Draft White Paper

FOCUSED REVIEW OF *"UNCERTAINTY AND VARIABILITY IN HISTORICAL TIME-WEIGHTED AVERAGE EXPOSURE DATA" (DAVIS AND STROM 2008)* AND ITS APPLICATION IN DOSE RECONSTRUCTION UNDER EEOICPA

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Record of Revisions

Revision Number	Effective Date	Description of Revision
0 (Draft)	11/04/2010	Initial issue
1 (Draft)	02/01/2011	Revised and updated in response to Revision 3 of the NIOSH report, *White Paper on the Use of FMPC DWE Reports for Estimation of Chronic Daily Intake Rate*.

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ABBREVIATIONS AND ACRONYMS

AAC	Alpha Air Concentration
ACGIH	American Council of Governmental Industrial Hygienists
Advisory Board or ABRWH	Advisory Board on Radiation and Worker Health
AEC	Atomic Energy Commission
AM	Arithmetic Mean
BZ	Breathing Zone
cm^3	cubic centimeters
cpm	counts per minute
CV	coefficient of variation
dof	degrees of freedom
dpm	disintegrations per minute
DR	Dose Reconstruction
DWA	Daily Weighted Average
DWE	Daily Weighted Exposure
EE	energy employee
EEOICPA	Energy Employees Occupational Illness Compensation Act of 2000
FMPC	Feed Materials Production Center
GA	General Area
GM	Geometric Mean
GSD	Geometric Standard Deviation
HASL	Health and Safety Laboratory
ISO	International Organization for Standardization
MAC	Maximum Allowable Concentration
m^3	cubic meter
NIOSH	National Institute for Occupational Safety and Health
NLO	National Lead of Ohio
pCi	picoCuries
REQ	Requisition
SC&A	S. Cohen and Associates (SC&A, Inc.)
SD	Standard Deviation

SEC	Special Exposure Cohort
TBD	Technical Basis Document
TWA	Time-Weighted Average

1.0 STATEMENT OF PURPOSE

The purpose of this revision is to update the findings presented in the SC&A white paper entitled, *Focused Review Of "Uncertainty and Variability in Historical Time-Weighted Average Exposure Data" (Davis And Strom 2008) and Its Application in Dose Reconstruction under EEOICPA* (SC&A 2010), to reflect recent changes in National Institute for Occupational Safety and Health (NIOSH) methodologies for using daily weighted exposure (DWE) data in the reconstruction of intakes of alpha-emitting airborne contaminants in cases where bioassay and/or in-vivo measurements are lacking. As part of that process, we identify aspects of that methodology that may require refinement to make it suitable for dose reconstruction (DR) under the Energy Employees Occupational Illness Compensation Act of 2000 (EEOICPA).

SC&A (2010) was prepared under the Advisory Board on Radiation and Worker Health's (Advisory Board or ABRWH) direction to determine the extent to which the concepts and methodology described in *Uncertainty and Variability in Historical Time-Weighted Average Exposure Data* (Davis and Strom 2008) have been adopted by NIOSH. A second aspect of that review was to ascertain whether alternative approaches recommended by SC&A in reviews of relevant NIOSH guidance documents are conceptually consistent with the methods outlined in Davis and Strom (2008). This report is particularly applicable to NIOSH's proposed approach for reconstructing thorium-232 (Th-232) intake rates at Fernald based on air sampling data.

2.0 HISTORICAL MILESTONES LEADING UP TO THIS REVIEW

In April 2005, SC&A released a draft review of Revision 01 of ORAUT-TKBS-0005, the site profile [or technical basis document (TBD)] for the Mallinckrodt Chemical Works (ORAUT 2005) entitled, *Draft Preliminary Review (Partial) of the Mallinckrodt Site Profile Revision 1 (Effective Date March 10, 2005)* (SC&A 2005). In that review, SC&A identified three findings regarding time-weighted average air concentrations as used in the TBD. Those findings broadly encompassed claimant favorability, proper accounting for uncertainty and variability, and source data confirmation. In that review, SC&A demonstrated a method for quantifying and propagating uncertainty in the generation of distributions of weighted air concentrations suitable for DR.

In March 2008, during a work group discussion on the Feed Materials Production Center (FMPC) Special Exposure Cohort (SEC), NIOSH was directed by the Advisory Board to post for review a large number of DWE reports, spreadsheets containing sample data derived from the reports, and a white paper describing NIOSH's approach for using the data to reconstruct intakes of Th-232. The NIOSH white paper was entitled, *White Paper on the Use of FMPC DWE Reports for Estimation of Chronic Daily Intake Rate*, Revision 2 (Morris 2009). SC&A was tasked to review the white paper and spreadsheet data to determine if the proposed method and supporting data were sufficiently robust for DR. In July 2009, SC&A released the draft report, *Draft Review of White Paper on the Use of FMPC DWE Reports for Estimation of Chronic Daily Intake Rate for Th-232 Internal Dose Reconstruction* (SC&A 2009). That report contained 20 findings, which were discussed at length at the January 2010 Fernald Work Group meeting.

In September 2010, SC&A audited a NIOSH DR for an energy employee (EE) who worked at the uranium mill in Monticello, Utah, from 1948 to 1952. Because no external or internal dosimetry data were available and there was no site profile for this facility, NIOSH used a report prepared by the predecessor to DOE in lieu of a site profile. The report, *Environmental Hazards Associated with the Mining of Uranium Ore, A Summary Report* (HASL 1958), presents DWE data for 12 uranium mills, including Monticello, that were used to estimate the EE's intake of airborne uranium dust. It is not clear from the DR Report, however, how the data were used to derive an air concentration for intake.

The use of Alpha Air Concentration (AAC) data in internal DR was most recently discussed at the work group meeting for the Weldon Spring Plant (October 19, 2010). At that meeting, NIOSH indicated that they followed the methods described in Davis and Strom (2008) for reconstructing distributions of airborne alpha contamination for assessing intakes of alpha-emitting radionuclides. Given the issues surrounding the applicability of AAC data for DR and unresolved questions regarding the credibility of the methods employed by NIOSH for using those data, the Advisory Board tasked SC&A to perform a focused review of Davis and Strom (2008), as described above in the Statement of Purpose.

In November 2010, in accordance with the Advisory Board's direction, SC&A submitted the draft white paper report referred to herein as SC&A (2010). That report focused on the methodologies in Revision 2 of the NIOSH white paper (Morris 2009). However, after the submission of SC&A (2010) and just prior to the November 9, 2010, Fernald Work Group meeting, NIOSH submitted a revision to their white paper on DWE entitled, *White Paper on the Use of FMPC DWE Reports for Estimation of Chronic Daily Intake Rate*, Revision 03 (Morris 2010). SC&A's initial review of Morris (2010) revealed that most of the 20 findings identified in SC&A (2009) had been addressed in a satisfactory manner, and that NIOSH appeared to have revised their white paper to be mostly in accordance with Davis and Strom (2008). After discussions held at the November 9 Work Group meeting, the Advisory Board asked SC&A to update our formal review to address the revisions in Morris (2010). This revised white paper comprises SC&A's response to that request.

3.0 DAILY WEIGHTED EXPOSURE DESCRIPTION

The concept of the DWE was introduced into the Atomic Energy Commission (AEC) complex by the AEC's Health and Safety Laboratory (HASL) staff beginning in the 1940s. Airborne activity concentration data were compiled from field surveys conducted by the Industrial Hygiene Branch of HASL. Data are presented, analyzed, and summarized in documents referred to as the "HASL reports." The HASL reports were created to (1) evaluate exposure to employees from radioactive dust, (2) define the sources of exposure, (3) provide recommendations to decrease excess exposure, (4) provide an exposure history for the employees, (5) evaluate any direct exposure to radiation, and (6) acquire general knowledge of the plant to better understand hazards and ways of correcting them (Davis and Strom, 2008). Morris (2009) provides a detailed description of the HASL reports, which were fairly consistent among the different sites and over time.

Air monitoring data were used to calculate an average airborne radioactive material concentration to which workers were exposed, based on the amount of time worked and the tasks performed. This time-weighted concentration is referred to as a "daily weighted average" (DWA) or "daily weighted exposure" (DWE), because it is the average of all exposure concentrations measured from random samples taken at short periods of time during a work day. Davis and Strom (2008) refer to the time-weighted average air concentration as the DWA, while the HASL reports and other historical documents refer to it as the DWE. For consistency with the historical record and previous SC&A and NIOSH reports, we use the term DWE in this review, except when quoting directly from Davis and Strom (2008) or describing their derived quantities.

The DWE is an assessment of the exposure potential in terms of the time-weighted average AAC for a specific job description at a specific facility. The AAC was reported in units of dpm per cubic meter of air (dpm/m^3) for each task associated with a job description. The high, low, and average AAC for each task and the time required to complete each task were reported on a Job Exposure Evaluation card; general air (GA) and breathing zone (BZ) samples were reported. Most job-specific tasks were BZ samples. Typically, GA samples represented ambient exposure, such as would occur in non-production areas while engaged in activities such as smoking, using the washroom, eating in the cafeteria, or changing out in the locker room. These ambient exposure operations typically involved low concentrations and were minor contributors to the exposure for a given job description. The average AAC for each task was multiplied by the time required to complete the respective task on a daily basis. The "average × time values" were summed for all tasks and divided by the total time for all tasks to yield the DWE (daily weighted average alpha air concentration) for the job description.

