THE ROYAL SOCIETY

The health hazards of depleted uranium munitions, part II
Annexe B: Estimates of DU intakes from resuspension of soil

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B1 Introduction

Two approaches have been used for estimating the intake of resuspended depleted uranium (DU): a resuspension factor approach and a dust loading approach. Another approach not used here is use of a resuspension rate Λ (s^{-1}), defined as the ratio of resuspension flux (Bq m^{-2} s^{-1}) to the surface deposit (Bq m^{-2}). This approach cannot easily be applied without site-specific data.

The only exposure pathway that has been considered here is the inhalation of resuspended DU. No consideration has been given to external exposures, ingestion of contaminated food or water, or inadvertent ingestion of contaminated soil. Two scenarios have been considered here: intakes of DU by soldiers over four weeks, and by a family over 50 years.

Uncertainties associated with estimates of resuspended air concentrations are large and are discussed later (Section B5).

B2 Scenario one

Soldiers spend four weeks in an area freshly contaminated with 1 g m^{-2} DU. All of the DU is assumed respirable, and the activities of the soldiers are assumed to cause enhanced resuspension of the DU owing to normal heavy vehicle movements. It is not assumed that the soldiers are undertaking digging, ploughing or clearance operations.

Two sets of estimates are provided, a 'best estimate' and 'worst case'. The best estimate assumes UK-like conditions and soldiers with breathing rates typical of average European adults engaged in a general range of activities. The worst-case estimates assume arid, dusty conditions and soldiers with enhanced breathing rates during the working day. The estimates have been provided for intakes over each one-week period during the four-week exposure.

B3 Scenario two

Families live normally in an area initially contaminated with 1 g m^{-2} DU for a number of years. The contamination is freshly deposited at the start of the time period. Intakes are estimated for exposure over the first month, the first year (including the first month), each subsequent year up to ten years and the total up to 50 years. Intakes are estimated for adults, ten year old children and one year old children in each time period. Average breathing rates for each of these age groups are adopted for all estimates.

Two sets of estimates are provided, a 'best estimate' and 'worst case'. The best estimate assumes UK-like conditions and that the individuals spend 90% of their time inside solidly constructed buildings. An appropriate reduction factor for exposure to resuspended material whilst indoors was estimated using literature values. It should be noted that this assumption is made for completeness, rather than because it makes a significant difference to the estimates, given the large uncertainties. The worst case estimates assume arid, dusty conditions and that the individuals are permanently outdoors during the exposure periods.

B4 Resuspension factor approach

One approach often used to calculate resuspended air concentrations uses the *resuspension factor* K, defined as

$$K(\mathrm{m}^{-1}) = \frac{\text{concentration in air due to resuspension } (\mathrm{g\,m}^{-3})}{\text{concentration of surface deposit } (\mathrm{g\,m}^{-2})} \qquad (1)$$

This allows a convenient way of expressing the observed relationship between surface and air concentrations, but with a number of limitations. There is an implicit assumption that the measured airborne concentration originates solely from an area local to the surface sampling position. In practice, the airborne contamination at any location will include resuspended material from a range of upwind sources, which may be contaminated at varying levels. Also, reported resuspension factors tend to be time averaged. They may give erroneous predictions of instantaneous air concentrations, for example in conditions when there is little or no wind or other disturbances. K has the drawback that it must depend on the variation of the surface deposit with distance from the point of measurement. The value of K will also depend on the depth of surface material sampled in order to determine surface contamination. Since the processes of transfer up into the atmosphere and down into the soil are poorly understood, there is no obvious basis for choice, and some of the variations in the values of K reported in the literature might be due to the adoption of different sampling depths.

A variation of resuspension rate with particle size would be expected because aerodynamic lift force will increase with wind speed and particle area. A change in chemical form of contaminant may have the effect of increasing or decreasing the effective size distribution of the contaminant. Chemical form may also dictate whether particles remain unattached, or attach to host material, effectively increasing their aerodynamic diameters. However, the magnitude of variations in K due to particle size and chemical form has not been quantified in the literature and has not been modelled here. For these estimations of intake, the assumption has been made that all the deposited material is resuspended equally, and that it is all of a respirable size.

Garland (1979, 1982) carried out studies on grassland and bare soil at controlled wind speeds in a wind tunnel, and found that an inverse power law fitted his wind tunnel data for experiments which ran for times varying from several minutes to a number of months.

The Garland resuspension factor is given by

$$K(t)=1.2\ 10^{-6}\ t^{-1}\ m^{-1} \qquad (2)$$

where t is the time after deposition in days.

