ORAU TEAM
Dose Reconstruction
Project for NIOSH

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EFFECTIVE DATE	REVISION NUMBER	DESCRIPTION
03/10/2008	00	Approved new technical information bulletin to establish a process for estimating dose to workers at AWE Facilities during residual radioactivity periods. Incorporates formal internal and NIOSH review comments. Training required: As determined by Task Manager. Initiated by Joseph S. Guido.

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1.0 PURPOSE

Technical information bulletins (TIBs) are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance to assist in the preparation of dose reconstructions at particular sites or categories of sites. They will be revised in the event additional relevant information is obtained about the affected site(s). TIBs may be used to assist NIOSH staff in the completion of individual dose reconstructions.

In this document the word “facility” is used as a general term for an area, building, or group of buildings that served a specific purpose at a site. It does not necessarily connote an “atomic weapons employer facility” or a “Department of Energy facility” as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 (42 U.S.C. § 7384l(5) and (12)).

The purpose of this document is to provide guidance for estimating dose to workers at Atomic Weapons Employers (AWEs) after operations were performed for the Manhattan Engineering District (MED) or Atomic Energy Commission (AEC) during periods when “significant residual contamination” existed as determined by *Report on Residual Radioactive and Beryllium Contamination at Atomic Weapons Employer Facilities and Beryllium Vendor Facilities* (NIOSH 2006). These time periods are referred to as the “residual radioactivity period” and are listed in the DOE Worker Advocacy Website as covered time periods for the purpose of determining eligibility for the EEOICPA program. Consideration of exposure during these periods is required in accordance with amendments to the EEOICPA program contained in Public Law 108-375.

For employment during the residual contamination period, only the radiation exposures defined in 42 U.S.C. § 7384n(c)(4) [i.e., radiation doses received from DOE-related work] must be included in dose reconstructions. That is, internal or external radiation exposure, associated with commercial sources of exposure, is not reconstructed. For example, the exposure incurred from the manufacture and distribution of commercial uranium and/or thorium products would not be reconstructed during the residual contamination period (NIOSH 2007).

Under subparagraph B of 42 U.S.C. § 7384n(c)(4), however, radiation from a source that cannot be reliably distinguished from radiation covered under subparagraph A (i.e., radiation doses received from DOE related work) is considered part of the employee’s radiation dose and must be reconstructed (NIOSH 2007).

During the residual contamination period, doses associated with radiation or radiation generating devices that were used at the AWE facility for commercial purposes that are distinguishable from the non-commercial sources are not included in the dose reconstruction. This includes, but is not limited to, doses from: 1) non-destructive testing devices such as radiography units; 2) process or flow gauges that employ radioactive sources; 3) moisture or density gauges; 4) electrostatic eliminators; and, 5) radiation generating laboratory instruments, such as x-ray diffraction units (NIOSH 2007).

2.0 BACKGROUND INFORMATION

2.1 RESUSPENSION MODELS

Methodology for the calculation of airborne radionuclide activity from particulate surface contamination has been expressed as either a “resuspension factor” or “resuspension rate” (Sehmel 1980). Alternatively, a “mass loading” approach has been applied in which the concentration of soil in air is used along with the assumption that the particulate in soil and air contains the same proportion of contaminant (Linsley 1978; Anspaugh et al. 1975).

2.1.1 Resuspension Factor

Resuspension factors are the ratio of the radionuclide airborne concentration per unit air volume divided by the surface concentration per unit area and are generally reported in units of m^{-1}. Resuspension factors have been extensively reviewed in the literature (Stewart 1964; Linsley 1978; Sehmel 1980; Brodsky 1980; DOE 1994) and have been reported to range from 10^{-10} m^{-1} to 10^{-2} m^{-1} (Sehmel 1980). A summary of these data is presented in Figure 2-1 (from Sehmel 1980).

