Draft

ADVISORY BOARD ON
RADIATION AND WORKER HEALTH

National Institute for Occupational Safety and Health

SUPPLEMENTARY COMMENTS ON REVISION 01 OF BATTELLE-TBD-6000

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ABBREVIATIONS AND ACRONYMS

ABRWH	Advisory Board on Radiation and Worker Health
ACGIH	American Conference of Governmental Industrial Hygienists
AEC	Atomic Energy Commission
AM	arithmetic mean
AMAD	activity median aerodynamic diameter
atm	atmosphere
AWE	Atomic Weapons Employer
BZ	breathing zone
C	surface concentration
CEDE	committed effective dose equivalent
CFR	Code of Federal Regulations
DCAS	Division of Compensation Analysis and Support
DOL	Department of Labor
dpm/d	disintegrations per minute per day
dpm/m^2	disintegrations per minute per square meter
dpm/m^3	disintegrations per minute per cubic meter
DWA	daily weighted average
g/m^3	gram per cubic meter
$g\text{-}U/m^3$	gram of uranium per cubic meter
GM	geometric mean
GSD	geometric standard deviation
ICRP	International Commission on Radiological Protection
IMBA	Integrated Modules for Bioassay Analysis
IREP	Interactive RadioEpidemiological Program
K	Kelvin (degrees)
kg/m^3	kilogram per cubic meter
m	meter
MED	Manhattan Engineering District
$mg\ U/ft^2$	milligram of uranium per square foot
mrem	millirem
NIOSH	National Institute for Occupational Safety and Health

µg/cc	microgram per cubic centimeter
µg/cm^3	microgram per cubic meter
µg-hr/cc	microgram per hour per cubic centimeter
µg/m^2	microgram per square meter
µg/m^3	microgram per cubic meter
µm	micrometer
MMD	mass median diameters
m/s	meters per second
NRC	Nuclear Regulatory Commission
OCAS	Office of Compensation Analysis and Support
ORAUT	Oak Ridge Associated Universities Team
POC	probability of causation
rem	Roentgen equivalent man
SC&A	S. Cohen and Associates (SC&A, Inc.)
SEC	Special Exposure Cohort
SRDB	Site Research Data Base
TBD	Technical Basis Document
TLV-STEL	Threshold Limit Value-Short-Term Exposure Limit
TWA	time-weighted average
U_3O_8	uranium oxide

1.0 INTRODUCTION

SC&A was recently tasked with reviewing several dose reconstructions, site profiles, and a petition evaluation report that relied on Battelle-TBD-6000 to provide the bases for completed dose reconstructions or possible future dose reconstructions (e.g., Joslyn). These reviews have provided additional insight into how TBD-6000 is used in practice and revealed some potential issues associated with using that document that were not apparent when the document was originally reviewed and proposed changes were discussed. SC&A had previously reviewed TBD-6000 (SC&A 2007) and based on our findings, the document was revised by NIOSH in 2011 (Battelle 2011). These supplementary comments address four issues:

- The suitability of using a terminal settling velocity of 0.00075 m/s and the time required to reach an equilibrium surface concentration
- The attenuation rate for surface contamination
- A comparison of site-specific air concentrations with generic data used in TBD-6000
- Operations not explicitly covered in TBD-6000

2.0 SETTLING VELOCITY AND TIME FOR EQUILIBRIUM DEPOSITION

Based on its initial review of TBD-6000, SC&A recommended that NIOSH consider the surface contamination levels presented in a report by Adley et al. (1952) and in the Simonds Saw and Steel TBD (ORAUT 2011) in addition to the data from Harris and Kingsley 1959, upon which exposures in TBD-6000 were constructed. At that time, SC&A questioned the appropriateness of using a 0.00075 m/s settling rate, as well as the use of 7 days deposition to achieve an equilibrium surface concentration. The velocity of 0.00075 m/s is the theoretical terminal velocity based on Stokes Law settling for 5 µm AMAD spherical particles.

In response to SC&A's concerns, NIOSH issued white papers showing that use of a velocity of 0.00075 m/s was claimant favorable based on an analysis of data in Adley et al. 1952, and that an equilibrium surface concentration could be achieved in 27 days (Allen 2009a, Allen 2009b). The NIOSH white papers were discussed at a meeting of the TBD-6000 Work Group on October 14, 2009, and SC&A indicated general agreement with the NIOSH approach, although SC&A did not review in detail the calculations supporting the NIOSH conclusions at that time.

In 2011, TBD-6000 was revised to reflect these additional data sources, as described in Section 3.4.2 (Exposures from Contaminated Surfaces) of Battelle-TBD-6000 (Rev. 01):

> *When measured floor contamination rates are not available the contamination on the floor may be estimated from measured air concentrations. The level of surface contamination is determined by first calculating a terminal settling velocity for 5-µm activity mean aerodynamic diameter[1] (AMAD) particles. The*

[1] We believe that this should read "activity median aerodynamic diameter."

calculated terminal settling velocity was 0.00075 meters per second. Next the amount of time necessary for the surface contamination to build up to an equilibrium value is needed. In order to determine this time, surface contamination values from Adley (Adley, Gill and Scott, 1952) and from Simonds Saw and Steel (AEC 1949) were used. Also, the inhalation values from Table 7.8 were converted to airborne activity and used in this analysis. The geometric mean of the Table 7.8 airborne activity was compared to the geometric mean of the Adley surface contamination values. It was determined that with a settling rate of 0.00075 m/s, a 27 days settling period was necessary to match the Adley surface contamination values. The analysis indicated a settling time of 15 days was necessary to match the Simonds Saw and Steel contamination values. Both values are within a factor of two indicating reasonable agreement. Based on this analysis, the higher value was rounded up to 30 days and used in this document. Using a 30 day deposition time and a 0.00075 m/s settling rate, a deposition factor of 1944 meters can be calculated. The floor contamination level is then estimated as Floor Concentration (dpm/m^2) = Air Concentration (dpm/m^3) × 1944 meters.

One of the key experiments reported in Adley[2] involves a number of plates placed around the Hanford Melt Plant Building upon which contamination was allowed to accumulate over several months. The data were summarized by Adley in Table XIII (see Table 1 below) as settling rates (mg U/ft^2 per day). However, the measured quantity on the plates would have been in units of mg U/ft^2. Adley divided the measured quantities by the total days of exposure (either 158 days for winter samples or 117 days for spring samples) to obtain a settling rate. This approach assumes that the settling rate was a linear function of time. NIOSH used these settling rates and the estimated air concentration from Table IX of Adley to calculate settling velocities. The calculated settling velocities based on each plate were, with one exception, lower than the TBD-6000 default assumption of a 0.00075 m/s terminal settling velocity for 5 µm AMAD particles. On this basis, NIOSH concluded that 0.00075 m/s was reasonable and claimant favorable.

SC&A's original concern about the use of the terminal settling velocity of 0.00075 m/s was not just about the validity of the numerical value of the settling velocity, but also whether the use of an air concentration coupled with the terminal settling velocity and a settling time resulted in a surface concentration that reflected all the processes that could contribute to the quantity of material that was present on the shop floor. For example, was part of the material on the floor large flakes that quickly dropped out of the air and were not captured by assuming Stoke's Law settling of small particles? Such particles could be ground up by foot or vehicular traffic, be resuspended, and moved throughout the work area. However, the Melt Plant Building main bay plate samples in the west end of the bay showed little dependency on sampling height above the floor (Adley et al. 1952, Table XIII). According to the authors, "In this area the turbulence arising from daily activity in the plant apparently results in more even settling of dust at different heights." In the east end of the main bay, on the other hand, some gradation in deposition with height was observed. Comparing the <u>average</u> settling rates for the east end and west end winter samples shows only about a 6% difference. Consequently, we believe that spatial differences

[2] Adley et al. 1952 will also be referred to as simply Adley in this report.

within the main bay related to sample height had little to no effect on the buildup of uranium on surfaces and can be ignored.

