KDEP

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KDEP: A Resource for Calculating Particle Deposition in the Respiratory Tract

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ABSTRACT

This paper presents KDEP, an open-source implementation of the ICRP lung deposition model developed by the authors. KDEP, which is freely available to the public, can be used to calculate lung deposition values under a variety of different conditions using the ICRP methodology. The paper describes how KDEP implements this model, and discusses some key points of the implementation. The published lung deposition values for intakes by workers were reproduced, and new deposition values were calculated for intakes by members of the public.

INTRODUCTION

Inhalation is an important mechanism for the intake of radioactive particles. Due to the high vascular permeability of the respiratory epithelium, soluble radionuclides can readily escape from particles deposited in the respiratory tract and be absorbed into the blood stream. Radioactive particles deposited in the respiratory tract can also directly irradiate sensitive tissues. In general, particles deposited in the lower regions of the respiratory tract are more apt to be absorbed into the blood stream, and to irradiate sensitive tissues. In contrast, particles deposited in the upper respiratory tract are more likely to be swallowed or removed through the nose. It follows that the committed effective dose (CED) resulting from inhaling an aerosol is strongly dependent on the location in which the particles were deposited. This is especially true for actinides, which have essentially zero uptake through the GI tract.

The deposition characteristics of an inhaled aerosol depends on a number of factors, which can be divided into characteristics of the environment and attributes of the individual. Important characteristics of the aerosol include the particle size distribution (defined in terms of aerodynamic and thermodynamic behavior), particle density, particle shape, and atmospheric pressure. Some important attributes of the individual include the person's age and gender (which determine various properties of the respiratory tract), breathing rate, and the extent to which inhalation occurs through the mouth. The relationship between these factors is complex, such that theoretical deposition models have needed to be supplemented with empirical observations. Different lung deposition models have been developed to meet different needs and reflect new theoretical and experimental data.

One such model is the Multiple Path Particle Dosimetry (MPPD) model, which was developed to assess the risk of threshold effects caused by inhaled particles (Anjilvel and Asgharian 1995; Miller et. al. 2016). However, the MPPD model was not developed to deal with radioactive particles, and was not optimized for that purpose. For example, it does not explicitly divide the respiratory tract compartments according to radiation sensitivity. Also, the model complexity required to predict threshold effects (e.g., modeling respiratory tract asymmetry) is unnecessary to predict stochastic effects, which is the area of chief concern for radiation protection.

In contrast, the ICRP and NCRP have independently developed respiratory tract models explicitly for use in radiation protection. In 1966, the ICRP Task Group on Lung Dynamics published a respiratory deposition model which would later be incorporated into ICRP Publication 30 (ICRP 1966; ICRP 1979). This was replaced in 1994 by ICRP Publication 66 (ICRP 1994), which incorporated a new deposition model as an essential part of its model of the human respiratory tract model (James 1991). The ICRP Publication 66 respiratory tract model was accompanied by tables of fractional depositions for males and females for a variety of ages and under a variety of conditions (ICRP 66 Appendix F). Those tables are credited to A.C. James, M. Roy, and A Birchall, and were generated using the computer program LUDEP (Birchall et. al. 1991; Jarvis, Birchall, et. al., 1996). In 2015, ICRP Publication 130 (ICRP 2015) described new revisions to the respiratory tract model, and published new deposition values for male radiation workers. While most of these revisions dealt with particle transport and absorption to blood, it did include a minor revision to the deposition values which can be applied directly to the ICRP Publication 66 deposition tables. The respiratory tract regions were also redefined slightly, such that the oral pharynx was excluded from the ET_2 region.

In 1996, the NCRP published its own independently developed model for lung deposition, clearance, and dosimetry (NCRP 1997; Phalen et al. 1991). Although this model defined the respiratory tract regions differently, the deposition fractions for a given particle size distribution, lung volume, and breathing conditions were broadly similar to ICRP Publication 66 for most particle sizes. However, the models were found to disagree significantly for nanoparticles – e.g., particles smaller than approximately 0.1 microns (Yeh et al. 1996). This difference was attributed to enhanced diffusional deposition caused by bifurcation of the airway, which is only taken into account by the NCRP model. This bifurcation may result in a diffusional deposition about twice that predicted for a straight tube (Cohen et al. 1990). It follows that the NCRP deposition model may be preferable for calculations involving nanoparticles.

Although other models are available, LUDEP has remained the only choice for those using the ICRP models. Unfortunately, the source code of LUDEP is not available for modification, peer review, or validation. Although the published deposition values seem to have been reproduced for particles between 0.01 and 50 microns AMAD (Fritsch 2006), this was not done with the goal of validating the method, and again the source code was never made available.

The authors developed a computer program to meet the need for an open-source implementation of LUDEP. For convenience, this program was given the working name ‘KDEP’ to reflect the name of the individual developing the code. Some consideration was given to calling the code LUDEP 3, but that was discarded to avoid the implication that it was officially sanctioned by the original developers of LUDEP, which had been formally licensed by the National

Radiological Protection Board (now Public Health of England). The name KDEP was therefore retained.

KDEP, which is written in Fortran 2003 and compatible with open source compilers, is freely available to public upon request. It is able to reproduce the respiratory tract deposition tables generated by LUDEP and published in ICRP Publication 66 and ICRP Publication 130. In addition, it allows deposition values to be calculated with the ICRP method under different conditions, such as acute intakes and log-normally dispersed thermodynamic diameters.

This paper outlines the calculations involved in reproducing the published values, focusing on the most crucial and challenging aspects. Although the validity and implications of some of the technical decisions made implicitly by the ICRP and the developers of LUDEP in calculating deposition values are discussed, this paper does not serve as a comprehensive technical review.

Finally, the authors present new deposition tables for members of the public exposed in an environmental release. These new tables were generated in a method consistent with that used to reproduce the previously published tables, incorporating the respiratory tract model modifications published in ICRP 130.

PARAMETERS

The following parameters are used as inputs for the program:

Particle size

Particle size can be defined in terms of the aerodynamic equivalent diameter, d_{ae}, defined as the diameter of a sphere having the same settling speed under gravity as the particle (e.g., a spherical particle with the same aerodynamic inertial properties) (Raabe 1994, Page 112) or the thermodynamic diameter, d_{th}, defined as the diameter of a sphere having the same diffusivity as the particle (e.g., a spherical particle with the same thermodynamic properties). If the aerosol is log-normally dispersed, the specified particle size will correspond to either the Activity Median Aerodynamic Diameter (AMAD) or the Activity Median Thermodynamic Diameter (AMTD). In that case, the size metric given will be considered log-normally dispersed (e.g., if the AMTD is given, the thermodynamic diameter will be considered log-normally dispersed). This is slightly different from LUDEP, which always integrates over a log-normally dispersed aerodynamic equivalent diameter. In all tables below, the median of the log-normally dispersed size parameter is shown in bold.

Particle size distribution

Aerosols are specified as being either ‘monodispersed,’ meaning that all particles have the same size, or ‘polydispersed,’ meaning that the particle sizes are log-normally distributed. Monodispersed aerosols are particularly useful for testing, debugging, and comparing to other calculations. The particles can be dispersed around the AMAD, which does not equate to a log-normal distribution of d_{th}, or the AMTD, which does not equate to a log-normal distribution of d_{ae}.

Particle Density

ICRP Publication 66 (1994) recommends a default particle density of $3\,\mathrm{g}\cdot\mathrm{cm}^{-3}$. This may be appropriate even for denser materials, which may rapidly bind to dust and water vapor in the air.

Particle Shape

The dynamic shape factor, χ, is related to a particle’s surface area to volume ratio, and is used in converting between a particle’s aerodynamic equivalent diameter and its thermodynamic diameter. Typical values are between 1 and 2 (ICRP 1994), and a default value of 1.5 is used.

Wind Speed

This is the speed at which air enters the respiratory tract (either through the mouth or nasal passages). It was found to have little impact on deposition for a wide range of plausible values. A default value of 1 $\mathrm{m \cdot s^{-1}}$. is used.

