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☐ New ☒ Total Rewrite ☐ Revision ☐ Page Change

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PUBLICATION RECORD

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.
03/05/2012	01	Revises the source term depletion rate from 0.01 day^{-1} to 0.00067 day^{-1}, removes NUREG-1400 source term approach, and deletes Attachment B. References updated. Incorporates formal internal and NIOSH review comments. Constitutes a total rewrite of the document. Training required: As determined by the Objective Manager. Initiated by Mutty M. Sharfi.

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ACRONYMS AND ABBREVIATIONS

AEC	U.S. Atomic Energy Commission
AWE	Atomic Weapons Employer
d	day
DOE	U.S. Department of Energy
dpm	disintegrations per minute
FGR	Federal Guidance Report
hr	hour
m	meter
min	minute
mo	month
mrem	millirem
NIOSH	National Institute for Occupational Safety and Health
NRC	U.S. Nuclear Regulatory Commission
pCi	picocurie
s	second
TIB	technical information bulletin
U.S.C.	United States Code
yr	year
§	section or sections
µg	microgram

1.0 INTRODUCTION

Technical information bulletins (TIBs) are not official determinations made by the National Institute for Occupational Safety and Health (NIOSH) but are rather general working documents that provide historic background information and guidance concerning 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 (DOE) facility" as defined in the Energy Employees Occupational Illness Compensation Program Act of 2000 [42 U.S.C. § 7384l(5) and (12)].

2.0 SCOPE

The purpose of this document is to provide guidance for estimating dose to workers at Atomic Weapons Employer (AWE) facilities during periods when NIOSH determined there was "significant residual contamination" in its *Report on Residual Radioactive and Beryllium Contamination at Atomic Weapons Employer Facilities and Beryllium Vendor Facilities* (NIOSH 2006) or any update to that report. These periods are referred to as the "residual radioactivity period". 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 period, only the radiation exposures defined in 42 U.S.C. § 7384n(c)(4) (i.e., radiation doses from DOE-related work) must be included in dose reconstructions; that is, internal or external radiation exposure from commercial sources of exposure is not reconstructed. For example, exposure from the manufacture and distribution of commercial uranium and/or thorium products would not be reconstructed for the residual period (NIOSH 2010a).

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 from DOE-related work) is considered part of the employee's radiation dose during the residual period and must be reconstructed (NIOSH 2010a).

During the residual period, doses from radiation or radiation-generating devices that were used at the AWE facility for commercial purposes that are distinguishable from the noncommercial sources are not included in the dose reconstruction. This includes, but is not limited to, doses from: (1) nondestructive 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 2010a).

3.0 BACKGROUND INFORMATION

3.1 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). As an alternative, 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).

3.1.1 Resuspension Factor

A resuspension factor is the ratio of the radionuclide airborne concentration per unit air volume divided by the surface concentration per unit area and is 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 3-1 (from Sehmel 1980).