Table 1. Settling Rates of Oxide Dust at Various Sites throughout the Melt Plant Building

General Location	Sampling Sites	Settling Rates (mg Uranium/ft^2 per day)	
		Winter Samples	Spring Samples
Main Bay – East End	On floor in storage bay near extrusion line	2.7	*
	Atop muffle furnace at middle of north wall	1.16	3.25
	South wall on motor switchbox	1.06	1.99
	Atop rotary furnace – southeast edge	0.70	0.91
	Northeast corner of autoclave crane platform	0.69	0.67
Main Bay – West End	Atop cabinet by door at middle of north wall	1.01	*
	Atop instrument panel for oxidizing furnace	1.11	*
	On roof of shop	1.01	1.47
	On roof of vacuum pump room	1.64	2.75
Furnace Room and Vacuum Pump Room	On screen above bus bars	0.22	0.89
Burnout Room	Front edge of oven – on top	5.72	*
Shop (Saw Room)	Shelf behind lathe part of time; on table opposite lathe remainder of time	1.14	0.88
Office and Toilet Area	Atop file cabinet at east wall of office	0.28	0.21

*Note: These samples lost by breakage of container, blowing away, or other accidental causes.
Source: Adley et al. 1952, Table XIII

In reviewing the NIOSH approach, SC&A also developed concerns about the way the average air concentration was calculated. NIOSH took the weighted daily exposures for the nine jobs listed in Adley Table IX and converted those values to an average air concentration for each job assuming an 8-hour day. NIOSH determined the geometric mean (GM) for the nine jobs and used this value as the air concentration. It is not apparent that this approach properly represents the air concentration that would correlate with the surface deposition since it is related to a person's location at various times during the work-day and not the air concentration at a particular location. To circumvent this problem, we used an average concentration of 1,400 µg/m^3 for the main bay area of the Melt Plant Building. This value is based on an observation in Adley that, if the amount of uranium deposited in a day were uniformly distributed throughout the air in the Melt Plant Building, the air concentration would be 1,400 µg/m^3. Specifically, Adley states, "If the 20 grams of U_3O_8 that settles out daily were dispersed evenly throughout the 500,000 cubic feet of the building, the resulting concentration of dust would be 28 times the maximum permissible level of 5×10^{-5} µg/cc."

Using this average air concentration, effective or net settling velocities were calculated using the settling rates from Adley Table XIII. The estimated settling velocity based on all plates in the main bay taken individually and averaged together are summarized in Table 2. The settling velocities in Table BB are subject to interpretation as to what the Adley expression "settles out daily" means. The settling velocities in Table 2 assume that the average air concentration of 1,400 µg/m^3 persists for 24 hours. Since the Melt Plant Building apparently operated on a single shift basis, the 20 grams that settle out daily could be that material which is generated during an

8-hour shift. Assuming a building height of 12 m (Gerber 1996), it would require 4.4 hours for a 5 µm AMAD particle to fall from the roof to the floor. All particles would have settled out in 12.4 hours. Thus, the average daily air concentration would be 1,150 µg/m^3 (1,400 × 8/12.4 + 700 × 4.4/12.4). With this interpretation, settling velocities in Table 2 would increase by a factor of 1.2.

Table 2. Estimated Settling Velocities in Main Bay Using Adley Table XIII Settling Rates and Average Air Concentration of 1,400 µg/m^3

Location	Settling Rate mgU/ft^2/day	Settling Rate µg/m^2/day	Measured Surf. Concentration µg/m^2	Air Concentration µg/m^3	Settling Velocity m/s
Main Bay – winter	1.23	13,296	2,100,768	1,400	1.10E-04
Main Bay – spring	1.84	19,872	2,325,024	1,400	1.64E-04
Autoclave platform – winter	0.69	7,452	1,177,416	1,400	6.16E-05
Autoclave platform – spring	0.67	7,236	846,612	1,400	5.98E-05
Rod straightener – winter	1.06	11,448	1,808,784	1,400	9.46E-05
Rod straightener – spring	1.99	21,492	2,514,564	1,400	1.78E-04
Storage bay – winter	2.7	29,160	4,607,280	1,400	2.41E-04
Oxide burning – winter	1.11	11,988	1,894,104	1,400	9.91E-05
Shop roof – winter	1.01	10,908	1,723,464	1,400	9.02E-05
Shop roof – spring	1.47	15,876	1,857,492	1,400	1.31E-04
Vac pump rm roof – winter	1.64	17,712	2,798,496	1,400	1.46E-04
Vac pump rm roof – spring	2.75	29,700	3,474,900	1,400	2.46E-04
North wall cabinet – winter	1.01	10,908	1,723,464	1,400	9.02E-05
Atop rotary furnace – winter	0.7	7,560	1,194,480	1,400	6.25E-05
Atop rotary furnace – spring	0.91	9,828	1,149,876	1,400	8.13E-05
Atop muffle furnace – winter	1.16	12,528	1,979,424	1,400	1.04E-04
Atop muffle furnace – spring	3.25	35,100	4,106,700	1,400	2.90E-04

All of the settling velocities are less than the terminal settling velocity for 5µm AMAD particles of 0.00075 m/s. The implications of this analysis are that the results do not change substantively whether one uses the uranium concentration in the breathing zone (BZ) or the overall average airborne uranium concentration for the purpose of deriving the deposition velocity. Possible reasons for these differences between the terminal settling velocity and the estimated settling velocities will be discussed subsequently.

Using air concentrations based on daily weighted average (DWA) exposures, NIOSH also showed that, with one exception, the estimated settling velocities were less than the terminal settling velocity for 5µ AMAD particles. While we believe the approach taken here to estimate air concentrations is more robust, it does not change the conclusion reached by NIOSH that use of a terminal settling velocity of 0.00075 m/s is claimant favorable.

There are several possible explanations as to why the estimated settling velocities (Table 2) are less than the terminal settling velocity for 5 µm AMAD particles. Possibilities include:

- Corrections to the terminal settling velocity are needed to account for particle slip and lack of sphericity

- The particle diameters were less than 5 µm AMAD
- The air concentration was lower than the estimated value of 1,400 µm/m^3 used here
- The measured settling rate is a net rate between deposition and removal

We will examine each of these points to see to what extent the differences can be explained.

Corrections to Terminal Settling Velocity

The terminal settling velocity in air for a 1.7 µm diameter particle of uranium oxide (U_3O_8) in the Stoke's Law flow regime is given by the equation (Whicker 2007):

$$V_t = D_p^2 \times g \times \rho_p / 18\mu$$

where V_t – terminal settling velocity m/s
D_p – physical particle diameter – 1.7E-06 m
g – gravity acceleration – 9.81 m/s
ρ_p – U_3O_8 particle density – 8380 kg/m^3
μ – viscosity of air – 1.8E-05 kg/m-s

For this example, V_t = 7.33E-04 m/s. This equation applies to rigid spherical particles. For particle physical diameters of less than about 20 µm, Stoke's Law reasonably reflects the effect of the drag force exerted by the air on a particle falling under the influence of gravity.

Alternatively, if we assume 5 µm AMAD particles (density – 1,000 kg/m^3), then V_t = 7.57E-04 m/s, which is essentially the same as 7.5 E-04 m/s used by NIOSH in its modeling and is essentially the same as a particle with a 1.7 µm physical diameter.

For small diameter particles (less than about 10 µm), the particles may "slip" between air molecules and not be retarded by the drag force of the air. The slip correction factor is given by the following equation (Flagan and Seinfeld 1988):

$$C_c = 1 + \lambda/D_p \, [2.514 + 0.8\exp(-0.55D_p/\lambda)]$$

where C_c – slip correction factor
λ – mean free path of air molecules - 0.0651 µm at 1 atm and 298 K

For 1.7 µm physical diameter particles, C_c is 1.098; this correction would increase the terminal velocity to 0.00080 m/s.

In addition to the slip correction factor, it is appropriate to consider a correction for the fact that the particles are not perfect spheres. It is proposed in ICRP 1994 that a factor of 1.5 be added to the denominator of the equation for the terminal settling velocity. This would reduce the terminal velocity for 5 µm AMAD particles to 0.00052 m/s. Thus, the use in TBD-6000 of a terminal velocity of 0.00075 m/s is conservative since it overstates the amount of activity deposited on a surface.

Using a terminal velocity of 0.00052 m/s and an air concentration of 1,400 µg/m^3 results in an average calculated surface concentration of 9.94E06 µg/m^2 for the main bay (winter), which is 4.8 times larger than the average measured surface concentration for the main bay (winter) using the settling rate shown in Table BB. As noted above, the sphericity correction factor of 1.5 was taken from ICRP 1994. This factor is characterized as the reference or typical value with reported values ranging from 1.1 to 1.9. Increasing this factor to the maximum value of 1.9 would reduce the terminal velocity to 0.00041 m/s and the calculated surface concentration to 7.85E+06 µg/m^2—a result that is still well above the measured value. Thus, it is not possible that adjustments to the terminal velocity for slip and sphericity can explain most of the difference between the measured and calculated values.