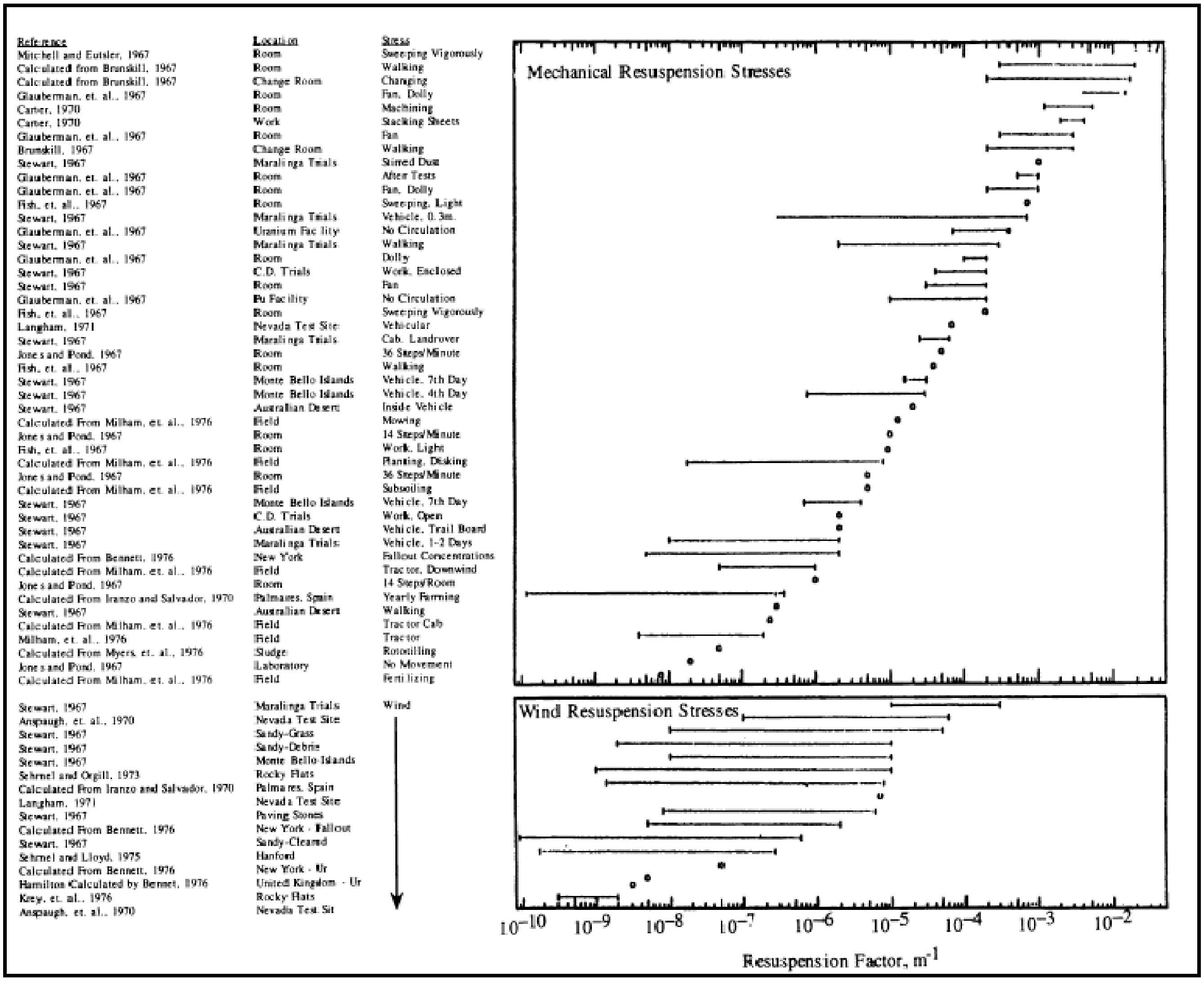

Figure 2-1. Resuspension factor range from mechanical and wind resuspension stresses (Sehmel 1980, Figure 2).

Application of resuspension factors in dose assessment has been studied by a number of authors. Generally, early conclusions of a value of 10^{-6} m^{-1} under "quiescent conditions" and a factor of 10 higher (10^{-5} m^{-1}) under conditions of moderate activity (Stewart 1964) have been supported by later analysis (Brodsky 1980).

The Nuclear Regulatory Commission (NRC) conducted an extensive review of resuspension factors for the purpose of estimating internal exposure of future occupants of decommissioned facilities and published these data in the NUREG/CR-5512 series of documents (Kennedy and Strenge 1992; Beyeler et al. 1999, Abu-Eid et al. 2002). Figure 2-2 below (Beyeler et al. 1999) contains a summary of the resuspension factors for indoor facilities based on the NRC research in 1999. The NRC initially proposed a resuspension factor in the form of a probability density function, with a median value of 5 $\times 10^{-5}$ m^{-1} (Figure 2-3). Note that the NRC approach was based on the loose contamination present and, if applied to total surface contamination, would have to be adjusted by the fraction of the total contamination that is removable (Beyeler et al. 1999). A typical value used is 10% (Beyeler et al. 1999).

Experimental condition	RF_o (m^{-1})
Reported by Jones and Pond (1964)	
Normal room ventilation	3.3×10^{-8}
Walking (14 steps/min)	9.1×10^{-6}
Walking (36 steps/min)	6.9×10^{-5}
Walking (100 steps/min) with wind stress (hair dryer directed toward floor)	1.5×10^{-4}
Reported by Glauberman et al. (1964)*	
Undisturbed	1.5×10^{-5} to 3.6×10^{-4}
Fans on	3.4×10^{-5} to 1.6×10^{-3}
Vibration (dolly)	1.2×10^{-4} to 1.9×10^{-4}
Fans + vibration	1.2×10^{-4} to 1.5×10^{-2}
Reported by Mitchell and Eutsler (1964)**	
Vigorous sweeping by two workmen	1.02×10^{-2} to 4.2×10^{-2}
Reported by Fish et al. (1964)	
Vigorous work activity, including sweeping	1.9×10^{-4}
Vigorous walking	3.9×10^{-5}
Light work activity	9.4×10^{-6}
Rapid air circulation	7.1×10^{-4}

Figure 2-2. Resuspension factors measured under various conditions (Beyeler et al. 1999, Figure 5-11).

Additional analysis on resuspension was published by the NRC in 2002 with the publication of NUREG-1720 (Abu-Eid et al. 2002). The justification for the revision was the fact that the earlier analysis used data from both freshly deposited and aged deposits. It was the NRC's contention that, for application at decommissioned facilities (which was the intended purpose of the analysis), values from fresh deposits would be overly conservative. Additionally, data from additional studies were included in the 2002 analysis. The proposed value (since this NUREG is still a draft document) selected was expressed as both a normal and lognormal distribution (Figure 2-4) with a 90th percentile value of 9.6 $\times 10^{-7}$ m^{-1} (lognormal fit).

2.1.2 Resuspension Rate

Resuspension rates indicate the fraction of a material that is released per unit time (units of hr^{-1} are common). Some authors report the resuspension rates as applicable to outdoor environments in order to calculate downwind contaminant concentrations and ground deposition (Sehmel 1980; Till and Meyer 1983), while others apply them in the indoor setting to determine exposure to occupants