Unlike many other resuspension factors in the literature (Anspaugh et al, 1975; Müller et al, 1999), in the Garland methodology there is no long-term resuspension term. This may be because this methodology was developed experimentally, with the longest experiment lasting seven months. This time would not be long enough to characterise fully the long-term resuspension factor. Because 10^{-9} m^{-1} has been observed by several authors (Anspaugh et al., 1975; Linsley, 1978) to be the resuspension rate for aged deposits, an additional long-term resuspension term can be added to Equation 2 to give

$$K(t)=1.2\ 10^{-6}\ t^{-1} + 10^{-9}\ m^{-1} \qquad (3)$$

B4.1 Scenario one: soldiers

Integrated resuspended air concentrations were calculated using the following formula:

$$C_{air} = \int_{t_1}^{t_2} K(t) \text{ x surface deposit } dt \qquad (4)$$

where C_{air} is the integrated air concentration due to wind-driven resuspension, t_1 to t_2 is the period of integration, K(t) is found from Equation (2) and the surface deposit is assumed to be 1 g m^{-2}. Average resuspended air concentrations and calculated time-integrated air concentrations are given in Table B1.

Table B1. Integrated resuspended air concentration calculated using the resuspension approach

Integration time	Average air concentration (g m^{-3} per g m^{-2})	Integrated air concentration (g s m^{-3} per g m^{-2})
Days 0 to 6	3.57×10^{-7}	2.16×10^{-1}
Days 7 to 13	1.07×10^{-7}	6.50×10^{-2}
Days 14 to 20	6.45×10^{-8}	3.90×10^{-2}
Days 21 to 27	4.79×10^{-8}	2.90×10^{-2}
1st year	1.94×10^{-8}	6.12×10^{-1}
2nd year	2.28×10^{-9}	7.20×10^{-2}
3rd year	1.33×10^{-9}	4.20×10^{-2}
4th year	9.20×10^{-10}	2.90×10^{-2}
5th year	7.61×10^{-10}	2.40×10^{-2}
6th year	5.71×10^{-10}	1.80×10^{-2}
7th year	5.07×10^{-10}	1.60×10^{-2}
8th year	4.44×10^{-10}	1.40×10^{-2}
9th year	3.81×10^{-10}	1.20×10^{-2}
10th year	3.49×10^{-10}	1.10×10^{-2}

The soldiers' integrated intake of DU was calculated using the following formula, assuming all resuspended material is respirable:

$$Intake_{DU} = [C_{air} \text{ x } I_{inh} \text{ x } R_{scale} \text{ x } (1\text{-}Occ_{rate})] + [C_{air} \text{ x } I_{inh} \text{ x } R_{scale} \text{ x } Occ_{rate} \text{ x } I/O] \qquad (5)$$

where C_{air} is the integrated air concentration due to wind-driven resuspension. (Resuspension can be divided into two types: wind driven, and mechanical or anthropogenic. Wind-driven resuspension assumes the only disturbance to the surface is as a result of natural weathering, while mechanical resuspension includes mechanical disturbances by pedestrians or vehicles and agricultural operations). I_{inh} is the inhalation rate, as recommended by the International Commission on Radiological Protection (ICRP 1994) (see Table B2). For the best estimate, the outdoor worker rate is used. For the worst case, the heavy worker rate is used.

Table B2: Generalised inhalation rates (24--hour averages)

Group	Inhalation rate ($m^3 s^{-1}$) (ICRP 1994)
Infant (one year old)	6.02×10^{-5}
Child (ten years old)	1.76×10^{-4}
Adult housewife	2.04×10^{-4}
Heavy worker	3.10×10^{-4}
Outdoor worker	2.92×10^{-4}

R_{scale} is the scaling factor for resuspension. Because the air concentrations have been calculated for wind-driven resuspension in UK conditions, a scaling factor must be applied to scale for desert conditions and to scale for mechanical resuspension.

B4.1.1 Best estimate

The best estimate assumes UK conditions and mechanical resuspension. Linsley (1978) recommended that in conditions of moderate activity (regular disturbance of the surface by vehicles or pedestrians) a resuspension factor of 10^{-5} m^{-1} may be more applicable.

R_{scale} used for the best estimate is ten.

Occ_{rate} is the indoor occupancy, assumed to be 50%, i.e. the outdoor worker value from habit surveys (Robinson 1996).

I/O is the indoor:outdoor concentration ratio to scale indoor:outdoor concentrations by outdoor concentrations. It is known that small particles can penetrate effectively into buildings, and the degree of equilibrium between indoor and outdoor air is dependent on particle size. Because, in this study, the range of particle sizes that can be resuspended spans the full range of respirable particle sizes, a value of 0.5 is chosen, on the basis of a dose-conversion factor suggested in Brown (1989). This is strictly applicable to active sheltering for limited periods. However, given the uncertainties on the resuspension factor adopted (see Section B5), the uncertainty associated with this reduction factor is considered unimportant.