Atmospheric Pressure

This is the ambient pressure in cm Hg at the time of inhalation. It depends on weather conditions, elevation, and latitude. For a pressure of 54 mm Hg (a typical ambient pressure in Los Alamos, NM, elevation: 7,200 ft), the depositions were found to be significantly different for aerosols with AMAD less than about 1 micron. See Appendix B for more details.

Subject Age and Gender

These are used to scale the filtering efficiencies of the respiratory tract compartments compared to an adult male. Options include: Adult Male, Adult Female, 15 year-old Male, 15 year-old Female, 10 year-old, 1 year-old, and 3 month-old.

Nose-Breather or Mouth-Breather

These categories were defined by ICRP Publication 66 (ICRP 1994). Nose-breathers breathe exclusively through their noses except during strenuous activities, while mouth-breathers breathe through their noses and mouths regardless of the activity.

Activity

Possible exercise levels (as defined by ICRP Publication 66, hereafter referred to as ‘activities’) include various combinations of sleep, rest, light exercise, and heavy exercise. Specific combinations of these activities for the Standard Worker, Heavy Worker, and Members of the Public (varies depending on age) in ICRP Publication 66 (ICRP 1994) and ICRP Publication 71 (ICRP 1995), respectively.

Acute

This indicates whether the intake is assume to be chronic or acute, which determines whether the activities will be weighted by time or by volume of air breathed.

CALCULATING DEPOSITION OF INHALED PARTICLES

What follows is a summary of the deposition calculations recommended by ICRP Publication 66 (ICRP 1994). The purpose is to present the steps and calculations in a clear and linear way, leaving out derivations and technical explanations.

For purposes of calculating particle depositions, the ICRP (ICRP 1994) models the respiratory tract as a series of filters, each of which retains a certain fraction of any material in the air which passes through it, as well as a total fraction of the air itself. The regions defined by the ICRP are: ET1 (anterior nasal), ET2 (Naso-oropharynx/Larynx), BB (Bronchi), bb (Bronchioles), and AI (Alveolar Interstitium). These are shown in Figure 1, which was reproduced with permission from ICRP Publication 66, Page 107, Figure 42 (ICRP 1994).

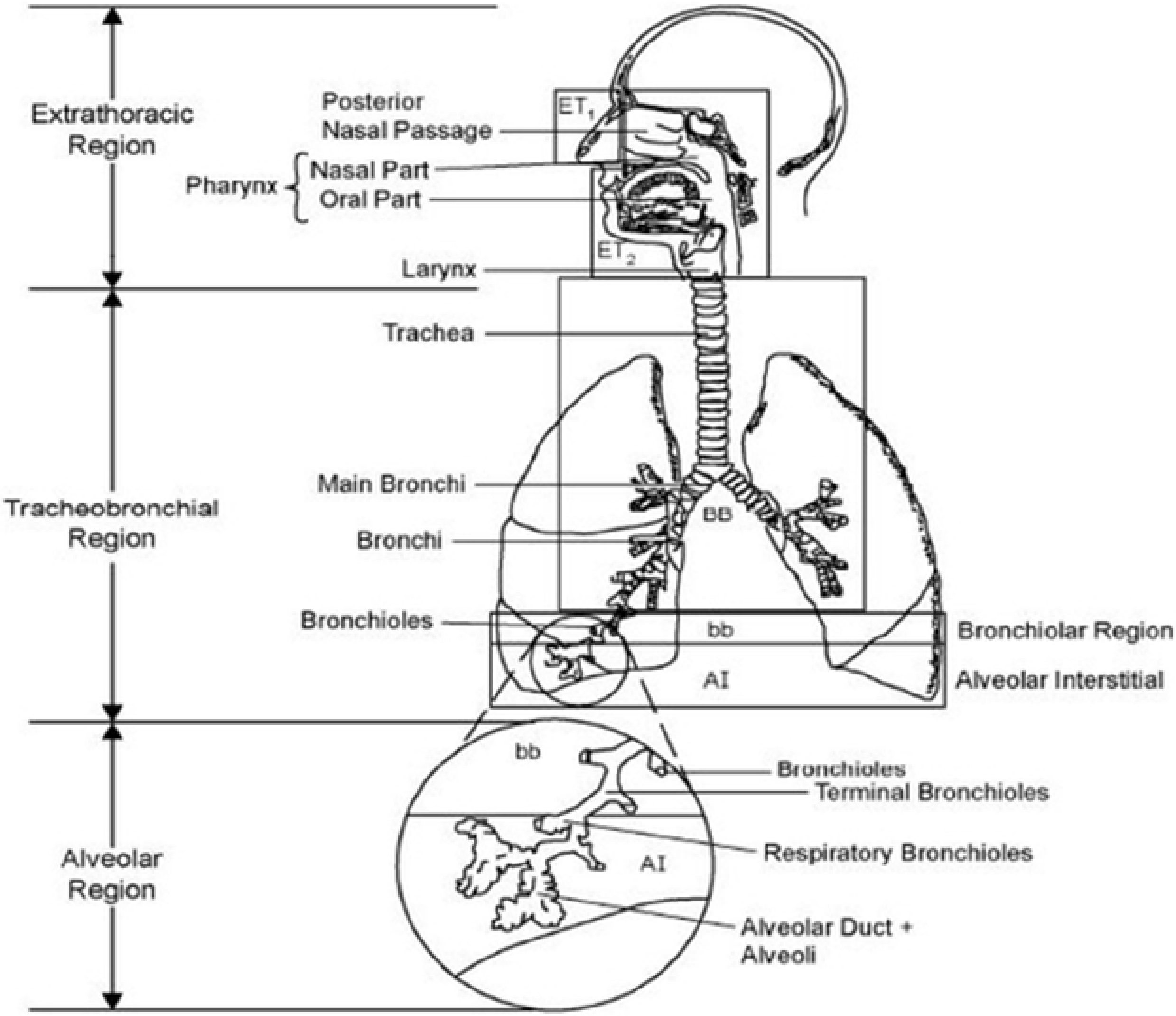

Figure 1: The anatomical regions defined in the ICRP Publication 66 lung deposition model.

For a given set of parameters, the steps to calculate the fraction of inhaled material which will be deposited in each region are as follows:

1. Calculate fractional depositions for nose breathing with a fixed particle size and activity (e.g., sleeping, light exercise, etc.), incorporating the modifications proposed in ICRP 130 (ICRP 2015).

2. Calculate depositions for mouth breathing with a fixed particle size and activity

3. Calculate the weighted sum of deposition values from steps 1 and 2 (based on fraction of air breathed through the mouth and fraction breathed through the nose associated with the activity)

4. If aerosol is log-normally dispersed, repeat steps 1 - 3 for a log-normally distributed sample of particle sizes

5. If the activity is ‘mixed,’ (e.g., Standard Work is a defined mixture of Rest and Light Exercise), repeat steps 1 - 4 for each activity

6. If the activity is ‘mixed,’ calculate the sum of deposition values from each activity, weighted by the fractional volume of air inhaled during each activity

7. Combine deposition values from inhalation and exhalation in each compartment

These steps, summarized in Figure 2, will be discussed individually. Steps 1 and 2 are significantly more complex than the others.

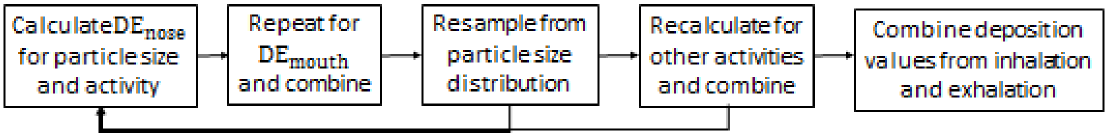

Figure 2: The steps to calculate deposition fractions using the ICRP Publication 66 model.