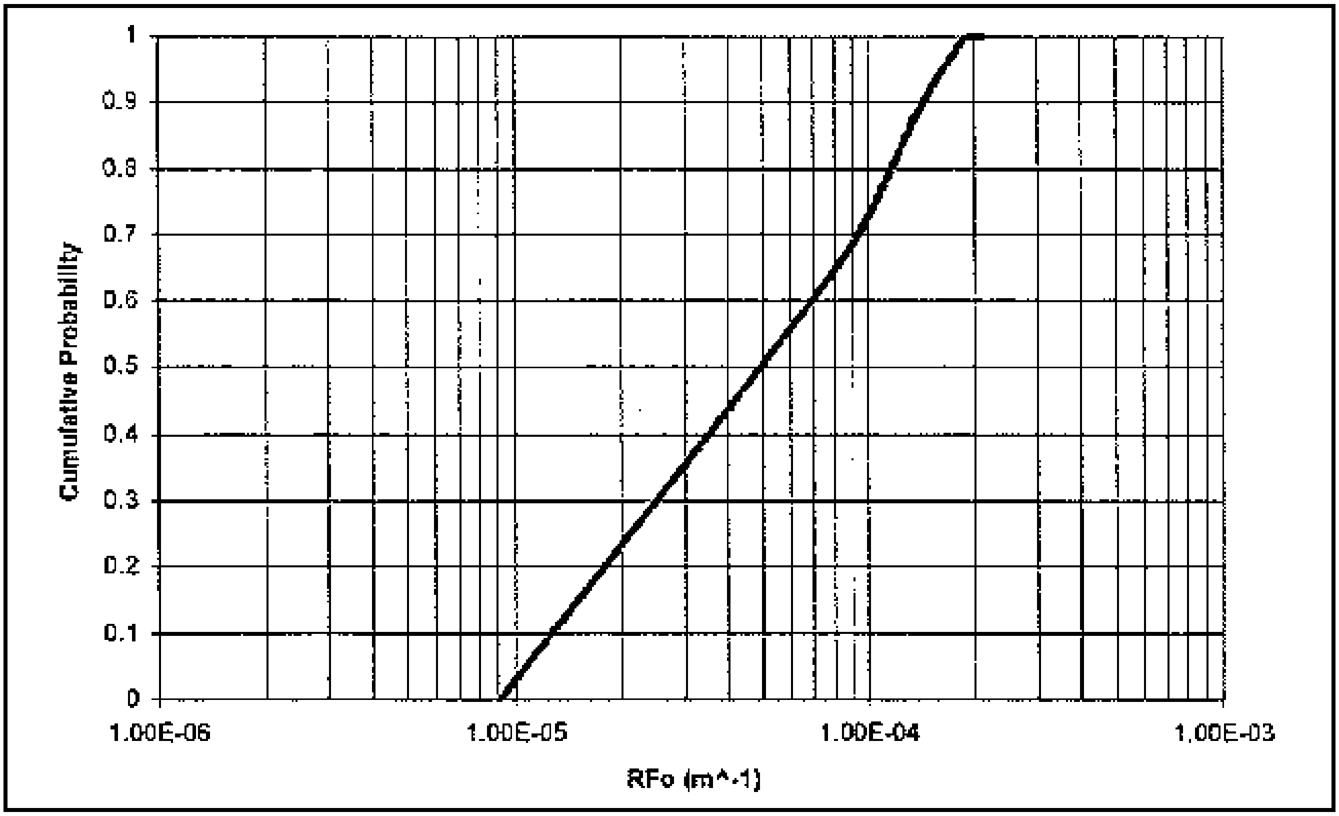

Figure 2-3. Cumulative probability function for RF (release fraction) (Beyeler et al. 1999, Figure 5-7).

Statistical Model	*Sample Mean*	*Sample Standard Deviation*	*90th Percentile RF*
Normal Fit to 5 site mean RF's	4.74×10^{-7} m^{-1}	3.11×10^{-7} m^{-1}	**8.7×10^{-7} m^{-1}**
Lognormal Fit to 5 site mean RF's	**$\log_{10} = -6.433$**	**$\log_{10} = 0.3247$**	**9.6×10^{-7} m^{-1}**

Figure 2-4. Parameters for normal and lognormal 'maximum likelihood' models of RF data (Abu-Eid et a. 2002, Table 5).

(Healy 1971). Healy cited studies that showed that the resuspension rate can exceed 1×10^{-3} h^{-1} for particles on non-carpeted surfaces (Healy 1971). Based on a review of resuspension data and assumptions regarding the amounts of time spent at different activities indoors, Healy estimated a time-weighted-average resuspension rate of 5×10^{-4} h^{-1} for a house (Table 2-1). The corresponding air activity (x) is determined by the expression (Healy 1971):

x = [(resuspension rate)(surface contamination level)(area contaminated)]/[(volume)(air changes/hr)]

Resuspension rates are used in the RESRAD-BUILD code to incorporate the contribution to airborne radioactivity from the resuspension of freshly deposited material (Figure 2-5, below).

Table 2-1. Derivation of weighted indoor resuspension rate (Healy 1971, p. 32).

Activity (description)	Duration	Resuspension rate
Vigorous activity in area. Includes cleaning or children at active play or running	1 hr/day	5×10^{-3} h^{-1}
Active. Normal traffic in the room. Children at normal play	5 hr/day	1×10^{-3} h^{-1}
Moderate. Low traffic with reading, watching TV and occasional movement	6 hr/day	1×10^{-4} h^{-1}
Quiet. No movement. Room unoccupied	12 hr/day	1×10^{-6} h^{-1}
Average Factor		5×10^{-4} h^{-1}