B4.1.2 Worst case

The worst case assumes desert conditions and high mechanical resuspension. Because it has been suggested (Cohen 1977) that humidity would be likely to reduce resuspension, a higher resuspension factor is assumed in desert conditions. Also, because it is assumed in the worst case that the soldiers are working in an area close to heavy vehicular movement, high mechanical resuspension needs to be considered.

R_{scale}=100 on the basis of measurements of Stewart (1964) in Australia. These measurements were made on the Maralinga test site, 0.3 m from a moving vehicle. The resuspension factors quoted ranged from 5.0×10^{-7} m^{-1} to 1.0×10^{-3} m^{-1}, so by using R_{scale} = 100 the effective resuspension factor used is 1.2×10^{-4} m^{-1}.

B4.2 Scenario two: family

Equations 4 and 5 are also valid here, with the following differences in parameter values:

- C_{air} as in section B4.1
- I_{inh} as recommended by ICRP (1994) (see Table B2).

B4.2.1 Best estimate

The best estimate assumes UK conditions and R_{scale}=1. Occ_{rate} is assumed to be 0.9 for a one year old infant, ten year old child and adult housewife, and 0.5 for an outdoor worker (Robinson 1996). I/O is as in Section B4.1.1.

B4.2.2 Worst case

The worst case assumes desert conditions, and R_{scale}=10 on the basis of measurements of Stewart (1964) in Australia. As in Section B4.1, resuspension may be increased in desert conditions due to lower humidity. In this case, the measurements by Stewart apply to measurements at the Maralinga test site for wind-driven resuspension.

B5 Dust -loading approach

The equivalent soil concentration or dust-loading approach can also be taken to relate the concentration of a radionuclide in soil to that in the air.

The resuspended air concentration can be expressed as

$$C_{air}\ (g\ m^{-3}) = C_{soil}\ (g\ kg^{-1})\ .\ S_E\ (kg\ m^{-3}) \qquad (6)$$

where C_{air} is the estimated concentration of the radionuclide in air, C_{soil} is the concentration in soil (in g of DU in one kg of soil) and S_E is the equivalent soil concentration or dust-loading.

There are recognised difficulties using the dust-loading approach. The soil concentration is expressed in terms of g kg^{-1}, or Bq kg^{-1}. As measurements are generally reported as g m^{-2} or Bq m^{-2}, knowledge of the depth of contamination is required. For fresh deposits, it is difficult to define the depth of the layer of surface soil and this will change with time. Most measurements and estimates given in the literature relate to aged deposits. This implies that the radionuclide is closely associated with the soil and so therefore not necessarily appropriate for use with fresh deposits. A fundamental difficulty with this approach is the implicit assumption that the contaminant and soil are resuspended equally, which will not be the case for many soil types. Vegetation cover is another important controlling factor in resuspension, and many dust-loading measurements have been made on land with sparse vegetative cover. There is no time dependence modelled in this approach. Activity may be lost through weathering, or through migration through soil, and this is not accounted for. In order to predict resuspension at later times, or integrated resuspension doses over periods of years, assumptions must be made about the loss of activity available for resuspension (or other models made use of).

B5.1 Soil modelling

To model the transport of radionuclides in the soil, a compartmental soil model was set up, using a generic undisturbed soil model (Brown 1995). This is based on migration in soil for a limited number of elements, particularly plutonium, caesium and strontium. The rate of movement into the soil of these elements is slow, although there is significant variation between the results of the various observations owing to differences in soil composition and annual rainfall. Modelling the migration of DU through soil introduces uncertainties and this is considered in Section B6.3.

The soil model consists of four compartments or boxes: the 0-1 cm box, 1-5 cm box, 5-15 cm box and 15-30 cm box. There are rate constants to express transfer between boxes and losses from boxes. Resuspension is assumed to occur only from the top one cm of soil, i.e. the upper box in the generic soil model.

To calculate the mass of DU at time zero in the top box:

- it is assumed that one g DU m^{-2} is uniformly distributed in the 0-1 cm box
- the volume of the top box (with dimensions 1 m x 1 m x 0.01 m) = 0.01 m^3
- 1 g deposited on box, therefore density of DU in top box = 10^2 g m^{-3}
- assume density of soil (generic dry soil) = 1.25 g cm^{-3}= 1.25 x 10^{-3} kg m^{-3}
- concentration of DU in top box = 8.0 x 10^{-2} g kg^{-1} (i.e. g of DU in one kg of soil)
- C_{soil}, the concentration of DU in the top box (i.e. the layer of soil available for resuspension), predicted by this model is given in Table B3.