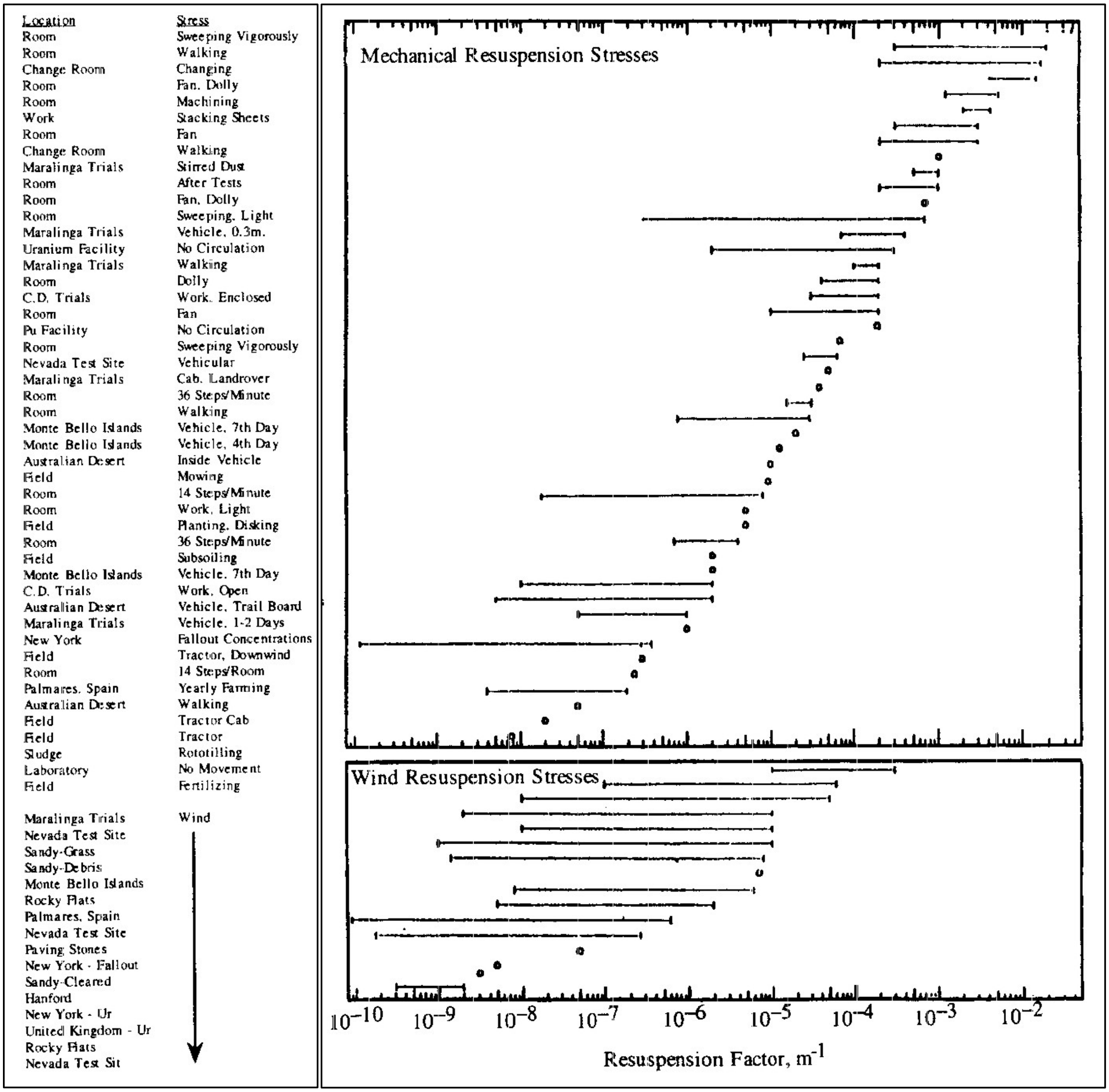

Figure 3-1. Resuspension factor range from mechanical and wind resuspension stresses (Sehmel 1980, Figure 2).

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 U.S. 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). Table 3-1 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 5×10^{-5} m^{-1} (Figure 3-2). 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. A typical value used is 10% (Beyeler et al. 1999).

Table 3-1. Resuspension factors measured under various conditions (Beyeler et al. 1999, Figure 5-11).

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

Additional analysis on resuspension factors was published by the NRC in 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 contention that, for application at decommissioned facilities (which was the intended purpose of the analysis), values from fresh deposits would be overly conservative. In addition, data from additional studies were included in the 2002 analysis. The proposed resuspension factor selected (because this NUREG is still a draft document) was expressed as both a normal and lognormal distribution (Table 3-2) with a 90th-percentile value of 9.6×10^{-7} m^{-1} (lognormal fit).