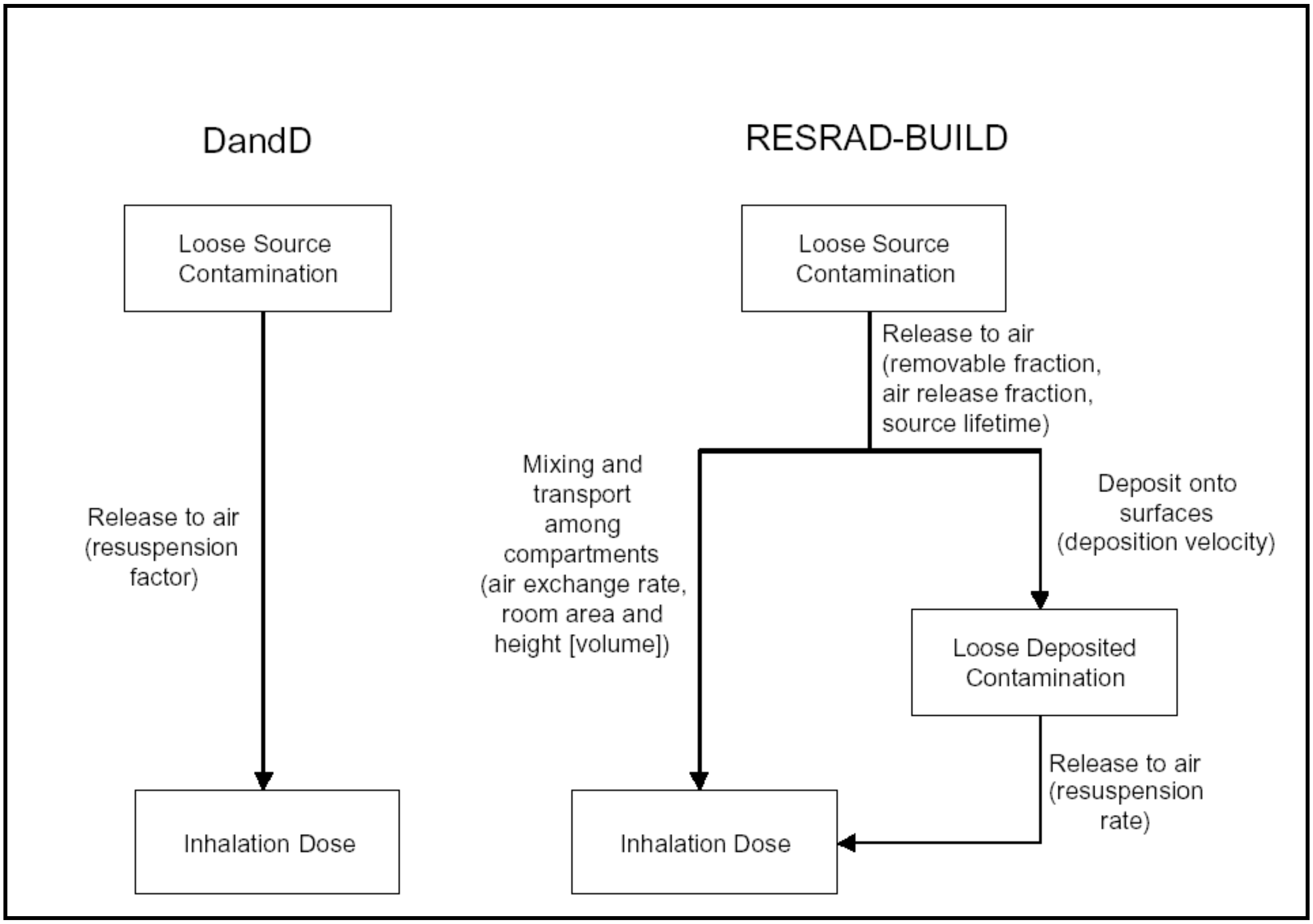

Figure 2-5. Inhalation pathway in DandD and RESRAD-BUILD codes (Biwer et al. 2002, Figure 2-2).

2.1.3 Mass Loading

An approach used to calculate the airborne concentration in outdoor areas due to resuspension of soils is to multiply the surface soil concentration (activity per unit mass) by the average mass loading of the atmosphere (mass per unit volume), yielding an air concentration in units of activity per unit volume (Anspaugh et al. 1975). Anspaugh et al. suggest a default value of 100 $\mu g/m^3$ based on particulate concentrations in 30 nonurban locations. This same approach was adopted by the NRC in NUREG/CR 5512 for the residential scenario for exposure outdoors, using a mass loading value of 100 $\mu g/m^3$ (Beyeler et al. 1999).

2.2 NUREG-1400 METHODOLOGY

NUREG-1400 (Hickey et al. 1993) provides a method for calculation of potential airborne emissions based on the total amount of radioactive material processed or stored. The methodology was developed for the determination of potential radionuclide intake and determination of the need to perform air sampling. The amount of material that may be inhaled by a worker (I) is determined as:

$$\text{Potential Intake} = Q \times 10^{-6} \times R \times C \times D$$

Where,

Q = quantity of material handled
R = release fraction (0.01 for nonvolatile powders; 0.001 for solids)
C = confinement factor (0.01 for glovebox; 0.1 for fumehood; 1.0 for open work area)
D = dispersability factor (10 if cutting, grinding, and heating are performed)

10^{-6} represents the fraction of the material in process that is available for intake.

2.3 COMPUTER MODELS (RESRAD-BUILD; DANDD)

Two common computer models that are available for the estimation of exposure from residual radioactive contamination inside building structures are RESRAD-BUILD (Yu et al. 1994) and DandD (McFadden et al. 2001). The RESRAD-BUILD code was developed for the Department of Energy (by Argonne National Laboratory) while the DandD code was developed for the Nuclear Regulatory Commission. Both models are intended to either develop activity-based release criteria for facility decommissioning or to demonstrate compliance with dose-based criteria. Table 2-2 below is a summary of the capabilities of both of these codes. Although both codes are suitable for modeling exposure from residual contamination in indoor environments, the DandD code is a much more simplistic code (Figure 2-5) with fewer input parameters and assumptions and is likely more appropriate in situations where the requisite parameters for the RESRAD-BUILD code are either not available or highly variable (such as airflow rates and building dimensions).

2.4 DEPOSITION VELOCITY

The deposition velocity characterizes the rate at which particles in the air deposit on a surface. Deposition velocity is determined experimentally by measuring the amount of material deposited per unit area during a particular time interval and dividing by the time-integrated air concentration at a particular reference height (Till and Meyer 1983). Deposition velocities can also be estimated empirically by considering the terminal settling velocity (which is a function of particle size and density) and factors related to atmospheric turbulence and Brownian motion (Till and Meyer 1983). Based on terminal settling velocity alone, a value of 0.00075 m/s has been used in previous program documents [ORAUT-OTIB-0004 (ORAUT 2006), Battelle-TBD-6000 (Battelle Team 2006a), and Battelle-TBD-6001 (Battelle Team 2006b)] to estimate the surface contamination resulting from airborne radioactive contamination. Alternatively, a loguniform distribution, with minimum and maximum values of 2.7×10^{-6} m/s and 2.7×10^{-3} m/s, has been proposed by the NRC for use in the RESRAD-BUILD code (Biwer et al. 2002).

2.5 DECLINE OF RESUSPENSION FACTOR WITH TIME

Decrease in particulate resuspension with time has been well-documented in experimental studies in outdoor environments (Sehmel 1980, Till and Meyer 1983). Measured resuspension factor “half-lives”

Table 2-2. Evaluation of the technical basis for the building occupancy scenario using the RESRAD-BUILD and DandD codes (Biwer et al. 2002, Table 2-1).

Component	RESRAD-BUILD	DandD	Remarks
Source description	• Up to 10 sources • Volume, area, line, or point source of any dimension	• Floor is contaminated • Infinite area source for the direct exposure pathway	
Handling of radionuclides	• 67 principal radionuclides • Half-lives 6 months or longer • In secular equilibrium with progeny of half-lives less than six months	• 249 primary radionuclides • Half-lives 10 minutes or longer • In secular equilibrium with progeny if half-lives are (1) less than 9 hours and (2) less than one tenth the listed parent half-life	DandD has many more short-lived radionuclides in its database.
Building description	• Up to a three-room structure • Air exchange.	• One large structure • Air exchange is not explicitly modeled	
Receptor location with respect to source	Up to 10 receptor locations at any distance from the source	Only one receptor at a fixed location (specified by FGR 12 geometry) with respect to the source	RESRAD-BUILD has an external exposure model to handle any source-receptor configuration.
Pathways	• Direct external exposure from surface source • Inhalation of airborne radioactive particulates • Inadvertent ingestion of source material directly • Inadvertent ingestion of deposited materials • Exposure to deposited materials • Exposure due to air submersion • Inhalation of aerosol indoor radon progeny	• External exposure due to surface source • Inhalation of resuspended surface contamination • Inadvertent ingestion of surface contamination	RESRAD-BUILD is a more sophisticated code and can model site-specific situations.
Time dependence	• 10 time steps in a single run • Calculates average time integrated dose over the exposure duration • Radionuclide concentration changes with radioactive ingrowth, decay, and mechanical erosion	• A single time step • Calculates average time-integrated dose over one-year duration • Radionuclide concentration changes with radioactive ingrowth and decay	
Air concentration	• Dynamic air quality model • Different source release mechanisms: diffusion and particulate injection	Simple and static linear relationship between air concentration and contamination	DandD assumes infinite source, and air concentration is derived from the resuspension factor, whereas in RESRAD-BUILD there is uniform depletion of source over the source lifetime.
Ingestion pathway	• Direct ingestion of removable material • Ingestion of deposited material	Direct ingestion of removable material	RESRAD-BUILD also considers ingestion from deposited materials.
External exposure pathways	• Directly from the source • Materials deposited on the floor • Air submersion	Directly from the source	RESRAD-BUILD considers two more external exposure pathways.
Shielding correction	Eight shielding materials	No shielding correction	