Table B3. Soil concentration in the top layer of soil predicted using compartmental modelling

Integration time	C_{soil} (g kg^{-1} s)
Days 0 to 6	4.83 x 10^4
Days 7 to 13	4.81 x 10^4
Days 14 to 20	4.78 x 10^4
Days 21 to 27	4.76 x 10^4
1st year	2.24 x 10^6
2nd year	1.76 x 10^6
3rd year	1.38 x 10^6
4th year	1.08 x 10^6
5th year	8.48 x 10^5
6th year	6.65 x 10^5
7th year	5.22 x 10^5
8th year	4.06 x 10^5
9th year	3.28 x 10^5
10th year	2.51 x 10^5

B5.2 Scenario one: soldiers

The integrated air concentration due to resuspension is defined as

$$C_{air}\ (g\ m^{-3}\ s) = C_{soil}\ (g\ kg^{-1}\ s) \times S_E\ (kg\ m^{-3}) \qquad (7)$$

where C_{soil} is the integrated concentration in soil and S_E is the dust-loading.

Calculated values of C_{air} are given in Table B4.

Table B4. Integrated air concentrations calculated for scenario one using the dust-loading approach.

	Integrated air concentration (g m^{-3} s per g m^{-2})	
Integration time (days)	Best estimate	Worst case
0 to 6	4.83 x 10^{-3}	1.45 x 10^0
7 to 13	4.81 x 10^{-3}	1.44 x 10^0
14 to 20	4.78 x 10^{-3}	1.43 x 10^0
21 to 27	4.76 x 10^{-3}	1.43 x 10^0

B5.2.1 Best estimate

The best estimate assumes UK conditions and soldiers carrying out a range of activities. S_E = 100 µg m^{-3} = 1.0 x 10^{-7} kg m^{-3}, as used by Wilkins et al (1994) as a reasonably cautious dust-loading.

B5.2.2 Worst case

The worst case assumes desert conditions, vehicular movement and S_E = 30,000 µg m^{-3} = 3.0 x 10^{-5} kg m^{-3} based on measurements from Maralinga and Emu nuclear test sites in Australia (Haywood and Smith 1990), which quoted values of S_E from 370 to 65,000 µg m^{-3} for sitting in or near a moving vehicle. A value mid-range is assumed, as the soldiers will not spend 24 hours per day close to the vehicles.

The integrated intake of DU can then be calculated by:

$$Intake_{DU} = [C_{air} \times I_{inh} \times (1\text{-}Occ_{rate})] + [C_{air} \times I_{inh} \times Occ_{rate} \times I/O] \qquad (8)$$

where the parameter values have the same values as in Section B4.1.

B5.3 Scenario 2: family

C_{air} is calculated as in Section B5.2. Calculated values of C_{air} are given in Table B5.

Table B5: Integrated air concentrations calculated for Scenario two using the dust-loading approach.

Integration time	Integrated air concentration (g m^{-3} s per g m^{-2}) Best estimate	Worst case
Up to 28 days	1.92 x 10^{-2}	3.83 x 10^{-1}
1st year	2.24 x 10^{-1}	4.48 x 10^{0}
2nd year	1.76 x 10^{-1}	3.51 x 10^{0}
3rd year	1.38 x 10^{-1}	2.76 x 10^{0}
4th year	1.08 x 10^{-1}	2.16 x 10^{0}
5th year	8.48 x 10^{-2}	1.70 x 10^{0}
6th year	6.65 x 10^{-2}	1.33 x 10^{0}
7th year	5.22 x 10^{-2}	1.04 x 10^{0}
8th year	4.06 x 10^{-2}	8.12 x 10^{-1}
9th year	3.28 x 10^{-2}	6.57 x 10^{-1}
10th year	2.51 x 10^{-2}	5.01 x 10^{-1}

B5.3.1. Best estimate

The best estimate assumes UK conditions and normal living conditions. S_E = 100 µg m^{-3} = 1.0 x 10^{-7} kg m^{-3} as used by Wilkins et al (1994) as a reasonably cautious dust-loading.