Steps 1 - 3: Calculating depositions for nose and mouth breathing with a fixed particle size and activity

The fraction of inhaled activity deposited in region j is called the deposition efficiency, DE_j. For computational purposes, it is convenient to consider each region as having separate deposition efficiencies for inhalation and exhalation (these are combined in step 7 to give the total fractional deposition in each region).

The deposition efficiencies of each region are a simple function of the filtration efficiencies and the volumetric factors of each region. The filtration efficiency of region j, η_j, is the fraction of activity entering the region which is deposited in that region. The volumetric factor of region j, ϕ_j, is the fraction of initially inhaled air which reaches that region. Using these definitions, the fractional deposition in each compartment can be calculated using the following recursive formula (Adapted from ICRP 66, Page 41, Equation 7)

$$DE_j = DE_{j-1}\eta_j \frac{\phi_j}{\phi_{j-1}}\left(\frac{1}{\eta_{j-1}} - 1\right), \text{for j} = 1, \mathrm{N} \qquad (1)$$

where N is the number of filters in the series. For each compartment, η_j and ϕ_j are calculated using the formulas on Tables 12 and 13 of ICRP Publication 66 (pages 45 and 46), which reference a range of other values which depend on the input parameters, and can be found in other tables throughout the report. The calculations of the volumetric fractions (ϕ_j) are straightforward and require no clarification or discussion. However, the calculation of the filtration efficiencies (η_j) is complex and not at all straightforward.

For computational purposes, each region is considered to have two filtration efficiencies - one for aerodynamic filtration (e.g., deposition via impaction and gravitational settling), η_{ae}, and one for thermodynamic filtration (e.g., deposition via diffusion), η_{th}. The total filtration efficiency of a compartment is given by the sum (in quadrature) of the aerodynamic and thermodynamic efficiencies (ICRP 66, Page 42, Eq. 10):

$$\eta = \left(\eta_{ae}^2 + \eta_{th}^2\right)^{1/2}. \tag{2}$$

The aerodynamic filtration efficiencies are reasonably straightforward to calculate given the aerodynamic equivalent diameter. However, calculating the thermodynamic filtration efficiencies requires a number of sensitive intermediate calculations.

The first step in calculating the thermodynamic filtration efficiencies is to convert the aerodynamic equivalent diameter to the thermodynamic diameter. This conversion requires establishing the correct formula for the 'slip coefficient,' $C(d, P)$, which describes the particle 'slip' in the human respiratory tract (ICRP 66, Page 239, Equations D.6 and D.7). The slip coefficient is a function of particle size, temperature in the respiratory tract (assumed to be 37°C), and atmospheric pressure. The original text contains an error in the value of λ which was later corrected (ICRP Errata for Publications 66, 68, 69, 71, 72, and 78). The correct value is $\lambda = 0.0683$. However, the correction only applies to the formula (Equation D.6) which assumes 76 cm Hg atmospheric pressure, leaving the pressure-dependent formula (Equation D.7) invalid. The correct formulation of equation D.7 can be computed as

$$C(d) = 1 + \frac{1}{Pd}\left(13.0497 + 4.153\exp(-0.106Pd)\right). \tag{3}$$

For particles smaller than 0.002 microns (2 nm) equivalent volume diameter, the particle size in the slip correction factor calculation must be modified as such (ICRP 66, Page 241, equation D.15)

$$d_{th} = d_e[1 + 3\exp(-2.20 \times 10^3 \times d_e)], \tag{4}$$

where d_e is the 'uncorrected' value of the diameter, and $d_{th}$is the updated value. In spite of the nomenclature and text (which both imply that this correction should only be applied to thermodynamic diameters), this small particle correction factor must be applied to both the aerodynamic equivalent diameter and the thermodynamic diameter. If it is not, the subsequent conversion between aerodynamic equivalent and thermodynamic diameters (essential for computing deposition of small particles) will disagree significantly with the results published by the ICRP. However, this interpretation is not explained or defended in any ICRP publication, and merits future scrutiny.

The next step is to calculate the thermodynamic diameter, which involves multiple calculations of the slip correction factor. This is accomplished using the following iterative formula (ICRP 66, Page 240, equation D.13):

$$d_{th} = d_{ae}\sqrt{\frac{\chi\rho_0}{\rho} \times \frac{C(d_{ae}, P)}{C(d_{th}, P)}}, \tag{5}$$

where χ is the dynamic shape factor, ρ is the particle density, ρ_0 is the unit density ($1\ \mathrm{g}\cdot\mathrm{cm}^{-3}$.), and P is the atmospheric pressure in mm Hg (76 cm Hg at sea level).

Having calculated the thermodynamic diameter, one can then calculate the diffusion coefficient, D, which is the quantity required to calculate η_{th} (analogous to d_{ae} in the calculation of η_{ae}), which is defined as (ICRP 66 Page 240, Equation D.11)

$$D = \frac{C(d_{th})kT}{3\pi\mu d_{th}}, \tag{6}$$

where $C(d_{th})$is the slip coefficient (using the small particle correction factor if $d_{th} < 0.002$ microns), k is Boltzman's constant (1.38×10^{-16} ergs-kelvin^{-1}), T is temperature in kelvin (310k = 37^{o}C, which is the default temperature of the respiratory tract), and μ is the dynamic efficiency of air ($1.88 \times 10^{-4}\ \mathrm{erg}\cdot\mathrm{second}\cdot\mathrm{cm}^{-3}$) . This calculation is straightforward, but requires care with units. In particular, the dynamic efficiency of air is given in units of cubic centimeters, while the diffusion coefficient and thermodynamic diameter must be in microns. If D and d_{th} are in microns, the formula can be simplified to

$$D = (2.414 \times 10^{-7}) \times \frac{C(d_{th})}{d_{th}}. \tag{7}$$

Having properly calculated the diffusion coefficient, the thermodynamic filtration efficiencies are easily calculated using the formulas on Tables 12 and 13 of ICRP Publication 66 (pages 45 and 46). Summed in quadrature with the aerodynamic filtration efficiencies calculated using the same table, one obtains the filtration efficiencies for each region in the respiratory tract. Once this is done, one must also calculate the prefiltration efficiency, η_0, of the respiratory tract (defined in ICRP 66, page 43, Equations 11 and 12), which is a delicate but not otherwise problematic calculation.

Once the prefiltration efficiency has been calculated, the deposition efficiency for the first compartment, DE_1 (which corresponds to ET1 or ET2, depending on whether the air is inhaled through the nose or mouth), is given by (ICRP 66, page 42, equation 8)

$$DE_1 = \eta_1(1 - \eta_0). \tag{8}$$

Given DE_1, the deposition efficiencies for the other compartments can be calculated using Eq. 1. ICRP Publication 130 (ICRP 2015) reported the empirical finding that, of the activity deposited in ET1 and ET2, 65% is deposited in ET1 and 35% is deposited in ET2 (ICRP 2015, Pages 154-155). The total activity deposited in these compartments is given by the sum of the depositions in each compartment on inhalation and on exhalation:

$$\mathrm{ET_{Tot}} = \mathrm{ET1_{in}} + \mathrm{ET2_{in}} + \mathrm{ET1_{ex}} + \mathrm{ET2_{ex}}, \tag{9}$$

where, for example, $\mathrm{ET1_{in}}$ is the fraction of activity deposited in ET1 on inhalation. These are then redistributed as follows:

$$\begin{aligned} \mathrm{ET1_{in}} &= 0.65 \times \mathrm{ET_{Tot}} \\ \mathrm{ET2_{in}} &= 0.35 \times \mathrm{ET_{Tot}} \end{aligned} \tag{10}$$

$$\mathrm{ET1}_{ex} = \mathrm{ET2}_{ex} = 0$$

Note that this redistribution of depositions only applies to nose-breathing, as mouth breathing can only deposit activity in ET2. Once the deposition efficiencies have been calculated for nose-breathing, they must be recalculated for mouth breathing. The deposition efficiencies for nose-breathing and mouth breathing are then averaged, weighted by the fraction of air breathed by each modality.