The DWE is typically expressed in units of dpm/m^3 or in multiples of the Maximum Allowable Concentration (MAC), which at FMPC was 70 alpha dpm/m^3 of air until it was changed to 100 alpha dpm/m^3 of air in 1963. In modern practice, the average DWE concept is similar to the Time Weighted Average (TWA) exposure that is in current use (ACGIH 1996), except that the TWA assumes an 8-hour work day, while the DWE uses the actual work day duration.

Descriptions of the tasks performed by employees of each site are laid out in job exposure evaluation sheets that are contained in an appendix to the HASL DWE reports. The sheets list job titles, number of employees per shift, number of shifts per day, and the total number of employees under that job title. Table 1 is an example of a job exposure evaluation sheet for a single job description—Chemical Process Area "Wet Area Helper"—from Building 9 of the FMPC in 1955, during a period of active thorium production (Stefanec 1955). This job category was assigned a DWE of 46.9 MAC (or 3,286 dpm/m^3 alpha). Note that the Job Exposure Evaluation card includes the time of the evaluated work shift. In almost all cases, the time represented on a job exposure evaluation sheet is 510 minutes or 8.5 hours.

Table 1. Excerpted Job Exposure Evaluation, FMPC Plant 9 (1955)
(Stefanec 1955)

NATIONAL LEAD OF OHIO
Job Exposure Evaluation

Building 9 Process Area Chemical
Operator: [Redacted] 1 men/shift 3 shifts/day 3 men/day

	Operation Operating Area	Time per Shift (T)	No. of Samples	Concentration (C) (dpm/m³) High	Low	Avg	T × C
BZ	Dumping TNT into dissolving tank	60	3	1,088	395	774	46,440
BZ	Cleaning predryer vents	16	5	1,876	1,040	1,532	24,512
BZ	Dumping recycle oxide into predryer	15	8	125,061	5,239	54,960	824,400
GA	Chemical area, upper deck	309	13	5,057	85	2,518	778,062
GA	Smoking area	20	6	190	7	79	1,580
GA	Washroom	10	4	68	22	54	540
GA	Process locker room	20	15	51	5	15	300
GA	Street locker room	10	20	25	1	6	60
GA	Cafeteria	30	20	33	0	4	120
GA	Travel time	20	4	3	0	1.2	24

$\sum T = 510$ $\sum (T \times C) = 1{,}676{,}038$

$$\frac{\sum (T \times C)}{\sum T} = 3{,}286 \text{ dpm/m}^3 = \mathbf{46.95\ MAC}$$

Inspection of Table 1 reveals that a total of 96 separate BZ and GA samples were used to construct the DWE for the Wet Area Helper in Building 9 in 1955. The data were sorted into 10 different work categories, with each category assigned a number of minutes per shift. For example, in Table 1, "dumping TNT into dissolving tank" required 60 minutes per day, and there were three BZ air samples taken during that operation in that building in that year [sampling times from 4.8 to 12.4 minutes (NIOSH 2009)]. The results reveal a low value of 395 dpm/m^3, an average of 774 dpm/m^3, and a high value of 1,088 dpm/m^3. The product of 774 dpm/m^3 × 60 minutes yields 46,440 dpm-minutes /m^3 (as indicated in the top line of the right-hand column in Table 1). This exercise was performed for each job category, resulting in a total of 510 minutes (8.5 hours) of exposure during 1 work day for a Wet Area Helper in Building 9 in 1955. The DWE for this category of worker in this building in 1955 is the sum of the values in the right-hand column, divided by 510 minutes per day; i.e., 3,286 dpm/m^3 or 46.9 MAC.

4.0 REVIEW – UNCERTAINTY AND VARIABILITY IN HISTORICAL TIME-WEIGHTED AVERAGE EXPOSURE DATA

Davis and Strom (2008) reviewed six HASL reports covering five sites that were visited between 1948 and 1955 to characterize radiological hazards arising from the processing of uranium (U), U ore, Th, or radium (Ra-226/Rn-222). Those five sites were Electrometallurgical Co. (HASL 1948), Middlesex Sample Room (Klevin et al. 1950), and American Machine and Foundry Co. (HASL 1954; Klevin 1952) for exposure to uranium; Horizons, Inc. (Harris 1955) for exposure to thorium; and Lake Ontario Ordinance Works (Heatherton 1951) for exposure to radon and its decay products. The site names, number of employees, and material processed at each site are listed in Table 2, which is extracted from Davis and Strom (2008).

Table 2. Sites Studied and Relevant Parameters
[Extracted from Table 1, Davis and Strom (2008)]

Site	Material Processed	Date of Survey	No. of Jobs	No. of Employees
Electrometallurgical Co.	Uranium	1948	21	66
American Machine and Foundry Co.	Uranium	1952	6	7
American Machine and Foundry Co.	Uranium	1954	10	33
Middlesex Sampling Plant	Uranium ore	1950	14	31
Horizons, Inc.	Thorium	1954	11	18
Lake Ontario Ordinance Works	Ra-226, Rn-222	1951	1	8

The HASL reports cover a total of 63 job titles for which DWEs were reported. Each job title was held by 1 to 12 employees from of a total of 165 employees across the sites. Job titles involved from 1 to 13 operations, and each operation is characterized by 1 to 27 air samples. A total of 428 air samples were reported.

4.1 Sources of Variability and Uncertainty in DWE

The DWE values from the HASL reports do not contain a quantitative expression of uncertainty. Because the uncertainty is necessary for DR, Davis and Strom (2008) outlined alternative methods for generating distributions of job-specific DWEs, based on the variability in the task AAC measurements. The authors utilized Monte Carlo methods to retrospectively assess the uncertainty and variability in DWE values for the 63 job titles.

Davis and Strom (2008) identified three main sources of uncertainty in DWE values, (1) variability and uncertainty in air sample data, (2) uncertainties associated with measurement (counting statistics), (3) and spurious errors, such as mathematical errors and transcription errors, that the International Organization for Standardization (ISO) terms "blunders"[1] (ISO 1995). Variability in air sample data can be large and is associated with several factors that can occur during the sampling process. The authors identified the following five factors that contribute to air sample variability:

(1) Changes in the way a task is performed
(2) Where the sampler is placed during task performance
(3) Consistency amongst staff while performing a task
(4) Consistency in size of particulates being measured
(5) Whether or not the sample represents the actual exposure experienced by the worker

[1] The ISO definition emphasizes that a blunder is a serious mistake caused by ignorance or confusion; stupidity, which is included in some U.S. English definitions of blunder, is not implied.

Observation #1: SC&A notes that the fifth item in the list of factors contributing to variability in the data, "whether or not the sample represents the actual exposure experienced by the worker," is not a source of variability in the AAC data, but is an uncertainty in assessing worker exposure based on the data. This source of uncertainty is especially important for DR, due to limitations in the sampling performed by HASL, both in space and time, as discussed in greater detail later in this report.

Because uncertainties associated with the counting statistics of measurement are generally small compared to the variability in the air sample data, they were not addressed in the study. Uncertainties arising from self-absorption for low specific activity materials like uranium and thorium were acknowledged to be potentially significant (Skrable et al. 1991), especially for large sample volumes or high concentrations or both, but were not addressed in the study. Uncertainties due to blunders were in some cases large and unexpected.

Davis and Strom 2008 began their assessment of uncertainty in the AAC values by reviewing the raw air sampling measurement data contained in the HASL reports. They indicate that the raw data were recorded in an appendix of the HASL report under a requisition (REQ) number, sample number, time, date, and description of collection areas. Total alpha counts, counting times and counting rates for alpha particles, and background counting rates, as well as air flow rates for sampling, were recorded and calculated. For some of the samples, correction factors were also listed.

Observation #2: It is noteworthy that the airborne dust reports (DWE reports) examined by SC&A in support of the review of Morris (2009) for its applicability in the reconstruction of Th-232 intakes did not contain the raw data (SC&A 2009). Those reports were prepared for FMPC by National Lead of Ohio (NLO). This aspect of the study continues to be important in light of revision 3 because the issue of availability of the raw data for use in assessing uncertainty in DWEs remains open. Note that this has been an ongoing topic of discussion for both Mallinckrodt and Fernald (see Finding #5, SC&A 2009).

To determine which air samples were used to calculate the DWE, the operations or operating area for each job title has to be matched to raw data in the HASL document. For BZ samples, it is fairly easy to match work descriptions with collection descriptions. The process for determining which samples were used to generate GA averages was considerably more complex and often required assumptions that introduced added uncertainty.

In their analysis of the raw data in the HASL reports, Davis and Strom (2008) identified five types of human errors or "blunders" that could influence the integrity of the DWE values.