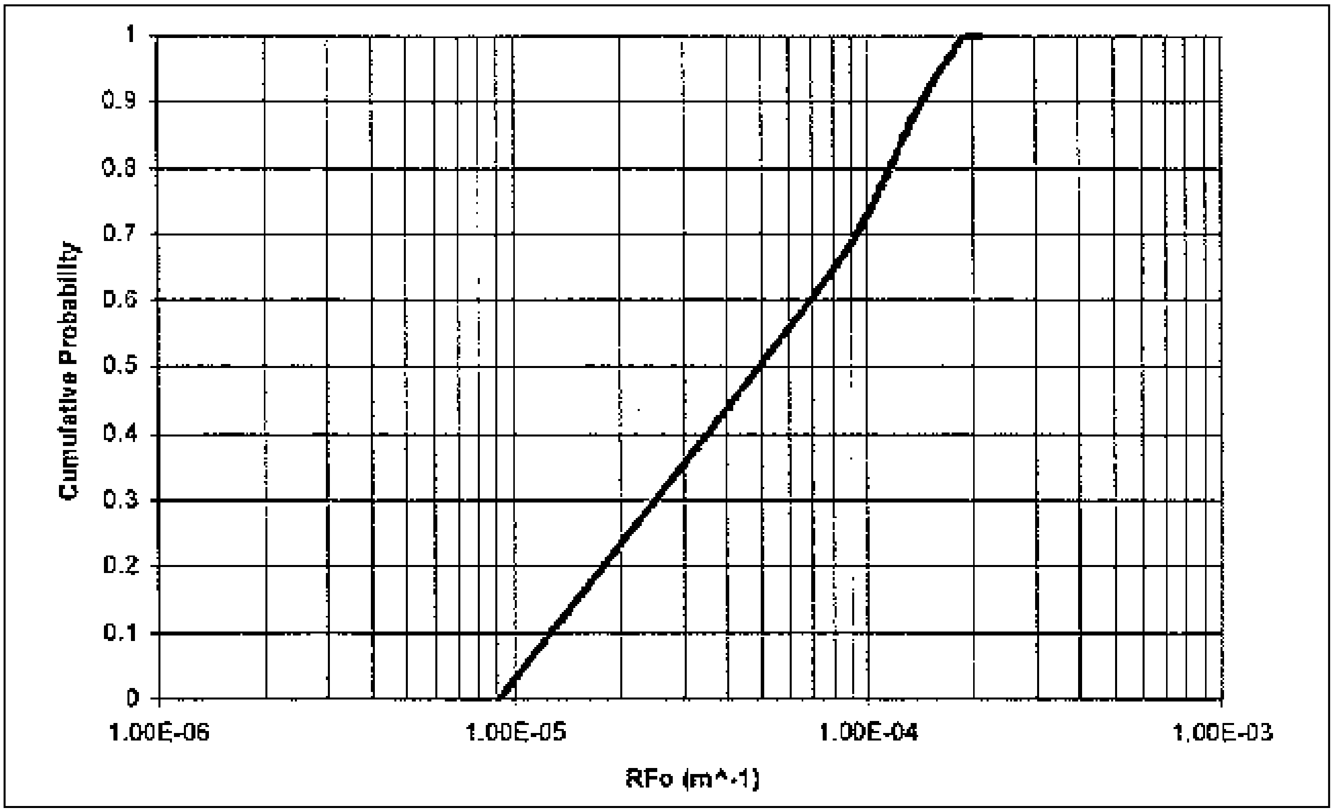

Figure 3-2. Cumulative probability function for resuspension factor (RF_O) (Beyeler et al. 1999, Figure 5-7).

Table 3-2. Parameters for normal and lognormal maximum likelihood models of resuspension factor data (Abu-Eid et al. 2002, Table 5).

Statistical model	Sample mean	Sample standard deviation	90th-percentile resuspension factor
Normal fit to 5 site mean RFs	4.74E-7 m^{-1}	3.11E-7 m^{-1}	8.7E-7 m^{-1}
Lognormal fit to 5 site mean RFs	$\log_{10}$ = -6.433	$\log_{10}$ = 0.3247	9.6E-7 m^{-1}

3.1.2 <u>Resuspension Rate</u>

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

$$x = [(\textit{resuspension rate})(\textit{surface contamination level})(\textit{area contaminated})]/[(\textit{volume})(\textit{air changes/hr})] \quad (3\text{-}1)$$

Table 3-3. Derivation of weighted indoor resuspension rate (Healy 1971, p. 32).

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

Resuspension rates are used in the RESRAD-BUILD computer program to incorporate the contribution to airborne radioactivity from the resuspension of freshly deposited material (Figure 3-3).

