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Review of Battelle-TIB-5000, "Default Assumptions and Methods for Atomic Weapons Employer Dose Reconstructions"

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Abbreviations and Acronyms

AMAD	activity median aerodynamic diameter
AP	antero-posterior
AWE	Atomic Weapons Employer
Battelle	Battelle Team, Dose Reconstruction Project for NIOSH
Bi	bismuth
BZ	breathing zone
d	day
DOE	U.S. Department of Energy
DR	dose reconstruction
f_1	fractional absorption in the gastrointestinal tract
GA	general area
GSD	geometric standard deviation
h	hour
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
IREP	Interactive RadioEpidemiological Program
ISO	International Organization for Standardization
K-65	radium-bearing waste generated during the processing of uranium ore from the former Belgian Congo
LOD	limit of detection
LOOW	Lake Ontario Ordinance Works
m	meter
MeV/m^3	megaelectron volts per cubic meter
µm	micrometer
NCRP	National Council on Radiation Protection and Measurements
NIOSH	National Institute for Occupational Safety and Health
OCAS	Office of Compensation Analysis and Support
ORAUT	Oak Ridge Associated Universities Team
PAEC	potential alpha energy concentration
Pb	lead
pCi/L	picocuries per liter

pdf	probability density function
PFG	photofluorography
Po	polonium
r	correlation coefficient
Ra	radium
Rn	radon
ROS	regression on order statistics
SCPR	Subcommittee for Procedures Review
SRDB	Site Research Database
TIB	technical information bulletin
TWA	time-weighted average
U	uranium
WL	working level (a unit of potential alpha energy concentration)

1 Introduction and Background

On March 15, 2021, the Subcommittee for Procedure Reviews (SCPR) of the Advisory Board on Radiation and Worker Health tasked SC&A with reviewing Battelle-TIB-5000, revision 00, "Default Assumptions and Methods for Atomic Weapons Employer Dose Reconstructions" (Battelle, 2007; "TIB-5000"). This technical information bulletin (TIB) consists of an introduction, followed by two main sections, plus a glossary and a list of references. The present review will briefly summarize each part of TIB-5000 and comment on its applicability to the performance of dose reconstructions (DRs) under Part B of the Energy Employees Occupational Illness Compensation Program Act of 2000 (42 U.S.C. 7384 et seq.). Detailed discussions will be presented only in cases where SC&A questions the methods or assumptions in TIB-5000. In the absence of such critical discussions, it can be assumed that SC&A agrees with the rationale and methodology presented in the TIB.

This TIB provides technical justifications and bases for assumptions in several areas needed for DRs for claimants from Atomic Weapons Employers (AWEs). It is important to understand that with the review of a 14-year-old document, there are many circumstances in which there are new methods and procedures for addressing particular issues. Consequently, this review includes an examination of the statistical literature produced since TIB-5000 was approved.

In general, the section numbers and titles are the same as those of the corresponding sections in the TIB. Additional numbered sections are inserted as needed—such sections do not disrupt the numbering of the succeeding sections. Tables and figures likewise refer to the TIB, unless otherwise noted.

2 Fitting Statistical Distributions to Data

Section 2, "Fitting Statistical Distributions to Data," presents statistical methods that are to be used to fit five of the seven uncertainty distributions that were available to users of the Interactive RadioEpidemiological Program (IREP) at the time of the release of TIB-5000:

1. Lognormal
2. Normal
3. Triangular
4. Uniform
5. Constant

Two additional distributions, logtriangular and loguniform, are listed in section 2 but not discussed further.[1]

2.1 Lognormal distributions

Section 2.1, "Lognormal Distributions," discusses the rationale for using such distributions and cites some of their characteristics. In cases where the data are positively skewed to the right, the lognormal is by far the most commonly used distribution.

Table 2.2, "Symbols, parameters, and relationships for the lognormal distribution," lists 14 symbols that characterize lognormal distributions. Ten of these symbols are accompanied by their mathematical relationships to other symbols in the table. Some of the relationships are implicit in the definitions of the respective quantities; others can be found in references such as Gilbert (1987, table 12.1). Two other major references for the properties of the lognormal distribution are Aitchison and Brown (1981) (cited by Battelle, 2007), and Crow and Shimizu (1998).

2.1.1 Uncensored individual observations

Section 2.1.1, "Uncensored Individual Observations," presents the maximum likelihood estimators of the geometric mean (median) of the data, the variance of the logarithms, the geometric standard deviation (GSD), and any given percentile or fractile of the lognormal distribution. The equations in this section can be used to calculate these quantities for "lognormally-distributed data in which all data points are positive values" (Battelle, 2007, p. 12).

2.1.2 Summary statistics

Section 2.12, "Summary Statistics," discusses the various statistical information that can be used to fit the underlying lognormal distribution. Table 2.3, "Fifteen distinct ways of determining a lognormal distribution from minimal information," as the title implies, lists 16 methods[2] to fit such a distribution. Fifteen employ the freeware computer program LOGNORM4, which is cited

[1] IREP currently allows eight distribution types to be entered. The eighth distribution type, Weibull, was added in the NIOSH-IREP 5.7 upgrade on January 24, 2013.

[2] The caption for this table erroneously cites 15 methods, while the table actually lists 16.

as a tool that computes the parameters of a lognormal distribution and facilitates a comparison of the different methods. However, LOGNORM4 is not currently available (Strom, 2021).

Observation 1: Battelle-TIB-5000 makes extensive use of the computer program LOGNORM4, which is no longer publicly available.

LOGNORM4 was developed prior to the issuance of TIB-5000. It was originally a 16-bit computer code, which cannot run on computers running Microsoft Windows 7 or later operating systems. Two options would be for the National Institute for Occupational Safety and Health (NIOSH) to (1) make a Windows 10-compatible version of the program available to the public or (2) revise TIB-5000, substituting other calculational methods for LOGNORM4. According to Taulbee (2021), "This program is no longer used. Considering the ongoing CyberSecurity Modernization Initiative, developing a Windows-10 compatible version is not likely to occur."

We make this an observation rather than a finding, since we presume that LOGNORM4 was an acceptable calculational tool at the time TIB-5000 was originally issued. However, we note that even that statement is speculative, since we have not had the opportunity to test this hypothesis.

The following five subsections present examples of methods of determining a lognormal distribution from minimal information.