Smaller Particles

It is also possible that the terminal velocity was lower because the particles had an AMAD of less than 5 µm. Adley et al. 1952 provides measurements in Table XI documenting mass median diameters (MMD) from 26 sets of particle measurements. Mass median diameters (MMDs) ranged from 0.7 to 3.4 µm with a median value for the 26 sets of 1.4 µm and an average value of 1.7 µm. Relevant data are summarized in Table 3.

Table 3. Terminal Settling Velocities Using Particle Size Measurements from Adley, Table XI

Sample	Particle Size (µmeters)
CI-26	0.7
CI-3	0.9
CI-28	1
CI-4	1.1
CI-8	1.1
CI-9	1.1
CI-12	1.1
CI-5	1.2
CI-7	1.2

Sample	Particle Size (µmeters)
CI-15	1.3
CI-13	1.3
CI-6	1.4
CI-21	1.4
CI-2	1.4
CI-18	1.7
CI-27	1.9
CI-1	1.9
CI-10	2

Sample	Particle Size (µmeters)
CI-17	2.2
CI-24	2.2
CI-16	2.3
CI-19	2.5
C-14	2.7
CI-22	3
CI-23	3.2
CI-25	3.4

Since the average physical particle diameter of 1.7 µm is basically the same as a 5-µm AMAD particle, it does not appear that the differences between measured and calculated values are attributable to reduced velocities associated with a particle size of less than the assumed 5 µm AMAD when averaged over time and space.

Lower Air Concentration

For the calculations presented here, we used an average air concentration of 1,400 µg/m^3 based on an estimate provided in Adley. Adley also provides data on all the individual measurements in Tables II through VII. The average of all samples in the main bay is about 9,500 µg/m^3 and the estimate of the standard error of the mean is 3,480 µg/m^3. Assuming the standard error of mean has an approximate normal distribution, there is a 1% probability that the mean could be less than 1,400 µg/m^3. On this basis, it does not appear that the lower observed uranium accumulation values observed in the plates, as compared to the levels predicted by the Stokes

law, are due to the possibility that the average airborne dust loading of uranium used in the Adley calculations was underestimated.

Measured Settling Rate is Net of Deposition and Removal Processes

Plates used to measure the settling rates in Adley were exposed for several months of conditions, which could alter the amount deposited on the plates. For example, air drafts could remove deposited material resulting in equilibrium between deposition and removal mechanisms where equilibrium was reached prior to the termination of the plate experiments. The time to reach equilibrium can be approximated by:

Measured surface concentration (mg U/m^2) ÷ air concentration (µg/m^3) ÷ settling velocity (m/s)

The measured surface concentration is taken from Table 2 and the settling velocity is the terminal settling velocity for 5 µm AMAD particle adjusted for slip and lack of sphericity (i.e., 0.00052 m/s). The results, which are summarized in Table 4, suggest that some removal mechanisms were active, offsetting the deposition on the plates. Using a velocity of 0.00052 m/s for 5 µm AMAD particles (velocity adjusted for slip and sphericity) and an air concentration 1,400 µg/m^3, the time to reach equilibrium based on main bay averages is 33 to 37 days. This value is in close agreement with the 30 days assumed in Revision 01 of TBD-6000. However, it should be noted that in some areas within the Main Bay, times of up to 73 days were required to reach equilibrium. The 95th percentile of the 15 Main Bay samples is 69 days to reach equilibrium. The estimate for the storage bay is 73 days (i.e., the 97th percentile). Based on these data, the claimant-favorable approach would be to use a value of 70 days to achieve an equilibrium surface concentration, where the rate of deposition equals the rate of removal. However, as noted previously in the discussion of Table 2, an alternative, and perhaps more likely interpretation of the data in Adley is that the dust settled in 12.4 hrs. Under this interpretation, the time to reach equilibrium would increase by 20%, suggesting an upper bound of 84 days.

Table 4. Time to Reach Equilibrium Surface Concentration

(V_t = 0.00052 m/s, Air Concentration = 1,400 µg/m^3)

Location	Days to Equilibrium
Main Bay – winter	33
Main Bay – spring	37
Autoclave platform – winter	19
Autoclave platform – spring	13
Rod straightener – winter	29
Rod straightener – spring	40
Storage bay – winter	73
Oxide burning – winter	30
Shop roof – winter	27
Shop roof – spring	30
Vac pump room roof – winter	44
Vac pump room roof – spring	55
North wall cabinet – winter	27
Atop rotary furnace – winter	19
Atop rotary furnace – spring	18

Table 4. Time to Reach Equilibrium Surface Concentration

(V_t = 0.00052 m/s, Air Concentration = 1,400 µg/m^3)

Location	Days to Equilibrium
Atop muffle furnace – winter	31
Atop muffle furnace – spring	65

3.0 REMOVAL RATE

The change in surface concentration (C) over time can be expressed by the equation:

$$dC/dt = R-\lambda C$$

where R is the deposition rate and λ is the removal rate. The average surface concentration (C) from all of the Main Bay Adley data is 2.18E+06 µg/m^2. The deposition rate (R) is the air concentration (µg/m^3) times the average settling velocity (m/s) or 0.73 µg/m^2/s (1,400 µg/m^3 × 0.00052 m/s). At equilibrium, the removal constant λ is R/C or 3.3E-07/s or 0.028/day.

It is noteworthy that the removal rate of 0.035/day is considerably higher than the removal rate of 0.00067/day developed in ORAUT-OTIB-0070 (ORAUT 2012) for the residual period. However, this difference is not surprising, since the rates in OTIB-0070 were based on assuming exponential decay between a starting point and an end point based on a measurement taken years afterward with no knowledge of whether the end point could actually have occurred much earlier. The value of 0.00067/day for the removal rate was the average of rates from four sites (Blockson, Dow Chemical, Simonds Saw and Steel, and General Atomic). In the case of Dow, for example, the duration of the residual period was 45 years. It is certainly possible that natural attenuation processes had reduced the residual contamination to the end point value in significantly less than 45 years. The calculations presented here support the position that the OTIB-0070 approach regarding time to reach equilibrium is claimant favorable.

4.0 COMPARISON OF SITE-SPECIFIC AIR CONCENTRATIONS WITH GENERIC DATA USED IN TBD-6000

This section compares generic air concentrations in the TBD-6000 (Battelle 2011) to the site-specific time-weighted air exposure values for the Hanford Melt Plant Building (Adley et al. 1952), Simonds Saw and Steel (ORAUT 2011), Joslyn (NIOSH 2012), and Bethlehem Steel (NIOSH 2010). Section 4.1explains the TBD-6000 values and how they were determined.

On several occasions in the past, SC&A has raised questions about the implementation of TBD-6000 in dose reconstruction. The questions did not involve the underlying dataset from Harris and Kingsley (1959) from which the data in TBD-6000 were derived, but rather how the data were used in dose reconstruction. The default NIOSH approach for selecting input to calculate the probability of causation (POC) with IREP has been to use a lognormal distribution with the GM taken from the appropriate table in TBD-6000 and assume a geometric standard deviation (GSD) of 5. NIOSH has argued that, by selecting conservative data from Harris and Kingsley, assuming a GSD of 5, choosing from several tasks the highest air concentration for a particular operation and using the 99th percentile for calculating the POC, the approach is claimant

favorable. As the discussion that follows will show, use of the GM from TBD-6000 with a GSD of 5 as compared to constant high-end exposure values from specific sites results in comparable POCs and substantiates the plausibility of the NIOSH approach.

Theoretically, there could be situations (e.g., exposures are near the 95th percentile of an assumed lognormal distribution) where use of the full lognormal distribution might result in a slightly lower POC than would use of the 95th percentile dose as a constant input into IREP. However, the likelihood that a worker was continuously exposed to very high concentrations is low, and with either calculational approach, the POC would be well above 50% for lung cancers.

4.1 TBD-6000 VALUES

The following tables are from the TBD-6000 and contain the values used to compare daily weighted exposures for workers at Joslyn, Simonds, Adley, and Bethlehem with TBD-6000 values based on comparable job categories for workers.