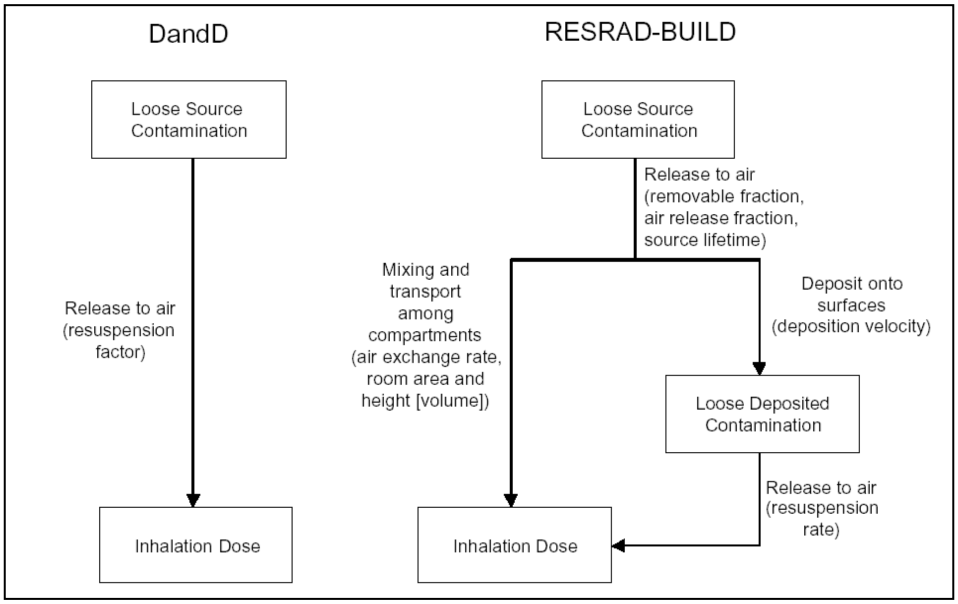

Figure 3-3. Inhalation pathway in DandD and RESRAD-BUILD programs (Biwer et al. 2002, Figure 2-2).

3.1.3 <u>Mass Loading</u>

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. suggests 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).

3.2 COMPUTER MODELS

Two common computer models 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). RESRAD-BUILD was developed for DOE by Argonne National Laboratory and DandD was developed for the NRC. Both models are intended to either develop activity-based release criteria for facility decommissioning or to demonstrate compliance with dose-based criteria. Table 3-4 is a summary of the capabilities of both of these models. Although both programs are suitable for modeling exposure from residual contamination in indoor environments, DandD is much more simplistic (Figure 3-3) with fewer input parameters and assumptions and is likely to be more appropriate for situations in which the requisite parameters for RESRAD-BUILD are either not available or highly variable (such as airflow rates and building dimensions).

Table 3-4. Evaluation of the technical basis for the building occupancy scenario using the RESRAD-BUILD and DandD models (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 mo or longer • In secular equilibrium with progeny of half-lives less than 6 mo	• 249 primary radionuclides • Half-lives 10 min or longer • In secular equilibrium with progeny if half-lives are (1) less than 9 hr 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 Federal Guidance Report 12[a] 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 1-yr 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.

Component	RESRAD-BUILD	DandD	Remarks
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	
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.

a. Eckerman and Ryman (1993).

3.3 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). In addition, deposition velocities can 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 Project documents [ORAUT-OTIB-0004 (ORAUT 2006) and Battelle-TBD-6000 (Battelle 2011)] to estimate the surface contamination from airborne radioactive contamination. As an alternative, 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 RESRAD-BUILD (Biwer et al. 2002).

3.4 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” 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 (1978) reported an expression:

$$K(t) = [10^{-6} \exp^{(-0.01t)} + 10^{-9}]\ \mathrm{m}^{-1} \tag{3-2}$$

where

> t = days, and 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 (1971) recommends a decay constant value of 0.1 d^{-1}, which represents the effects of source depletion with time. 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.

3.5 SOURCE TERM DEPLETION

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

$$T_{1/2} = \frac{0.693A}{KnR}\,\text{hr} \quad (3\text{-}3)$$

where

- A = is the contaminated area
- K = resuspension factor
- n = ventilation rate (air changes per unit time)
- R = room volume
- R = $A \times H$
- H = room height

Therefore the decay constant (λ) is

$$\lambda = \text{KnH}\ (\text{hr}^{-1}) \quad (3\text{-}4)$$

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

$$\lambda = 24\text{KnH}\ (\text{d}^{-1}) \quad (3\text{-}5)$$

NUREG-1720 (Abu-Eid et al. 2002) presents an analysis of experimental data from a uranium processing facility. Measurements were collected over a weekend during which uranium operations were not conducted. Analysis of these 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}.

3.6 INGESTION CONSIDERATIONS

If inhalation intakes are calculated from air concentrations, ingestion intakes are to be considered. The ingestion rate, in terms of disintegrations per minute (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 d/yr. The same f1 value as that used for inhalation dose calculations is to be used for ingestion dose calculations (NIOSH 2004).