2.1.2.1 Example using two data points

Section 2.1.2.1, "Example Using Two Data Points," demonstrates the derivation of a lognormal distribution when only two data points are available. Equations are presented for the derivation of the geometric mean and geometric standard deviation, which can be solved with the aid of the Microsoft Excel function NORMSINV.

2.1.2.2 Using minimum, mean, and maximum values with number of observations to determine the parameters of a lognormal distribution

Section 2.1.2.2, "Using Minimum, Mean, and Maximum Values with Number of Observations to Determine the Parameters of a Lognormal Distribution," outlines a method using the equations derived in section 2.1.2.1. Absent a mean value, the minimum and maximum values are assumed to represent the 25th and 75th percentile values, respectively.

2.1.2.3 Using range and mean value without number of observations to determine the parameters of a lognormal distribution

Section 2.1.2.3, "Using Range and Mean Value without Number of Observations to Determine the Parameters of a Lognormal Distribution," derives equations to compute the mean and standard deviation, assuming that the minimum and maximum values of the logarithms are symmetric about the geometric mean. This section then applies this methodology to derive lognormal distributions from data on measurements of uranium contamination presented by Christofano and Harris (1960).

2.1.2.4 Use of range and average value data that are inconsistent with a lognormal distribution

Section 2.1.2.4, "Use of Range and Average Value Data that are Inconsistent with a Lognormal Distribution," discusses the possible use of a triangular distribution, or the use of the minimum and maximum values as the 5th and 95th percentiles in cases where the range and average value data are inconsistent with a lognormal distribution. Battelle (2007) then dismisses these approaches and recommends ignoring the minimum and maximum values, instead deriving a lognormal distribution, using the arithmetic mean and the GSD to calculate the geometric mean. In such cases, Battelle (2007) recommends adopting a GSD of 5 for data from a single process and a GSD of 10 for an entire facility and provides an expression for calculating the geometric mean derived from these values.

2.1.2.5 Use of a single measurement value

Section 2.1.2.5, "Use of a Single Measurement Value," recommends assigning the single measurement to the arithmetic mean and applying the method of the preceding section to derive a lognormal distribution.

2.1.2.6 Reviewers' comment

Since the methods in the preceding five subsections require as little as one data point, one would expect large uncertainties in the estimates. In some cases, the estimates are based on a single measurement. In other cases, the measurement data are presented in the form of summary statistics, such as averages and/or empirical cumulative distribution functions, that may actually be based on far more measurements.

2.1.3 Censored individual observations

As stated in section 2.1.3, "Censored Individual Observations," censored data sets contain some results that are reported only as "greater than" some value or "less than" some value. Thus, the only information retained is that a measurement was made and that it was part of a "high group" or a "low group."

2.1.3.1 Left-censored data

Section 2.1.3.1, "Left-Censored Data," prescribes a methodology for fitting lognormal distributions to data that contain "values [that] are reported as 'less-than' some number or as zero" (Battelle, 2007, p. 17). This method has been called "regression on order statistics" (ROS) and is described by Anigstein and Gogolak (2020, p. 4).

Observation 2: There are more modern methods for treating censored data.

Helsel (2005, 2012) provides updated methods for treating censored data. A function, ros, that implements these methods can be found in the R package NADA (Lee, 2020) and is described by Anigstein and Gogolak (2020, p. 8).

2.1.3.2 Finney weighting factors

Section 2.1.3.2 covers "Finney Weighting Factors." Herein, data at extreme high or low values are given less weight than those nearer the center of the distribution in order to reduce the influence of outliers.[3]

[3] As an editorial note, we observe that in figure 1, the ordinate axis is labeled "y" but the text refers to the factor as "w."

2.1.3.3 Right-censored data

Section 2.1.3.3, "Right-Censored Data," covers the case of data sets containing values reported as "greater than"—such data sets are sometimes referred to as "right censored." The methodology is analogous to the ROS method described in section 2.1.3.1, except that the censored data appear at the end of the list. Observation 2 applies to this methodology as well.

2.1.4 Grouped, censored observations

Section 2.1.4, "Grouped, Censored Observations," contains examples of censored data that are also grouped. The data are fit to a lognormal distribution using weighted regression. The weights are derived from the number of observations in each group and also from the Finney weighting factors described in section 2.1.3.2. Airborne uranium concentration measurements presented in table 2.4, "Exposure to soluble uranium compounds . . . ," were fit using several different weighting schemes. In this case, there is grouping as well as left- and right-censoring. It is stated that at least three data points are required by some data fitting routines that calculate statistics other than the slope and the intercept. The fitting procedure referenced is from Strom (1986). All of the weightings fit the data quite well.

Another example of left-censored, grouped data, using thermoluminescent dosimeter measurements, is illustrated in figure 5, "Lognormal fits to grouped annual deep dose equivalent measurements for 458 persons. . ." The different weighting methods exhibit significantly different slopes, which can be used to calculate the GSDs. However, the curves yield very similar 95th percentiles. The Finney frequency weighting appears to give the best fit and is also the most claimant favorable.

2.1.4.1 Frequency weighting for grouped data

Section 2.1.4.1, "Frequency Weighting for Grouped Data," states, "Grouped, censored observations will require additional weighting considerations. The first data point in 1949 represents 13 of the 119 total observations; the second, 14; the third, 31, and the final point, 64" (Battelle, 2007, p. 20). The last value appears to be an error: Battelle (2007), table 2.4, lists the number of observations corresponding to each of the four data points in 1949 as 13, 14, 31, and 61, respectively.[4] The sum of the numbers of observations corresponding to this latter set of data points is 119, so 61 is most likely the correct number for the fourth data point.

Observation 3: The number of observations in the highest airborne uranium concentration group in 1949 is stated to be 64 by Battelle-TIB-5000, section 2.1.4.1. This value is inconsistent with the value of 61 shown in TIB-5000, table 2.4, and with the 119 total observations in 1949 listed by TIB-5000.

We make this an observation rather than a finding, since it does not alter any conclusions or instructions in the TIB. However, it does indicate a quality assurance shortcoming in this document.

[4] TIB-5000 (pp. 14, 68) attributes these values to "Eisenbud M and JA Quigley. 1956. 'Industrial hygiene of uranium processing.' AMA.Arch.Ind.Health 14(1):12-22." SC&A has been unable to retrieve this reference.

2.1.5 *“Reasonableness” of a lognormal distribution*

Section 2.1.5, “‘Reasonableness’ of a Lognormal Distribution,” states that a GSD ≤ 5 indicates a reasonable lognormal distribution, while GSD > 10 is a sign that the data “are not plausibly drawn from a single population” (Battelle, 2007, p. 22).