Table 5. Air Sampling Data for Facilities Rolling Uranium Rods

Job Category	Short duration measured air concentrations (dpm/m^3)	Geometric Mean (dpm/m^3)
Furnace Operator	180	80.5
Roughing Roll Operator	1,620–13,700	4,710
Finishing Roll Operator	800–8,400	2,590
Cooling	1,470	657
Stamper	1,940	868
Drag Down Operator	730	327
Shear Man	1,500	671
Operator DWA	–	3,533
General Laborer DWA	–	651
Supervisor DWA	–	326
Clerical DWA	–	33

Source: Battelle 2011, Table 7.3

Table 6. Air Sampling Data for Facilities Forging Uranium

Job Category	DWA Measured air concentrations (dpm/m^3)	Geometric Mean (dpm/m^3)
Press forging – salt bath	1.7	0.8
Press forging – press	16	7.2
Press forging – quench tank	6.2	2.8
Hammer forging – front hammer operator, DWA	2,480	1,110
Hammer forging – backside hammer operator, DWA	2,610	1,170[a]
Hammer forging – furnace operator & helper, DWA	810	362
Operator, DWA	–	1,170
General Laborer, DWA	–	362
Supervisor, DWA	–	181
Clerical, DWA	–	18

a – Should be 715 dpm/m^3.
Source: Battelle 2011, Table 7.4

Table 7. Air Sampling Data for Facilities Machining Uranium

Job Category	DWA Measured air concentrations (dpm/m^3)	Geometric Mean (dpm/m^3)
Automatic lathe, DWA	200–300	245
Turret lathe, DWA	150	67
Facing, DWA	100	45
Cutoff, DWA	100	45
Milling, DWA	100	45
Slotting, DWA	100	45
Drill, DWA	20	9
Radius Cutting, DWA	100–300	173
Milling, DWA	40	18
Shaping, DWA	<10	4
Planning, DWA	<10	4
Surface Grinder, DWA	2000–5000	3160
Portable Grinder, DWA	400	179
Belt Sander, DWA	3000	134
Centerless Grinder, DWA	5000–6000	5480
Straightening, DWA	1500–1900	1690
Operator DWA	–	5480
General Laborer DWA	–	2740
Supervisor DWA	–	1370
Clerical DWA	–	137

Source: Battelle 2011, Table 7.5

Table 8. Air Sampling Data for Uranium Slug Production and Canning

Job Category	Short duration measured air concentrations (dpm/m^3)	Geometric Mean (dpm/m^3)
Stamping slug	590	264
Filing slug	440	197
Wire-brush cleaning die section	260	116
Cleaning end slugs	220	98
Cleaning die liners	220	98
Operator DWA	–	198[a]
General Laborer DWA	–	99

a – Should be 121 dpm/m^3

Source: Battelle 2011, Table 7.6

Table 9. Air Sampling Data for Uranium Scrap Recovery

Job Category	DWA Measured air concentrations (dpm/m^3)	Geometric Mean (dpm/m^3)
Straightening, DWA	1,500–1,900	1,690
Drawing, DWA	Nil	4
Swaging, DWA	<10	4
Degreasing, DWA	260	116
Briquetting, DWA	250	112
Briquette discharge, DWA	600	268
Operator DWA	–	1,690
General Laborer DWA	–	845
Supervisor DWA	–	423
Clerical DWA	–	42

Source: Battelle 2011, Table 7.7

There are several generalized Job Categories listed in the tables above (Operator, General Laborer, Supervisor, and Clerical). The values associated with each of these generic job categories were determined by assessing the relevant, available data and using the "worst case" value to determine the Operator Job Category value. It is assumed that, on average, operators were exposed to this worst case value 75% of the time. In other words, the "worst case" value was multiplied by 0.75 to obtain the DWA for the Operator Job Category. For example, in Table 5, there are four types of operators (Furnace Operator, Roughing Roll Operator, Finishing Roll Operator, and Drag Down Operator). Of these operators, the Roughing Roll Operator has the highest GM exposure value (4,710 dpm/m^3). Therefore, this value is used to determine the generic Operator DWA for facilities rolling uranium rods. The GM air concentration of 4,710 dpm/m^3 is multiplied by 0.75 (the assumed fractional exposure time) to obtain a DWA of 3,533 dpm/m^3 as listed in the table. In the case of operations included in Tables 6, 7, and 8, the data were reported in the original source document (Harris and Kingsley 1959) as DWA values, so no further adjustment was required.

For entries in the above tables from TBD-6000, where a range of values was not reported, the single value measured air concentration was assumed to be the arithmetic mean (i.e., the expected value). The GM was calculated using the arithmetic mean and a GSD of 5. This can be done using the following equation from Table 2.2 in Strom 2007:

$$x = \exp(\mu + \sigma^2/2)$$

where x is the arithmetic mean, μ = ln GM, and σ = ln GSD.

In reviewing the data in the above tables from TBD-6000, it appears that some of the GM values are in error. Consider the General Laborer in Table 5. According to that report, the General Laborer DWA is based on the Stamper job category adjusted for 75% exposure (Stamper GM of 868 dpm/m^3 × 0.75 = 651 dpm/m^3). However, the Stamper arithmetic mean (AM) is 1,940 dpm/m^3. Applying the above equation, the calculated GM is 531 dpm/m^3, not 868 dpm/m^3, as shown in Table 5. This would also affect the generic supervisor and generic clerical worker, whose exposures are factored from the General Laborer. Another example is the forging operator in Table 6, whose DWA GM is listed as 1,170 dpm/m^3, but we calculate a DWA GM of

715 dpm/m^3. NIOSH needs to check the GM calculations in all tables to insure that the GMs are correct.

Arithmetic Mean

In the comparison tables below, the TBD-6000 values are expressed as the GM and the AM. We believe that the AM serves as a better comparison to the DWA sample data from the four sites. The AM can be determined if one knows the GM and the GSD. The default assumption in the TBD-6000 is that the GSD = 5. We are not suggesting that the AM be used as the basis for dose reconstruction, but rather that the DWA AM is the appropriate basis of comparison for the generic TBD-6000 values with DWAs reported for various specific sites.

4.2 SITE COMPARISONS

The following four sections compare the sample values found at particular sites to the values found in the TBD-6000.

4.2.1 Hanford Melt Plant Building

Data on uranium fabrication operations at the Hanford Melt Plant Building were taken from Adley et al. 1952 and are summarized in Table 10.

Table 10. Hanford Melt Plant Building vs. TBD-6000 Values

Hanford (Adley)*	DWA (dpm/m^3)	TBD-6000 Equivalent Description (TBD-6000 Table No.)	GM (dpm/m^3)	AM (dpm/m^3)	Is TBD-6000 Limiting?[a]
Furnace Operator	3,013	Scrap Recovery Operator (7.7)	1,690	6,171	Yes
Furnace Assistant	1,229	Scrap Recovery Operator (7.7)	1,690	6,171	Yes
Saw Room Operator	4,243	Machining Operator (7.5)	5,480	20,010	Yes
Oxide Operator	12,400	Scrap Recovery Operator (7.7)	1,690	6,171	No
Rod Handler	384	General Laborer (7.7)	845	3,085	Yes
Autoclave Operator	80	Slug Production Operator (7.6)	198	723	Yes
Rod Receiving-unloading	1080	General Laborer (7.3)	651	2,377	Yes
Rod Receiving-weighing	116	General Laborer (7.3)	651	2,377	Yes
Rod Receiving-stacking	456	General Laborer (7.3)	651	2,377	Yes
a – Based on comparison of DWA and AM. *The Adley et al. 1952 report provides nine time-weighted average air exposure values in Table IX. The values are presented in units of x10^{-5} µg-hrs/cc-day.					
Analysis: With the exception of the Oxide Operator, TBD-6000 is limiting for all Hanford (Adley) job descriptions.					

The only DWA that exceeds the TBD-6000 average is for the Oxide Operator whose exposure is at the 84th percentile of a lognormal distribution. However, as discussed in Adley, the Furnace Assistant, the Saw Room Operator, and Oxide Operator actually rotated jobs from day-to-day, so the adjusted DWA for each would be 5,957 dpm/m^3, a value below the TBD-6000 AM.