Step 4: If aerosol is log-normally dispersed, repeat steps 1 - 3 for a log-normally distributed sample of particle sizes

If the aerosol is log-normally dispersed, then either the AMAD or the AMTD will be given as a parameter. ICRP 66 allows either d_{ae} or d_{th} to be log-normally distributed (Page 47, equations 17 and 18) both with a geometric standard deviation which is a function of the AMTD (Page 47, equation 16). As a result, the deposition values for a log-normally dispersed aerosol always depend on the AMTD, even when thermodynamics do not play an important role in the deposition itself. Although the aerodynamic equivalent and thermodynamic diameters cannot be log-normally distributed in the same aerosol, the deposition efficiencies are broadly similar for both cases. Nonetheless, the differences are significant enough to strongly suggest that the published values were calculated by integrated over d_{ae} for all particle sizes.

While integrating over a log-normal distribution is straightforward in principal, care must be taken to accommodate a wide range of particle sizes (approximately 0.001 nm - 100 microns). In particular, the particle size intervals must be small enough to ensure accuracy, but large enough so that the probability density in that interval is never rounded to zero.

Steps 5 - 6: If the activity is 'mixed,' (e.g., Standard Work is a defined mixture of Rest and Light Exercise), repeat steps 1 -4 for each activity. Calculate the sum of deposition values from each activity, weighted by the fractional volume of air inhaled during each activity.

Conceptually, activities can be categorized as either 'pure' or 'mixed.' Sleeping, sitting, light exercise, and heavy exercise are the 'pure' activities defined in ICRP 66 as 'exercise levels.' For a given age, gender, and breathing type, each 'pure' activity involves a constant breathing rate and a specific fraction of air which is breathed through the nose. For example, a sleeping nose-breather will breathe relatively slowly and exclusively through the nose, while a mouth breather engaged in heavy exercise will breathe relatively quickly, with roughly equal volumes passing through the nose and mouth.

Mixed activities involve some combination of the pure activities. For example, ICRP Publication 66 (ICRP 1994) describes "standard work" and "heavy work," each of which assumes a certain fraction of an 8-hour work day engaged in sitting, light exercise, and heavy exercise. While the published values for occupational intakes only apply to adult males, it is straightforward to apply these calculations to women, and environmental intakes for all age groups. In addition, ICRP Publication 71 (ICRP 1995) defines standardized distributions of 'pure' activities to members of the public over a range of ages (e.g., in a typical day a 15-year-old is presumed to spend 10 hours sleeping, 5.5 hours resting, 7.5 hours doing light exercise, and 1 hour doing heavy exercise).

If the subject is engaged in a 'mixed' activity, deposition efficiencies must be calculated for each constituent 'pure' activity. These are then averaged, weighted either by the fraction of air breathed during each activity, or the fraction of time spent at each activity. Because the ICRP model was designed to model chronic, rather than acute, intakes, the published values are weighted by the fraction of air breathed, which implicitly assumes an intake which occurs over hours or days. This assumption is implicit in the definition of radiation safety quantities such as DACs and Working Levels, and is also likely a valid assumption for environmental intakes. However, users of the

ICRP respiratory tract model should keep in mind that these values are not applicable for acute intakes, which may represent a significant fraction of occupational intakes. For acute intakes, activities should be weighted by time when calculating deposition fractions. Doing so causes the fractional depositions to vary by as much as 30% in certain compartments of the respiratory tract (Table 1).

Table 1 shows that the difference in fractional depositions between chronic and acute intakes is significant, especially in the dosimetrically dominant bb and AI compartments. It is therefore important to use the correct deposition values if an intake is known to have been acute. If the type of intake is not known, this must be regarded as a significant source of uncertainty in the dose calculation.

Table 1: The percent difference in fractional deposition for intakes by the standard worker between acute and chronic intakes, calculated by KDEP.

AMAD (μm)	AMTD (μm)	ET1	ET2	BB	bb	AI	Total
0.0009	**0.0006**	0.49%	0.49%	0.64%	-12.03%	-19.74%	0.00%
0.002	**0.001**	0.76%	0.76%	3.57%	-8.89%	-18.88%	-0.02%
0.004	**0.002**	1.23%	1.23%	6.98%	-3.94%	-15.67%	-0.11%
0.006	**0.003**	1.53%	1.53%	8.66%	-0.54%	-12.57%	-0.22%
0.010	**0.005**	1.83%	1.83%	10.09%	3.12%	-8.83%	-0.44%
0.02	**0.01**	1.85%	1.85%	10.80%	5.94%	-4.98%	-0.64%
0.04	**0.02**	1.14%	1.14%	10.14%	6.58%	-2.03%	0.20%
0.06	**0.03**	0.98%	0.98%	10.07%	6.93%	-0.89%	0.89%
0.09	**0.05**	0.69%	0.69%	10.27%	7.40%	0.00%	1.50%
0.17	**0.1**	-3.67%	-3.67%	9.43%	8.01%	0.93%	1.23%
0.31	**0.2**	-8.36%	-8.36%	3.57%	9.02%	2.41%	-1.09%
0.3	0.19	-8.20%	-8.20%	4.11%	8.92%	2.27%	-0.89%
0.5	0.33	-8.90%	-8.90%	-2.20%	10.42%	4.32%	-2.92%
0.7	0.47	-8.49%	-8.49%	-4.84%	11.92%	6.13%	-3.56%
1	0.68	-7.72%	-7.72%	-6.03%	13.86%	8.29%	-3.65%
2	1.39	-5.82%	-5.82%	-5.35%	17.86%	12.78%	-2.86%
3	2.10	-4.65%	-4.65%	-3.98%	20.10%	15.50%	-2.21%
5	3.51	-3.27%	-3.27%	-1.69%	23.00%	19.07%	-1.43%
7	4.92	-2.47%	-2.47%	0.09%	25.09%	21.54%	-1.01%

10	7.05	-1.75%	-1.75%	2.18%	27.55%	24.27%	-0.65%
15	10.58	-1.10%	-1.10%	4.79%	30.70%	27.54%	-0.36%
20	14.12	-0.76%	-0.76%	6.80%	33.20%	29.97%	-0.23%

Step 7: Combine deposition values from inhalation and exhalation in each compartment

For purposes of calculating depositions, it has been convenient to consider each compartment (except AI) twice – once for inhalation and once for exhalation. The last step is to combine these into a single compartment. For example, the fraction of activity deposited in ET1 is given by $ET1 = ET1_{in} + ET1_{ex}$.

COMPARISON TO PUBLISHED VALUES

Using the methods discussed above, the published deposition values were reproduced with excellent precision. Considering ICRP Publication 130 (ICRP 2015) values for the standard worker, the percent difference, $(KDEP - ICRP)/ICRP$, is less than 3% for all compartments for all particle sizes, and is less than 0.5% in the vast majority of compartments. This demonstrates broad agreement between KDEP and the values published in ICRP Publication 130. Differences of this magnitude are easily explained by differences in numerical precision and specifics of the integration algorithm. Table 2 shows the percent differences for the standard worker.

Table 2: The percent difference in calculated fractional deposition between KDEP and LUDEP for intakes by the standard worker.