4.0 GUIDANCE

4.1 INTERNAL DOSE CALCULATIONS

4.1.1 Consideration of Bioassay Data

If bioassay data from the residual period might be affected 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 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. The source-term depletion rates during the residual radiation periods have been previously determined for the four sites listed in Table 4-1 (NIOSH 2010b; Battelle 2011; ORAUT 2008; ORAUT 2011). In these cases, contemporary estimates of airborne radioactivity at the beginning and end of each site's residual radiation period were used to estimate the effective exponential clearance of the contamination over an extended period for each site.

Table 4-1. Calculated source-term depletion rates during residual periods for various sites.

Facility	Depletion rate (d^{-1})
Blockson	0.00076
Dow Madison	0.00027
General Atomics	0.00116
Simonds Saw and Steel	0.00049
Average	**0.00067**

Based on the average depletion rate of 0.00067 d^{-1}, source term depletion adjustment factors are presented in Table 4-2. This average depletion rate should be used for facilities without site-specific data.

Table 4-2. Adjustment factors to account for depletion of source term during the residual period.

Year	Factor
1*	1.00E+00
2	7.83E-01
3	6.13E-01
4	4.80E-01
5	3.76E-01
6	2.94E-01
7	2.31E-01
8	1.81E-01
9	1.41E-01
10	1.11E-01
11	8.67E-02
12	6.79E-02
13	5.32E-02
14	4.16E-02
15	3.26E-02
16	2.55E-02
17	2.00E-02
18	1.56E-02
19	1.23E-02
20	9.60E-03
21	7.51E-03
22	5.88E-03
23	4.61E-03
24	3.61E-03
25	2.83E-03
26	2.21E-03
27	1.73E-03
28	1.36E-03
29	1.06E-03
30 on	8.32E-04

* Year one is applied to the first year of the residual period.

4.1.2 Maximizing Conditions

Overestimating methods for residual radioactivity periods are presented in ORAUT (2006) and Battelle (2011).

4.1.3 Surface Activity

Estimates of internal dose from surface activity measurements are accomplished using resuspension factors (Section 3.1.1) for indoor calculation and mass loading factors (Section 3.2) 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 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 (2011)]. Using estimated airborne radioactivity levels, surface activity can be estimated using a deposition velocity and duration. This approach enables the estimation of airborne activity due to residual surface activity that has been deposited during operations. Values of 0.00075 m^{-1} and 1 year of deposition velocity and duration, respectively, would be favorable to claimants.

To ensure an assessment that is favorable to claimants, a resuspension factor of 1×10^{-6} m^{-1} should be used for undisturbed areas to estimate airborne activity from surface contamination. This value is consistent with the research (Section 3.1.1), and bounding at the 95th percentile based on a probabilistic analysis using RESRAD-BUILD (Attachment A). In cases, where the contaminated area is still involved in active operations, a site-by-site analysis of the appropriateness of the 1×10^{-6} m^{-1} resuspension factor should be done.

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 value of 100 $\mu g/m^3$ is favorable to claimants and should be applied.

4.1.4 Exponential Interpolation

Contemporary estimates of airborne radioactivity (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 3.4), an exponential model should be used to fit the operational period data and the postoperational data. In practice, the postoperational airborne activity and the operational activity would be related by the following equation:

$$A(residual\ period) = A(operations) \times e^{-\lambda t} \tag{4-1}$$

where

> t = the length of time between the two air concentration measurements (residual and operational)

This equation is then solved for λ. Calculation of intakes between the measured operational and residual period values should be based on integration of Equation 4-1 on an annual basis.

If no data are available for airborne radioactivity levels during the operational period, a value that is favorable to claimants can be estimated based on applicable values based on data from Battelle (2011).

If no data are available for airborne radioactivity levels during the residual period, a source term depletion factor of 0.00067 d^{-1} (Section 2.5) 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 30 years (as in Table 4-2).

4.1.5 Computer Models

Application of either the RESRAD-BUILD or DandD models (Section 2.2) would yield a detailed assessment of exposure conditions based on input assumptions. However, such an assessment would only be as accurate as the input parameters on which the calculations were based. If such parameters could be determined with confidence, application of such a method would be appropriate. DandD, being a more simplistic model, would require a less detailed understanding of the exposure conditions and might be more appropriate for situations in which knowledge of facility conditions is limited.