An observation from this table (and the tables that follow) is that in a majority of cases, the GM values in TBD-6000 are higher than the DWA values for the data at individual sites (such as in

Table 10 for the Hanford Melt Plant). However, even in the cases where the TBD-6000 GM is lower than the DWA (as is the case in Table 10 for the Oxide Operator), the use of a GSD of 5 on the GM as input to IREP results in a POC that is comparable to what one would derive if a fixed higher value were used. This occurs because the POC is derived at the 99th percentile level, and a GSD of 5 generally results in a very claimant-favorable POC, even though the actual DWA for the operator at the facility is higher than the TBD-6000 GM [and greater than the arithmetic mean (AM) for the Oxide Operator in Table 10].

To demonstrate this, we compared the POC for a hypothetical oxide operator whose 1-year intake in an IMBA/IREP simulation was based on a constant air concentration of 12,400 dpm/m^3 and in the other simulation was based on a GM of 1,690 dpm/m^3 and a GSD of 5. In both examples, the POCs for lung cancer were comparable, being 99.0% for the constant air concentration and 98.6% for the lognormal air concentration. Details are summarized in Attachment B.

4.3 SIMONDS STEEL AND SAW

Air samples were taken during natural uranium rolling operations at Simonds Saw and Steel on 15 dates between October 27, 1948, and January 21, 1953 (ORAUT 2011, Table 7). These highest air concentrations were observed during the initial sampling (October 27, 1948), so only those samples (AEC 1948) are included here for comparison with TBD-6000 in Table 11.

Table 11. Simonds Saw and Steel Natural Uranium Rolling vs. TBD-6000 Values

Simonds Saw and Steel TBD	DWA (dpm/m^3)	TBD-6000 Equivalent Description (TBD-6000 Table No.)	GM (dpm/m^3)	AM (dpm/m^3)	Is TBD-6000 Limiting?[a]
Foreman	1,760	Supervisor (7.3)	326	1,190	No
West side roller #1	1,620	Rolling Operator (7.3)	3,533	12,901	Yes
West side roller #2	797	Rolling Operator (7.3)	3,533	12,901	Yes
East side roller #1	13,700	Rolling Operator (7.3)	3,533	12,901	No
East side roller #2	8,394	Rolling Operator (7.3)	3,533	12,901	Yes
Pressure quencher	1,471	General Laborer (7.3)	651	2,377	Yes
Drag down operator	620	General Laborer (7.3)	651	2,377	Yes
Furnace man	527	General Laborer (7.3)	651	2,377	Yes
Rod stamper	1,944	General Laborer (7.3)	651	2,377	Yes
a – Based on comparison of DWA and AM.					
Analysis: TBD-6000 is limiting for all Simonds Saw and Steel job descriptions except for the Foreman and East Side Roller #1. These values are slightly higher than the DWA values for the arithmetic mean.					

Values were also reported for rolling enriched uranium (either 2.75 or 7.2% U-235) on a 10-in mill (ORAUT 2011, Table 12). The highest DWA (stranner, north side) was 9,001 dpm/m^3, a value less than the TBD-6000 DWA value of 12,901 dpm/m^3 for a rolling operator.

Limited uranium forging operations were also conducted at Simonds Saw and Steel. Air concentrations from two campaigns were reported in Tables 14 and 15 of ORAUT 2011 and are summarized here in Table 12. The highest average BZ value was 20,000 dpm/m^3 for a tong man on the east side of the forge. Using the TBD-6000 methodology, the DWA associated with this

measurement would be 15,000 dpm/m^3 (75% of the expected value). The comparable value from Table 7.4 of TBD-6000 would be 2,610 dpm/m^3 (DWA AM) and the 95th percentile value for TBD-6000 would be 36,800 dpm/m^3. The adjusted value of 15,000 dpm/m^3 at Simonds is encompassed within the 95th percentile of the lognormal distribution. This example is similar to the Oxide Operator example discussed above where the hypothetical POC was essentially the same whether a constant dose based on the measured air concentration or a lognormal dose based on the TBD-6000 GM and a GSD of 5 are used. The DWA for several other operations is above the TBD-6000 AM, but less than the 84th percentile (for the Operator, east side forge).

Table 12. Simonds Saw and Steel Uranium Forging vs. TBD-6000 Values

Simonds Saw and Steel TBD	DWA (dpm/m^3)*	TBD-6000 Equivalent Description (TBD=6000 Table No.)	GM[b] (dpm/m^3)	AM (dpm/m^3)	Is TBD-6000 Limiting?[a]
Operator, east side of forge	8,250	Operator DWA (7.4)	1,170	2,610	No
Tong Man, east side of forge	15,000	Operator DWA (7.4)	1,170	2,610	No
Hammer operating position downward	270 (avg. of 3)	Operator DWA (7.4)	1,170	2,610	Yes
Charg. Atop unit	253 (avg. of 3)	Operator DWA (7.4)	1,170	2,610	Yes
NW corner of hammer- two ingots	2,025 (avg. of 2)	Operator DWA (7.4)	1,170	2,610	Yes
Around hammer	2,895 (avg. of 4)	Operator DWA (7.4)	1,170	2,610	No
Opening furnace door removing ingot	3,375	Operator DWA (7.4)	1,170	2,610	No
SW of 7 ton hammer	3,450 (avg. of 3)	Operator DWA (7.4)	1,170	2,610	No
NE of 7 ton hammer	1,208 (avg. of 4)	Operator DWA (7.4)	1,170	2,610	Yes

* BZ average multiplied by 0.75 for comparison with TBD-6000.
a – Based on comparison of DWA and AM.
b – The corrected GM based on an AM of 2,610 dpm/m^3 from Table 7.3 of TBD-6000 should be 715 dpm/m^3.

4.4 JOSLYN

Data on uranium fabrication operations at Joslyn were taken from NIOSH 2012 and are summarized in Table 13.

Table 13. Joslyn Rolling and Machining vs. TBD-6000 Values

Joslyn Work Area/ Job Description	DWA (dpm/m^3)	TBD-6000 Equivalent Description (TBD-6000 Table No.)	GM (dpm/m^3)	AM (dpm/m^3)	Is TBD-6000 limiting?[a]
18" Rough Roll East	3,322	Rolling Operator (7.3)	3,533	12,901	Yes
18' Rough Roll West	375	Rolling Operator (7.3)	3,533	12,901	Yes
Roller Foreman	725	Supervisor (7.3)	326	1,190	Yes
Ass't Foreman	725	Supervisor (7.3)	326	1,190	Yes
Furnace Heaters	16	General Labor (7.3)	651	2,377	Yes
Recorder	16	General Labor (7.3)	651	2,377	Yes
12" Rough Roll East	605	Operator (7.3)	3,533	12,901	Yes
12" Rough Roll West	570	Operator (7.3)	3,533	12,901	Yes
Drag Down (Billet)	310	General Labor (7.3)	651	2,377	Yes
9" Finishing Roll East	16,542	Operator (7.3)	3,533	12,901	No
9" Finishing Roll West	5,791	Operator (7.3)	3,533	12,901	Yes
Quench Tank	155	General Labor (7.3)	651	2,377	Yes

Table 13. Joslyn Rolling and Machining vs. TBD-6000 Values

Joslyn Work Area/ Job Description	DWA (dpm/m^3)	TBD-6000 Equivalent Description (TBD-6000 Table No.)	GM (dpm/m^3)	AM (dpm/m^3)	Is TBD-6000 limiting?[a]
Draggers	831	General Labor (7.3)	651	2,377	Yes
Rod Stamper	242	General Labor (7.3)	651	2,377	Yes
Rod Bundler	128	General Labor (7.3)	651	2,377	Yes
Lathe Operator	12	Machining Operator (7.5)	5,480	20,010	Yes
Centerless Grinder	100	Machining Operator (7.5)	5,480	20,010	Yes
Grinder (portable)	277	Machining Operator (7.5)	5,480	20,010	Yes
Cutomatic	191	Machining Operator (7.5)	5,480	20,010	Yes
Analysis: With the exception of the 9" Finishing Roll Operator East, TBD-6000 is limiting for all Joslyn job descriptions.					

a – Based on comparison of DWA and AM.

The DWA for the Finishing Roll Operator East is at the 83rd percentile of a lognormal distribution. All other DWAs are less than the AM.