AMAD (µm)	AMTD (µm)	ET1	ET2	BB	bb	AI	Total
0.0009	0.0006	0.00%	0.00%	0.20%	-0.34%	-0.09%	-0.01%
0.002	0.001	-0.01%	-0.03%	0.25%	-0.24%	-0.06%	-0.02%
0.004	0.002	0.51%	0.52%	0.45%	-0.89%	-2.87%	0.04%
0.006	0.003	0.14%	0.18%	0.43%	-0.17%	-0.49%	0.00%
0.010	0.005	0.02%	0.08%	0.34%	-0.10%	-0.05%	-0.02%
0.02	0.01	-0.03%	0.00%	0.36%	-0.09%	-0.03%	-0.03%
0.04	0.02	0.01%	-0.01%	0.33%	-0.15%	-0.03%	-0.03%
0.06	0.03	-0.01%	0.01%	0.29%	-0.09%	-0.03%	-0.03%
0.09	0.05	-0.01%	-0.05%	0.32%	-0.10%	-0.03%	-0.04%
0.17	0.1	-0.04%	-0.04%	0.29%	-0.10%	-0.05%	-0.06%
0.31	0.2	-0.05%	-0.06%	0.18%	-0.12%	-0.05%	-0.05%
0.3	0.19	-0.06%	-0.06%	0.19%	-0.10%	-0.03%	-0.05%
0.5	0.33	-0.07%	-0.06%	0.06%	-0.08%	-0.05%	-0.07%
0.7	0.47	-0.08%	-0.05%	0.01%	-0.10%	-0.06%	-0.07%
1	0.68	-0.06%	-0.09%	0.02%	-0.05%	-0.03%	-0.05%
2	1.39	-0.05%	-0.02%	0.02%	-0.04%	-0.04%	-0.04%
3	2.10	-0.05%	-0.04%	-0.06%	-0.09%	-0.04%	-0.04%
5	3.51	-0.04%	-0.05%	-0.07%	-0.06%	-0.03%	-0.05%
7	4.92	-0.02%	-0.01%	-0.04%	-0.02%	-0.02%	-0.02%
10	7.05	0.02%	0.02%	-0.03%	0.02%	0.02%	0.02%
15	10.58	0.15%	0.13%	0.21%	0.20%	0.19%	0.15%
20	14.12	0.36%	0.35%	0.59%	0.57%	0.56%	0.37%

Similar agreement can be found with the published values for environmental intakes. Depositions from environmental intakes as a function of AMAD based on ICRP Publication 66 (ICRP 1994) and ICRP Publication 71 (ICRP 1995) were published in digital form, and are freely distributed by the ICRP (Eckermam et. al. 2001). The percent difference between KDEP and the published values for environmental intakes of default 1 micron AMAD intakes in male nose-breathing subjects (ICRP 71, page 12, Table 7) is less than 0.5% for all subjects and in all compartments (Table 3). All calculations assume 1 micron AMAD aerosols and a nose-breathing subject. This shows broad agreement between KDEP and the environmental deposition values published in ICRP Publication 71. The close agreement indicates that KDEP has duplicated the LUDEP implementation of the ICRP respiratory tract deposition model.

Table 3: The percent difference in fractional deposition between KDEP and LUDEP for intakes by members of the public. All calculations assume 1 micron AMAD aerosols and a nose-breathing subject.

Subject	ET1	ET2	BB	bb	AI	Total
3 Month-Old	0.19%	0.22%	0.26%	-0.48%	-1.38%	-0.04%
1 Year-Old	-0.17%	-0.18%	0.00%	0.04%	0.81%	-0.01%
5 Year-Old	-0.33%	-0.34%	0.36%	0.15%	0.09%	-0.22%
10 Year-Old	0.10%	0.12%	-0.37%	-0.34%	0.67%	0.19%
15 Year-Old (male)	0.07%	0.14%	-0.05%	-0.27%	-0.50%	-0.05%
Adult (male)	-0.05%	-0.02%	-0.31%	-0.09%	-0.06%	-0.05%

NOTEWORTHY FEATURES THE CALCULATION OF PUBLISHED VALUES

The agreement between the authors' code and the published values does not verify the published values, but rather confirms the above description of how the published values were calculated. As discussed below, the calculation of deposition values for particles in the thermodynamic size range contains several concerning aspects. These include:

-Only integrating over aerodynamic equivalent diameter:

Integrating over the aerodynamic equivalent diameter rather than thermodynamic diameter can change the deposition fractions by as much as 10% in the 0.1 - 0.5 micron AMTD range. Even when the published values are reported as a function AMTD (In ICRP Publication 130, this is done for particle sizes of 0.2 microns or less), they should be assumed to correspond to an aerosol log-normally distributed around the corresponding aerodynamic equivalent diameter. Table 4 shows the percent difference between KDEP and ICRP Publication 130 (ICRP 2015) for the standard worker when KDEP integrates over the thermodynamic diameter rather than the aerodynamic equivalent diameter.

Integrating over the thermodynamic diameter has the greatest impact when the AMTD is in the range of 0.1 - 0.2 microns. The authors speculate that the differences become more apparent for larger aerosols because the geometric standard deviation approaches unity when the AMTD is less than about 0.1 micron.

Table 4: The percent difference in fractional deposition for intakes by the standard worker between a log-normally distributed thermodynamic diameter and a log-normally distributed aerodynamic diameter, calculated by KDEP.

AMAD (µm)	AMTD (µm)	ET1	ET2	BB	bb	AI	Total
0.0009	**0.0006**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.002	**0.001**	0.00%	0.00%	0.00%	0.00%	0.01%	0.00%
0.004	**0.002**	-0.03%	-0.03%	-0.01%	0.04%	0.15%	0.00%
0.006	**0.003**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.010	**0.005**	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
0.02	**0.01**	-0.02%	-0.02%	-0.02%	0.00%	0.03%	0.01%
0.04	**0.02**	-0.13%	-0.13%	-0.17%	-0.01%	0.33%	0.19%
0.06	**0.03**	-0.26%	-0.26%	-0.35%	-0.05%	0.58%	0.34%
0.09	**0.05**	-1.56%	-1.56%	-0.95%	-0.60%	0.26%	-0.16%
0.17	**0.1**	-8.33%	-8.33%	-3.60%	-2.74%	-2.33%	-3.60%
0.31	**0.2**	-6.78%	-6.78%	-5.86%	-5.04%	-4.76%	-5.60%

-Applying the small particle correction factor to small aerodynamic diameters:

As mentioned in the discussion of steps 1-3 of calculating depositions, it is not clear whether the small particle correction factor for particles smaller than 2 nm should be applied to aerodynamic equivalent diameters as well as thermodynamic diameters in the iterative formula converting between d_{ae} and d_{th}. In practice this should be irrelevant, because at this size range the AMAD is virtually irrelevant for deposition and impossible to measure. The correct practice would be to start with the AMTD and integrate over d_{th}. However, it is not possible to attain agreement with the published values using that method. Table 5 shows the percent difference between KDEP and ICRP Publication 130 (ICRP 2015) for the standard worker when KDEP only applies the small particle correction factor to the thermodynamic diameter. As expected, the difference is only significant in aerosols composed of very small particles.

Table 5: The percent difference in fractional deposition for intakes by the standard worker between when the small particle correction factor is applied only to the thermodynamic diameter and when it is applied to thermodynamic and aerodynamic diameters.

AMAD (μm)	AMTD (μm)	ET1	ET2	BB	bb	AI	Total
0.0009	0.0006	-3.66%	-3.66%	16.46%	49.97%	209.30%	-0.27%
0.002	0.001	-1.38%	-1.38%	1.97%	7.84%	23.95%	-0.11%
0.004	0.002	-0.13%	-0.13%	-0.04%	0.20%	0.74%	-0.01%

Dealing with the specific concerns related to calculating depositions of aerosols in the thermodynamic size range is outside the scope of this paper, and will be examined closely in a future publication. For the time being, the published values for particles smaller than 0.002 nm AMTD should be used with caution.

NEW DEPOSITION TABLES FOR ENVIRONMENTAL INTAKES

Having demonstrated an ability to reproduce the published values, KDEP can be used with confidence to generate deposition values for other sets of parameters. It is also straightforward to apply the changes implemented for workers in ICRP Publication 130 (ICRP 2015) to environmental intakes. This was done for male and female members of the public across a range of particle sizes. The results are presented in Appendix A.

Because this paper does not set out to implement specific improvements to the model, the issue regarding the small particle correction size was not addressed. However, for cases where the thermodynamic diameter is dominant (i.e., when the AMAD is less than 0.3 microns), depositions were calculated for a log-normally dispersed thermodynamic diameter rather than a log-normally dispersed aerodynamic equivalent diameter. This is in disagreement with the LUDEP implementation, but the authors felt it was more consistent with the ICRP method.