According to the ISO (1995):

> *Blunders in recording or analyzing data can introduce a significant unknown error in the result of a measurement. Large blunders can usually be identified by a proper review of all the data; small ones could be masked by, or even appear*

as, random variations. Measures of uncertainty are not intended to account for such mistakes.

The five types of blunders identified by the authors included:

(1) Transcription errors (most of these were minor and occurred in only two places).
(2) Calculation errors (occur in five cases).
(3) Rounding errors (two occurrences).
(4) Self contradictions (three occurrences). These are errors for which the data that are used do not support the statements that are made.
(5) Data imputation required. These are situations where data are listed as "0" or as "< 1."

Although this study made no attempt to incorporate uncertainty due to blunders as a parameter in the DWE distribution, it did assess the impacts of such errors.

4.2 Constructing Uncertainty Distributions for DWEs

In developing distributions of DWE, Davis and Strom 2008 limited their analysis to variability in the air sample data. To assist the reader in understanding the methods employed in generating distributions of DWEs, the nomenclature and notation used in the report are first defined (the authors use the term DWA instead of DWE, though the terms mean the same thing).

$T_{S,i}$ (min), is the total time to complete an operation [equivalent to Time per Shift (T) in Table 1].

$C_{i,k}$ is the k^{th} air sample value for operation i in units of dpm/m^3. This value is the fundamental unit used to construct the DWE distribution.

$C_{OA,i}$ is the operation average concentration in units of dpm/m^3 (equivalent to "Avg" in Table 1) of all air sample values ($C_{i,k}$) for each exposure.

$$C_{OA,i} = \frac{\sum_{k=1}^{N_{S,i}} C_{i,k}}{N_{S,i}}$$

Equation 1

$N_{S,i}$ denotes the number of air samples representing the i^{th} operation.

Equation 2 shows the method used by the HASL authors to calculate the DWA for the job title j having N_j operations:

$$DWA_j = \frac{\sum_{i=1}^{N_j} T_{S,i} \times C_{OA,i}}{\sum_{i=1}^{N_j} T_{S,i}}$$

Equation 2

The numerator of Equation 2 is the sum of products of concentration and time, and the denominator is the total amount of time worked per shift. Davis and Strom (2008) refer to the

HASL-method DWE calculation in Equation 2 as DWA_H. No variability or uncertainty is assumed or quantified for $T_{S,I}$, the time to complete task *i*.

DWA_H is equivalent to $\frac{\sum (T \times C)}{\sum T}$ in Table 1.

4.2.1 Imputing Missing or Incomplete Data

The first step undertaken by the authors in building DWE uncertainty distributions involved imputing concentration data for values recorded as "0" or "<1" (blunder Type 5). On some of the sites, samples taken between or outside buildings with operations had task average concentrations listed as zero. The authors indicated that, because it is unlikely that there would be no exposure, they substituted a nominal value of 1 dpm/m^3 for the zero value. This adjustment was done under the assumption that the elevated dust concentration levels inside should have led to some exposure in the area outside.

Many of the samples were recorded with exposure or count totals "<1." For those values, Davis and Strom (2008) believed that it was necessary to use the data that were present to impute estimated concentrations for the "less than" values. The authors describe a method for imputing individual task concentration values ($C_{i,k}$) based on several assumptions and inferences:

> *… a net counting rate was assumed by subtracting the inferred background rate of 0.2 cpm from 1.0 cpm to obtain a net counting rate of 0.8 cpm. This value was used to compute five concentration values based on the provided flow rate and inferred counting yield. Assuming that the values follow a lognormal distribution, they were run through the lognormal fitting utility* [Strom 2006] *to find the mean. Using a standard assumption documented by* [Strom 2007], *the calculated mean was divided by two and this imputed value entered into a program called LOGNORM4* [Strom and Stansbury 2000], *with a GSD of 2 to produce five values from a lognormal distribution with these parameters.*

4.2.2 DWA Distributions based on Sampling Discrete Concentration Measurements

The authors performed Monte Carlo simulations with Crystal Ball using the discrete $C_{i,k}$ values to determine the distribution of DWA_H values. For each job title *j*, and each operation *i*, one air sample concentration measurement $C_{i,m}$ was randomly selected and multiplied by its corresponding $T_{S,i}$. The value of the product $C_{i,m}\times(T_{S,i})$ was summed for all operations *i* in job *j* and divided by the time worked per shift to obtain a single value:

$$DWA_{j,m} = \frac{\sum_{i=1}^{n_j} T_{S,i} \times C_{i,m}}{\sum_{i=1}^{n_j} T_{S,i}}$$

Equation 3

where *m* denotes a particular combination of $C_{i,k}$ values (i.e., an index denoting the outcome of a single trial), so that the $DWA_{j,m}$ is considered to be the outcome of one trial. The simulation was run for 10,000 trials for each job *j*. After all trials were run, all 10,000 $DWA_{j,m}$ realizations were extracted and summary statistics computed. The authors refer to the distribution of $DWA_{j,m}$ as the deterministic DWA, or DWA_D. It is noteworthy that in Equation 3, the only modeled value is the concentration per task, $C_{i,m}$.

4.2.3 DWA Distributions based on Sampling Lognormal Fits to Concentration Measurements

In their literature review, Davis and Strom (2008) cite several references that recommend the lognormal distribution for modeling limited air sampling data:

> *The NIOSH Occupational Exposure Sampling Strategy Manual suggests that DWA calculations are not the best way of measuring an eight-hour exposure* [Leidel et al. 1977]. *This recommendation is due to the large amount of variability in each air sample. … When random grab samples are used,* [Leidel et al. (1977)] *suggest that a lognormal distribution be assumed. Variability will still remain high due to differences in work habits and the possibility of moving between numerous locations during a work day. Studies conducted by* [Linkov and Burmistov (2001)] *using 400 air sample measurements show that the between-area variability is not as great as the variability that exists in a single area on a month to month basis. They suggest that a single value should not be used to measure exposure. Rather a lognormal distribution should be used that will assign appropriate probability to all possible concentrations. The same conclusion was reached by* [Nicas and Jayjock (2002)] *where, in cases where only a few air samples can be taken, modeling the exposure using a lognormal distribution would give a more accurate estimate of the true exposure.*

The lognormal DWE distribution was constructed as follows:

For each operation *i*, a lognormal distribution was fit to the $C_{i,k}$ values. For those operations *i* where $k = 1$, or where the $C_{OA,i}$ from the HASL report was used in place of missing data, the operational average concentration was assumed to be the arithmetic mean (C_{avg}) of a lognormal distribution with a *GSD* of 2. Based on examination of the data, the authors believed that a *GSD* of 2 was fairly representative of the average for most samples and state that the assumed $GSD = 2$ is supported by Leidel et al. (1975), who analyzed sets of airborne chemical vapor and aerosol data. The value of the geometric mean (GM) was calculated by:

$$GM = C_{avg} \times \exp\left[-\ln(GSD)^2/2\right]$$

Equation 4

which amounts to dividing C_{avg} by 1.27.

When the operation had two or more samples, the numbers were placed in a lognormal fitting utility (Strom 2006) to calculate the arithmetic mean, *SD*, coefficient of variation (*CV*), *GM*, and the *GSD*. For each job *j* and each operation *i*, a sample $C_{i,n}$ was taken at random from a lognormal distribution fit to the $C_{i,k}$ measurements, and $C_{i,n}$ was multiplied by the corresponding

$T_{S,i}$. The value of the product of $C_{i,n} \times (T_{S,i})$ was summed for all operations i in job j and divided by the time worked per shift to obtain a single value:

$$DWA_{j,n} = \frac{\sum_{i=1}^{N_{Sj}} T_{S,i} \times C_{i,n}}{\sum_{i=1}^{N_j} T_{S,i}}$$

Equation 5

where n denotes a particular sample from the lognormal distribution. The simulation was run for 10,000 trials for each job title. After all trials were run, all 10,000 $DWA_{j,n}$ values were extracted and summary statistics computed. The *DWA* calculated using lognormal distributions is referred to as a DWA_L. In Equation 5, the only modeled value is the concentration per task, $C_{i,m}$; $T_{S,i}$ is assumed not to vary.

Finding #1: The formulations for DWA_D and DWA_L treat $T_{S,i}$, the time required to complete task i, as a constant. Given that these are, in fact, average times to complete a task, they have associated variability (among workers) that should be addressed in generating uncertainty distributions of DWE. In the 2005 review of the Mallinckrodt report, SC&A noted that these uncertainties could be significant in high dust, short-duration operations that dominate time-integrated exposure.

To allow time periods to vary in length is a multivariate problem, since if one is made longer, some other(s) must be made shorter; times are mutually negatively correlated. We are really asking how to divide the day into percentage blocks, $p_1, \ldots p_N$, which always sum to 100%, yet are random. SC&A is aware of a distribution for this modeling task, which is the multivariate Dirichlet. The vector of specified times T_{Si} are the expected values of this distribution. Dirichlet is the multivariate generalization of the beta distribution on interval [0,1]. In Crystal Ball, the multivariate Dirichet distribution is simulated as $p_i = X_i / \sum(X_1, \ \ , X_N)$, where Xi have ***independent*** gamma distributions.