5.0 CONCLUSIONS

Table 5-1 presents the methods reviewed for estimation of internal exposure to residual radioactivity at AWE facilities.

Table 5-1. Recommended methods.

Air sample		Surface contamination		
Operational	**Post-operational**	**Operational**	**Post-operational**	**Recommended methodology**
X	X			Exponential fit of operational and postoperational data.
X				Calculate annual intake quantities based on a source term depletion factor of 0.00067 d^{-1} (Section 3.5).
	X			Exponential fit of postoperational data and estimate of operational airborne radioactivity based on ORAUT (2006) or Battelle (2011).
		X	X	Conversion of surface activity to airborne concentrations using resuspension factor* or 1×10^{-6} m^{-1} 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 0.00067 d^{-1} (Section 3.5).
			X	Conversion of postoperational surface activity data to airborne concentrations using resuspension factor* of 1×10^{-6} m^{-1}. Estimate of operational airborne radioactivity based on ORAUT (2006) or Battelle (2011). Exponential fit of two quantities.

* In cases, where the contaminated area is still involved in active operations, a site-by-site analysis of the appropriateness of the 1×10^{-6} m^{-1} resuspension factor should be done.

6.0 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 (Yu et al. 1994, Equation J.4.10-5):

$$C^n = \frac{f_R f C_{surf}}{24 T_R \lambda_b^a H} \tag{A-1}$$

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 (hr^{-1}), 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 (Yu et al. 1994, Equation J.4.10-6):

$$R_F = \frac{f_R f}{24 T_R \lambda_b^a H} \tag{A-2}$$

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Because the RESRAD-BUILD probabilistic module 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 (Yu et al. 1994, Equation D.3):

$$D_{inh}^{n}(t) = F_{in} \times F_{i} \times IR \times \bar{C}_{i}^{n}(t) \times ED \times DCF_{h}^{n} \qquad \text{(A-3)}$$

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 ($m^3 d^{-1}$),
$\bar{C}_{i}^{n}(t)$ = 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 duration (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 factor) was verified by calculating these values using both the described technique and the closed form analytical solution (based on Yu et al. 1994, Equation J.4.10-6) and comparing them with the RESRAD-BUILD output air activity value (provided on the detailed output report). 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%.

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, and (4) air exchange rate. A deterministic value of room height (2.5 m) was selected to represent a reasonable approximation that is favorable to claimants. The default distributions applied (as documented in Appendix J of Yu et al. 1994) are based on a detailed literature review by Argonne National Laboratory and are summarized in Table A-1 and shown in Figures A-1 to A-4. Detailed analyses of these distributions are provided in Appendix J of 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	Yu et al. 1994, Figure J.14
Air release fraction (unitless)	Probabilistic	Triangular distribution Minimum = 1E-6, Maximum = 1 Most likely = 0.07	Yu et al. 1994, Figure J.13
Source lifetime (d)	Probabilistic	Triangular distribution Minimum = 1,000 Maximum = 100,000 Most likely = 10,000	Yu et al. 1994, Figure J.15
Air exchange rate (hr^{-1})	Probabilistic	Truncated lognormal distribution Mean = 0.4187 Standard deviation = 0.88 Lower quantile = 0.001 Upper quantile = 0.999	Yu et al. 1994, Figure J.9
Height (m)	Deterministic	2.5	Realistic value that is favorable to claimant

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

Value	Type	Value	Comment
Source activity (pCi/m^2)	Deterministic	1,000	
Source area (m^2)	Deterministic	36	
Breathing rate ($m^2\ d^{-1}$)	Deterministic	28.8	Equal to 1.2 m^3/hr
Indoor fraction (unitless)	Deterministic	0.23	Equal to 2,000 hr/yr
Time fraction (unitless)	Deterministic	1	Single-room model
Exposure duration (d)	Deterministic	365	