CONCLUSION

This paper presents KDEP, an open-source implementation the ICRP lung deposition model. In presenting KDEP, it describes how this model was implemented. The description was validated by reproducing the published values which were originally calculated by LUDEP. KDEP is freely available to the public, and can be used to calculate fractional depositions of radioactive aerosols under a variety of different conditions.

It was pointed out that all published deposition values correspond to chronic intakes (weighting activities by volume of air breathed rather than time). The difference in deposition values for chronic and acute intakes is significant, so it is important to use deposition values corresponding to the correct mode of intake whenever possible. KDEP meets the need of generating deposition values for acute intakes using the ICRP methodology.

Some of the technical aspects of the implementation of the ICRP model were found to be questionable, particularly aspects related to aerosols described by their AMTD (0.2 microns and smaller). KDEP is able to generate deposition values by integrating over the thermodynamic diameter using the ICRP methodology. This is appropriate in cases where the thermodynamic diameter is known to be log-normal. The correct application of the small particle correction factor, affecting particles less than 0.002 microns AMAD, is uncertain, so published deposition values for aerosols in that size range should be used with caution.

Finally, fractional depositions were calculated for inhalation of radioactive aerosols by members of the public. This does for the deposition tables generated via ICRP Publication 71 what ICRP Publication 130 did for the deposition tables ICRP Publication 66, except that it integrates over the thermodynamic diameter where appropriate.

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APPENDIX A

Fractional depositions for environmental exposures of members of the public are presented. These values were calculated using KDEP, which implements a method consistent with that used to generate the values published in ICRP Publication 66 (ICRP 1994), ICRP Publication 71 (ICRP 1995), and ICRP Publication 130 (ICRP 2015). All depositions are weighted by the volume of air breathed rather than by the time spent at each activity, as is appropriate for environmental intakes where individuals may breathe a contaminated aerosol for many hours or days. The time spent at each activity was taken from ICRP Publication 71. In accordance with ICRP Publication 130, 65% of the total deposition in the ET compartments is assigned to ET1, while the other 35% is assigned to ET2. All values are for nose-breathing members of the public using aerosols with log normally dispersed aerodynamic or thermodynamic diameters.

Note that the deposition of log-normally dispersed thermodynamic diameters will be slightly different from that of log-normally dispersed aerodynamic diameters. The diameter which is log-normally dispersed is shown in bold. The deposition values were calculated using the LUDEP implementation of the small particle correction factor. Although the authors have questioned the practice of applying small particle correction factors to aerodynamic diameters in the LUDEP implementation, proposing a change would be outside the scope of this paper. However, the source code can be easily modified to implement an alternative interpretation of the correction factor.

Table A1: The fractional deposition for chronic environmental intakes by an adult male, calculated by KDEP.

AMAD (µm)	**AMTD (µm)**	**ET1**	**ET2**	**BB**	**bb**	**AI**	**Total**
0.0009	**0.0006**	0.5745	0.3208	0.0608	0.0363	0.0004	0.9927
0.002	**0.001**	0.5182	0.2882	0.0846	0.0898	0.0036	0.9844
0.004	**0.002**	0.4028	0.2230	0.0955	0.2044	0.0372	0.9629
0.006	**0.003**	0.3156	0.1744	0.0846	0.2626	0.1050	0.9422
0.010	**0.005**	0.2160	0.1191	0.0612	0.2693	0.2471	0.9127
0.02	**0.01**	0.1212	0.0668	0.0338	0.1999	0.4458	0.8675
0.04	**0.02**	0.0727	0.0401	0.0196	0.1347	0.4736	0.7408
0.06	**0.03**	0.0565	0.0312	0.0152	0.1064	0.4074	0.6167
0.09	**0.05**	0.0420	0.0232	0.0114	0.0778	0.3076	0.4621
0.17	**0.1**	0.0364	0.0200	0.0079	0.0496	0.2015	0.3154
0.31	**0.2**	0.0626	0.0340	0.0067	0.0312	0.1399	0.2745
0.3	0.19	0.0642	0.0349	0.0071	0.0338	0.1497	0.2896
0.5	0.33	0.1134	0.0615	0.0083	0.0246	0.1251	0.3328
0.7	0.47	0.1600	0.0868	0.0101	0.0213	0.1181	0.3963
1	0.68	0.2193	0.1192	0.0129	0.0195	0.1147	0.4856
2	1.39	0.3435	0.1877	0.0186	0.0185	0.1043	0.6727
3	2.10	0.4047	0.2221	0.0207	0.0176	0.0900	0.7551
5	3.51	0.4527	0.2500	0.0205	0.0148	0.0645	0.8025
7	4.92	0.4631	0.2568	0.0185	0.0121	0.0468	0.7973
10	7.05	0.4571	0.2546	0.0154	0.0089	0.0303	0.7663
15	10.58	0.4352	0.2435	0.0112	0.0056	0.0164	0.7119
20	14.12	0.4150	0.2328	0.0084	0.0037	0.0098	0.6697

Table A2: The fractional deposition for chronic environmental intakes by an adult female, calculated by KDEP.

AMAD (µm)	AMTD (µm)	ET1	ET2	BB	bb	AI	Total
0.0009	**0.0006**	0.5750	0.3225	0.0615	0.0336	0.0002	0.9927
0.002	**0.001**	0.5195	0.2901	0.0870	0.0851	0.0026	0.9843
0.004	**0.002**	0.4049	0.2250	0.1003	0.2016	0.0302	0.9620
0.006	**0.003**	0.3179	0.1762	0.0899	0.2660	0.0902	0.9401
0.010	**0.005**	0.2180	0.1205	0.0657	0.2812	0.2225	0.9079
0.02	**0.01**	0.1224	0.0677	0.0365	0.2148	0.4169	0.8583
0.04	**0.02**	0.0733	0.0406	0.0212	0.1469	0.4501	0.7322
0.06	**0.03**	0.0570	0.0315	0.0165	0.1166	0.3887	0.6103
0.09	**0.05**	0.0424	0.0235	0.0123	0.0856	0.2943	0.4581
0.17	**0.1**	0.0373	0.0205	0.0085	0.0548	0.1930	0.3141
0.31	**0.2**	0.0649	0.0353	0.0071	0.0345	0.1340	0.2759
0.3	0.19	0.0665	0.0362	0.0075	0.0374	0.1433	0.2908
0.5	0.33	0.1170	0.0635	0.0085	0.0271	0.1193	0.3355
0.7	0.47	0.1644	0.0893	0.0103	0.0233	0.1122	0.3995
1	0.68	0.2242	0.1221	0.0129	0.0211	0.1084	0.4886
2	1.39	0.3478	0.1906	0.0183	0.0196	0.0977	0.6740
3	2.10	0.4079	0.2247	0.0202	0.0185	0.0839	0.7552
5	3.51	0.4544	0.2520	0.0199	0.0154	0.0600	0.8016
7	4.92	0.4639	0.2585	0.0179	0.0125	0.0435	0.7962
10	7.05	0.4572	0.2560	0.0148	0.0092	0.0282	0.7652
15	10.58	0.4348	0.2446	0.0107	0.0057	0.0152	0.7111
20	14.12	0.4144	0.2338	0.0080	0.0038	0.0091	0.6692

Table A3: The fractional deposition for chronic environmental intakes by a 15 year-old male, calculated by KDEP.