2.1.6 *Summary of default assumptions for fitting lognormal distributions*

Section 2.1.6, “Summary of Default Assumptions for Fitting Lognormal Distributions,” calls out recommendations made in prior sections and provides useful information on how to verify the results.

2.2 Triangular distributions

Section 2.2, “Triangular Distributions,” presents a mathematical description of the probability density functions (pdfs) and other parameters that define triangular distributions. Table 2.7 shows a comparison of attempts to fit data from Christofano and Harris (1960), using triangular and lognormal distributions. The section concludes: “All things considered, the lognormal distributions generally are more successful in describing this kind of data than are triangular distributions” (Battelle, 2007, p. 25).

2.3 Normal distributions

According to section 2.3, “Normal Distributions,” most exposure measurements are unlikely to have normal distributions, except for measurements associated with individuals. Uncertainties in such measurements may be inferred from the literature. Despite its title, this section is not about the fitting of data to a normal distribution. Rather, it is about the sum of a lognormal concentration with the addition of normally distributed measurement uncertainties.

2.3.1 *Normally-distributed measurement uncertainty and an underlying lognormally distributed measurand: Mirror image method*

One issue that appears often when data are fit to a lognormal distribution is what to do about negative values of the measurand.[5] The most important conclusion given in the TIB is that negative values of a concentration with added uncertainty are not just important but are essential to the analysis of the data set. There have been a number of approaches to this issue in the literature, two of which appear in this document. Recognizing that negative values are *not* anomalous when a normally distributed background value with a mean of zero is added to a positive distribution such as the lognormal is an important part of this TIB. One suggestion for dealing with this issue is the “mirror image” method (Strom, 1984).

The mirror image method is a way to characterize zero or negative results. To use this method, the analyst first deletes all data with values greater than zero (data with negative or zero values are unchanged). For each negative or zero value, the analyst adds a new record equal to the absolute value of the negative or zero record. The result is a symmetric distribution centered on

[5] “‘Measurand’ is the ISO term used by the International Organization for Standardization (ISO) . . . for the true but unknown value of ‘the specific quantity subject to measurement” (Battelle, 2007, p. 27, footnote 3).

zero, with the positive half being a mirror image of the negative half. The analyst then computes the standard deviation of the new symmetric distribution and constructs a normal distribution with a mean of zero and the new standard deviation. "A preliminary version of the method was used in 1983 to deduce measurements uncertainty in uranium urinalysis results at the Y-12 plant in Oak Ridge, Tennessee (Strom 1984). An example for 1971 results is shown in Figure 7" (Battelle, 2007, p. 26).

2.3.2 Normally-distributed measurement uncertainty and an underlying lognormally distributed measurand: Preserved mean and variance method

Section 2.3.2, "Normally-Distributed Measurement Uncertainty and an Underlying Lognormally-Distributed Measurand: Preserved Mean and Variance Method," proposes the preserved mean and variance method as "a more sophisticated alternative to the crude 'mirror image' technique" (Battelle, 2007, p. 27) that is based on four assumptions:

1. "The observed . . . pdf is the result of combining a normally-distributed measurement uncertainty with a lognormally-distributed measurand."

   This statement is ambiguous because there at least two ways of doing this "combining," namely: (1) treating the random variable (data) as a mixture of a normal pdf and a lognormal pdf; and (2) treating the data as the sum, $Z = X + Y,$ of a lognormally distributed random variable (X) and a normally distributed random variable (Y). In the context of the TIB, the second of these is likely what is meant. There are thus four parameters: the mean and variance of the uncertainty, and the mean and variance of the lognormal dose distribution.

2. "The mean of the lognormal 'true state of nature' is equal to the mean of the observations" (Battelle, 2007, p. 28).

3. The mean of the uncertainty is zero. Therefore, the mean of the lognormal pdf is equal to the mean of the observations.

4. The variance of the sum, $X + Y,$ is equal to the sum of the variance of X and the variance of Y, provided that X and Y are uncorrelated. If there are enough data to estimate the variance of the uncertainty of the measurement procedure, say by repeated measurements of blank samples, then there remains only one parameter to be estimated: the variance of the lognormal dose distribution.

2.3.2.1 Test of the preserved mean and variance method

As described in section 2.3.2.1, the Hanford in vivo cesium-137 measurements on unexposed workers in 2000–2002 were analyzed by the preserved mean and variance method. The author concludes that examining the residuals for the fits reveals systematic but not large differences in the observations based on the assumptions listed in section 2.3.2 of this report.

2.3.3 Reviewers' comments

It is difficult to ascertain the objective of figures 7–11. The two methods described in sections 2.3.1 and 2.3.2 are not supported by any technical background in statistical theory of which the authors of the present review are aware. The examples given are just that: examples, not proofs. Conclusions are based on the specific data sets used in the analyses but are not necessarily applicable to other data sets. The fits of the data to a lognormal appear to the eye to be pretty good, but again this does not show that methods are in any way optimal. An alternate approach to this problem is presented in the next section of the present review.

Observation 4: The mirror image and preserved mean and variance methods are not supported by any technical background in statistical theory of which we are aware.

We make this an observation rather than a finding because, even though the methods are questionable on technical grounds, their use is unlikely to have a significant impact on DRs.

2.3.4 Convolution of a normal uncertainty distribution and a lognormal concentration distribution

An alternative to combining a normally distributed measurement uncertainty and an underlying lognormally distributed measurand is to model the measurand as a lognormal random variable to which a normal random error is added. This approach is discussed by Hawkins (1988), Savoie (1988), Armstrong (1998), and Richardson and Ciampi (2003). The discussion in the manuscript by Hawkins is by far the most complete.

2.4 Uniform distributions

Battelle (2007) uses the term "Rectangular Distributions" as the title of section 2.4 and in the body of this section. This term is inconsistent with the distribution types listed by table 2.1 of the TIB, which lists uniform but not "rectangular" distributions. As described in this section, such distributions are described by two parameters—a lower and an upper bound—and a uniform distribution between these two values. This description is consistent with the meaning of a uniform distribution. "Uniform" (but not "rectangular") distributions are cited in a basic IREP reference document (NIOSH, 2002a).

As acknowledged by Battelle (2007, p. 32), such distributions "are non-physical, but can be used to represent a limited state of knowledge."

2.5 Constant "distributions"

A constant "distribution" is described by a single value, which is usually selected to be an overestimate of dose, intake, or concentration of a radioactive contaminant.