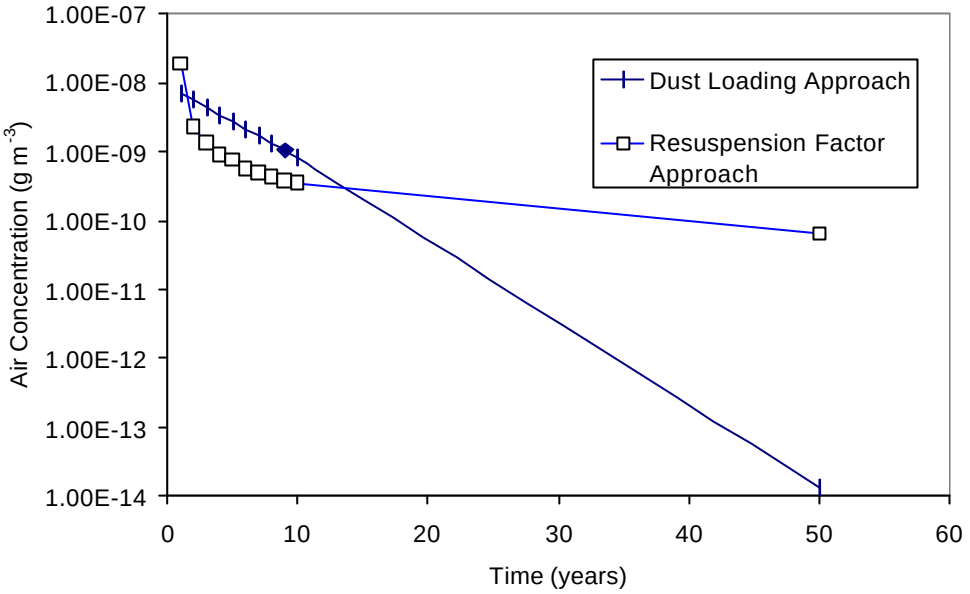
B5.3.2 Worst case

The worst case assumes desert conditions and normal living conditions. S_E = 2000 µg m^{-3} = 2.0 x 10^{-6} kg m^{-3} based on measurements from Maralinga and Emu nuclear test sites in Australia (Haywood and Smith 1990) for children playing. The intake of DU is calculated using Equation 8, with parameter values as defined in Section B4.2.

B6 Results and discussion

Figure B1 shows the air concentration (averaged over a year) predicted by each approach.

Figure B1. Air concentration (g m^{-3}) of DU each year up to 50 years following initial deposit, assuming best-estimate conditions.



As discussed earlier, the Garland resuspension factor is empirical, derived from wind-tunnel measurements, many of which were made hours and days after initial deposit. The dust-loading data available only apply to aged deposits, and therefore may not be appropriate for use with fresh deposits. Garland's experiments lasted up to several months, but the Garland resuspension factor has been applied to Chernobyl data and has been found to be a good fit (Garland et al 1992; Garger et al 1997) even eight years later, although in one of these studies (Garger et al 1997), which examined data up to 1994, the Garland factor tended to overestimate by up to one order of magnitude. For years two to ten, the dust-loading approach estimates higher air concentrations than the Garland factor due to the assumed slow migration of the DU through the soil, and the absence of a modelled retention of material by surface vegetation.

B6.1 Scenario one

The soldiers' intake of resuspended DU calculated using a resuspension factor approach is given in Table B6 and using a dust-loading approach in Table B7. There are substantial differences between the results of the two approaches, particularly in the first week, with the resuspension factor approach predicting higher intakes than the dust-loading approach. This is primarily due to an assumption made when modelling the transport of radionuclides in soil. It was assumed that the 1 g m^{-2} is dispersed uniformly in the top one cm of soil as the generic soil model used in this study can only be used in this way. However, over short timescales, the concentration in the upper few millimetres will be significantly higher than in the next few millimetres, and therefore the resuspended air concentrations could well be higher than those predicted using the dust-loading approach.

Table B6. Intake of resuspended DU for Scenario one calculated using the resuspension factor approach

Integration time	Intake (g) Best estimate	Worst case
0 to 6 days	4.73×10^{-4}	5.03×10^{-3}
7 to 13 days	1.42×10^{-4}	1.51×10^{-3}
14 to 20 days	8.54×10^{-5}	9.07×10^{-4}
21 to 27 days	6.35×10^{-5}	6.75×10^{-4}