AMAD (μm)	AMTD (μm)	ET1	ET2	BB	bb	AI	Total
0.0009	**0.0006**	0.5435	0.3417	0.0639	0.0412	0.0008	0.9911
0.002	**0.001**	0.4911	0.3040	0.0870	0.0939	0.0055	0.9815
0.004	**0.002**	0.3827	0.2324	0.0970	0.2017	0.0429	0.9568
0.006	**0.003**	0.3004	0.1808	0.0859	0.2553	0.1110	0.9334
0.010	**0.005**	0.2060	0.1230	0.0622	0.2607	0.2482	0.9001
0.02	**0.01**	0.1161	0.0693	0.0345	0.1950	0.4320	0.8468
0.04	**0.02**	0.0702	0.0420	0.0202	0.1327	0.4448	0.7099
0.06	**0.03**	0.0546	0.0327	0.0157	0.1049	0.3780	0.5859
0.09	**0.05**	0.0406	0.0243	0.0117	0.0766	0.2827	0.4359
0.17	**0.1**	0.0348	0.0203	0.0082	0.0488	0.1836	0.2957
0.31	**0.2**	0.0589	0.0330	0.0074	0.0307	0.1270	0.2569
0.3	0.19	0.0604	0.0339	0.0078	0.0332	0.1361	0.2714
0.5	0.33	0.1062	0.0591	0.0098	0.0244	0.1139	0.3135
0.7	0.47	0.1497	0.0837	0.0127	0.0213	0.1082	0.3756
1	0.68	0.2051	0.1156	0.0169	0.0199	0.1060	0.4636
2	1.39	0.3216	0.1859	0.0260	0.0199	0.0981	0.6516
3	2.10	0.3794	0.2234	0.0296	0.0193	0.0855	0.7373
5	3.51	0.4250	0.2569	0.0299	0.0165	0.0620	0.7904
7	4.92	0.4352	0.2676	0.0272	0.0136	0.0453	0.7889
10	7.05	0.4300	0.2690	0.0225	0.0100	0.0295	0.7610
15	10.58	0.4098	0.2608	0.0163	0.0063	0.0160	0.7092
20	14.12	0.3910	0.2513	0.0121	0.0041	0.0096	0.6681

Table A4: The fractional deposition for chronic environmental intakes by a 15 year-old female, calculated by KDEP.

AMAD (µm)	AMTD (µm)	ET1	ET2	BB	bb	AI	Total
0.0009	**0.0006**	0.5447	0.3418	0.0644	0.0398	0.0007	0.9913
0.002	**0.001**	0.4924	0.3042	0.0883	0.0918	0.0050	0.9818
0.004	**0.002**	0.3841	0.2329	0.0995	0.1995	0.0412	0.9571
0.006	**0.003**	0.3017	0.1812	0.0885	0.2542	0.1078	0.9335
0.010	**0.005**	0.2069	0.1234	0.0644	0.2618	0.2430	0.8997
0.02	**0.01**	0.1166	0.0694	0.0358	0.1974	0.4269	0.8461
0.04	**0.02**	0.0703	0.0421	0.0209	0.1347	0.4433	0.7113
0.06	**0.03**	0.0547	0.0327	0.0162	0.1066	0.3780	0.5883
0.09	**0.05**	0.0407	0.0243	0.0121	0.0780	0.2835	0.4386
0.17	**0.1**	0.0357	0.0208	0.0085	0.0497	0.1845	0.2992
0.31	**0.2**	0.0619	0.0346	0.0076	0.0313	0.1274	0.2627
0.3	0.19	0.0633	0.0355	0.0080	0.0339	0.1365	0.2772
0.5	0.33	0.1110	0.0618	0.0099	0.0247	0.1138	0.3212
0.7	0.47	0.1557	0.0869	0.0127	0.0215	0.1075	0.3843
1	0.68	0.2120	0.1193	0.0167	0.0199	0.1046	0.4726
2	1.39	0.3285	0.1896	0.0253	0.0196	0.0958	0.6588
3	2.10	0.3853	0.2266	0.0287	0.0189	0.0830	0.7425
5	3.51	0.4293	0.2590	0.0287	0.0162	0.0599	0.7931
7	4.92	0.4384	0.2690	0.0261	0.0132	0.0437	0.7904
10	7.05	0.4322	0.2698	0.0215	0.0098	0.0284	0.7617
15	10.58	0.4113	0.2611	0.0155	0.0061	0.0154	0.7094
20	14.12	0.3921	0.2514	0.0115	0.0040	0.0092	0.6682

Table A5: The fractional deposition for chronic environmental intakes by a 10 year-old, calculated by KDEP.

AMAD (µm)	AMTD (µm)	ET1	ET2	BB	bb	AI	Total
0.0009	**0.0006**	0.5859	0.3155	0.0609	0.0301	0.0002	0.9926
0.002	**0.001**	0.5293	0.2850	0.0875	0.0792	0.0027	0.9836
0.004	**0.002**	0.4124	0.2221	0.1020	0.1913	0.0319	0.9597
0.006	**0.003**	0.3237	0.1743	0.0918	0.2524	0.0941	0.9362
0.010	**0.005**	0.2219	0.1195	0.0672	0.2652	0.2282	0.9020
0.02	**0.01**	0.1248	0.0672	0.0375	0.2012	0.4195	0.8502
0.04	**0.02**	0.0751	0.0405	0.0219	0.1371	0.4464	0.7211
0.06	**0.03**	0.0584	0.0315	0.0170	0.1086	0.3838	0.5993
0.09	**0.05**	0.0439	0.0236	0.0127	0.0795	0.2895	0.4493
0.17	**0.1**	0.0426	0.0230	0.0088	0.0507	0.1889	0.3140
0.31	**0.2**	0.0811	0.0437	0.0073	0.0314	0.1289	0.2924
0.3	0.19	0.0824	0.0444	0.0077	0.0340	0.1381	0.3066
0.5	0.33	0.1440	0.0775	0.0084	0.0239	0.1116	0.3654
0.7	0.47	0.1985	0.1069	0.0097	0.0197	0.1022	0.4370
1	0.68	0.2643	0.1423	0.0117	0.0169	0.0957	0.5309
2	1.39	0.3915	0.2108	0.0152	0.0143	0.0815	0.7133
3	2.10	0.4484	0.2415	0.0159	0.0129	0.0679	0.7867
5	3.51	0.4872	0.2623	0.0148	0.0104	0.0469	0.8216
7	4.92	0.4908	0.2643	0.0130	0.0083	0.0333	0.8095
10	7.05	0.4782	0.2575	0.0104	0.0059	0.0211	0.7732
15	10.58	0.4504	0.2425	0.0074	0.0036	0.0111	0.7151
20	14.12	0.4271	0.2300	0.0054	0.0024	0.0065	0.6715

Table A6: The fractional deposition for chronic environmental intakes by a 5 year-old, calculated by KDEP.

AMAD (µm)	AMTD (µm)	ET1	ET2	BB	bb	AI	Total
0.0009	**0.0006**	0.5932	0.3194	0.0636	0.0166	0.0000	0.9929
0.002	**0.001**	0.5396	0.2905	0.0988	0.0540	0.0006	0.9836
0.004	**0.002**	0.4252	0.2290	0.1246	0.1645	0.0139	0.9572
0.006	**0.003**	0.3361	0.1810	0.1160	0.2429	0.0539	0.9298
0.010	**0.005**	0.2320	0.1249	0.0873	0.2806	0.1626	0.8875
0.02	**0.01**	0.1304	0.0702	0.0492	0.2258	0.3518	0.8274
0.04	**0.02**	0.0770	0.0414	0.0284	0.1553	0.4150	0.7172
0.06	**0.03**	0.0596	0.0321	0.0220	0.1238	0.3702	0.6077
0.09	**0.05**	0.0446	0.0240	0.0165	0.0915	0.2874	0.4641
0.17	**0.1**	0.0416	0.0224	0.0113	0.0590	0.1921	0.3264
0.31	**0.2**	0.0768	0.0414	0.0085	0.0367	0.1330	0.2965
0.3	0.19	0.0783	0.0422	0.0090	0.0397	0.1418	0.3110
0.5	0.33	0.1377	0.0742	0.0085	0.0276	0.1153	0.3633
0.7	0.47	0.1915	0.1031	0.0091	0.0223	0.1055	0.4315
1	0.68	0.2572	0.1385	0.0103	0.0185	0.0986	0.5232
2	1.39	0.3869	0.2083	0.0130	0.0145	0.0831	0.7059
3	2.10	0.4459	0.2401	0.0137	0.0126	0.0688	0.7812
5	3.51	0.4867	0.2621	0.0130	0.0098	0.0471	0.8186
7	4.92	0.4911	0.2644	0.0115	0.0077	0.0331	0.8078
10	7.05	0.4789	0.2579	0.0093	0.0054	0.0208	0.7723
15	10.58	0.4510	0.2429	0.0067	0.0033	0.0109	0.7148
20	14.12	0.4276	0.2303	0.0050	0.0021	0.0063	0.6714

Table A7: The fractional deposition for chronic environmental intakes by a 1 year-old, calculated by KDEP.