3 Default Assumptions

3.1 Introduction

The introduction to section 3, "Default Assumptions," lists 15 of the topics covered in the section.

3.2 External irradiation geometry

According to section 3.2, "External Irradiation Geometry," "Default assumptions of irradiation geometry may be reasonably justified, as described in Table 4.2 on page 53 of NIOSH OCAS-IG-001 (2002)" (Battelle, 2007, p. 33). We note that this apparently refers to OCAS-IG-001, revision 1 (NIOSH, 2002b), which was issued in August 2002. (Section 5.0, "References," does not specify the revision number.) We compared NIOSH (2002b), table 4.2, with the corresponding table in the current version of this document, NIOSH (2007, table 4.2)—the two tables are identical.

However, we note that table 4.2 is no longer used. After SC&A's initial review of NIOSH (2007), we determined that, except for the antero-posterior (AP) geometry, the dose conversion factor values listed in appendices A and B are incorrect. Thereafter, NIOSH recommended that, for most cases, the DR should use only the AP geometry.

Section 3.2 lists three job categories that are specified for a uranium facility by NIOSH (2007, table 4.2). According to Battelle (2007, p. 33), "These are detailed in a 326-line spreadsheet entitled 'Irradiation_Geometry_by_Job_Title.xls.'" According to Taulbee (2021), "This reference apparently has been lost." Consequently, we cannot review conclusions based on these data.

3.3 The 95%ile and "constant" uncertainty distribution for limited data sets

Section 3.3, "The 95%ile and 'Constant' Uncertainty Distribution for Limited Data Sets," addresses the assignment of radiation exposures to workers based on sparse air sampling data or a few film badge readings. "The inference is that the distribution these samples represent applies to the entire facility. For people who move around, such as crafts and maintenance personnel, the average may be appropriate" (Battelle, 2007, p. 34).

3.4 Uncertainty in biokinetic models

According to section 3.4, "Uncertainty in Biokinetic Models":

> The National Council on Radiation Protection and Measurements (NCRP) used an expert group of internal dosimetrists to create a subjective quantification of the reliability of ICRP Publication 30 [(ICRP, 1979)] biokinetic and dosimetric models (National Council on Radiation Protection and Measurements (NCRP) 1998). While IMBA [Integrated Modules for Bioassay Analysis] uses the newer ICRP Publication 66 [(ICRP, 1994; "ICRP 66")] respiratory tract model and newer biokinetic models**, the results of these models may not be that much better than the ICRP 30 models for some radionuclides in cases where f_1**

> [fractional absorption in the gastrointestinal tract] **is the dominant uncertainty**. [Battelle, 2007, p. 34; emphasis added]

Battelle (2007) then proceeds to present results of the NCRP assessment of the reliability of the International Commission on Radiological Protection (ICRP) Publication 30 models.

It is SC&A's opinion that Battelle-TIB-5000 lacks a sound basis for speculating that the ICRP (1994) models are not "that much better than the ICRP 30 models for some radionuclides in cases where f_1 is the dominant uncertainty," and that the NCRP evaluation of the reliability of the ICRP (1979) models is applicable to the ICRP (1994) models.

Battelle (2007) cites an email communication from Bihl et al. to support the use of a lognormal distribution with GSD = 3.[6] Battelle claims this "is reasonably consistent with the [NCRP] findings" (p. 35). SC&A requested a copy of this email from NIOSH. According to Taulbee (2021), "We are actively searching older email archives but this is taking longer than anticipated and this email may not be retrievable." Consequently, SC&A cannot determine if this document supports the use of a GSD of 3 for the uncertainty in internal dose.

Observation 5: Battelle-TIB-5000 lacks a sound basis for asserting that the NCRP assessment of the reliability of the ICRP Publication 30 models can be applied to the currently used ICRP Publication 66 respiratory tract and biokinetic models.

3.5 Aerosol particle size and respirable fraction

Section 3.5, "Aerosol Particle Size and Respirable Fraction," discusses the relationship between aerosol concentrations measured by air samplers and inhaled particles. The discussion concludes with the statement: "Default assumptions of ICRP Pub. 66, i.e., 5 µm AMAD [activity median aerodynamic diameter], will be used in the absence of other information" (Battelle, 2007, p. 36).

3.5.1 Reviewers' comment

An AMAD of 5 micrometers (µm) is the default particle size distribution recommended by ICRP (1994, p. 49) for workplace exposures. This is consistent with OCAS-IG-002, revision 0 (NIOSH, 2002c, p. 16), which states, "In the absence of any measurements or studies, default values from . . . ICRP 66 . . . will be used."

3.6 Use of time-period-specific, process-based GSDs for published mean aerosol concentration data

Section 3.6, "Use of Time-Period-Specific, Process-Based GSDs for Published Mean Aerosol Concentration Data," states that "the current default assumption when no information is available on uncertainty in aerosol measurements is that they are lognormally-distributed with a *GSD* of 5 for a single process or activity, and 10 for an entire site, plant, or factory" (Battelle, 2007, p. 36). The author based the first assumption on 108 sets of data on aerosol concentrations or worker exposures tabulated by Christofano and Harris (1960), who listed measured and calculated data

[6] Cited as "Bihl DE, EM Brackett, and RE Toohey. 2006. *Basis for GSD = 3 for internal dose used by NIOSH*. E-mail of July 21, 2006 to Hickey EE, Traub RJ, copied to MacLellan JA, Strom DJ, Pacific Northwest National Laboratory, Richland, Washington" (Battelle, 2007. p. 67).

for a number of processes at seven uranium refining plants. SC&A disagrees with the inclusion of data from a single process that would be responsible for episodic exposures of one or more workers and does not represent the chronic exposures used in DR calculations. We reviewed the data in Christofano and Harris and identified 33 instances of daily weighted average or simply "weighted average" concentrations that represent the chronic exposures of workers from a given process. In each case, the range of concentrations was listed, along with the average. We applied the methodology described by Battelle (2007, section 2.1.2.3) for determining a lognormal distribution based on such data. SC&A calculated σ = ln(GSD) by applying Battelle (2007), Equation 10, reproduced here:

$$\sigma = \sqrt{2\ln\bar{x} - lnx_{min} - lnx_{max}}$$

where

$\bar{x}$ = arithmetic mean of x
x_{min} = minimum value of x
x_{max} = maximum value of x

In four cases, the quantity under the square root sign was negative, indicating that the data most likely could not be fitted to a lognormal distribution. In the remaining 29 cases, the GSD ranged from 1.07 to 4.57, with a mean of 2.27 and a standard deviation of 0.80. SC&A thus concurs that a GSD of 5 constitutes a plausible upper bound for the exposures of a single worker at a uranium refining plant.