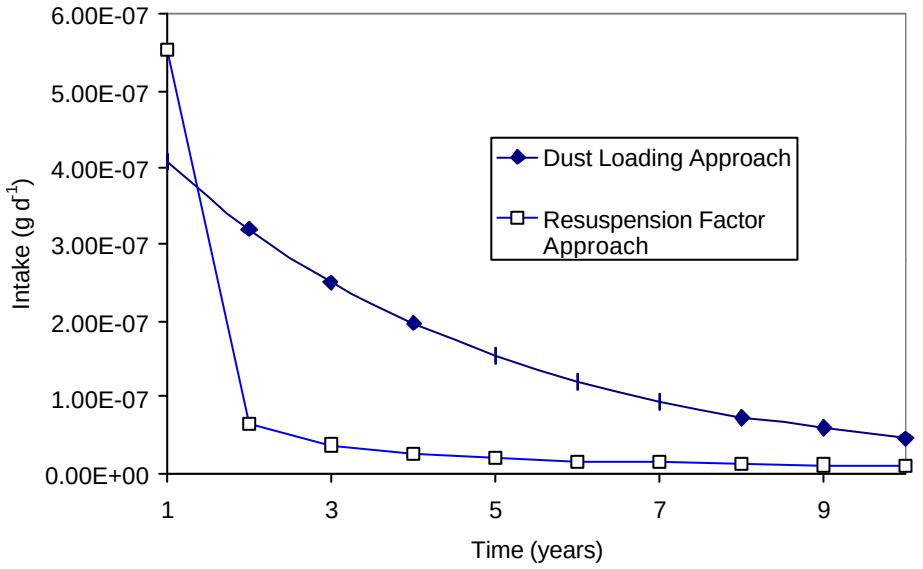
Table B7. Intake of resuspended DU for Scenario one calculated using the dust-loading approach

Integration time	Intake (g) Best estimate	Worst case
0 to 6 days	1.06×10^{-6}	3.37×10^{-4}
7 to 13 days	1.05×10^{-6}	3.35×10^{-4}
14 to 20 days	1.05×10^{-6}	3.33×10^{-4}
21 to 27 days	1.04×10^{-6}	3.32×10^{-4}

B6.2 Scenario two

Intakes of resuspended DU to an infant, child and adult (female housewife and male outdoor worker) are given in Tables B8 to B15. For intakes integrated over the first year, the resuspension factor approach predicts higher intakes than the dust-loading approach. After the first year, the dust-loading predictions exceed the resuspension factor predictions. Because the Garland resuspension factor is an inverse function of time ($\propto t^{-1}$), a rapid decrease of resuspended air concentrations is predicted in the initial time periods. The dust-loading approach is also time dependent; however, this decrease is much slower. This can be seen in Figure B2.

Figure B2. Intake rate (g d^{-1}) of depleted uranium predicted for an infant (Scenario two best estimate) each year up to ten years following initial deposit.



The total intake from the time of initial deposit to ten years and to 50 years is shown in Table B16 and Table B17 calculated using the resuspension factor approach and the dust-loading approach.

Table B8. Intake of resuspended DU to infants (Scenario 2) calculated using the resuspension factor approach

Integration time	Intake (g) Best estimate	Worst case
28 days	9.60×10^{-7}	9.60×10^{-6}
1st year	2.03×10^{-5}	2.03×10^{-4}
2nd year	2.38×10^{-6}	2.38×10^{-5}
3rd year	1.39×10^{-6}	1.39×10^{-5}
4th year	9.60×10^{-7}	9.60×10^{-6}
5th year	7.94×10^{-7}	7.94×10^{-6}
6th year	5.96×10^{-7}	5.96×10^{-6}
7th year	5.30×10^{-7}	5.30×10^{-6}
8th year	4.63×10^{-7}	4.63×10^{-6}
9th year	3.97×10^{-7}	3.97×10^{-6}
10th year	3.64×10^{-7}	3.64×10^{-6}

Table B9. Intake of resuspended DU to infants (Scenario 2) calculated using the dust-loading approach

Integration time	Intake (g) Best estimate	Worst case
28 days	6.35×10^{-7}	1.27×10^{-5}
1st year	7.42×10^{-6}	1.48×10^{-4}
2nd year	5.82×10^{-6}	1.16×10^{-4}
3rd year	4.56×10^{-6}	9.12×10^{-5}
4th year	3.58×10^{-6}	7.16×10^{-5}
5th year	2.81×10^{-6}	5.62×10^{-5}
6th year	2.20×10^{-6}	4.40×10^{-5}
7th year	1.73×10^{-6}	3.45×10^{-5}
8th year	1.34×10^{-6}	2.69×10^{-5}
9th year	1.09×10^{-6}	2.17×10^{-5}
10th year	8.29×10^{-7}	1.66×10^{-5}

Table B10. Intake of resuspended DU to children (Scenario 2) calculated using the resuspension factor approach