Component	RESRAD-BUILD	DandD	Remarks
Transport of contamination from one room to another	• With an indoor air quality model • Air exchange between the rooms and with outside air • The deposition and resuspension of particulates • Radioactive decay and ingrowth	No transport considered	
H-3 (tritium)	Special H-3 model for volume source	No special H-3 model	
Radon	Radon diffusion and radon flux model	Not included	Not required for NRC compliance

in the range of 35 days to years have been reported (Sehmel 1980). Models for this effect have been proposed in the form of a constant (steady state component) and a second component with an exponential term. For example, Linsley reported an expression (Linsley 1978):

$$K(\text{t in days}) = [10^{-6}\exp^{(-0.01t)} + 10^{-9}]\text{m}^{-1}$$ with the 10^{-6} factor being replaced by 10^{-5} for periods of "regular disturbance by vehicular or pedestrian traffic."

Fewer data are available on the variation of resuspension factors with time in indoor environments. However, Healy recommends a decay constant value of 0.1 d^{-1} which represents the effects of source depletion with time (Healy 1971). While no experimental studies were identified for indoor facilities, an exponential decrease in resuspension is expected to occur due to conservation of mass and the depletion of easily suspended contaminants.

2.6 SOURCE TERM DEPLETION

The half-life of the surface contamination is given by (Steward 1964):

$$T_{½} = \frac{0.693A}{KnR} hr$$

where

A	=	is the contaminated area
K	=	resuspension factor
n	=	ventilation rate (airchanges per unit time)
R	=	room volume, rearranging and realizing that R = A * H (height of room)
λ	=	KnH, hr^{-1}

Expressed in units of day^{-1} this becomes

$$\lambda = 24KnH, \text{day}^{-1}$$

Accordingly, the assumption of a 1% per day source depletion factor (consistent with research summarized in Section 2.5, above) would be achieved solely from removal by the ventilation system for resuspension factors of $8\text{x}10^{-5}$ m^{-1} (assuming a nominal ventilation rate of 1 air change per hour and a room height of 5 meters). Increases in either of these factors would result in a higher depletion rate. This application assumes that depletion through removal in the ventilation system is the only source of reduction, which is known not to be the case.

NUREG-1720 presents an analysis of experimental data from a uranium processing facility. Measurements were collected over a weekend during which uranium operations were not being conducted. Analysis of this data to determine the rate at which the airborne activity was being depleted yielded an average time constant of 0.0378 hr^{-1} and a minimum value of 0.00946 hr^{-1}(Abu-Eid et al. 2002).

2.7 INGESTION CONSIDERATIONS

In the case where inhalation intakes are calculated from air concentrations, ingestion intakes are also to be considered. The ingestion rate, in terms of dpm for an 8-hour workday, can be estimated by multiplying the air concentration in dpm per cubic meter by a factor of 0.2 (NIOSH 2004). To adjust this to ingestion intake per calendar day, the calculated ingestion rate is multiplied by 250 workdays per year and divided by 365 days per year. The same f1-value as used for inhalation dose calculations is to be used for ingestion dose calculations (NIOSH 2004).

3.0 GUIDANCE

3.1 INTERNAL DOSE CALCULATIONS

3.1.1 Consideration of Bioassay Data

When bioassay data collected during the residual period may be impacted by continued site operations (non-AEC/DOE) it is necessary to account for the fact that only a portion of the exposure during the residual contamination period is from resuspended residual contamination versus exposure due to continued site operations. Therefore calculated intakes must be adjusted by a weighting factor to account for the continued depletion of the operational source term during the residual period. A source term depletion factor of 1% of the surface activity per day based on Section 2.6 is suggested for this purpose. Use of this 1% depletion factor is favorable to claimants, based on the depletion behavior reported above; however, to account for the observed steady-state resuspension conditions (Linsley 1978), this factor is held constant after 3 years. Calculated depletion factors based on a 1% per day depletion rate are presented in Table 3-1, below.

Table 3-1. Adjustment factors to account for depletion of source term during the residual contamination period.

Year	Factor
1	1
2	0.03
3 on	0.0007

3.1.2 Maximizing Conditions

Overestimating methods for residual radioactivity periods are presented in ORAUT (2006) and Battelle Team (2006a,b), and are summarized in Table 3-2 below.

3.1.3 Source Term

Estimates of internal dose from source term data can be performed using the NUREG-1400 (Hickey et al. 1993) methodology (Section 2.2) or by applying a resuspension rate (Section 2.1.2).

Application of NUREG-1400 methodology requires that the total annual material handled be used in the calculation. A specific evaluation would have to be performed based on knowledge of the facility and processes in order to determine appropriate release fraction and dispensability factors. Without

Table 3-2. Efficiency methods for AWE residual radioactivity period dose reconstruction.

Document	Applicability	Summary
ORAUT 2006	AWE facilities, subject to applicability matrix in attachment B.	Add one year of additional exposure based on operational exposure matrix.
Battelle Team 2006a	AWE uranium metal facilities.	Inhalation–413 pCi/d (uranium) Ingestion–Tabulated value (Battelle Team 2006a, Table 7.9).
Battelle Team 2006b	AWE uranium refineries.	Inhalation–413 pCi/d (uranium) Ingestion–Tabulated value (Battelle Team 2006a, Table 8.30).

additional information, favorable to claimant values of 0.01 for release fraction and 10 for dispersability should be used.

Application of the resuspension rate methodology requires knowledge of the volume of area into which the material is released and the associated ventilation rate. Selection of an appropriate release rate could be based on knowledge of the facility characteristics, otherwise a favorable to claimant value of 5×10^{-3} hr^{-1} could be used (Healy 1971).

3.1.4 Surface Activity

Estimates of internal dose from surface activity measurements are accomplished using resuspension factors (Section 2.1.1) for indoor calculation and mass loading factors (Section 2.3) for outdoor areas (or where surface activity is available in activity per unit mass).

