30E+08	Not available	Not available	Not available	Not available

a. Source: TRS 403, Table 4.XI.

ATTACHMENT B
BENCHMARKING THE SPECTRUM-WEIGHTED RESPONSE METHOD WITH PUBLISHED LITERATURE

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ATTACHMENT B
BENCHMARKING THE SPECTRUM-WEIGHTED RESPONSE METHOD WITH PUBLISHED LITERATURE (continued)

B.1 COMPARISON OF ORAU TEAM SPECTRUM-WEIGHTED RESPONSE VALUES TO REPORTED FILM SENSITIVITIES

The SWR method described in this document was compared to a small number of NTA film sensitivity values in the literature. Further comparisons will be made as additional resources are discovered.

Cusimano [no date] reported that the effective sensitivity of NTA film to a PoBe source at the National Reactor Testing Station (now the Idaho National Laboratory) was 5.87×10^{-4} track/neutron. Hart and Hale [1956] calculated 6.9×10^{-4} track/neutron for the sensitivity of NTA film with a PoBe source. Using the SWR method in TRS 318 and TRS 403 as modified in this document, the ORAU Team calculated a PoBe NTA film sensitivity of 3.28×10^{-4} track/neutron. The differences are likely attributable to differences in spectra used for analysis.

Lehman [1961] discussed an unpublished report by Cheka, who described neutron monitoring with NTA film at Oak Ridge National Laboratory in 1950. According to Lehman, Cheka measured an NTA film response of 4×10^{-4} track/neutron for fission neutrons with a mean energy of 1.5 MeV. The neutron spectrum to which Cheka exposed the film is unknown, but a “Pure Fission” spectrum from the “Standard Reactor Fields” section of TRS 318 yields an SWR value of 3.97×10^{-4} track/neutron.

B.2 ADDITIONAL COMPARISONS OF THE SPECTRUM-WEIGHTED RESPONSE METHOD TO MEASUREMENTS IN THE LITERATURE

B.2.1 Massand et al. [1979]

In *Energy Dependence of Kodak NTA Neutron Personnel Monitoring Film*, Massand et al. [1979] exposed NTA film to ^{252}Cf, AmBe, and a 14.6-MeV neutron generator. Table 1 of their paper presents published DE conversion factors (rem/neutron/cm^2) and NTA mean response (tracks/cm^2/rem) for these sources. Using neutron fluence-to-dose conversion factors in Table 2-II of TRS 318 and calculating the SWR response for these sources by the method described in this document, the ORAU Team was able to benchmark against the values in Table 1 of Massand et al.

The ORAU Team calculated a ^{252}Cf DE conversion factor of 3.43×10^{-8} rem/neutron/cm^2 and an NTA mean response of 1.24×10^{4} tracks/cm^2/rem, giving a +9% and +26% error (overestimate), respectively, in comparison with the published values.

The ORAU Team calculated an AmBe DE conversion factor of 3.75×10^{-8} rem/neutron/cm^2 and an NTA mean response of 1.60×10^{4} tracks/cm^2/rem. The DE values were equal, and the Team mean response had a +6% error.

A variety of 14-MeV neutron spectra from TRS 318 were analyzed for comparison to values in Massand et al. [1979]. The ORAU Team DE and mean response values fluctuated around −30% to −40% error (underestimate) in comparison with the published ones.

B.2.2 Oshino [1973]

In *Response of NTA Personnel Neutron Monitoring Film Worn on Human Phantom*, Oshino [1973] exposed NTA film to a variety of neutron sources to determine the relationship between proton track density and DE exposure. Neutron sources included ^{252}Cf, $^{238}PuBe$, ^{238}PuF, and the Bevatron. The

ATTACHMENT B
BENCHMARKING THE SPECTRUM-WEIGHTED RESPONSE METHOD WITH PUBLISHED LITERATURE (continued)

ORAU Team used the SWR method to benchmark against flux-to-DE conversion factors and film mean response values calculated in the paper.