4.3 Results

4.3.1 Job-Specific DWE Distributions

For each job title *j*, 10,000 Monte Carlo trials were performed by Davis and Strom. In each trial, airborne radioactive dust concentrations were randomly sampled for each task *i* either from the discrete measurements reported by HASL (with blunders corrected) or from lognormal distributions fit to those measurements. The result of each trial was a DWA_D or a DWA_L. To demonstrate the characteristics of a DWA_L distribution for a specific job type, Davis and Strom created a z-score plot of ranked DWA_L values generated from 1,000 Monte Carlo trials for the "foreman" job title at Electrometallurgical Co. (Figure 3 of Davis and Strom 2008). The plot demonstrates that the simulated data are well described by the lognormal distribution. Figure 4 of the report, which is reproduced below as Figure 1, depicts overlain distributions of simulated DWA_D and DWA_L for each of three job titles.

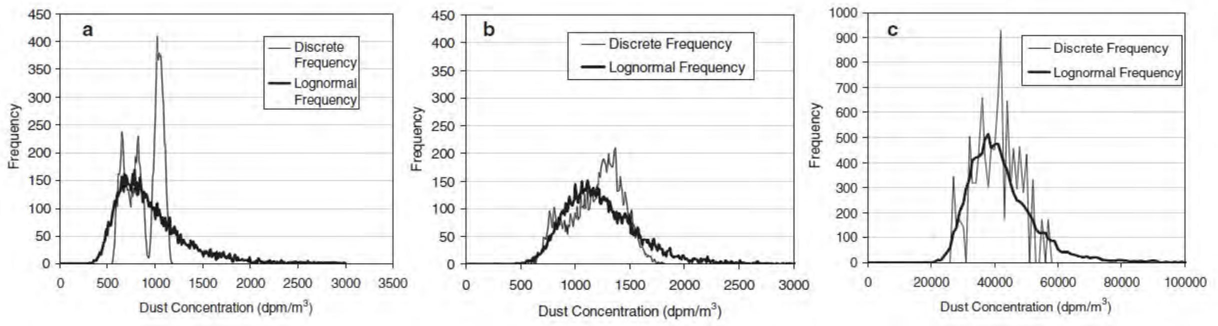

Figure 1. Distributions of Simulated DWA for Each of Three Job Titles
[Extracted from Davis and Strom (2008)]

In Figure 1, each histogram represents a different job title from Electrometallurgical Co. in 1948, which are (a) "Remelt Operator," (b) "Bomb Unloader," and (c) "Greenroom Operator." It is noteworthy that the discrete distributions do not appear to be lognormal for any of the three job types displayed in Figure 1, though visual inspection suggests that the discrete distribution for the Greenroom Operator is the closest match to the lognormal.

The authors indicate that the means calculated using the discrete method closely resemble those calculated using the HASL method for all sites. They go on to state that, for all three simulations in Figure 1, the means of the DWA_D and DWA_L distributions were consistent with one another, but that the standard deviations (SDs) for DWA_L exceeded that for DWA_D by factors of 1.4 (Bomb Unloader) to 2.4 (Remelt Operator); for all datasets, the SDs for DWA_L were higher or equal to those for DWA_D. The upper tails of the DWA_L distributions are higher because the lognormal allows for the possibility that exposures can be larger than those actually observed. Because BZ and GA sampling, as reported by HASL, was limited in space and time and may have missed some of the higher air concentrations, the use of DWA_L may be more claimant favorable for DR.

In summary, Davis and Strom (2008) state that for the HASL dataset, most groups of repeated air samples are well described by lognormal distributions, and that combining samples associated with different tasks often results in a reduction of the geometric standard deviation (GSD) of the job DWE to less than those GSD values typical of individual tasks. They indicate that their results support the assumption of a GSD value of 5, when information on uncertainty in DWE exposures is unavailable.

Finding #2: The histograms in Figure 1 call into question the assumption of log-normality for the task AAC data. If the source data were lognormally distributed, as suggested by the authors and advocated in citations quoted in the literature review, one would expect that a DWE distribution constructed from those data would, in most cases, appear lognormal (as was true for DWA_L, which was based on lognormal fits to the AAC data).

SC&A believes that a careful review of the source data should be conducted prior to modeling to determine if a lognormal fit is appropriate, or if some other distribution is appropriate. For source AAC that are not lognormal, another alternative would be to assign a percentile of the sorted DWE_D distribution. Notwithstanding unresolved issues regarding the completeness and applicability of the AAC data (SC&A 2009), SC&A believes that, for a credible dataset (i.e., sufficient number of samples that are free of blunders) that appears lognormal, the job-specific DWA_L distributions provide a claimant-favorable construct that accounts to some extent for the possibility that exposures could have been larger than those actually observed.

Impact of Blunders

Some of the sites analyzed in this project reveal a high rate of blunders that add to the uncertainty in the DWE values. Davis and Strom 2008 note that the ratio of DWA_D or DWA_L to DWE_H is a good index to the impact of blunders on DWE. Only those blunders that result in differences between DWA_H and the two simulations of ± 20% were deemed to be significant. For the Electrometallurgical Co. site, at least 6 of the 21 job titles had errors that resulted in differences between the DWA_D and DWA_H of ≥20%. Less significant errors occur in nearly all the job titles, due to errors for general areas or tasks that recurred in most of the job titles. For American Machine and Foundry in 1952, imputed data lead to differences of ≥20% in two cases. For American Machine and Foundry in 1954, half of the job title worksheets contain errors that led to significant impacts on the DWAs. Significant errors also were present in half of the job titles for Horizons, Inc. Of all the sites, the HASL report for the Middlesex Sampling Plant contained the fewest errors, having only one that made a significant impact.

One example of a blunder involves $T_{S,i}$, the time required to complete task *i*. In one case, the time of work was not fully recorded; what was recorded was almost 50% less than the actual time. While variability in the time to complete a task is expected, SC&A did not expect major time exclusions. Note that this uncertainty in $T_{S,i}$ is due to blunders and is not the same as the variability/uncertainty in $T_{S,i}$ measurement, per Finding #1.

Table 6 of Davis and Strom 2008 demonstrates that for those job titles in which significant blunders occurred (7 for DWA_D and 16 for DWA_L), average blunders cause a two-fold underestimate of exposure. Figure 5 of Davis and Strom (2008) illustrates that for 5 out of the 63 jobs, blunders resulted in overestimates of DWA values by factors of 2 to 2.5, and **in 2 cases, DWA values were underestimated by factors of 3 to 10**.

Davis and Strom conclude the discussion of blunders with the following statement:

> *This work does not resolve the problem of how to handle the contribution to uncertainty in dose assessments of blunders in historical data analysis.* ***In two cases, blunders are definitely unfavorable to the worker, had he or she been a claimant.*** [Emphasis added.]

Finding #3: The impact of blunders on calculated air concentration values (AAC) was unexpected and in some cases significant. SC&A believes that this is a problem, even if it happened in only a few cases, and underscores the critical importance of validated source data in constructing uncertainty distributions for DWE. Note that this issue was raised in the 2005 SC&A review of the Mallinckrodt TBD.

4.3.2 Site-Wide AAC Distributions

For the six HASL reports studied, the distributions for all the $C_{i,k}$ data show a wide range of site-wide average values (C_{site}) among sites. The smallest C_{site} value is at American Machine and Foundry in 1954, at 117 ± 315 dpm m^{-3}. Electrometallurgical has the highest C_{site} of 20,301 ± 61,180 dpm m^{-3}. Horizons had the highest GSD at 17.27 and the smallest is at American Machine and Foundry in 1954 with a GSD of 7.88. Amongst all sites, the BZ samples show the highest individual concentration ($C_{i,k}$) values. For those BZ samples that had more than 3 samples, the GSDs for the task averages ($C_{\text{OA},i}$) were all less than 2. It is interesting that for the data evaluated for this study, the GA samples had the highest GSDs, with most greater than 2.

Davis and Strom 2008 state that using the distribution of all air samples from a plant without time weighting or assignment to specific jobs does not produce a DWE or GSD that is representative of any individual worker for that site. They report that the means of site-wide average concentrations (C_{site}) exceed the DWAs for all workers in 60 of 63 cases, and in all but 1 case, the upper 95th percentile of the site-wide distribution exceeds the DWAs for all workers. For the three job titles for which $C_{\text{site}} < \text{DWE}_j$, the ratios of DWE/$C_{\text{site}}$ were 469%, 198%, and 118%. The one job title for which the DWA exceeds the 95th percentile of the site-wide distribution did so by only 7%, and it is at the site with the smallest GSD of 7.88 (American Machine and Foundry in 1954). C_{site} exceeded the average DWA_D at the site by factors of 8.0, 6.7, 1.5, 6.1, and 10.8, respectively, for the first five sites listed in Table 1. **The authors conclude that using the upper 95th percentile of site-wide air concentration data will almost always be favorable to the claimant, if unrealistically high for almost everyone**.