SC&A also fitted a lognormal distribution to the average aerosol concentrations for the 136 processes tabulated by Christofano and Harris (1960). We derived a GSD of 9.05, which is close to the value of 9.01of the "uniform prediction" displayed by Battelle (2007), figure 12, "Lognormal plot of mean airborne U concentrations for 136 different processes in uranium refining (Christofano and Harris 1960)." However, SC&A disagrees with the author's interpretation of this result. The 136 data points represent a mixture of short-term measurements of individual processes and of weighted averages of worker exposures at seven uranium refining plants. Since these processes are included in the weighted averages, inclusion of both types of data is redundant. Instead, we fitted the mean values for the 29 cases used to calculate the GSDs of the weighted average concentrations discussed, and obtained a GSD of 5.47. Since these 29 measurements span exposures at seven uranium refining plants, it is reasonable to assume a GSD of 5 can be applied to the exposures of an individual worker at a single plant. A GSD of 10 is not a plausible value to use in DRs. However, since NIOSH has adopted a default GSD of 5 when no other information is available, this result is not being applied in current practice.

Observation 6: A GSD of 10, derived from redundant data across seven uranium refining plants, is excessive for a sitewide assessment of an individual worker.

SC&A makes this an observation rather than a finding, since NIOSH is using a GSD of 5 as the default value in DRs when no other uncertainty data is available.

3.7 Use of distributions to describe multiple populations

According to section 3.7, "Use of Distributions to Describe Multiple Populations," "It is the policy of the Battelle Dose Reconstruction Team to minimize the combining of populations into a single distribution. When possible, job- or task-specific data are to be used in constructing time-weighted averages" (Battelle, 2007, p. 38). SC&A agrees that multiple populations should not be combined into a single distribution—we discussed such examples in the preceding section of this review. This section of the TIB appears to contain a typographical error on page 38: "One data set, shown in Figure 2, is not, in the judgment of a panel of health physicists and industrial hygienists, taken from the same population." The author was most likely referring to figure 12, "Lognormal plot of mean airborne U concentrations for 136 different processes in uranium refining (Christofano and Harris 1960)," which appears on the preceding page of the TIB.

3.8 Use of time-weighted averages, breathing zone air samples, and general area air samples, process air samples, and considerations of sample duration

According to section 3.8, "Use of Time-Weighted Averages, Breathing Zone (BZ) Air Samples, and General Area (GA) Air Samples, Process (P) Air Samples, and Considerations of Sample Duration," "the preferred (although not always possible) approach is to use time-weighted averages (*TWA*s) of airborne concentrations to assess worker exposures, and assess uncertainty of the *TWA*" (Battelle, 2007, p. 38). The TIB lists six operations involving "tower workers" at the Lake Ontario Ordinance Works (LOOW). The workers were exposed to the inhalation of radon-222 (^{222}Rn)[7] and its short-lived progeny emitted from the radium-bearing K-65 wastes[8] stored at LOOW. For each operation, table 3.3, "Daily weighted Rn. exposure to tower workers . . . ," lists the exposure duration per shift, the number of samples, and the low, high, and average radon concentration of the samples. Lognormal distributions can be fitted to the data for five of these operations, using the methods described by Battelle (2007), section 2.1.2, including subsections. The first operation, titled "B. Z. Removing covers from Drums" in table 3.3, exhibits a large range of values, as shown in table 1.

Table 1. Radon air sample data for "BZ removing covers"

Date	Time			Concentration
	Start	Stop	At minutes [(a)]	× 100 pCi/L
5/8	2:55p	2:56.5p	1.5	16.7
5/8	2:58p	3:02p	4.0	1.1
5/9	12:50p	—	<.5	2,370
5/9	12:51p	—	<.5	4.5
5/9	12:53p	—	<.5	450
5/9	12:55p	—	<.5	580

Source: Excerpted from Heatherton (1951, table II).

[(a)] The meaning of "At" is unclear, but the data in the column are equal to the sampling duration.

[7] Hereafter referred to as "radon."

[8] "The term 'K-65' was used at Fernald to describe the processing of the Belgian Congo ores" (DOE, n.d., p. 1). "The Fernald site is a former Department of Energy (DOE) uranium processing facility located approximately 18 miles northwest of Cincinnati, Ohio" (DOE, n.d., p. 1).

According to section 3.8,

> The 6 individual results for "removing covers from drums" in Table 3.3 are clearly not from the same population: 3 were in the range of 1.1 to 17 and 3 were in the range 450 to 2370. Separating the two data triplets, plausible *GSD*s were found for each and for the other data sets by simply finding the average and standard deviations of the natural logs of each result as described in Section 2.1.1. Allocating 12 minutes exposure time to each of the two lognormal distributions derived for "removing covers from drums," and using the Shift (min) values for the other distributions, a mean TWA was computed from 10,000 Monte Carlo trials. [Battelle, 2007, p. 39]

SC&A does not agree with the conclusion nor with the proposed solution. As shown in table 1 of the present review, the first two samples, with relatively low radon concentrations, were collected on May 8, 1951, in rapid succession, while the remaining four samples were collected the next day over a comparably brief period: about 5 minutes. These four samples included three with high values (450–2,370 × 100 picocuries per liter (pCi/L)) and one with a much lower value: 4.5 × 100 pCi/L. Since these four samples were taken within the same brief time span, there is no basis for assigning them to two distinct populations.

One simple approach to this problem is to fit the six sample values to a lognormal distribution, as described by ORAUT (2005d). Since the duration of the two samples collected on May 8 was longer than those collected on May 9, each sample value should be weighted by its duration. SC&A has performed such an analysis and obtained a median value of 5.65 × 100 pCi/L with a GSD = 31. The square of the correlation coefficient, $r^2 = 0.944$, indicates a good fit to a lognormal distribution. Because of the large GSD, we do not propose assigning the entire distribution to the worker's exposure to radon during this process. However, the derived distribution yields a 95th percentile value of 1,612 × 100 pCi/L, which is within the range of the measured values. (Because the values are weighted by the sample collection time, the lower values, which had a longer collection time, have more weight.)