4.5 BETHLEHEM STEEL

Only a limited number of BZ samples were taken at Bethlehem Steel and no DWA values were reported (Bethlehem 1952, Heatherton 1952). The BZ samples were for billet stamping and rod shearing operations only. Consequently, we used the TBD-6000 approach and multiplied the expected or average values by 0.75. We presume that these activities would be assigned to the Operator job category for uranium rolling. Results are summarized in Table 14 and compared with generic TBD-6000 values.

Table 14. Bethlehem Steel vs. TBD-6000 Values

Bethlehem	DWA* (dpm/m^3)	TBD-6000 Equivalent Description	GM (dpm/m^3)	AM (dpm/m^3)	Is TBD-6000 Limiting?[a]
Shear Operator set-up And cut 1 rod 4 cuts	4	Rolling Operator (Table 7.3)	3,533	12,901	Yes
Kickoff for Shear Rods	26	Rolling Operator (7.3)	3,533	12,901	Yes
Kickoff of Sheared Rods	6	Rolling Operator (7.3)	3,533	12,901	Yes
Kickoff of Sheared Rods	61	Rolling Operator (7.3)	3,533	12,901	Yes
Kickoff of Sheared Rods	34	Rolling Operator (7.3)	3,533	12,901	Yes
Shear 1 rod 4 cuts	270	Rolling Operator (7.3)	3,533	12,901	Yes
Shear 2 rods 8 cuts	149	Rolling Operator (7.3)	3,533	12,901	Yes
Shear 3 rods 13 cuts	80	Rolling Operator (7.3)	3,533	12,901	Yes
Shear 3 rods 12 cuts	119	Rolling Operator (7.3)	3,533	12,901	Yes
Stamping Billets by Shear	2,483 (avg. of 3)	Rolling Operator (7.3)	3533	12,901	Yes
*BZ multiplied by 0.75 to compare with TBD-6000. a – Based on comparison of DWA and AM.					
Analysis: For Bethlehem, all DWA-adjusted BZ samples less than TBD-6000.					

In addition to the limited BZ samples included in Table 14, a larger number of process and general area air samples were also taken at Bethlehem (Bethlehem 1952, Heatherton 1952). None of these samples exceeded the TBD-6000 AM for a generic rolling operator.

4.6 CONCLUSIONS

In the preceding tables, those values for DWAs at the various sites that exceed the AM DWAs from TBD-6000 are highlighted. None of the values exceed the 95th percentile, indicating that the operations in TBD-6000 characterized here would be claimant favorable if the 95th percentile of the lognormal distribution is used in dose reconstruction. However, this is not the NIOSH default approach, which uses the full lognormal distribution with the GM from TBD-6000 and a GSD of 5. For the high-end site-specific examples provided here, the NIOSH approach produces results that are at least comparable to those using the high-end site-specific values. Hence, overall, the data and strategy adopted in TBD-6000 for internal intakes is found to be fundamentally sound and claimant favorable.

5.0 OPERATIONS NOT EXPLICITLY COVERED IN TBD-6000

There are several operations that took place at early AWE facilities and are not explicitly covered in TBD-6000 that could have significant impacts on dose reconstructions. These involve practices such as vigorous floor sweeping, indoor chip fires during machining uranium, and outdoor uranium pit burning. This section provides some information on these practices.

5.1 CHIP FIRES DURING MACHINING

Uranium fires during machining have been documented since the early days of the Manhattan Project. In a 1943 letter, DuPont summarized the situation and identified the types of protective measures that should be undertaken to keep the process under control (Daniels 1943):

> *The turnings have proved to be highly inflammable and subject to spontaneous ignition. Several experiments have been conducted at Herring-Hall-Marvin Safe Company, Hamilton, Ohio, and Baker Brother, Inc., Toledo, Ohio, and in addition there have been a number of accidental fires, of which at least three were spontaneous. Fires of quantities ranging from several pounds to several hundred pounds have been experienced and a number of extinguishers have been tried. Records of this work are available in our files. While the work to date does not constitute an exhaustive survey of the problem, we believe that it is now safe to outline precautionary and protective measures.*

Thus, as early as 1943, handling methods to reduce the consequences of uranium fires were well documented. This information was periodically updated, as demonstrated by a 1950 report authored by Kehoe et al. (1950) of the New York Operations Office of the AEC. That report suggested safe procedures for storage, laboratory handling, disposal, and shipment of uranium scrap. The report also describes the best procedures for extinguishing uranium scrap fires.

Harris and Kingsley (1959) also noted that fires during uranium machining occur frequently, and they provide extensive guidance on practices that should be used to prevent such fires. These authors do not provide specific data on this issue, and it is not known if effects of chip burning are included in the quantitative machining data that they do provide. However, some relevant information is included in their discussion of chip briquetting during scrap recovery, where they note that:

The operator of the machine may receive an excessive exposure, primarily working at the discharge of briquetting machine. Here the concentration of uranium has been found to average 600 d/m/M^3. The sources of contamination are the fume emanating from the burning edges of the briquette and that from burning chips which accompany the briquettes as they are ejected from the machine die. These fumes result from uranium ignited by the heat created in the press.

Assuming that air concentrations from the burning of chips during briquetting are similar to those arising from chip burning during uranium machining, then the effects of chip burning during machining are encompassed by the TBD-6000 machining operator whose AM DWA is 20,010 dpm/m^3. Adley provides several measurements taken during various machining operations where either burning or fume generation are cited. These measurements are presented in Table 15.

Table 15. Air Concentrations from Burning of Uranium during Machining

Operation	Air Concentration	
	(10-5 µg/cc)	(dpm/m^3)
Turning down deeply pitted billet. Sparks and burning metal.	27	410
Deep cut with dull tool. Heavy fume.	97	1,470
Same time and place as above sample.	20	304
Sampled during three cuts; dull saw much fume.	12	182
Sample at breathing level only; much fume from saw case vent.	154	2,340
Fume from vent of saw case – fume barely visible 20-minute sample.	122	1,850
Sawing large chunks of metal from crucible. Sample 15" above cut. Considerable fume observed.	127	1,930

The individual air concentration measurements made by Adley where machining was accompanied by uranium burning are all substantially less than the generic DWA for machining based on Table 7.5 of TBD-6000. Hence, we believe that the generic uranium dust loading used in TBD-6000 for machining operations accounts for the possibility that uranium fires occurred periodically at these facilities.

5.2 FLOOR SWEEPING

Adley provided dust concentration data related to floor sweeping as summarized in Table 16.

Table 16. Air Concentrations of Uranium from Floor Sweeping

Operation	Air Concentration		Sweeping Time (hr/day)
	(10-5 µg/cc)	(dpm/m^3)	
Sweeping floor after stripping billets and sawing	86	1,310	0.1
Sweeping after emptying crucibles	582	8,850	0.1
Sweeping floors in oxide burner area using saw dust	5.9	90	0.5
Sweeping entire area, using saw dust sweeping compound (avg. of 2)	39.5	600	0.2
Sweeping in main bay [non-production areas] of building	1.1	17	Not stated
Sweeping floor at opposite end of furnace	35	532	Not stated

The highest observed exposure of 8,850 dpm/m^3 was for an oxide operator sweeping in the burnout room as part of scrap recovery operations. Based on Table 7.7 of TBD-6000, the AM exposure for a scrap recovery operator was 6,170 dpm/m^3, which is a daily weighted exposure. Since the exposure from sweeping was limited to 0.1 hr per day, it contributed about 1% of the operator's daily exposure. It is apparent that the exposures from floor sweeping at the Hanford Melt Plant Building are captured by generic exposures from scrap recovery operations in TBD-6000.

5.3 OUTDOOR URANIUM PIT BURNING

Information on exposures from outdoor pit burning of uranium to reduce the possibility of chip fires and promote scrap recovery is limited. Some outdoor burning results were reported for the Melt Plant Building at Hanford in Adley et al. 1952. Both an open hearth furnace and a graphite burner were located outside the Melt Plant Building. The open hearth furnace was used to burn crucible heels, floor sweepings, used gloves, and some material from a chip recovery process conducted in another building. The graphite burner was used for burning broken and discarded crucibles and stopper rods. Operations associated with graphite burner produced less dust than did operations associated with the open hearth furnace. The operation that resulted in the highest dust concentrations was shoveling the residue from the open hearth burning into barrels or buckets. In some cases, the burned material was sifted through a coarse screen before being loaded into a container. Adley et al. (1952) note that, while these operations were very dusty, they were of brief duration. They characterized the air concentrations for three operations:

- Operation A – burning in open hearth furnace
- Operation B – loading oxide from open hearth furnace into buckets and barrels
- Operation C – graphite burning

Air sampling results, including the average values, are summarized in Table 17 (Adley et al. 1952, Table V). As noted above, Operation B was described in Adley as being of brief duration. If "brief duration" was one-half hour per day, then the weighted exposure for Operation B would be 4,800 dpm/m^3—a value less than the mean DWA of 6,200 dpm/m^3 for a scrap recovery operator in TBD-6000.