The authors note that on a site-wide basis, the job DWEs increase with the amount of time spent in direct contact with materials or time spent in processing areas and that, due to site-specific variation in the tasks associated with a given job title, the trend is more significant within a site than across sites. When viewed across all sites, administrative employees who spent no time in processing areas have DWEs of 0.39 to 0.45 MAC. Support staff, such as laundry workers, guards, and janitors, who spent limited to no time in processing areas, have DWEs of 1.09 to 3.07 MAC. Foremen, supervisors, and maintenance personnel, who spent most of their time roaming the sites, have DWEs of 0.33 to 3.64 MAC. Laborers, who spent a majority of their shift in direct contact with materials or in the processing areas, have DWEs that range from 0.007 to 594 MAC. Thus, it can be inferred that office workers and support staff did not experience large exposures. For construction workers and other employees considered to be “roamers,” the range of possible exposures is higher than that of the office and support staff, but does not exceed many of the exposures for laborers. It can be expected that the laborers ran the highest risk of large exposures. **It is noteworthy that while the authors note a correlation between job type and exposure potential, they neither advocate nor present a method for estimating exposure by job type on a site-wide basis (Finding #8).**

5.0 USE OF DAVIS AND STROM (2008) IN NIOSH METHODOLOGY FOR ESTIMATING INTAKES BASED ON AAC DATA

In this section, SC&A investigates the extent to which the methods outlined in Davis and Strom (2008) have been applied in a key NIOSH guidance document pertaining to the estimation of intakes of airborne radioactive dusts based on AAC data. In October 2010, NIOSH released Revision 3 of their draft white paper entitled, *White Paper on the Use of FMPC DWE Reports for Estimation of Chronic Daily Intake Rate* (Morris 2010), which presented revised methods for using DWE data to reconstruct intakes of alpha-emitting radionuclides when bioassay and/or lung counting data are not available. NIOSH has indicated that Morris (2010) closely follows the methods in Davis and Strom (2008) and is intended as a generalized methodology to be applied in DR for Fernald and also for Weldon Spring and other sites. Accordingly, the discussion in this section focuses on those revised methods. Note that SC&A has recently audited a case for an EE who worked at the Monticello uranium mine in Utah in the late 1940s to early 1950s. Because that worker's intakes were calculated from DWE, we include a brief comparison of the methods employed in that DR to Morris (2010) and Davis and Strom (2008).

5.1 White Paper on the Use of FMPC DWE Reports for Estimation of Chronic Daily Intake Rate

Morris (2010) describes a method for estimating chronic daily intake rates of uranium and thorium, their progeny, and other associated radionuclides using DWE data. The intent of that document is to demonstrate that DWE data may be used to estimate the daily intake rate when in-vivo data are unavailable or inadequate (e.g., the period prior to the introduction of in-vivo chest counting at FMPC). Morris (2010) has introduced significant changes from the previous version, most of which appear to be methodologically consistent with Davis and Strom (2008).

The outline presented below contrasts the methods in Revision 2 and Revision 3 of the NIOSH white paper; a discussion of the revisions follows:

Revision 2 (Morris 2009):

- Proposes to use DWE data to estimate chronic daily intake rates for workers
- Proposes to use job-specific data when data on job type are available in a worker's file (not available in most cases)
- For all others, seeks to construct log-normal facility (Plant) distributions of alpha air concentration
    - Assigns intakes to workers based on exposure potential using three quantiles of the facility distribution (low, medium, or high)
        - Low: admin, clerical, secretarial, managerial (up to GM - GSD)
        - Medium: not in low or high (maintenance, construction) (GM ± GSD)
        - High: process operators and helpers, machine operators/helpers, welders/helpers, furnace operators/helpers (GM + GSD)

Revision 3 (Morris 2010):

- Proposes to use DWE data to estimate chronic daily intake rates for workers.
- Proposes to assign the DWE value associated with the job title or job description with the highest DWE in the FMPC plant where thorium was handled for a specific year to every worker in that facility, with a GSD of 5.
- Proposes to use the upper 95th percentile of the air sampling data for a facility when time-weighted average data are not available.
- Proposes to assign a high DWE value from an adjacent year when neither DWE data nor air sampling data are available, or when they are judged to be inadequate or incomplete. A GSD of 5 is recommended.
- If it is determined that thorium exposure may have occurred in a facility not shown in the thorium timeline (Morris 2010, Figure 1, p. 2), NIOSH recommends searching the SRDB for DWE data by using the keywords "exposure study." A draft summary of the FMPC DWE data (Unknown 1990) can be used as an indicator of the data that are likely to be found in the SRDB.

5.1.1 Sources of Variability and Uncertainty in the DWE Data

A salient feature of Davis and Strom (2008) is the detailed discussion of the types of variability and uncertainty inherent in the DWE data and those sources addressed in their method, namely variability in the task AAC measurements. Their identification of human error (blunders) as a significant source of uncertainty in the AAC data and the need to carefully review those data is particularly relevant to DR under the EEOICPA (see Finding #3).

Morris (2010) proposes to use an upper bound DWE or unweighted air concentration to account for sources of variability and uncertainty in the source data. The upper bound for a plant or building is to be based on the job with the highest DWE in the facility as a central estimate, with a GSD of 5. Regarding the GSD of 5, Morris (2010) states:

> *Based on their analysis Davis and Strom state it is reasonable to conclude that the upper 95th percentile value of the GSD distribution is about 4 and the upper 99th percentile is between 7 and 8. This lends support to their generalization of assuming a GSD of 5 when a DWE concentration value is available but there is no information on uncertainty.* (Morris 2010, p. 11)

This statement is consistent with Davis and Strom (2008), p. 15:

> *By examining the data themselves rather than a fit, one can conclude that the upper 95th percentile of the GSD values is about 4, and the upper 99th percentile is between 7 and 8. This observation supports the practice of assuming a GSD of 5 when a concentration measurement is available but there is no information on uncertainty.*

By using a shortcut method that relies extensively on the analysis in Davis and Strom (2008), NIOSH can circumvent the need to generate a set of site-specific DWE fits from the Fernald source data. To help justify their reliance on Davis and Strom rather than site-specific data, NIOSH states the following:

> *The sampling methods and data analysis used by the HASL staff were the same as those used at FMPC. The engineered controls in these AWE facilities were similar to, but likely inferior to those employed at FMPC, since FMPC was purpose-built in light of experience at earlier operating facilities.* (Morris 2010, p. 10)

Thus, NIOSH appears to believe that the data from Fernald are less variable and uncertain than those from the sites investigated by Davis and Strom because engineering controls had improved, based principally on experience gained from those earlier operations. However, NIOSH has not yet demonstrated that the data from Electrometallurgical Co., American Machine and Foundry Co., Middlesex Sampling Plant, Horizons, Inc., and Lake Ontario Ordnance Works collected from 1948 to 1955 can serve as a reasonable surrogate for bounding exposures in the Fernald thorium processing facilities during the proposed SEC period. That is, NIOSH has not analyzed the site-specific data to determine if a GSD of 5 is adequate for bounding Fernald DWEs. As noted in SC&A 2009, we have identified some of the raw air sampling data and matched it to DWE data for some plants and years. However, as stated in Observation #2, it is not clear to what extent the Fernald source data are available for analysis. Moreover, SC&A understands that NIOSH has not yet conducted a thorough investigation into the availability of the data.

Finding #4: Morris (2010) has not demonstrated that the data analyzed in Davis and Strom (2008) constitutes a reasonable surrogate for bounding the Fernald DWEs during the proposed SEC period. SC&A believes that NIOSH should determine the extent of DWE source data availability for Fernald and perform an uncertainty analysis on those data to ascertain if a GSD of 5 is sufficiently bounding.

As a corollary to Findings #3 and #4, NIOSH should review the available Fernald source data for blunders. As noted in the discussion leading to Finding #3, Davis and Strom demonstrated that for the subject datasets, blunders could result in underestimated intakes up to an order of magnitude. Furthermore, this type of uncertainty was not considered in their analysis. If blunders of this magnitude were found to exist at Fernald, upper-bound doses could potentially be underestimated (for example, a GSD of 5 combined with an underestimate of 10 from blunders would result in a factor of 2 underestimate of upper-bound dose). While SC&A understands the remote likelihood of such an occurrence, we believe it is incumbent upon NIOSH to provide reasonable documentation of the frequency and magnitude of blunders in their source data.

Finding #5: Morris (2010) has not investigated the issue of blunders as a significant source of error in Fernald DWE source data. SC&A believes that NIOSH should determine the frequency and magnitude of blunders in their source data. If significant blunders are identified, their influence should be taken into account in uncertainty metrics (e.g., GSD).

5.1.2 DWE for a Facility in a Specified Year

SC&A believes that once NIOSH has satisfied our concerns per Findings #4 and #5, the proposed method for bounding intakes based on the highest DWE in the FMPC plant where thorium was handled for a specific year, with a bounding GSD (nominally 5), is reasonable.

5.1.3 DWE for a Facility Based on Adjacent Years

SC&A believes that once NIOSH has satisfied our concerns per Findings #4 and #5, the proposed method of assigning a high DWE value from an adjacent year for bounding intakes when neither DWE data nor air sampling data are available, or when they are judged to be inadequate or incomplete, is reasonable. However, NIOSH should quantify what is meant by a "high DWE."