AMAD (μm)	**AMTD (μm)**	**ET1**	**ET2**	**BB**	**bb**	**AI**	**Total**
0.0009	**0.0006**	0.5959	0.3209	0.0682	0.0100	0.0000	0.9950
0.002	**0.001**	0.5435	0.2927	0.1124	0.0390	0.0002	0.9879
0.004	**0.002**	0.4303	0.2317	0.1521	0.1434	0.0080	0.9654
0.006	**0.003**	0.3411	0.1837	0.1462	0.2316	0.0375	0.9400
0.010	**0.005**	0.2362	0.1272	0.1130	0.2896	0.1312	0.8971
0.02	**0.01**	0.1323	0.0712	0.0645	0.2446	0.3216	0.8341
0.04	**0.02**	0.0750	0.0404	0.0359	0.1646	0.4356	0.7516
0.06	**0.03**	0.0571	0.0308	0.0275	0.1305	0.4156	0.6614
0.09	**0.05**	0.0436	0.0235	0.0206	0.0972	0.3411	0.5260
0.17	**0.1**	0.0496	0.0267	0.0142	0.0635	0.2373	0.3913
0.31	**0.2**	0.1038	0.0559	0.0105	0.0395	0.1625	0.3721
0.3	0.19	0.1045	0.0562	0.0111	0.0426	0.1720	0.3863
0.5	0.33	0.1801	0.0970	0.0099	0.0287	0.1317	0.4474
0.7	0.47	0.2425	0.1306	0.0099	0.0222	0.1129	0.5181
1	0.68	0.3139	0.1690	0.0104	0.0171	0.0972	0.6075
2	1.39	0.4405	0.2372	0.0115	0.0109	0.0701	0.7702
3	2.10	0.4905	0.2641	0.0115	0.0085	0.0536	0.8283
5	3.51	0.5172	0.2785	0.0101	0.0059	0.0336	0.8454
7	4.92	0.5128	0.2761	0.0086	0.0044	0.0225	0.8245
10	7.05	0.4930	0.2655	0.0068	0.0029	0.0134	0.7816
15	10.58	0.4590	0.2471	0.0047	0.0017	0.0066	0.7191
20	14.12	0.4326	0.2329	0.0034	0.0011	0.0037	0.6737

Table A8: The fractional deposition for chronic environmental intakes by a 3 month-old, calculated by KDEP.

AMAD (µm)	AMTD (µm)	ET1	ET2	BB	bb	AI	Total
0.0009	**0.0006**	0.6016	0.3240	0.0659	0.0040	0.0000	0.9956
0.002	**0.001**	0.5519	0.2972	0.1188	0.0212	0.0000	0.9891
0.004	**0.002**	0.4414	0.2377	0.1799	0.1054	0.0025	0.9669
0.006	**0.003**	0.3522	0.1897	0.1829	0.1980	0.0167	0.9396
0.010	**0.005**	0.2455	0.1322	0.1483	0.2854	0.0779	0.8892
0.02	**0.01**	0.1382	0.0744	0.0874	0.2702	0.2354	0.8056
0.04	**0.02**	0.0778	0.0419	0.0489	0.1904	0.3547	0.7137
0.06	**0.03**	0.0589	0.0317	0.0373	0.1527	0.3506	0.6312
0.09	**0.05**	0.0447	0.0241	0.0280	0.1150	0.2957	0.5075
0.17	**0.1**	0.0499	0.0269	0.0193	0.0760	0.2099	0.3819
0.31	**0.2**	0.1034	0.0557	0.0135	0.0478	0.1447	0.3650
0.3	0.19	0.1041	0.0561	0.0143	0.0513	0.1525	0.3784
0.5	0.33	0.1796	0.0967	0.0116	0.0348	0.1164	0.4390
0.7	0.47	0.2421	0.1304	0.0107	0.0268	0.0990	0.5090
1	0.68	0.3138	0.1689	0.0104	0.0204	0.0844	0.5980
2	1.39	0.4410	0.2374	0.0105	0.0125	0.0600	0.7614
3	2.10	0.4912	0.2645	0.0102	0.0094	0.0457	0.8210
5	3.51	0.5179	0.2789	0.0090	0.0063	0.0286	0.8406
7	4.92	0.5134	0.2764	0.0077	0.0046	0.0192	0.8212
10	7.05	0.4934	0.2657	0.0060	0.0030	0.0115	0.7796
15	10.58	0.4592	0.2472	0.0042	0.0017	0.0057	0.7181
20	14.12	0.4327	0.2330	0.0031	0.0011	0.0032	0.6731

APPENDIX B

The authors used KDEP to evaluate the effects of atmospheric pressure at altitude on lung deposition. The expected percent difference in lung deposition between Los Alamos, NM (altitude 7,200 ft. typical atmospheric pressure around 54 mm Hg) and sea level (76 mm Hg) is shown in Table B1. The differences are particularly significant for the dosimetrically dominant AI region, and should be accounted for with aerosols with an AMAD less than about 1 micron.

Table B1: The percent difference in fractional deposition for intakes by the standard worker between the atmospheric pressure at 7,200 feet (approximately 54 mm Hg) and the default atmospheric pressure at sea level (76 mm Hg).

AMAD (µm)	AMTD (µm)	ET1	ET2	BB	bb	AI	Total
0.0009	**0.0006**	3.61%	3.61%	-21.27%	-43.23%	-79.49%	0.25%
0.002	**0.001**	5.75%	5.75%	-10.97%	-31.82%	-65.89%	0.43%
0.004	**0.002**	9.44%	9.44%	1.35%	-15.99%	-44.88%	0.74%
0.006	**0.003**	11.91%	11.91%	7.88%	-6.38%	-32.54%	0.92%
0.010	**0.005**	14.37%	14.37%	13.88%	3.36%	-20.40%	0.97%
0.02	**0.01**	15.36%	15.36%	17.35%	10.18%	-8.40%	1.52%
0.04	**0.02**	12.51%	12.51%	15.48%	10.55%	2.66%	5.79%
0.06	**0.03**	11.61%	11.61%	14.86%	11.01%	7.25%	8.65%
0.09	**0.05**	9.90%	9.90%	14.18%	11.11%	9.95%	10.22%
0.17	**0.1**	-0.13%	-0.13%	10.15%	8.90%	8.50%	6.89%
0.31	**0.2**	-2.99%	-2.99%	3.31%	5.35%	4.56%	1.68%
0.3	0.19	2.13%	2.13%	10.59%	13.44%	11.54%	8.21%
0.5	0.33	0.62%	0.62%	5.22%	11.35%	8.51%	4.15%
0.7	0.47	0.26%	0.26%	2.79%	9.02%	6.03%	2.26%
1	0.68	0.09%	0.09%	1.32%	6.22%	3.75%	1.08%
2	1.39	0.01%	0.01%	0.27%	2.18%	1.21%	0.22%
3	2.10	0.00%	0.00%	0.10%	1.04%	0.58%	0.08%
5	3.51	0.00%	0.00%	0.03%	0.39%	0.23%	0.02%
7	4.92	0.00%	0.00%	0.01%	0.20%	0.12%	0.01%
10	7.05	0.00%	0.00%	0.00%	0.10%	0.07%	0.00%
15	10.58	0.00%	0.00%	0.00%	0.04%	0.03%	0.00%
20	14.12	0.00%	0.00%	0.00%	0.02%	0.02%	0.00%