Table 17. Atmospheric Concentrations of Uranium at Hanford Melt Plant Outdoor Burning Operations

Operation	Number of Samples	Range of Uranium Concentrations		AM Uranium Conc.
		10^{-5} µg/cm^3	dpm/m^3	dpm/m^3
A	9	1.4 to 260	21 to 3,950	996
B	3	3,930 to 6,370	59,700 to 96,800	76,800
C	2	1.4 to 9.8	21 to 149	85.1

Christofano and Harris (1960) provide some information on **indoor** burning of uranium as part of the scrap recovery process. These authors note that:

> *Scrap has been calcined to oxide in open trays and in multiple hearth calcining furnaces. Both methods led to similar occupational exposures of about 1000 d/min/cu. m.*

This statement is a little confusing since other data included in Table 17 of Christofano and Harris (1960) describe the average exposure of furnace operators prior to 1952 as 3,000 dpm/m^3 and 300 to 1,000 dpm/m^3 after 1952. The average exposure of 3,000 dpm/m^3 is less than the average exposure of 6,200 dpm/m^3 (DWA) for a generic scrap recovery operator from Table 7.7 of TBD-6000.

Kehoe et al. (1950) list dry burning as a safe disposal practice for uranium scrap. They state that:

> *For a quantity not exceeding 5#, the scrap may be spread out on a steel plate in an open area and burned to oxide by the flame of an oxy-acetylene torch. The worker should be protected by a welders face shield and a metal fume respirator. The scrap should be raked to insure that all the metal goes to oxide.*

Some useful anecdotal information on the burning of uranium outdoors can be distilled from the U.S. military experience with depleted uranium armor-piercing projectiles. On July 1991, there was a large fire at the U.S. Army motor pool at Camp Doha, Kuwait, involving combat-ready vehicles and ammunition (Scherpelz et al. 2000). During the course of the fire, which lasted about 24 hours, many of the depleted uranium rounds were burned.

With regard to exposures to depleted uranium from the fire plume, the authors stated that:

- *During the phase of the fire that produced the highest uranium air concentrations, the estimated average air concentration was 3.5×10^{-7} g-U/m^3 at the location of highest concentration. This concentration is well below the ACGIH limit of 2×10^{-4} g-U/m^3 for workers exposed daily to uranium in air and represents a low concentration. This air concentration is also below the NRC limit for exposures of the general public to insoluble uranium.*

- *The maximum radiological dose to a worker located in the position of highest air concentration for the full duration of the fire was calculated to be 0.000003 rem (CEDE), well below the annual limit of 0.10 rem for exposure by a member of the public.*

Considering exposures during clean-up, Scherpelz et al. concluded that:

- *During the recovery and cleanup activities, the estimated air concentrations ranged from 3.8×10^{-5} g/m^3 to 4.2×10^{-4} g/m^3. These air concentrations, when averaged over the course of a year, are below the NRC limit when adjusted for particle size distribution for occupational exposure to airborne uranium, but they are greater than the NRC limits for exposure of the general public to uranium. These estimated air concentrations are greater than 2×10^{-4} g/m^3, which is the ACGIH limit for continuous exposure to uranium (the TWA), but are lower than 6*

$\times 10^{-4}$ g/m^3, the ACGIH limit for short-term exposures (TLV-STEL). The ACGIH air concentration limit was exceeded for only three weeks.

- *The estimated radiological dose received by the most highly exposed workers was 0.065 rem. This dose is less than 0.1 rem, which is the NRC annual dose limit for individual members of the public.*

It was estimated that 465 kg of uranium oxides were produced during the fire and about 0.1% became airborne (http://www.gulflink.osd.mil/camp_doha_report_18may00.pdf).

As noted above, the dose to a worker exposed to the highest air concentration for the full duration of the fire was 3E-06 rem. If we assume that the exposure was for 24 hours, then the exposure for a normal 8-hour work day would be 1E-06 rem and, adjusting this for the ratio of the specific activity of depleted uranium to natural uranium, the equivalent natural uranium exposure would be 1.7E-06 rem/day or 0.425 mrem/yr. From another perspective, the highest estimated uranium concentration of 3.5×10^{-7}g-U/m^3 for the Camp Doha, when adjusted to natural uranium, is only 0.6 dpm/m^3. This value is well within the exposure limits for scrap recovery, as defined in Table 7.7 of TBD-6000.

Exposures during recovery and clean-up activities at Camp Doha were considerably higher due to resuspension of uranium oxide particles. The maximum estimated air concentration of 4.2×10^{-4} g/m^3 is equivalent to 640 dpm/m^3, as compared to an average of 6,200 dpm/m^3 (DWA) for an operator involved in uranium scrap recovery (Battelle 2011, Table 7.7).

Based on the evidence presented here, it appears that exposures from open pit burning of uranium are encompassed by the generic scrap recovery operations explicitly covered in TBD-6000.

6.0 SUMMARY

Over the past several months, SC&A was in a position to perform a very detailed analysis of TBD-6000 as it applied to many site profiles, Special Exposure Cohort (SEC) petition evaluation reports, and dose reconstructions. These analyses have been collected and reorganized into this report as a means to revisit SC&A's original review of TBD-6000. This expanded and in-depth review confirms that TBD-6000 can be used to place a plausible upper bound on the airborne uranium exposures experienced by workers at Atomic Weapons Employer (AWE) facilities in the early years of the Manhattan Engineer District (MED) and Atomic Energy Commission (AEC) programs. However, care must be taken to insure that TBD-6000 data are properly applied.

Specific conclusions include:

- The use in TBD-6000 of a terminal settling velocity of 0.00075 m/s for 5 µm AMAD particles is supported by available experimental evidence and is claimant favorable.

- The assumption that equilibrium between deposition and removal processes is reached in 30 days as specified in TBD-6000 should be re-examined. The analyses presented here based on average settling rates in Main Bay of the Hanford Melt Plant Building indicate that 33–37 days are required to reach equilibrium based on 24 hr/day of settling and 40–44 days based on 12.4 hr/day of settling. The 95th percentile of the 15 Main Bay samples is 69 days to reach equilibrium. Based on these calculations, the claimant-favorable approach would be to use a value of 70 days to achieve an equilibrium surface concentration where the rate of deposition equals the rate of removal. However, if the settling time for dust is 12.4 hr, the time to reach equilibrium would increase by 20% suggesting an upper bound of 84 days.

- Comparison of generic air concentrations for various operations included in TBD-6000 with similar operations at specific sites indicates that some site-specific DWA air concentrations exceed the GM values (and in a few cases the AM values) in TBD-6000. These high site-specific values are subsumed within the full distribution (i.e., lognormal with a GSD = 5) and comparable POCs result whether the lognormal distribution or the high site-specific value is used.

- Chip fires during the machining of uranium were a common occurrence at AWE facilities. Two sources of information show that the air concentrations from machining operations where burning was observed do not exceed the generic values for a machining operator from Table 7.5 of TBD-6000.

- The removal rate at equilibrium of uranium oxide particles deposited on surfaces was estimated to be 0.035/day. This rate is considerably higher than the removal rate of 0.00067/day developed in ORAUT-OTIB-0070 (ORAUT 2012). The calculations presented here support the position that the OTIB-0070 approach regarding time to reach equilibrium is claimant favorable.

- Measured dust concentrations from floor sweeping, when weighted for duration of the sweeping activity, were less than the generic DWA values for a scrap recovery operator from Table 7.7 of TBD-6000. Thus, floor sweeping is adequately covered by TBD-6000.

- Outdoor burning of uranium can result in brief high dust concentrations associated with transfer of the ashes. If "brief duration" of exposure was one-half hour per day, then the weighted exposure for handling oxide dust would be 4,800 dpm/m^3—a value less than the mean DWA of 6,200 dpm/m^3 for a scrap recovery operator in TBD-6000. Corroborating data from Christofano and Harris (1960) indicate indoor exposures 3,000 dpm/m^3 from similar operations, and air concentrations from burning of depleted uranium in a military accident were about an order of magnitude lower than the TBD-6000 generic value.