5.1.4 Unweighted Air Concentration Data when Time-Weighted Data are Not Available

NIOSH proposes to use the upper 95th percentile of the air sampling data for a facility when time-weighted average data are not available. Morris (2010) draws from the following statement in Davis and Strom (2008) as the basis for this approach:

> *Thus, using the upper 95th percentile of site-wide air concentration data will almost always be favorable to the claimant, if unrealistically high for almost everyone. Clearly, C_{site} is a biased estimator of exposure, but it can be used in making compensation decisions when it is required to be favorable to a claimant.* (Davis and Strom 2008, p. 15)

While there is no doubt that such a high intake assignment would be claimant favorable, the following statement from Davis and Strom (2008) suggests that it may not meet the plausibility requirement for DR under EEOICPA:

> *Using the distribution of all air samples from a plant without time weighting or assignment to specific jobs does not produce a DWA or GSD that is representative of any individual worker for that site.* (Davis and Strom, 2008, p. 15)

Table 2 from Morris (2010) summarizes the recommended DWE values for years and facilities in which thorium work is known to have occurred. These values represent the job description in each facility with the highest DWE value for that year. That table is replicated below as Table 3, for convenience. "NA" indicates that thorium is not known to have been processed in that facility during that year.

Table 3. DWE Values, in Units of Multiples of the MAC, Recommended for use in Estimation of Thorium Intake Rates
[From Table 2, Morris (2010)]

Year	54	55	56	57	58	59	60	61	62	63	64	65	66	67
Plant 1	a	16.4	4.3	1.5	1	2.1	0.5	0.6	1.1	0.6	0.7	0.6	1	1.2
Plant 4	4.5	3.2	0.9	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Plant 6	N/A	N/A	N/A	N/A	N/A	0.8	4.3	1.6	2.8	17	N/A	N/A	N/A	N/A
Plant 8	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	7.1	N/A
Plant 9	b	686	b	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Pilot Plant	5.9	c	2	N/A	N/A	N/A	N/A	N/A	N/A	N/A	d	d	d	**77**

Notes:
a: Data are not available. Instead use the value for Plant 1, 1955.
b: Data are not available. Instead use the value for Plant 9, 1955.
c: Data are not available. Instead use the value for Pilot Plant 1954.
d: DWE data are not available. The value for Pilot Plant 1967 is based on the 95th percentile value of 18 air samples taken during thorium operations. Use this value for Pilot Plant 1964 through 1966.

NIOSH indicates that the proposed intake assignment of 77 MAC for the Pilot Plant for 1964–1967 is based on the 95th percentile of 18 unweighted air samples taken in 1967. SC&A reviewed the raw air sampling data that were downloaded to support our review of Morris (2009) and found that NIOSH assigned the air concentration as described. However, we believe that an upper-bound AAC assignment without time weighting is unrealistic and highly implausible, due to the huge variability of such data in space and time. Moreover, we find it perplexing that NIOSH suggests using unweighted air sampling data when time-weighted data from the same plant for other years or from another plant are available.

A closer inspection of the highest DWE for Plant 9 in 1955 helps illustrate our concerns regarding the assignment of unweighted AAC data. We note that the value of 686 MAC for Plant 9, while nearly an order of magnitude higher than the Pilot Plant assignment of 77 MAC, is nonetheless plausible, because it is based on a sufficiently robust set of time-weighted BZ and GA measurements for laborers involved in thorium metal production during that year. That is, it reflects actual exposure potential for a class of workers who were subject to heavy dust loading in the facility for the year in question. As an extreme example of NIOSH's proposed approach, SC&A notes that the highest air concentration measured for Plant 9 in 1955 was a BZ sample for cleaning furnace pots inside an enclosure, a task that required about 75 minutes to complete. The highest measured concentration among 7 samples was 976,798 dpm/m^3 (9,768 MAC), though the samples were highly variable (low of 1,887 dpm/m^3 and an average of 321,549 dpm/m^3). Clearly, assigning the 95th percentile of these unweighted air concentrations to every worker in the plant that year would be claimant favorable, though not representative of reasonable exposure potential to any worker (nominally 13–14 times higher than the DWE for that job description).

Finding #6: The use of the upper 95th percentile of the air sampling data for a facility when time-weighted average data are not available probably does not meet the plausibility requirement for DR under EEOICPA. SC&A finds it perplexing that NIOSH suggests using unweighted air sampling data, particularly when time-weighted data from other years or from another plant are available.

5.1.5 Thorium Exposures Not in Timeline

SC&A believes that it is incumbent on NIOSH to locate and make available all AAC data that may be related to thorium exposure. A simple directive to the dose reconstructor to search the SRDB for such information if thorium exposure is suspected places an undue burden on the dose reconstructor and is likely to result in inconsistencies. SC&A's concern regarding the completeness of the thorium timeline was identified as a finding (#8) in SC&A (2009) and is restated below:

> *There are a number of years and plants in the thorium timeline that have no DWE reports. NIOSH has not provided a method for estimating thorium intakes in these cases.*

Finding #7: It is incumbent on NIOSH to update the thorium timeline and locate and make available all AAC data that may be related to thorium exposure. Reliance on the dose reconstructor to search the SRDB for such information if thorium exposure is suspected places an undue burden on the dose reconstructor and is likely to result in inconsistencies.

5.2 Independent Audit of the Dose Reconstruction for an Energy Employee at the Uranium Mill in Monticello, Utah

SC&A recently performed an independent audit of a DR performed by NIOSH for an EE who worked as a [redacted] at the Uranium Mill in Monticello, Utah, from October [redacted], through December [redacted]. Because NIOSH used DWE to assess the internal dose to this EE, SC&A believes that a comparison of the methods applied in this case to those in Morris (2009) and Davis and Strom (2008) is instructive.

The DR Report explains that no external or internal dosimetry data are available for this EE. Also, there is apparently no site profile for this facility. However, NIOSH took advantage of material provided in a report prepared by the predecessor to DOE (HASL 1958). Because of the degree to which the DR for this EE is based on HASL (1958), we reviewed HASL (1958) as if it were a site profile. The DR Report states that it was not possible to determine whether the EE was in a position to experience internal exposures, and there are no air sampling or bioassay data for this facility. As a result, the data in HASL (1958) were used to assign internal exposures to this EE. HASL (1958) presents the results of a detailed investigation performed by HASL of the exposures of workers to internal emitters from 12 uranium mills operating in 1957.

The emphasis of the HASL air sampling program was to determine the air concentration of alpha-emitting dust, its composition, particle size, and silica content (the latter for industrial hygiene reasons). The air samples consisted of GA samples collected in occupied areas, and a second set of BZ samples for employees engaged in specific potentially dusty operations. Many samples were replicates, and the average of the replicates was reported. The data were used to derive DWEs for different job categories using well established DWE techniques.

Table 2 of the DR Report provides annual intakes in units of pCi/yr, but does not explain how the values in HASL (1958) were used to derive these intakes. Assuming the EE worked with uranium ore, the total annual intake is estimated in Table 2 of the DR to be 2.1×10^4 pCi/yr. If the EE worked with yellowcake, the total annual intake rate of long-lived alpha emitters is 5.1×10^4 pCi/yr. SC&A estimated the average airborne gross alpha activity (expressed in units of dpm/m^3) required to reach the stated intakes by applying a 2,000-hour work year and a breathing rate of 1.2 m^3/hr. This results in average air concentrations of 19.44 and 47.21 dpm/m^3 for uranium ore and yellowcake, respectively.

Upon completion of SC&A's review, it was determined that Mill A in HASL (1958) is the Monticello facility. A review of the air sampling data for Mill A reveals that it lies in the mid range of the levels observed among the 12 mills investigated by the HASL. Table II of HASL (1958) indicates that the DWE for Mill A was 12.5×10^{-11} µCi/cm^3, which converts to 278 dpm/m^3 (rounded):

$$12.5 \times 10^{-11}\ \mu\text{Ci/cm}^3 \times 10^6\ \text{cm}^3/\text{m}^3 \times 3.7 \times 10^{10}\ \text{d/s-}10^6\ \mu\text{Ci} \times 60\ \text{s/min} = 278\ \text{dpm/m}^3$$

Therefore, the NIOSH values are equivalent to 7% and 17% of the average for Mill A for uranium ore and yellowcake, respectively. It appears from the limited information regarding the methods employed in this DR that the EE was assigned a "low" exposure, based on the EE's [redacted] for the facility DWE (Mill A). This approach would be consistent with the NIOSH approach for assigning exposures based on job category in Morris (2009), to the extent that it is transparent to SC&A. SC&A understands that the DR Report was prepared prior to the issuance of Revision 3 of the NIOSH white paper and is, therefore, not consistent with the methods in Davis and Strom 2008.

Finding #8: It appears that NIOSH has applied the methods described in Morris (2009) in assigning the intake to this EE as a percentile of the facility DWE based on job category. This approach is not consistent with Davis and Strom (2008) and does not appear to be a statistically valid method of using DWE data to estimate intake.