Application of resuspension factors requires some information on the average surface contamination level present in the facility. If this value is not known, an estimate could be made based on typical airborne radioactivity levels during operations [or worst-case values based on data from ORAUT (2006) or Battelle Team 2006a,b)]. Using estimated airborne radioactivity levels, surface activity can be estimated using a deposition velocity and duration. This approach would allow the estimation of airborne activity due to residual surface activity which has been deposited during operations. Values of 0.00075 m^{-1} and 1 year would be favorable to claimant estimates of deposition velocity and duration, respectively.

To ensure a favorable to claimant assessment, a resuspension factor of 1×10^{-6} m^{-1} should be used to estimate airborne activity from surface contamination. This value is consistent with the research presented in Section 2.1.1, and bounding at the 95th percentile based on a probabilistic analysis using RESRAD-BUILD presented in Attachment A.

Application of a mass loading approach could be appropriate for outdoor areas or for indoor areas where there is debris that has been characterized as activity per unit mass. Based on the analysis reviewed by the NRC, a favorable to claimant value of 100 $\mu g/m^3$ should be applied.

3.1.5 Exponential Interpolation

Contemporary estimates of airborne radioactivity (either directly measured or calculated using surface activity measurements) can be used in conjunction with measurements of airborne activity during the operational period to develop an exposure matrix during the residual radioactivity period. Based on an understanding of the removal mechanisms (Section 2.5), an exponential model should be used to fit the operational period data and the post-operational data. In practice, the post-operational airborne activity and the operational activity would be related by the following equation:

A(residual period) = A(operations) * $e^{-\lambda t}$ with t being the length of time between the two air concentration measurements (residual and operational). This equation is then solved for the factor λ. Calculation of intakes between the measured operational and residual period values should be based on integration of the equation above on an annual basis.

If no data are available for airborne radioactivity levels during the operational period, a favorable to claimant value can be estimated based on applicable values based on data from Battelle Team (2006a,b) (uranium facilities) or Attachment B (thorium facilities).

If no data are available for airborne radioactivity levels during the residual period, a source term depletion factor of 1% per day (Section 2.6) can be used in conjunction with the available operational period data. To account for the observed steady-state resuspension conditions (Linsley 1978), source term depletion should be held constant after 3 years (as in Section 3.1.1).

3.1.6 Computer Models

Application of either the RESRAD-BUILD or DandD computer models (Section 2.3) would yield a detailed assessment of exposure conditions based on input assumptions. However, such an assessment would only be as robust as the input parameters on which the calculations are based. If such parameters could be determined with confidence, then application of such a method would be appropriate. The DandD code, being a more simplistic model, would require less of a detailed understanding of the exposure conditions and may be more appropriate for situations in which knowledge of facility conditions is limited.

4.0 CONCLUSIONS

Table 4-1 below presents a summary of the methods reviewed for estimation of internal exposure to residual radioactivity at AWE facilities

Table 4-1. Summary of recommended methods.

Data sources					
Air sample		**Surface contamination**			
Operational	**Post-operational**	**Operational**	**Post-operational**	**Source term**	**Recommended methodology**
X	X				Exponential fit of operational and post operational data.
X					Calculate annual intake quantities based on a source term depletion factor of 1% per day (Section 2.6).
	X				Exponential fit of post operational data and estimate of operational airborne radioactivity based on ORAUT (2006), Battelle Team (2006a,b), or Attachment B (thorium facilities).
		X	x		Conversion of surface activity to airborne concentrations using resuspension factor or $1x10^{-6}$ followed by an exponential fit of derived levels.
		x			Conversion of surface activity to airborne concentrations using resuspension factors. Calculate annual intake quantities based on a source term depletion factor of 1% per day (Section2.6).
			x		Conversion of post operational surface activity data to airborne concentrations using resuspension factor of $1x10^{-6}$. Estimate of operational airborne radioactivity based on ORAUT (2006), Battelle Team (2006a,b), or Attachment B (thorium facilities). Exponential fit of two quantities.
				x	Estimate of potential intake using NUREG-1400 (Hickey et al. 1993) intake fraction.

5.0 ATTRIBUTIONS AND ANNOTATIONS

All information requiring identification was addressed via references integrated into the reference section of this document.

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Methodology

The air concentration (C^n) in a one room air quality model under equilibrium conditions for a surface source of long-lived radionuclide contamination in which the contamination covers the entire floor can be expressed as:

$$C_n = \frac{f_R f C_{surf}}{24 T_R \lambda_b^a H} \qquad \text{(Yu et al. 1994, equation J.4.10-5)}$$

where

C^n = air concentration of radionuclide n in the room (pCi/m^3),
f_R = removal fraction of the source material
f = fraction of removed material that becomes indoor dust (air release fraction),
C_{surf} = surface concentration (pCi/m^2),
T_R = time to remove material from the source (source lifetime) (d),
λ_b^a = air exchange rate (1/h), and
H = height of compartment (m).

The resuspension factor is defined as the ratio of the air activity to the surface activity. Using the notation above, the resuspension factor (R_F) can be expressed as:

$$R_F = \frac{f_R f}{24 T_R \lambda_b^a H} \qquad \text{(Yu et al. 1994, equation J.4.10-6)}$$

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Since RESRAD-BUILD probabilistic does not directly provide an air activity output, it is necessary to derive it based on the inhalation dose output value, based on the relationship:

$$D_{inh}^{n}(t) = F_{in} \cdot F_i \cdot IR \cdot \overline{C}_i^{\,n}(t) \cdot ED \cdot DCF_h^n \qquad \text{(Yu et al. 1994, equation D.3)}$$

where

$D_{inh}^{n}(t)$	=	total effective dose equivalent due to inhalation of radionuclide n in compartment I from time t to t+ED (mrem),
F_{in}	=	fraction of time spent indoors (indoor fraction) (dimensionless),
F_i	=	fraction of indoor time that is spent at compartment i (time fraction) (dimensionless),
IR	=	inhalation rate (m^3/d),
$\overline{C}_i^{\,n}(t)$	=	average concentration of radionuclide n (pCi/m^3) over the exposure duration ED starting at time t in the indoor air of compartment I,
ED	=	exposure dudration (d), and
DCF_h^n	=	inhalation dose conversation factor for radionuclide n (mrem/pCi).

The appropriateness of this methodology for deriving the air activity (and in effect the resuspension rate) was verified by calculating these values using both the described technique and the closed form analytical solution (based on equation J.4.10-6) and comparing them with the RESRAD-BUILD output air activity value (provided on the detailed output report). Note that the requisite parameters necessary to perform this comparison are only available for the deterministic RESRAD-BUILD cases.