The preceding discussion presents an example of how the data for the drum cover removal can be used to assign radon exposures to workers performing this operation—other solutions, using later methods than the one presented by ORAUT (2005d) are possible. However, SC&A believes that dividing this operation into two 12-minute periods is arbitrary and not claimant favorable.

Observation 7: Dividing the operation—"removing covers from drums"—that was observed to take 24 minutes per shift, into two 12-minute periods, characterized by low and high radon concentrations, respectively, is arbitrary and not claimant favorable.

SC&A makes this an observation rather than a finding because designated workers at LOOW who worked from January 1, 1944, through December 31, 1953, were designated as members of the Special Exposure Cohort. The operation described in this section took place during that period; no DRs were required for energy employees who worked a total of 250 workdays during this period. We have no information on any DRs performed on behalf of LOOW workers; thus, there is no available evidence that the methodology described by section 3.8 was ever utilized in a DR for LOOW or for energy employees at any other AWE site.

3.9 Particle solubility (ICRP 66 transportability classes F, M, S) and f_1 (gastrointestinal absorption fractions)

Section 3.9, "Particle Solubility (ICRP 66 Transportability Classes F, M, S) and f_1 (Gastrointestinal Absorption Fractions)," discusses the assignment of intakes of radionuclides to one of the three lung absorption types specified by the ICRP (1994) human respiratory tract model. Current NIOSH procedures specify that DRs should assume that intakes are characterized by the lung type, selected from among the plausible choices for a given exposure scenario, that results in the highest probability of causation.

3.10 Exposure time and intake calculations

Table 3.5, "Default exposure time assumptions as a function of date," specifies the default workweek for energy employees during three time periods: prior to 1951, 1951–1955, and post-1955. These work-hour assignments are consistent with the guidance of NIOSH (2011) and with current NIOSH practice. Section 3.10, "Exposure Time and Intake Calculations," provides further guidance for allocating daily intakes for running IMBA.

3.11 Ingestion

Section 3.11, "Ingestion," discusses earlier studies of the inadvertent ingestion of uranium contamination, concluding: "ingestion intakes are determined following the OCAS [Office of Compensation Analysis and Support] method ([NIOSH] 2004)" (Battelle, 2007, p. 42). The guidance in the referenced document is still used for assessing ingested intakes during the operational period at AWE sites. For residual periods, however, the

> procedure of calculating intakes from inadvertent ingestion was addressed by the . . . SCPR . . . during meetings held on November 1, 2012, and February 5, 2013. During these meetings, it was brought out that . . . NIOSH . . . had incorrectly assigned the ingestion rate during the residual periods at some sites by estimating it to be equal to 20 percent of the airborne activity from resuspension of the surficial contamination levels during the residual period. All parties involved—the SCPR, NIOSH, and SC&A—agreed that this was an underestimate. NIOSH proposed that the ingestion rate at the start of the residual period be set equal to that at the end of the operational period and then reduced by OTIB-0070 [(ORAUT, 2012)] annual depletion factors. This methodology was accepted by SC&A and the SCPR, and the issue was closed. [Anigstein, 2020, p. 2]

Observation 8: The procedure for assessing inadvertent ingestion for residual periods at AWE sites has been updated since the issuance of TIB-5000.

3.12 Occupational medical doses

Section 3.12, "Occupational Medical Doses," states, "The default assumptions in OTIB-0006 ([ORAUT, 2005a]) will be used if no other information is available" (Battelle, 2007, p. 42). The referenced document has been supplanted by ORAUT (2018), which constitutes a total rewrite of the earlier versions of this document. In particular, we note:

> Because PFG [photofluorography] was primarily a mass screening technique most suitable to large populations, and therefore unlikely to have occurred on a mass scale at AWE sites, PFG should not be assumed to have occurred at AWE sites unless there is evidence to the contrary. [ORAUT, 2018, p. 28]

Observation 9: The revised guidance on dose reconstruction from occupational medical x-ray procedures (ORAUT-OTIB-0006, revision 05) should be used for the assessments of external doses from such procedures.

3.13 External dose conversion factors

Section 3.13, "External Dose Conversion Factors," states, "Correction of radiation survey instrument readings, dosimeter readings, and conversion of recorded neutron doses to correct neutron doses using a w_R/Q ratio will be determined using existing OTIBs and IG-001 [(NIOSH, 2002b)]" (Battelle, 2007, p. 43). The current version of the referenced document is denoted revision 3. However, it is used for the same purpose as the earlier version.

3.14 External missed dose when there was monitoring

Section 3.14, "External Missed Dose When There Was Monitoring," prescribes the procedures presented by NIOSH (2002b) and ORAUT (2005b) for assigning external doses to normally monitored workers whose doses were not reported or recorded for one or more time periods. We note that both documents have been extensively revised since the release of TIB-5000 (refer to NIOSH, 2007, and ORAUT, 2011). The procedures in the revised documents should be followed for assigning missed dose. In particular, the alternate procedure suggested by Battelle (2007, p. 43)—"substitute a value for each dosimeter reading . . . . assign a triangular distribution with minimum = 0, mode = 0.5×*LOD* [limit of detection], and maximum = *LOD*"—is no longer recommended.

Observation 10: Missed doses should be assigned according to the current procedures: OCAS-IG-001, revision 3, and ORAUT-OTIB-0020, revision 03. Assigning a triangular distribution with minimum = 0, mode = 0.5 × LOD, and maximum = LOD is not consistent with current guidance.

SC&A makes this an observation rather than a finding, since the recommended procedures were acceptable under the guidance in effect when TIB-5000 was released.

3.15 Internal missed dose when there was monitoring

Section 3.15 is marked "reserved." We include that heading in the present review to preserve the numbering of subsequent sections.

3.16 Environmental dose

Section 3.16, "Environmental Dose," lists five components of environmental dose but does not discuss these pathways. The ingestion pathway was omitted.

Observation 11: Ingestion should be added to the pathways of environmental doses.

SC&A makes this an observation rather than a finding, since current NIOSH guidance (NIOSH, 2011) specifically lists the contribution of ingestion to environmental doses.

3.16.1 Reviewers' comment

If the topic "Environmental Dose" merits mention by Battelle (2007), it should merit some further discussion. NIOSH (2002b, 2002c, 2007) provide guidance on evaluating environmental doses, as does Battelle-TBD-6000 (NIOSH, 2011).

3.17 Radon and thoron and their short-lived decay products

According to section 3.17, "Radon and Thoron and Their Short-Lived Decay Products," the discussion of radon follows ORAUT (2006).