6.0 CONCEPTUAL CONSISTENCY OF SC&A-SUGGESTED APPROACHES FOR ESTIMATING INTAKES BASED ON AAC DATA WITH DAVIS AND STROM (2008)

In this section, SC&A ascertains whether alternative approaches we have recommended in reviews of relevant NIOSH guidance documents are conceptually consistent with the methods outlined in Davis and Strom (2008).

6.1 Feed Materials Production Center (SC&A 2009)

Attachment 1 of SC&A 2009 contains a detailed examination of the DWE data for one FMPC plant/year combination; Plant 1 in 1955. The DWE data for Plant 1 in 1955 are for 28 workers apportioned among 12 jobs that included a total of 95 separate tasks. The AAC data used to create the DWEs were transcribed by NIOSH from job evaluation sheets and compiled in spreadsheets.

To verify the DWE_H values generated from the NIOSH spreadsheets and also evaluate the degree to which the AAC data and job DWEs follow a lognormal distribution, SC&A performed a Monte Carlo simulation on the AAC data by task for 12 jobs for Plant 1 in 1955. We conducted a simulation using Crystal Ball with the exposures for each task being random, and a weighted DWE for each job was calculated using the (fixed) time weights. To conduct the simulation, we constructed a separate lognormal distribution for each of the 95 tasks using the sample size and average, high, and low exposures taken from the spreadsheets. If the reported low value was zero, a value equal to one-half of the smallest reported non-zero value was used. The means of the estimated lognormal distributions were plotted versus the spreadsheet averages for each task in Figure 1-1 of the report, as a check on the estimated parameters. That plot is replicated here as Figure 2.

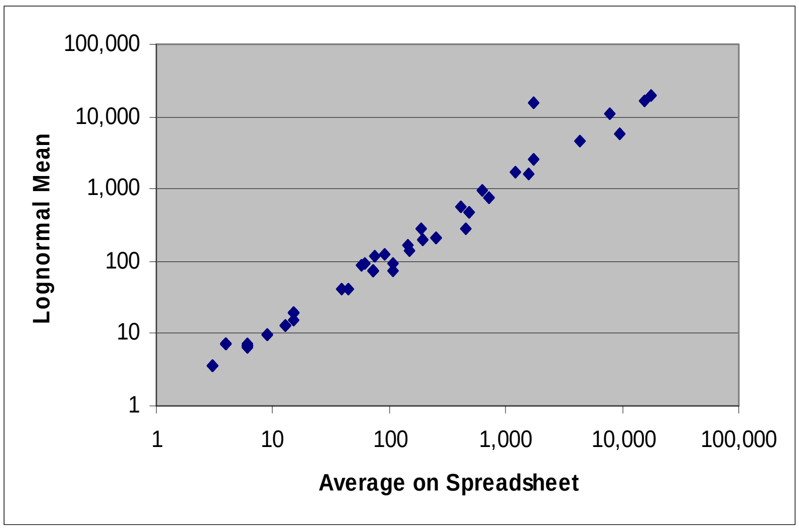

Figure 2: Scatter Plot - Lognormal Mean for Each Task versus Actual Average Exposure

Figure 2 illustrates that SC&A's Monte Carlo simulation yielded task averages that are consistent with the values calculated in the spreadsheets, which indicates that the task AAC distributions are well approximated by the lognormal. That this AAC dataset appears to be lognormal, while those from Figure 1 do not, underscores the wide variation in measurement distributions among job DWEs and across sites.

Results of the Crystal Ball simulation are shown in Table 4 and compared to the DWE_H values calculated from the NIOSH spreadsheets. Values are reported in units of dpm/m^3.

Table 4. Simulation Results for Job Descriptions and Facility Mean as Performed by SC&A

Job Title	DWE_H	Mean	Median	Standard Deviation	95th Percentile
Sample Preparation Operations	1568	1,370.77	557.74	3,579.95	4,686.68
General Plant Operations	468	530.49	448.71	397.25	1,014.13
Leadman	97	82.22	47.20	130.75	263.61
Production Foreman	38	33.30	22.13	38.95	89.06
Sample Preparation Foreman	28	28.74	17.71	38.40	87.96

Table 4. Simulation Results for Job Descriptions and Facility Mean as Performed by SC&A

Job Title	DWE_H	Mean	Median	Standard Deviation	95th Percentile
General Foreman	22	20.49	14.79	20.25	50.78
Superintendent	15	14.10	10.39	13.18	35.98
Storage Pad Foreman	12	12.42	12.23	1.92	15.78
Storage Pad Operator	11	12.09	11.90	1.93	15.43
Storage Pad Laborer	10	11.32	11.12	2.21	15.38
Production Records Clerk	7.7	8.45	7.85	3.15	14.29

The means resulting from the Crystal Ball simulation in Table 4 are consistent with the DWE_H calculated from the historical AAC data. Note that because this exercise was conducted to match the HASL DWEs, no attempt was made to account for variability in the time for each task.

Finding #9: The method outlined above to generate distributions of job DWEs from lognormal fits to the task AAC data is practically identical to the DWA_L distribution proposed in Davis and Strom (2008), and is presented in SC&A (2009) as a statistically credible alternative to the methods that were presented in Morris (2009). The SC&A approach seeks to account for the sources of variability and uncertainty in the raw data that were identified in Davis and Strom (2008), as summarized in Findings 1–6, 8, and 18 from SC&A (2009). Overall, SC&A believes that this method is conceptually consistent with Davis and Strom (2008).

6.2 Mallinckrodt Chemical Works Site Profile Review

SC&A's review of ORAUT-TKBS-0005 (Rev. 01), *Draft Preliminary Review (Partial) of the Mallinckrodt Site Profile Revision 1 (Effective Date March 10, 2005)* (SC&A 2005), raises several concerns regarding the use of time-weighted averages for assigning intakes of airborne uranium dust. Those concerns are summarized in Finding 5.5 and are reproduced below:

- *The TBD's use of time-weighted averages to quantify uranium dust inhalation dose does not take into account a number of variables, such as variation of the air concentration experienced by individual workers from the average, high episodic dust concentrations, the representativeness of measurements being taken over short periods of time, and uncertainties about job categories. The last problem would disproportionately affect survivor claimants.*
- *Time-weighted averages as presented in Rev. 00 cannot be used to reliably estimate anything other than minimum doses.*
- *Additional raw data confirmation, determination of uncertainties, and use of the upper 95th percentile values, estimated by sampling the various locations, are needed in order to provide a more claimant-favorable dose reconstruction.*

SC&A (2005) makes the following observation regarding Rev. 01 of the TBD:

> *Rev. 01 does not contain any analysis or indication that NIOSH has examined the raw data and evaluated the uncertainties so as to develop a claimant-favorable approach to estimating time-weighted averages. This is necessary in view of the small number of measurements that were made at each station.*

In order to illustrate the importance of uncertainty in the raw AAC data, SC&A was able to obtain the data for the job title of "[[redacted]]" and evaluated it for the tasks "mixing and charging," the two tasks with the highest exposure potential. BZ samples were collected for these operations, which were done 12 times per shift, with the time estimate for the 2 operations being 1.5 minutes and 5 minutes, for total times of 18 and 60 minutes, respectively, as illustrated in Table 5 (from SC&A 2005). Note that uncertainties in the time for each operation were not indicated, and are therefore ignored in this computation (Finding #1). Note also that the original time-weighted average contains a typographical error in one value, indicating the need for checking the original calculations (Finding #3).

Table 5. Time-Weighted Data for [[redacted]], Plant [[redacted]], September and October 1948

[From SC&A (2005)]

Operation	Total min.	Avg dpm/m^3	Time-integrated Avg dpm-min/m^3	# Samples	Range dpm/m^3
Mixing	**18**	**3.53E+04**	**6.35E+05**	**3**	**12,000 to 62,600**
Charging	**60**	**4.97E+03**	**2.98E+05**	**3**	**1,920 to 6,680**
Gen. air during operation	102	2.70E+03	2.75E+05	2	1,605 to 3,790
Gen. air when not operating	235	1.10E+03	2.59E+05	3	712 to 1,720
Gen. air, locker	35	6.10E+01	2.14E+03	4	39 to 110
Gen. air, lunch	45	2.62E+02	1.18E+04	2	262 to 272
Total	495		1.48E+06		
Time-weighted Avg.		2.99E+03			

As stated in SC&A 2005, it is clear from the ranges reported in the far right column of Table 5 that for each of the tasks/areas that make significant contributions to the total time-integrated concentration over the workday, there are significant uncertainties. For instance, the empirical lognormal 95th percentile value for the largest time-integrated item, mixing, is about 2 million dpm-min/m^3 based on the 95th percentile value of the air concentration estimated from the three data points.[2] This is about 3.2 times larger than the value of 6.35×10^5 dpm-min/m^3 derived from the average. This one uncertainty alone would increase the annual intake estimate by almost a factor of two. This estimate ignores the uncertainty in the variance due to the small number of measurements, as well as the fact that a worker would perform the operation many times. These two factors pull the 95th percentile estimate of an individual worker's exposure in opposite directions.