According to Oshino [1973], the energy distribution of ^{252}Cf neutrons can be fitted with a Maxwellian distribution (Equation 5 in that paper) with the Maxwellian energy of the distribution equal to two-thirds the average energy (1.8 MeV). The ORAU Team calculated DE conversion factors and mean response values for a bare ^{252}Cf source in TRS 318 (Table 4-VII) and for a Maxwellian distribution with an average energy of 1.8 MeV. These values were compared to average DE conversion factors (neutrons/cm^2/mrem) in Table 1 of the paper and in-air, front normal NTA response (tracks/cm^2/mrem) in Table 6 of the paper.

Calculations with the bare ^{252}Cf source resulted in a −1% error when the ORAU Team DE conversion factor was compared to Oshino [1973] and a +127% error when mean response values were compared. Calculations for the Maxwellian distribution yielded a +125% error for the conversion factor and a +30% error for the mean response values.

The ORAU Team benchmarked to the PuBe values in the paper using a TRS 403 PuBe spectrum from CERN positioned 1 m from the detector (Table 4.X). This resulted in errors of +33% and +8% for DE conversion factors and mean response values, respectively.

Plutonium fluoride (^{238}Pu) values in the paper were benchmarked against two spectra in TRS 403 – a spectrum for a bare PuF_4 source at a distance of 1 m (Table 4.XII) and a PuF_4 spectrum from the Valduc Centre for Nuclear Studies in France. The bare PuF_4 yielded errors of −57% and +137% for conversion factor and mean response values, respectively, and the Valduc spectrum resulted in errors of −9% and +82% for these values, respectively.

Published values for Bevatron neutrons were benchmarked against two neutron spectra from Lawrence Berkeley Laboratory in TRS 318 – a Bevatron spectrum (Table 5-XXIII) and Bevatron neutrons measured at Location B-25/D (Table 5-XXVI). Bevatron neutrons measured by Oshino [1973] consisted of two populations of neutrons with average energies of 3.3 and 4.2 MeV, respectively. Rather than providing average DE conversion factors for these populations in Table 1, Oshino presents an equation for calculating DE (mrem) for each energy group based upon fluence measurements in Table 4 for a BF_3 proportional counter and a plastic scintillator. Conversion factors were calculated for each energy group, and an average factor was calculated for the average neutron energy of the two populations combined. Comparison of the average Oshino Bevatron conversion factor with ORAU Team calculations resulted in +4% and +2% errors for the Berkeley Bevatron and Bevatron measurement at B-25/D, respectively. Benchmarking mean response resulted in an average error of −47% for the Bevatron spectrum and an average error of +7% for the spectrum at position B-25/D.

B.2.3 Korba and Hoy [1969]

In *A Thermoluminescent Personnel Neutron Dosimeter*, Korba and Hoy [1969] investigated detector response for three types of neutron dosimeters exposed to different sources to determine the DEs recorded by each of them. A 12-in. Bonner sphere and a thermoluminescent personnel neutron dosimeter were exposed to an unmoderated PuF_4 source; a PuBe source moderated with 0, 15, or 33 cm of D_2O; and an unknown spectrum from a plutonium finishing area to compare response. These measurements were also compared to NTA film calibrated with the unmoderated PuBe source

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and exposed to each of these sources. The ORAU Team benchmarked the SWR method against the DE values in Table 1 of that paper for these detectors and sources.

Following the procedure described in this document, an unmoderated PuBe spectrum (Table 4.X) was selected from TRS 403 and the SWR (track/neutron) and SWDE (mrem/neutron/cm^2) were calculated. The quotient of these determined the DE SWR (tracks/cm^2/mrem) expected for NTA film exposed to the PuBe calibration source.