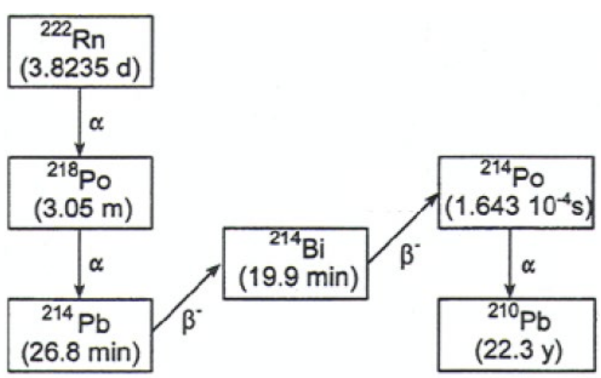
3.17.1 Radon and thoron

Section 3.17.1, "Radon and Thoron," discusses the radioactive decay and progeny of ^{220}Rn and ^{222}Rn. The latter isotope is commonly referred to as "radon," while the former is sometimes called "thoron." Comparable considerations apply to both radon and thoron. Since exposure to thoron is rarely a significant factor in DRs, the following discussion will focus on ^{222}Rn.

3.17.2 Potential alpha energy exposure and concentration

Exposures of workers to the inhalation of ^{222}Rn results in radiation dose to the lungs, almost entirely from the short-lived alpha-emitting progenies: polonium-214 (^{214}Po) and ^{218}Po. Radon-222 gives rise to the radioactive decay chain displayed in figure 1.

Figure 1. Radon-222 radioactive decay chain



Source: Excerpted from ORAUT (2005c), figure 1.

Note: Values in parentheses indicate the radioactive half-life of each radionuclide. The accepted values of all these half-lives (with the exception of ^{222}Rn) have changed slightly since the release of ORAUT (2005c). These changes do not affect the discussion in the present review.

The short-lived progeny of radon present in air usually form aerosols or attach to particulates (dust particles) already present in the atmosphere. Because of the physical removal of some fraction of the progeny from the ambient air, these short-lived progeny cannot be assumed to be in secular equilibrium with their relatively long-lived parent ($t_{½}$ = 3.8235 d), which would be the case if both the parent and the progeny underwent the same physical and/or chemical interactions in the environment. Instead, doses to workers can be assessed on the basis of the potential alpha energy concentration (PAEC), which is expressed in units of mega-electron volts per cubic meter

(MeV/m^3), and is derived from the airborne concentrations of ^{218}Po, lead-214 (^{214}Pb), and bismuth-214 (^{214}Bi).

As a practical matter, the concentrations of these progeny are usually unknown, so the calculation of doses to the lung is generally not feasible. Instead, input to IREP is in the form of working level months, which is the product of the working level (WL) and the exposure duration in work-months. The adopted convention is that 1 WL = 1.3×10^8 MeV/m^3 and that 1 work-month = 170 h (United Nations, 2009).

3.17.3 Equilibrium factors

If radon concentrations in ambient air are known, but the actual concentrations of short-lived progeny are unknown, the WL can, in principle, be estimated by assigning equilibrium factors (F_{Rn} for radon and F_{Tn} for thoron), which are defined "as the ratio of the actual . . . PAEC . . . to the PAEC that would prevail if all the decay products in each series were in equilibrium with the parent radon or thoron, as the case may be" (United Nations, 2009, p. 203). Section 3.17.3, "Equilibrium Factors," provides a method for deriving equilibrium factors, based on concentrations of the short-lived progenies; however, the necessary measurements are often not available. An acceptable method is to assume a default indoor value of $F_{\mathrm{Rn}} = 0.4$ for radon. This is confirmed by United Nations (2009, p. 206).

Table 3.6, "Uncertainty distributions for equilibrium factors for converting radon and thoron gas measurements to working levels (WL)," provides an analysis of the uncertainty distributions for the commonly used equilibrium factors of F_{Rn} for radon and F_{Tn} for thoron. Analyses of both triangular distributions and lognormal distributions are provided; however, for computational simplicity, lognormal distributions are assumed for equilibrium factors with mean values of 0.4 for radon and 0.02 for thoron.

With respect to thoron, United Nations (2009, p. 207) notes that,

> More caution should be exercised in assuming the average values of the equilibrium factor for dose assessment from inhalation of thoron decay products. An objection to the use of thoron gas measurements for dosimetric purposes is that thoron may not be well mixed in the indoor air because of its short half-life. . . . some data indicate that indoor thoron concentrations vary with the distance from walls and floors . . . . In many samples, the thoron concentrations in the centre of the room or more than 1 m from the surface of building material containing ^{224}Ra were as low as in outdoor air, while the thoron concentration near the surface of the building material was more than 10 times that in the centre of the room. Only where a room fan is used would thoron be well mixed and a large variation of the thoron concentration in the room not be found. . . .
>
> Thus the use of an equilibrium factor for thoron should be limited to situations where large spatial variation is not found.

More recently, Harley et al. (2010), derived an equilibrium factor "for both outdoor and indoor ^{220}Rn environments (0.004±0.001 outdoors and 0.04±0.01 indoors)" (Harley et al., 2010, p. 357).

Observation 12: Using a lognormal distribution with a mean value of 0.02 to represent an equilibrium factor for thoron is questionable. A bounding, site-specific equilibrium factor should be derived as needed, based on available data.

3.17.4 Summary of radon and thoron quantities and conversions factors

Numerical conversion factors for ^{222}Rn and ^{220}Rn quantities are given in table 3.7, "Summary of numerical conversions for radon and thoron quantities, regardless of the precision of measurements." SC&A reviewed the conversion factors and found that they were presented in useful units. They were technically correct, except for the default value of 0.02 for the equilibrium factor for thoron, as noted in observation 12.

3.18 Radium monitoring by breath radon analysis

Section 3.18, "Radium Monitoring by Breath Radon Analysis," accepts the conclusion that "1 pCi/L of ^{222}Rn in exhaled breath indicated the presence of 0.252 µCi of ^{226}Ra in the body" (Battelle, 2007, p. 48) that is prescribed by ORAUT (2005c) and is utilized by NIOSH in performing DRs.

3.19 Determination of the uncertainty distribution for annual organ doses summed over multiple intakes

According to section 3.19, "Determination of the Uncertainty Distribution for Annual Organ Doses Summed Over Multiple Intakes," "Assumptions favorable to the claimant are needed regarding the uncertainty distribution and uncertainty parameters for annual doses from intakes in all prior years" (Battelle, 2007, p. 48). Current NIOSH practice in performing DRs is to utilize a web-based tool, the chronic annual dose workbook (WebCAD), that calculates annual internal doses from annual intakes in current and previous years. Thus, there is no need to determine the uncertainty distribution for annual doses from intakes in prior years.