[2] The three measurements are 1.2×10^4, 3.12×10^4 and 6.26×10^4 dpm/m^3. The average of the natural logarithms is 10.26 and the estimate of the standard deviation is 0.829. This yields a 95th percentile value for air concentration of 1.12×10^5 dpm/m^3. Hence, the time integrated value = 18*112,000 = 2.02×10^6 dpm-min/m^3.

SC&A demonstrated a method to address both the small number of measurements and task repetition by using the Student's t distribution to estimate the 95th percentile of the *average* of the task AAC distribution (still assuming the measurements themselves are lognormally distributed). **This method could provide a claimant-favorable value for workers repeating the same operation in the same way, all other things being equal**. The estimate of the 95th percentile value of the average of the natural logarithms of the "mixing" AAC measurements is about 116,000 dpm/m^3, which is about 3.3 times the average value of the three measurements. The overall integrated exposure (95th percentile) goes up by a factor of about two as a result of the uncertainty in air concentration in this one operation alone.[3]

SC&A (2005) notes that the uncertainty from the other operations must also be taken into account and is expected to vary considerably. For example, the effect of the uncertainty in the lunchroom measurements on the time-integrated exposure will be relatively small, since the two measurements are close together and the total time-integrated value is low relative to the other operations. By contrast, the effect of the uncertainty in the general air concentration during operations will be considerable, because (1) there were only two measurements, (2) the spread between the measurements was large, and (3) the total time for the operation per day is large (102 minutes per day as opposed to 18 minutes per day for mixing). The 95th percentile value for the average air concentration at this station, using the t statistic (which is 6.314 in the case of 2 measurements and a 5% tail) is about 37,000 dpm/m^3, which is nearly 14 times the arithmetic average. As a result the uncertainty in this factor (air concentration for general air during operation) raises the total integrated exposure by a factor of about 3.4.[4]

The uncertainties in air concentration during various operations will have to be combined by an appropriate statistical method of propagation of errors, in order to develop an overall 95th percentile value for the time-weighted job exposure.[5] It is clear that in this example, the result would be several times greater than the time-weighted average value used by NIOSH. The effect in other cases will be different, depending on the number of measurements and the spread in the measurements. In cases where there is only one measurement of air concentration, a calculation of uncertainties is not possible for that task, since at least two measurements are needed to estimate a variance.

Given the above issues, SC&A re-affirms that only minimum doses can be estimated based on the time-weighted averages in the TBD. Rather, an approach that takes into account the

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[3] The average is computed by the expression $\hat{y} = \mu + t*s/\sqrt{n}$, where $\hat{y}$ is the estimate of the average for the specified percentile, μ is the average, t is the t distribution statistic for the given number of measurements and percentile value, s is the estimate of the SD, and n is the number of measurements. The t statistic for 3 measurements (2 degrees of freedom) and a 5% tail is 2.92. The average of the logarithms of the 3 measurements for the mixing operation is 10.26 and the SD is 0.829. Therefore, the 95th percentile estimate of the mean is = 10.26 + 2.92*0.829/√3 = 11.66. The corresponding value for the 95th percentile value of the average of the measurements = $e^{11.66}$ = 116,000 dpm/m^3, where e is the base of natural logarithms. All values are rounded. Note that the 95th percent upper confidence bound, which means a 2.5% tail on either side, would provide a higher estimate.

[4] The computation is done by using μ= 7.81, t= 6.314, s = 0.6076, and n = 2 in $\hat{y} = \mu + t*s/\sqrt{n}$, which yields $\hat{y}$ = 10.52, and the value for the air concentration of $e^{10.52} \approx$ 37,000 dpm/m^3.

[5] In Crystal Ball, the t random variable can be simulated by drawing an SD from a gamma distribution, then generating a normal random variable using the random SD. A word of warning though; when the degrees of freedom (dof) of the t distribution is 2 or less, the variance of the simulated values may be infinite (i.e., not defined). When dof is 1 or less, the mean is not defined. Therefore, the distribution must be artificially truncated.

sparseness of the data and the uncertainties that that creates for individual dose estimation is necessary to address the issue.

Finding #10: The approach outlined above is conceptually consistent with Davis and Strom (2008), in that it seeks to account for the sources of variability and uncertainty in the raw data by generating probability distributions for each task and combining them in a statistically valid way to arrive at distributions of job-specific weighted exposure. In addition, SC&A 2005 identified the problem of human error and the need to validate the raw data prior to use. This method, however, goes beyond the methods of Davis and Strom (2008), in that it seeks to account for the effects of task repetition by individual workers over time, which tends to narrow the uncertainty distribution.

7.0 SUMMARY OF FINDINGS AND OBSERVATIONS

7.1 Davis and Strom (2008)

Observation #1: SC&A notes that the fifth item in the list of factors contributing to variability in the data, "whether or not the sample represents the actual exposure experienced by the worker," is not a source of variability in the AAC data, but is an uncertainty in assessing worker exposure based on the data.

Observation #2: It is noteworthy that the airborne dust reports (DWE reports) examined by SC&A in support of the review of Morris (2009) for its applicability in the reconstruction of Th-232 intakes did not contain the raw data (SC&A 2009). Those reports were prepared for FMPC by National Lead of Ohio (NLO). This aspect of the study is very important, because the issue of availability of the raw data for use in assessing uncertainty in DWEs has been an ongoing topic of discussion for both Mallinckrodt and Fernald (see Finding #5, SC&A 2009).

Finding #1: The formulations for DWA_D and DWA_L treat $T_{S,i}$, the time required to complete task i, as a constant. Given that these are, in fact, average times to complete a task, they have associated variability (among workers) that should be addressed in generating uncertainty distributions of DWE. In the 2005 review of the Mallinckrodt report, SC&A noted that these uncertainties could be significant in high dust, short-duration operations that dominate time-integrated exposure.

Finding #2: The histograms in Figure 1 call into question the assumption of log-normality for the task AAC data. If the source data were lognormally distributed, as suggested by the authors and advocated in citations quoted in the literature review, one would expect that a DWE distribution constructed from those data would, in most cases, appear lognormal (as was true for DWA_L, which was based on lognormal fits to the AAC data).

Finding #3: The impact of blunders on calculated air concentration values (AAC) was unexpected and in some cases significant. SC&A believes that this is a problem, even if it happened in only a few cases, and underscores the critical importance of validated source data in constructing uncertainty distributions for DWE. Note that this issue was raised in the 2005 SC&A review of the Mallinckrodt TBD.

7.2 Morris (2010)

Finding #4: Morris (2010) has not demonstrated that the data analyzed in Davis and Strom (2008) constitute a reasonable surrogate for bounding the Fernald DWEs during the proposed SEC period. SC&A believes that NIOSH should determine the extent of DWE source data availability for Fernald and perform an uncertainty analysis on those data to ascertain if a GSD of 5 is sufficiently bounding.

Finding #5: Morris (2010) has not investigated the issue of blunders as a significant source of error in Fernald DWE source data. SC&A believes that NIOSH should determine the frequency and magnitude of blunders in their source data. If significant blunders are identified, their influence should be taken into account in uncertainty metrics (e.g., GSD).

Finding #6: The use of the upper 95th percentile of the air sampling data for a facility when time-weighted average data are not available probably does not meet the plausibility requirement for DR under EEOICPA. SC&A finds it perplexing that NIOSH suggests using unweighted air sampling data, particularly when time-weighted data from other years or from another plant are available.

Finding #7: It is incumbent on NIOSH to update the thorium timeline and locate and make available all AAC data that may be related to thorium exposure. Reliance on the dose reconstructor to search the SRDB for such information if thorium exposure is suspected places an undue burden on the dose reconstructor and is likely to result in inconsistencies.

7.3 Monticello Uranium Mill DR Audit

Finding #8: It appears that NIOSH has applied the methods described in Morris (2009) in assigning the intake to this EE as a percentile of the facility DWE based on job category. This approach is not consistent with Davis and Strom (2008) and does not appear to be a statistically valid method of using DWE data to estimate intake.

7.4 SC&A Methods

7.4.1 FMPC

Finding #9: The method outlined above to generate distributions of job DWEs from lognormal fits to the task AAC data is practically identical to the DWA_L distribution proposed in Davis and Strom (2008), and is presented in SC&A (2009) as a statistically credible alternative to the methods that were presented in Morris (2009). The SC&A approach seeks to account for the sources of variability and uncertainty in the raw data that were identified in Davis and Strom (2008), as summarized in Findings 1–6, 8, and 18 from SC&A (2009). Overall, SC&A believes that this method is conceptually consistent with Davis and Strom (2008).

7.4.2 Mallinckrodt

Finding #10: The approach outlined above is conceptually consistent with Davis and Strom (2008), in that it seeks to account for the sources of variability and uncertainty in the raw data by generating probability distributions for each task and combining them in a statistically valid way to arrive at distributions of job-specific weighted exposure. In addition, SC&A (2005) identified the problem of human error and the need to validate the raw data prior to use. This method, however, goes beyond the methods of Davis and Strom (2008), in that it seeks to account for the effects of task repetition by individual workers over time, which tends to narrow the uncertainty distribution.

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