Input Values
The probabilistic module of RESRAD-BUILD allows any parameter to be specified as a probability density function. The resultant output is provided for the 5th through 100th percentile in intervals of 5 percent.

The resuspension factor at the 95th percentile was calculated using default probability density functions for the following parameters: 1) removable fraction, 2) fraction of removed material that becomes indoor dust, 3) time to remove material, 4) air exchange rate. A deterministic value of room height (2.5 m) was selected to represent a reasonable, albeit favorable to claimant approximation. The default distributions applied (as documented in Appendix J of Yu et al. 1994), are based on a detailed literature review conducted by Argonne National Laboratory and are summarized in Table A-1 and graphically depicted in Figures A-1 – A-4, below. Detailed analysis of these distributions are provided in Appendix J to Yu et al. 1994.

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Table A-1. Input parameters (sensitive).

Value	Type	Value	Comment
Removable fraction (unitless)	Probabilistic	Triangular distribution Minimum = 0 Maximum = 1.0 Most likely = 0.1	From Yu et al. 1994, Figure J.14
Air release fraction (unitless)	Probabilistic	Triangular distribution Minimum = 1E-6, Maximum = 1 Most likely = 0.07	From Yu et al. 1994, Figure J.13
Source lifetime (d)	Probabilistic	Triangular distribution Minimum = 1,000 Maximum = 100,000 Most likely = 10,000	From Yu et al. 1994, Figure J.15
Air exchange rate (1/h)	Probabilistic	Truncated lognormal distribution Mean = 0.4187 Standard deviation = 0.88 Lower quantile = 0.001 Upper quantile = 0.999	From Yu et al. 1994, Figure J.9
Height (m)	Deterministic	2.5	Realistic, favorable to claimant value

Table A-2. Input values (insensitive – no impact on analytical results).

Value	Type	Value	Comment
Source activity (pCi/m^2)	Deterministic	1000	
Source area (m^2)	Deterministic	36	
Breathing rate (m^2/d)	Deterministic	28.8	Equal to 1.2 m^3/h
Indoor fraction (unitless)	Deterministic	0.23	Equal to 2000 h/y
Time fraction (unitless)	Deterministic	1	Single room model
Exposure duration (d)	Deterministic	365	

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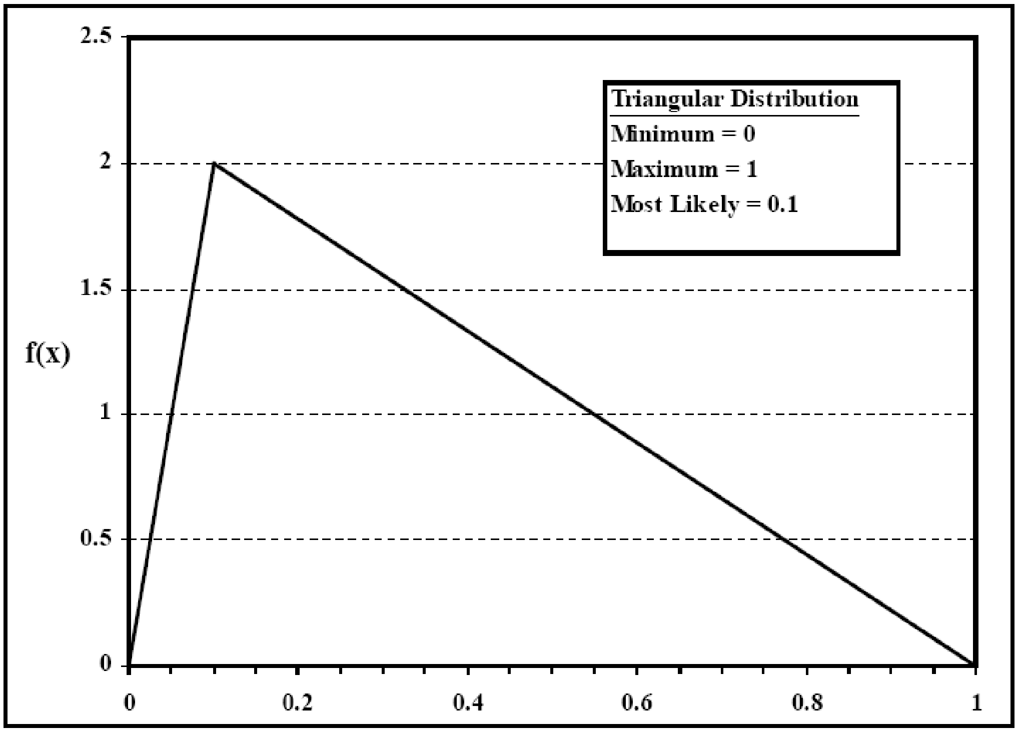

Figure A-1. Removable fraction (from Yu et al. 1994, Figure J.14).

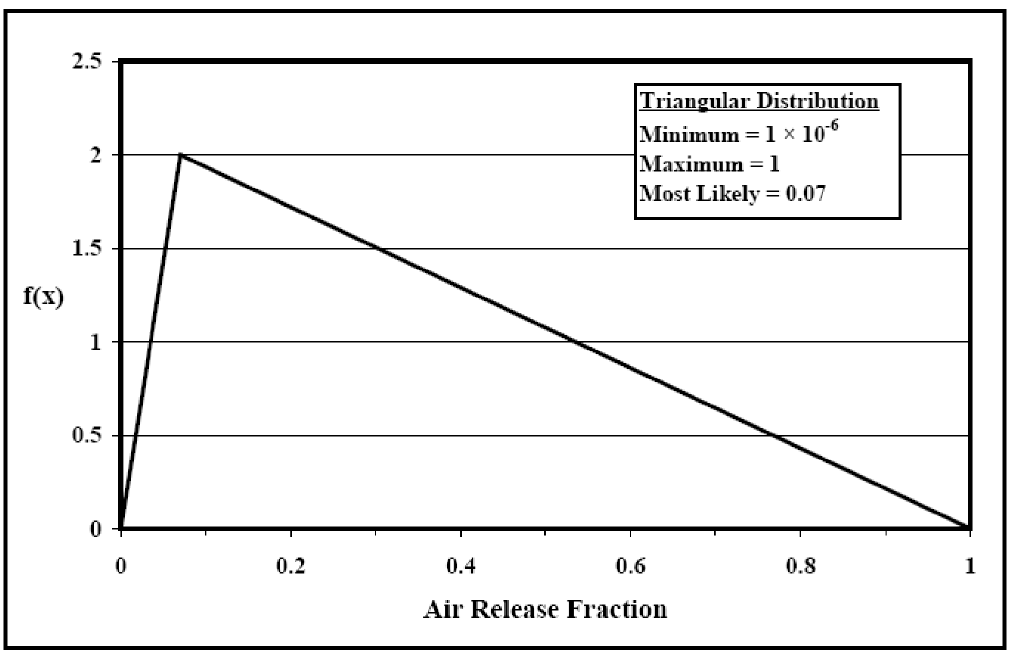

Figure A-2. Air release fraction (from Yu et al. 1994, Figure J.13).