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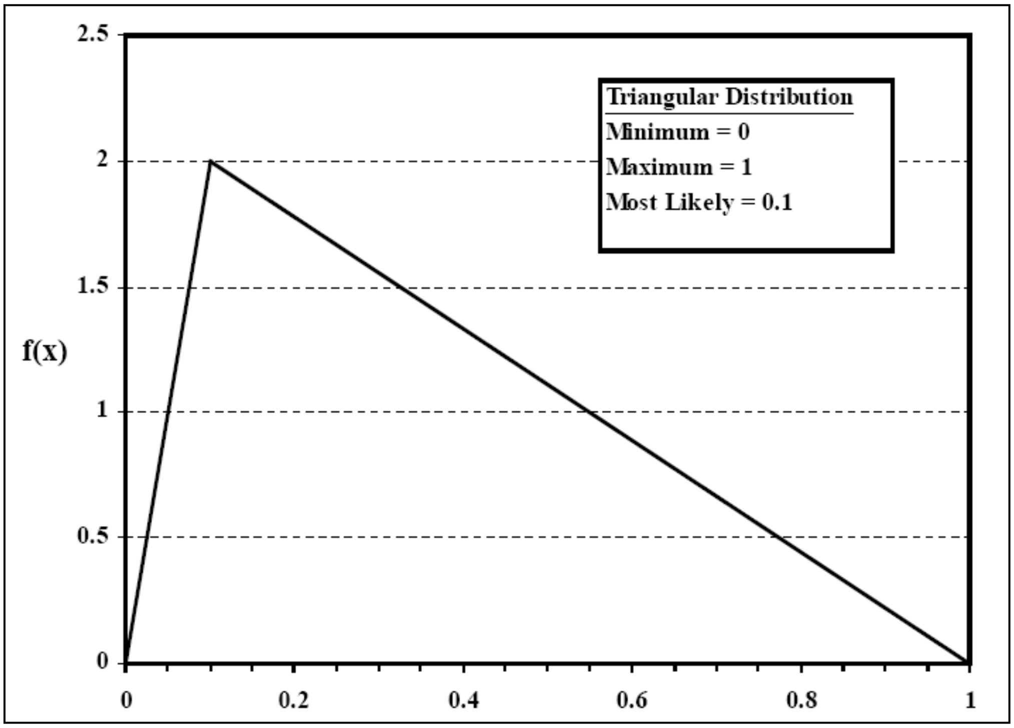

Figure A-1. Removable fraction (Yu et al. 1994, Figure J.14).

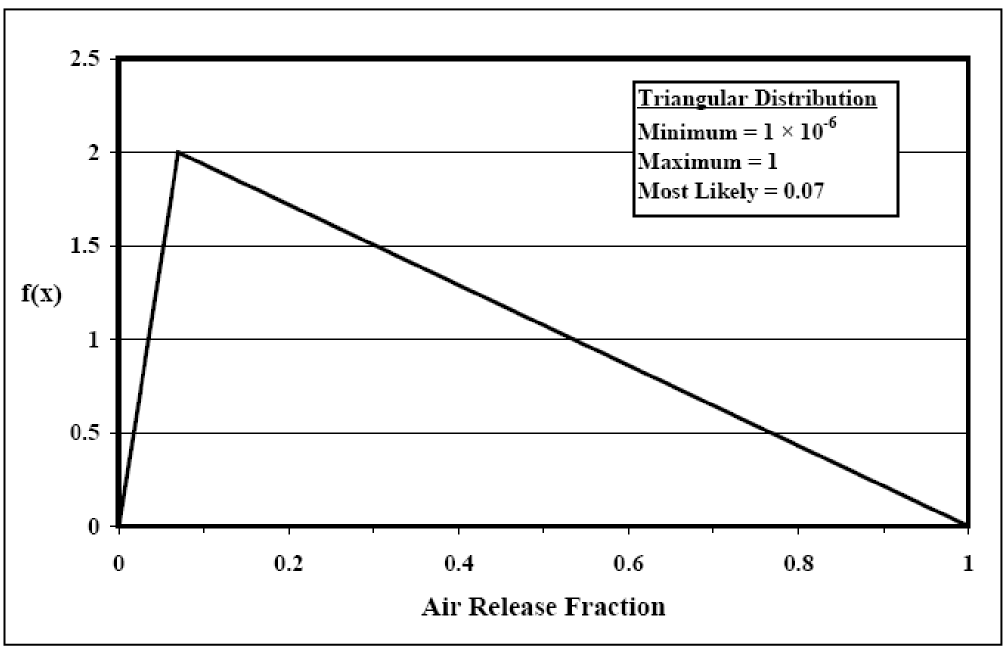

Figure A-2. Air release fraction (Yu et al. 1994, Figure J.13).