3.20 Representativeness of air samples

Section 3.20, "Representativeness of Air Samples," assumes

> that, on the average and in the absence of evidence to the contrary, an air sample distribution is unbiased. Thus the uncertainty distribution due to lack of representativeness must be unbiased, that is, have an arithmetic mean of 1. [Battelle, 2007, p. 52]

Table 3.9 is titled "Parameters of the lognormal uncertainty distribution due to lack of representativeness of an air sample distribution." BZ samples are assigned a GSD = 2, while GA and unknown type samples have a GSD = 5.

Observation 13: Even if the true underlying distribution of concentrations were lognormal, there is no real reason to assume that the distribution of the uncertainty of the representativeness parameter is also lognormal.

This is why the convolution of a lognormal with a normal, discussed in section 2.3.4 of the present review, is of interest.

3.20.1 Inferring representativeness by comparing BZ with GA samples

According to section 3.20.1, "Inferring Representativeness by Comparing BZ with GA Samples," there have been many studies of the representativeness of air samples. Table 3.10, "Breathing zone (BZ or lapel) air sampling and general area (GA) air sampling . . . ," lists eight results for GA samples and the presumably corresponding BZ measurements.[9] SC&A calculated the correlation coefficient for these eight pairs of values and obtained a value, $R^2 = 0.00147$, indicating that the activity concentrations of the BZ and GA samples are very weakly correlated. The BZ:GA ratios span a range of 14.5 to 458. Figure 16 presents a graph of the eight BZ samples plotted against "early fecal clearance," which appears to show a good correlation between the two sets of data. The log-log plot suggests a power law relationship. The relationship between the corresponding GA samples and the fecal measurements visually shows little correlation, as would be expected given the weak BZ-to-GA correlation.

Section 3.20.1 describes a comparison of over 1,000 BZ and GA samples collected at the Nuclear Materials and Equipment Corp. plant in Apollo, PA, and analyzed for uranium and plutonium. The 594 plutonium BZ:GA ratios exhibit a lognormal distribution, with a GSD = 4.33 and a calculated mean of 9.92. Clearly, the GA samples per se constitute a poor basis for estimating BZ air concentrations.

3.20.2 Inferring representativeness by comparing excretion rates predicted from air samples with measured excretion rates

Section 3.20.2, "Inferring Representativeness by Comparing Excretion Rates Predicted from Air Samples with Measured Excretion Rates," reviewed published accounts of urinary excretion rates of exposed workers and the corresponding airborne uranium contamination in the workplace. The data were weekly averages for groups of workers. While individual results varied, the data exhibited a trend: The weekly average uranium excretion rates were correlated with average airborne uranium concentrations, with a correlation coefficient, $r^2 = 0.73$. Figure 18, "Lognormal fit to the ratio of daily uranium excretion divided by the average airborne uranium concentration for maintenance workers . . . ," displays three curves with GSDs ranging from 1.49 to 1.58, depending on the statistical model used to fit the data. Another published study on monthly exposure data on two workers yielded comparable results. Battelle (2007, p. 56) concluded that "using a GSD = 2 for BZ air samples is realistic." Based on further analysis, Battelle (2007) adopted a GSD = 5 for GA representativeness.

3.20.2.1 Reviewers' comment

NIOSH (2011, section 7.1.2) lists air sampling results for six operations involving workers in various job categories who performed uranium fabrication, as reported by Harris and Kingsley (1959). NIOSH adopted a GSD = 5 for assigning inhaled intakes to such workers, consistent with the results cited by Battelle (2007).

[9] Battelle (2007) cites the following reference as the source of these data: "Strom DJ, CR Watson, and PS Stansbury. 2002. 'Predicting Consequences of Radiological Contamination. PNNL-SA-35292.' Health Physics In Press." However, SC&A has been unable to obtain this reference. According to Taulbee (2021), "We believe this is a submitted abstract to the 2002 HPS Annual Meeting. We should have this in hard copy at the NIOSH Offices but we do not have access remotely."

3.21 Propagation of medians and uncertainties for lognormal distributions

As noted in section 3.21, "Propagation of Medians and Uncertainties for Lognormal Distributions," multiplying two lognormal distributions yields a new distribution that is also lognormal.

3.21.1 Propagation of medians (not means) for products of lognormal distributions

Section 3.21.1, "Propagation of Medians (Not Means) for Products of Lognormal Distributions," observes that the median of the product of two lognormal distributions is equal to the product of the medians. However, the product of the arithmetic means is equal to the mean of the product only if the GSDs of the two distributions are equal. Battelle (2007) reminds users of IMBA that the calculated doses will have the same form as the intakes input to the program: Geometric and arithmetic mean intakes yield geometric and arithmetic mean doses, respectively.

3.21.2 Propagation of uncertainties for lognormal distributions

Section 3.21.2, "Propagation of Uncertainties for Lognormal Distributions," states that the variance of an intake can be estimated by adding the variances of the factors used to calculate its value. The GSD can then be equated to the exponential of the square root of the total variance:

$$GSD = \exp\left(\sqrt{\sum_i \sigma_i^2}\right)$$

where

σ_i = standard deviation of logarithms of uncertainty distribution *i*.

3.22 Adding doses with differing distributions

As stated in section 3.22, "Adding Doses with Differing Distributions," the sum of the doses in a DR report may not accurately represent the actual total doses if the individual doses are represented by the arithmetic means of uncertainty distributions. However, IREP correctly uses the uncertainty distributions input by the analyst to calculate the probability of causation, which is the quantity used to make a compensation decision for the claimant.

3.23 Adjusting process-specific dose rates or air concentrations for time trends over periods of years

According to section 3.23, "Adjusting Process-Specific Dose Rates or Air Concentrations for Time Trends over Periods of Years":

> When average dose rates or air concentrations are available for a given span of years for processes or locations, and when separate information on time trends over periods of years are available, it is possible to adjust the average values for temporal changes. [Battelle, 2007, p. 58]

Battelle (2007) then proceeds to derive temporal adjustment factors based on uranium air concentrations derived from Christofano and Harris (1960), figure 16.[10]

[10] Battelle (2007), figure 19, erroneously refers to Christofano and Harris, (1960), figure 1.

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