- There appear to be errors calculating the GMs in the tables in Section 7 of TBD-6000. NIOSH should check to be sure that the values are correct.

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ATTACHMENT A: DERIVATION OF AIR CONCENTRATIONS AT HANFORD MELT PLANT BUILDING

This attachment describes how air concentrations were estimated by NIOSH (Allen 2009b) for the Hanford Melt Plant Building based on data from Table IX in Adley et al. 1952. Table A-1 summarizes the Adley data.

Table A-1. DWA Exposures for Various Job Descriptions at the Hanford Melt Plant Building

Job Title	Weighted Daily Exposure (C x t) (µg-hr/cc)	Avg Air Conc. (µg/cc)
Furnace operator	1.59E-02	1.98E-03
Furnace assistant	6.47E-03	8.09E-04
Saw room operator	2.23E-02	2.79E-03
Oxide operator	6.52E-02	8.16E-03
Rod handler	2.02E-03	2.53E-04
Rod receive unload	5.68E-03	7.10E-04
Rod receive weigh	6.10E-04	7.63E-05
Rod receive stack	2.40E-03	3.00E-04
Autoclave operator	4.20E-04	5.25E-05

The data in column 2 of Table A-1 are taken directly from Adley Table IX. The data in column 3 are the column 2 data divided by 8 hours per work-day.

From Table A-1, the GM and average inhalation air concentrations for the data set are 584 and 1,680 µg/m^3, respectively.

ATTACHMENT B: IREP RUNS FOR HYPOTHETICAL OXIDE OPERATOR

NIOSH-Interactive RadioEpidemiological Program
Probability of Causation Results

Uploaded file: **LUNG; Type S, 11,112 dpm/d; (GM) (1-yr)**
Date of Run: 5/6/2013
Time of Run: 2:06:13 PM
NIOSH ID #: 123456
Claimant Name: John Q. Doe

DOL District Office: CL
NIOSH-IREP version: 5.7
Analytica/ADE version: 3.0
DOL Case No: 123-45-6789

Claimant Cancer Diagnoses:

Primary Cancer #1:	N/A	Date of Diagnosis:	N/A
Primary Cancer #2:	N/A	Date of Diagnosis:	N/A
Primary Cancer #3:	N/A	Date of Diagnosis:	N/A
Secondary Cancer #1:	N/A	Date of Diagnosis:	N/A
Secondary Cancer #2:	N/A	Date of Diagnosis:	N/A
Secondary Cancer #3:	N/A	Date of Diagnosis:	N/A

Claimant Information Used In Probability of Causation Calculation:

Gender: Male
Race (skin cancer only): N/A
Birth Year: 1914
Year of Diagnosis: 1974
Cancer Model: Lung (162)
Should alternate cancer model be run?: No
Smoking history (trachea, bronchus, or lung cancer only): Never smoked

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NIOSH-IREP Assumptions and Settings:

User Defined Uncertainty Distribution: Lognormal(1,1)
Number of Iterations: 2,000
Random Number Seed: 99

General Exposure Information:

#	Exp. Year	Organ Dose (cSv)	Exp. Rate	
1	1948	Lognormal (127, 5)	chronic	
2	1949	Lognormal (41.1, 5)	chronic	
3	1950	Lognormal (20.6, 5)	chronic	
4	1951	Lognormal (15, 5)	chronic	
5	1952	Lognormal (11.1, 5)	chronic	
6	1953	Lognormal (8.47, 5)	chronic	
7	1954	Lognormal (6.62, 5)	chronic	
8	1955	Lognormal (5.31, 5)	chronic	
9	1956	Lognormal (4.38, 5)	chronic	
10	1957	Lognormal (3.68, 5)	chronic	
11	1958	Lognormal (3.16, 5)	chronic	
12	1959	Lognormal (2.77, 5)	chronic	
13	1960	Lognormal (2.46, 5)	chronic	
14	1961	Lognormal (2.2, 5)	chronic	
15	1962	Lognormal (1.98, 5)	chronic	
16	1963	Lognormal (1.8, 5)	chronic	
17	1964	Lognormal (1.65, 5)	chronic	
18	1965	Lognormal (1.51, 5)	chronic	
19	1966	Lognormal (1.39, 5)	chronic	
20	1967	Lognormal (1.28, 5)	chronic	
21	1968	Lognormal (1.19, 5)	chronic	
22	1969	Lognormal (1.1, 5)	chronic	
23	1970	Lognormal (1.01, 5)	chronic	
24	1971	Lognormal (0.939, 5)	chronic	
25	1972	Lognormal (0.872, 5)	chronic	
26	1973	Lognormal (0.806, 5)	chronic	
27	1974	Lognormal (0.326, 5)	chronic	

Radon Exposure Information:

N/A (applies only to cases of Lung Cancer with Radon Exposures)

Probability of Causation (PC) *

1st percentile	8.17 %
5th percentile	16.46 %
50th percentile	67.76 %
95th percentile	95.94 %
99th percentile	98.63 %

NIOSH-Interactive RadioEpidemiological Program

Probability of Causation Results

Uploaded file: **LUNG; Type S, 81,534 dpm/d; (Constant) (1-yr)**
DOL District Office: CL
Date of Run: 5/6/2013
NIOSH-IREP version: 5.7
Time of Run: 2:30:21 PM
Analytica/ADE version: 3.0
NIOSH ID #: 123456
DOL Case No: 123-45-6789
Claimant Name: John Q. Doe

Claimant Cancer Diagnoses:

Primary Cancer #1: N/A — Date of Diagnosis: N/A
Primary Cancer #2: N/A — Date of Diagnosis: N/A
Primary Cancer #3: N/A — Date of Diagnosis: N/A
Secondary Cancer #1: N/A — Date of Diagnosis: N/A
Secondary Cancer #2: N/A — Date of Diagnosis: N/A
Secondary Cancer #3: N/A — Date of Diagnosis: N/A

Claimant Information Used In Probability of Causation Calculation:

Gender: Male
Race (skin cancer only): N/A
Birth Year: 1914
Year of Diagnosis: 1974
Cancer Model: Lung (162)
Should alternate cancer model be run?: No
Smoking history (trachea, bronchus, or lung cancer only): Never smoked

---

NIOSH-IREP Assumptions and Settings:

User Defined Uncertainty Distribution: Lognormal(1,1)
Number of Iterations: 2,000
Random Number Seed: 99

General Exposure Information:

#	Exp. Year	Organ Dose (cSv)	Exp. Rate	Radiation Type
1	1948	Constant (935)	chronic	alpha
2	1949	Constant (301)	chronic	alpha
3	1950	Constant (151)	chronic	alpha
4	1951	Constant (110)	chronic	alpha
5	1952	Constant (81.8)	chronic	alpha
6	1953	Constant (62.2)	chronic	alpha
7	1954	Constant (48.6)	chronic	alpha
8	1955	Constant (39)	chronic	alpha

9	1956	Constant (32.2)	chronic	alpha
10	1957	Constant (27)	chronic	alpha
11	1958	Constant (23.2)	chronic	alpha
12	1959	Constant (20.3)	chronic	alpha
13	1960	Constant (18)	chronic	alpha
14	1961	Constant (16.1)	chronic	alpha
15	1962	Constant (14.6)	chronic	alpha
16	1963	Constant (13.2)	chronic	alpha
17	1964	Constant (12.1)	chronic	alpha
18	1965	Constant (11.1)	chronic	alpha
19	1966	Constant (10.2)	chronic	alpha
20	1967	Constant (9.42)	chronic	alpha
21	1968	Constant (8.72)	chronic	alpha
22	1969	Constant (8.04)	chronic	alpha
23	1970	Constant (7.44)	chronic	alpha
24	1971	Constant (6.89)	chronic	alpha
25	1972	Constant (6.4)	chronic	alpha
26	1973	Constant (5.91)	chronic	alpha
27	1974	Constant (2.4)	chronic	alpha

Radon Exposure Information:

N/A (applies only to cases of Lung Cancer with Radon Exposures)

Probability of Causation (PC) *

1st percentile	23.66 %
5th percentile	46.21 %
50th percentile	86.82 %
95th percentile	97.77 %
99th percentile	99.01 %