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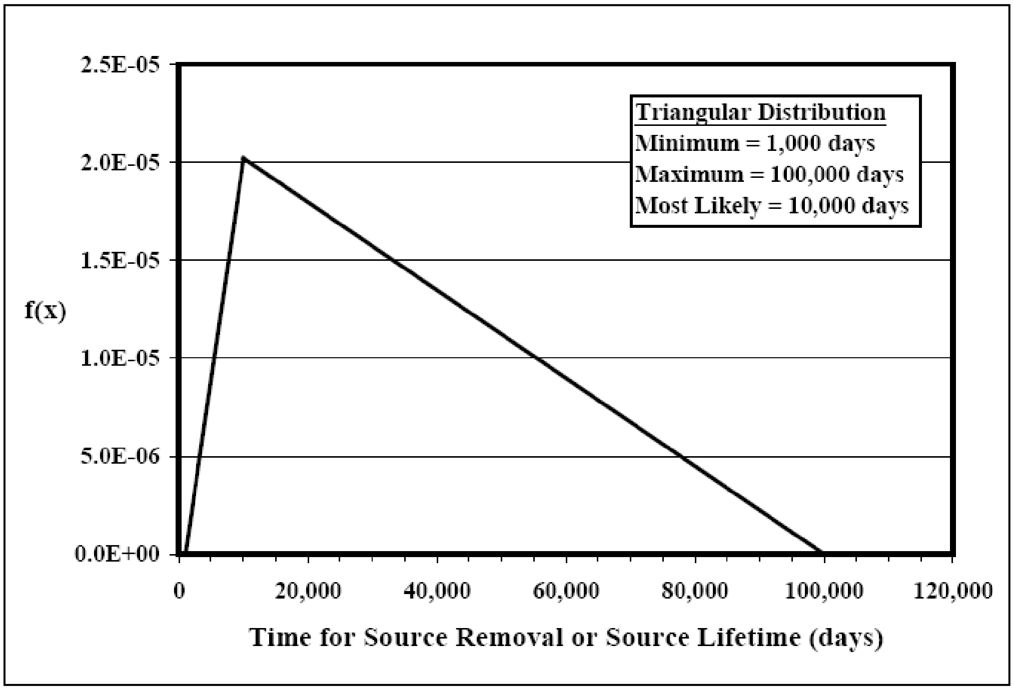

Figure A-3. Source lifetime (Yu et al. 1994, Figure J.15).

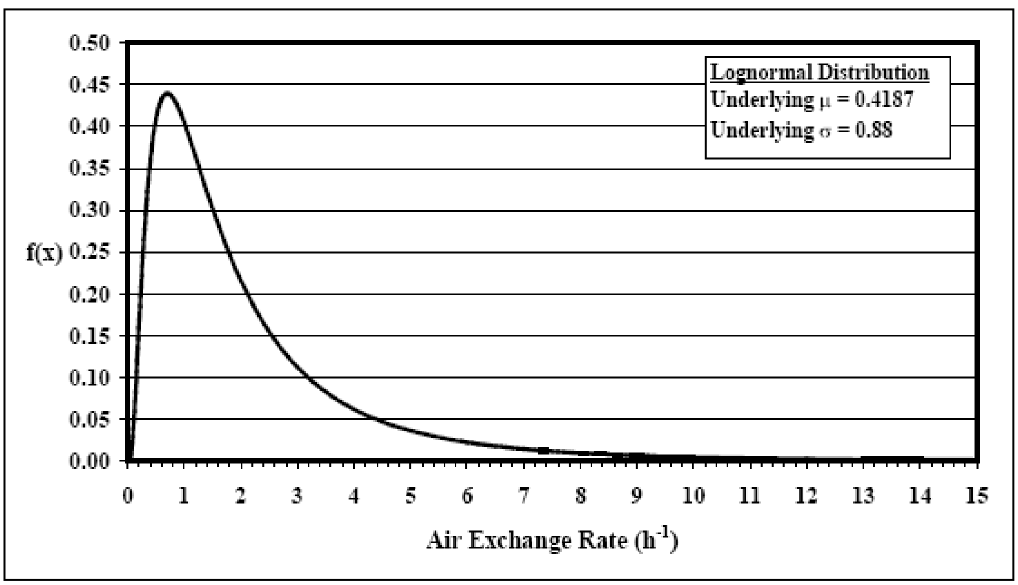

Figure A-4. Air exchange rate (Yu et al. 1994, Figure J.9)

Results

Table A-3 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 4.5×10^{-7} is derived.

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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