Integration time	Intake (g) Best estimate	Worst case
28 days	2.81×10^{-6}	2.81×10^{-5}
1st year	5.93×10^{-5}	5.93×10^{-4}
2nd year	6.98×10^{-6}	6.98×10^{-5}
3rd year	4.07×10^{-6}	4.07×10^{-5}
4th year	2.81×10^{-6}	2.81×10^{-5}
5th year	2.33×10^{-6}	2.33×10^{-5}
6th year	1.75×10^{-6}	1.75×10^{-5}
7th year	1.55×10^{-6}	1.55×10^{-5}
8th year	1.36×10^{-6}	1.36×10^{-5}
9th year	1.16×10^{-6}	1.16×10^{-5}
10th year	1.07×10^{-6}	1.07×10^{-5}

Table B11. Intake of resuspended DU to children (Scenario 2) calculated using the dust-loading approach

Integration time	Intake (g) Best estimate	Worst case
28 days	1.86×10^{-6}	3.72×10^{-5}
1st year	2.17×10^{-5}	4.34×10^{-4}
2nd year	1.70×10^{-5}	3.41×10^{-4}
3rd year	1.34×10^{-5}	2.67×10^{-4}
4th year	1.05×10^{-5}	2.10×10^{-4}
5th year	8.23×10^{-6}	1.65×10^{-4}
6th year	6.45×10^{-6}	1.29×10^{-4}
7th year	5.06×10^{-6}	1.01×10^{-4}
8th year	3.94×10^{-6}	7.87×10^{-5}
9th year	3.18×10^{-6}	6.37×10^{-5}
10th year	2.43×10^{-6}	4.86×10^{-5}

Table B12. Intake of resuspended DU to adult (female) (Scenario 2) calculated using the resuspension factor approach

Integration time	Intake (g) Best estimate	Worst case
28 days	3.26×10^{-6}	3.26×10^{-5}
1st year	6.87×10^{-5}	6.87×10^{-4}
2nd year	8.08×10^{-6}	8.08×10^{-5}
3rd year	4.72×10^{-6}	4.72×10^{-5}
4th year	3.26×10^{-6}	3.26×10^{-5}
5th year	2.69×10^{-6}	2.69×10^{-5}
6th year	2.02×10^{-6}	2.02×10^{-5}
7th year	1.80×10^{-6}	1.80×10^{-5}
8th year	1.57×10^{-6}	1.57×10^{-5}
9th year	1.35×10^{-6}	1.35×10^{-5}
10th year	1.24×10^{-6}	1.24×10^{-5}

Table B13. Intake of resuspended DU to adult (female) (Scenario 2) calculated using the dust-loading approach

Integration time	Intake (g) Best estimate	Worst case
28 days	2.15×10^{-6}	4.31×10^{-5}
1st year	2.52×10^{-5}	5.03×10^{-4}
2nd year	1.97×10^{-5}	3.95×10^{-4}
3rd year	1.55×10^{-5}	3.09×10^{-4}
4th year	1.21×10^{-5}	2.43×10^{-4}
5th year	9.53×10^{-6}	1.91×10^{-4}
6th year	7.47×10^{-6}	1.49×10^{-4}
7th year	5.86×10^{-6}	1.17×10^{-4}
8th year	4.56×10^{-6}	9.12×10^{-5}
9th year	3.69×10^{-6}	7.37×10^{-5}
10th year	2.81×10^{-6}	5.63×10^{-5}

Table B14. Intake of resuspended DU to adult (male outdoor worker) (Scenario 2) calculated using the resuspension factor approach

Integration time	Intake (g) Best estimate	Worst case
28 days	6.35×10^{-6}	6.35×10^{-5}
1st year	1.34×10^{-4}	1.34×10^{-3}
2nd year	1.58×10^{-5}	1.58×10^{-4}
3rd year	9.20×10^{-6}	9.20×10^{-5}
4th year	6.35×10^{-6}	6.35×10^{-5}
5th year	5.26×10^{-6}	5.26×10^{-5}
6th year	3.94×10^{-6}	3.94×10^{-5}
7th year	3.50×10^{-6}	3.50×10^{-5}
8th year	3.07×10^{-6}	3.07×10^{-5}
9th year	2.63×10^{-6}	2.63×10^{-5}
10th year	2.41×10^{-6}	2.41×10^{-5}

Table B15. Intake of resuspended DU to adult (male outdoor worker) (Scenario 2) calculated using the dust-loading approach

Integration time	Intake (g) Best estimate	Worst case
28 days	4.20×10^{-6}	8.40×10^{-5}
1st year	4.91×10^{-5}	9.81×10^{-4}
2nd year	3.85×10^{-5}	7.70×10^{-4}
3rd year	3.02×10^{-5}	6.04×10^{-4}
4th year	2.37×10^{-5}	4.74×10^{-4}
5th year	1.86×10^{-5}	3.72×10^{-4}
6th year	1.46×10^{-5}	2.91×10^{-4}
7th year	1.14×10^{-5}	2.29×10^{-4}
8th year	8.89×10^{-6}	1.78×10^{-4}
9th year	7.19×10^{-6}	1.44×10^{-4}
10th year	5.49×10^{-6}	1.10×10^{-4}