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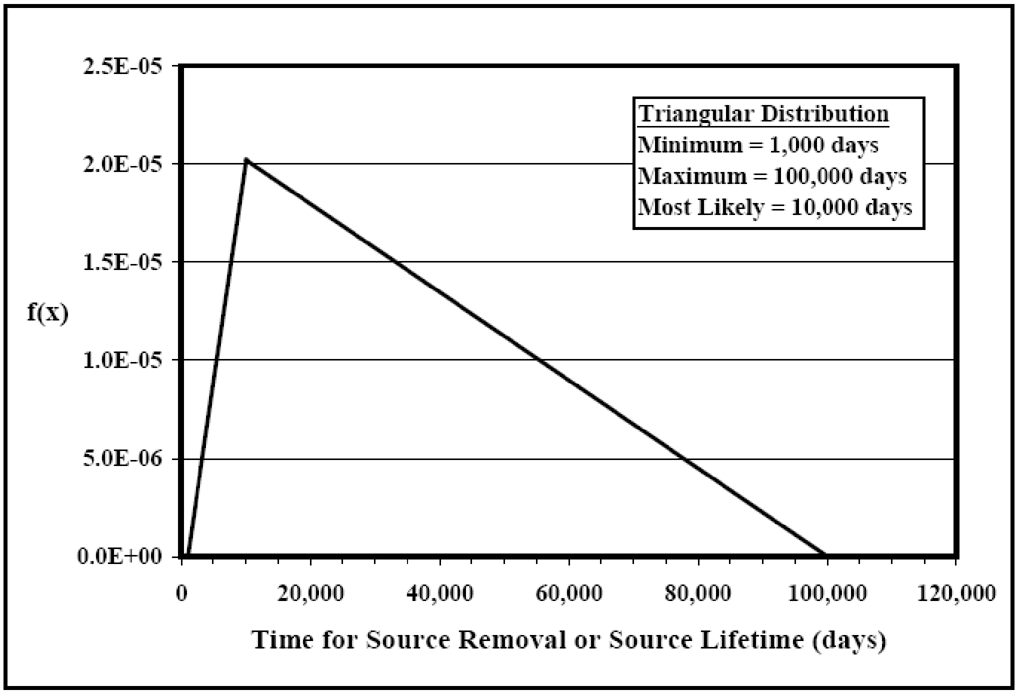

Figure A-3. Source lifetime (from Yu et al. 1994, Figure J.15).

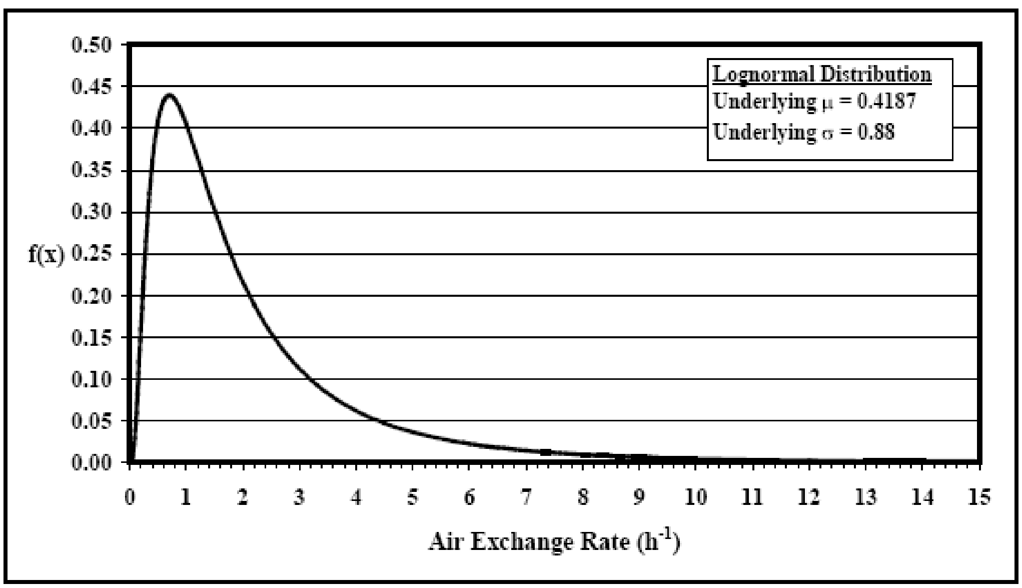

Figure A-4. Air exchange rate (from Yu et al. 1994, Figure J.9)

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Results

Table A-3, below presents the calculated resuspension factor, based on the RESRAD-BUILD probabilistic model runs for the inputs described above. At the 95th percentile, a resuspension factor of 4.5E-7 is derived.

Table A-3. Calculated resuspension factor.

Statistic	Resuspension factor
5%	2.6E-09
10%	5.2E-09
15%	7.1E-09
20%	9.5E-09
25%	1.2E-08
30%	1.6E-08
35%	2.0E-08
40%	2.3E-08
45%	2.9E-08
50%	3.3E-08
55%	4.2E-08
60%	5.0E-08
65%	6.0E-08
70%	7.6E-08
75%	9.3E-08
80%	1.3E-07
85%	1.6E-07
90%	2.2E-07
95%	**4.5E-07**
100%	2.6E-06

ATTACHMENT B
THORIUM SOURCE TERM DATA

This attachment contains a summary of general area air sample results gathered from operational air sampling studies conducted by the Health and Safety Laboratory (HASL). Studies conducted at indicated facilities were reviewed and air sample results which were deemed indicative of general area conditions. Breathing zone and process samples were excluded.

Facility	Summary of general area airborne radioactivity data	Reference
Horizons	GM – 4.8 dpm/m^3 GSD – 2.8 dpm/m^3 95th percentile -26 dpm/m^3	AEC 1955
Nuclear Metals, INC	GM – 1.2 dpm/m^3 GSD – 3.9 dpm/m^3 95th percentile -11 dpm/m^3	AEC 1958
Lindsay	GM – 41 dpm/m^3 GSD – 4.0 dpm/m^3 95th percentile -411 dpm/m^3	Klevin 1953