The process was repeated using the two PuF_4 neutron spectra evaluated in Section B.2.2 (a bare PuF_4 source at 1 m and the Valduc PuF_4 source) to determine the DE SWR (tracks/cm^2/mrem) expected for NTA film exposed to these PuF_4 sources. A DE correction factor was then calculated by taking the ratios of the calibration source DE SWR value and the exposure source DE SWR. The correction factor for each PuF_4 source was multiplied by the average NTA DE value for that source in Table 1 of the paper to calculate the expected DE in mrem, and this DE was compared with the recorded Bonner sphere DE for PuF_4. Analysis of the bare PuF_4 source at 1 m resulted in an error of −24% in comparison with the published DE value, and analysis with the Valduc spectrum resulted in a −2% error.

A spectrum representative of a PuBe source moderated with 15 or 33 cm of D_2O could not be found in TRS 318 or TRS 403, but Table 4.XI of TRS 403 did have a spectrum for a PuBe source moderated with 25 cm of D_2O. The ORAU Team realizes that a 25-cm moderated PuBe spectrum is not the same as the average between the 15- and 33-cm moderated spectra but, with no better surrogate spectrum to consider, analysis of the 25-cm moderated spectrum was conducted to benchmark the average DE value between the 15- and 33-cm moderated spectra. Following the procedure described above for the PuF_4 spectra, an expected NTA dose response was calculated and compared with the average of the published NTA DE values in Table 1 for exposure to a PuBe source moderated with 15 and 33 cm of D_2O. The ORAU Team expected dose response had an error of −38% in comparison with the published values.

The spectrum for the plutonium-finishing area was unknown to Korba and Hoy [1969], but several plutonium spectra were found in TRS 403 for comparison. Using the spectrum for bare plutonium metal at 0.5 m in Table 4.XI, the calculations yielded an expected dose response with a −53% error in comparison with the benchmark value. Table 5.XXXIX presents spectra from five locations around a plutonium reprocessing plant, each with a different degree of shielding. Analysis of these spectra resulted in dose response errors between −5% and −59%.

B.2.4 ISO 8529-1:2021

The International Organization for Standardization (ISO) is a worldwide federation of national standards bodies. ISO 8529-1:2021 is the 2021 publication of the first part of a three-part set of international standards for calibrating neutron dosimeters and dose rate meters [ISO 2021]. Part 1 describes the characteristics and methods of production of reference neutron radiation fields used for calibrations. The standard tabulates the source strength, or neutron emission rate, for four neutron sources commonly used for detector calibration: bare ^{252}Cf, ^{252}Cf moderated with 15 cm of D_2O, a “small” ^{241}AmBe source that contains on the order of 40 GBq of americium, and a “large” ^{241}AmBe source that contains on the order of 185–555 GBq of americium.

Source strength is the number of neutrons emitted in all directions from the source over time and is normalized to 1 neutron/s for each source. Californium source strengths are tabulated for thermal

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neutron energy to 20 MeV and AmBe source strengths are tabulated for thermal neutron energy to 11 MeV.

TRS 318 was published in 1990. Previous benchmarking efforts, described above, benchmarked the method described in this OTIB against values published before 1990. Therefore, the method must also be benchmarked against current standards; the ORAU Team chose the spectra in ISO 8529-1:2021 for this purpose [ISO 2021].

To allow a direct comparison between calculations with TRS 318 spectra and ISO spectra, the ORAU Team interpolated the source strengths in ISO [2021] into the energy bin structure of TRS 318 [ORAUT 2024]. The source strengths were then integrated over all solid angles at a distance of 100 cm from each source to generate tables for the fluence rate for each energy bin of these sources. After the procedures described in this document, the SWR, SWDE, and DE SWR values for each ISO source were then compared to TRS 318 values in Table C-1 below.

The SWR for the bare ^{252}Cf source is 3.54×10^{-4} track/neutron compared to 4.23×10^{-4} track/neutron in Table C-1. The SWDE is 3.04×10^{-8} rem/neutron/cm^2 compared to 3.42×10^{-8} rem/neutron/cm^2 in Table C-1. The DE SWR is 1.17×10^4 tracks/cm^2/rem compared to 1.24×10^4 tracks/cm^2/rem in Table C-1, which is 6% lower than that calculated with older data.

The SWR for the ^{252}Cf source moderated with 15 cm of D_2O is 3.12×10^{-5} track/neutron compared to 1.03×10^{-4} track/neutron in Table C-1. The SWDE is 4.44×10^{-9} rem/neutron/cm^2 compared to 9.92×10^{-9} rem/neutron/cm^2 in Table C-1. The DE SWR is 7.02×10^3 tracks/cm^2/rem compared to 1.04×10^4 tracks/cm^2/rem in Table C-1, which is 49% lower than that calculated with older data.

The SWR for the “small” AmBe source is 2.75×10^{-4} track/neutron compared to 6.00×10^{-4} track/neutron in Table C-1. The SWDE is 2.43×10^{-8} rem/neutron/cm^2 compared to 3.74×10^{-8} rem/neutron/cm^2 in Table C-1. The DE SWR is 1.13×10^4 tracks/cm^2/rem compared to 1.60×10^4 tracks/cm^2/rem in Table C-1, which is 42% lower than that calculated with older data.

The SWR for the “large” AmBe source is 2.31×10^{-4} track/neutron compared to 6.00×10^{-4} track/neutron in Table C-1. The SWDE is 2.18×10^{-8} rem/neutron/cm^2 compared to 3.74×10^{-8} rem/neutron/cm^2 in Table C-1. The DE SWR is 1.06×10^4 tracks/cm^2/rem compared to 1.60×10^4 tracks/cm^2/rem in Table C-1, which is 52% lower than that calculated with older data.

ATTACHMENT C
A SUMMARY OF VARIOUS SPECTRUM-WEIGHTED RESPONSE AND SPECTRUM-WEIGHTED DOSE EQUIVALENT VALUES

Table C-1. NTA SWR values for common sources.

Source	SWR (track/neutron)	SWDE (rem/neutron/cm^2)	DE SWR (tracks/cm^2/rem)
2.5-MeV neutron anterior-posterior broad parallel beam	3.61E−04	3.26E−08	1.11E+04
14-MeV neutron anterior-posterior broad parallel beam	6.47E−04	4.01E−08	1.61E+04
AmB (Am-241)	5.43E−04	3.98E−08	1.36E+04
AmBe (Am-241)	6.00E−04	3.74E−08	1.60E+04
AmF_4 (Am-241)	4.62E−04	3.89E−08	1.19E+04
AmLi (Am-241)	9.68E−05	1.69E−08	5.73E+03
Cf-252	4.23E−04	3.42E−08	1.24E+04
Cf-252 in 15-cm radius D_2O sphere	1.03E−04	9.92E−09	1.04E+04
CmBe (Cm-242)	7.03E−04	4.04E−08	1.74E+04
NaBe (Na-24)	1.64E−04	2.27E−08	7.22E+03
NaD_2O (Na-24, H-2)	5.70E−06	6.86E−09	8.31E+02
PoBe (Po-210)	3.28E−04	2.73E−08	1.20E+04
PuBe (Pu-238)	5.58E−04	3.56E−08	1.57E+04
PuBe (Pu-239)	6.56E−04	3.95E−08	1.66E+04
PuF_4 (Pu-239)	2.86E−04	3.02E−08	9.47E+03
PuLi (Pu-238)	1.13E−04	1.91E−08	5.92E+03
Pu metal at 0.5 m (unknown composition)	2.99E−04	2.67E−08	1.12E+04
PuO_2 (Pu-238)	4.49E−04	3.73E−08	1.20E+04
RaBe (Ra-226)	6.45E−04	3.97E−08	1.62E+04
Pure thermal fission of U-235	3.97E−04	3.30E−08	1.20E+04