Table B16. Intakes of DU (from time of initial deposit) for all age groups calculated using the resuspension factor approach

Exposed age group	Integration period (years)	Intake (g) Best estimate	Worst case
Infant	10	2.81×10^{-5}	2.81×10^{-4}
	50	3.38×10^{-5}	3.38×10^{-4}
Child	10	8.24×10^{-5}	8.24×10^{-4}
	50	9.89×10^{-5}	9.89×10^{-4}
Adult	10	9.54×10^{-5}	9.54×10^{-4}
(female)	50	1.15×10^{-4}	1.15×10^{-3}
Adult	10	1.86×10^{-4}	1.86×10^{-3}
(male outdoor worker)	50	2.23×10^{-4}	2.23×10^{-3}

Table B17. Intakes of DU (from time of initial deposit) for all age groups calculated using the dust-loading approach

Exposed age group	Integration period (years)	Intake (g) Best estimate	Worst case
Infant	10	3.14×10^{-5}	6.27×10^{-4}
	50	3.44×10^{-5}	6.88×10^{-4}
Child	10	9.19×10^{-5}	1.84×10^{-3}
	50	1.01×10^{-4}	2.02×10^{-3}
Adult	10	1.06×10^{-4}	2.13×10^{-3}
(female)	50	1.17×10^{-4}	2.33×10^{-3}
Adult	10	2.08×10^{-4}	4.15×10^{-3}
(male outdoor worker)	50	2.28×10^{-4}	4.55×10^{-3}

B6.3 Uncertainties in intake estimates

The uncertainties in the estimates of intake are at least two to three orders of magnitude. The reasons for these uncertainties are discussed below.

B6.3.1 Resuspension factor approach

The resuspension factor approach is useful in localised situations for characterisation of the relationship between surface and airborne contamination. In practice, however, there are no homogeneously contaminated surfaces, and the airborne concentration is a sum of the local resuspended contamination and contamination carried from upwind resuspension (Smith et al 1982), minus that carried away by the wind. Another deficiency is that resuspension factors are applicable only for the conditions for which they were determined. In a recent paper (Garger et al 1997) it was found that even where local conditions such as vegetative cover and climate were taken into account, the calculated values of K might differ from measured values by over one order of magnitude. In that study, uncertainty in K has been found to reach two to three orders of magnitude for calculations where K has been determined in a generic way, such as in this study.

The large uncertainty in the resuspension factor approach is the resuspension at time zero, i.e. K(0), which can range from 10^{-9} to 10^{-5} m^{-1} (Linsley 1978). In the resuspension factor approach adopted here, K(0) is assumed to be 10^{-6} m^{-1}, indicating that while the intake calculation may be two to three orders of magnitude lower than calculated, it is unlikely to be more than two orders of magnitude higher than calculated. Several studies (Garland et al 1992; BIOMOVS II 1996; Garger et al 1999) have been carried out to test existing resuspension models against experimental data. In each of these studies, Garland's resuspension factor has been found to overpredict the resuspended air concentration.

Another source of uncertainty is transport of resuspended material from the contaminated area. This has not been modelled here. Studies (Garger et al 1998; Underwood 1990) indicate that small particles (less than 20m) may travel distances greater than one km after undergoing mechanical resuspension under particular atmospheric conditions. Therefore transportation of resuspended material may reduce the predicted air concentration in the contaminated area, if surrounded by a less contaminated area.

B6.3.2 Dust-loading approach

There are several areas of uncertainty in the dust-loading approach: (1) uncertainty in the migration of radionuclides through the soil column; (2) uncertainty in the effective thickness of the superficial layer of dust; (3) uncertainty in the homogeneity of the dust layer; and (4) uncertainty in the choice of the mass concentration (S_E) of dust. Each of these areas of uncertainty contributes to the total uncertainty, but (1) and (4) combine to produce possible uncertainty of several orders of magnitude.

B6.3.3 Other uncertainties

Uncertainties in other parameters used to calculate intake will all contribute to uncertainty, but will not be as large as those discussed in Sections B5.1 and B5.2. The occupancy rates and indoor/outdoor concentration ratio can only vary between zero and one, R_{scale} is inherently considered in Section B5.1 and the uncertainty on inhalation rates is expected to be substantially lower than one order of magnitude. Therefore, the other uncertainties are very low compared with the uncertainties associated with the calculation of the resuspended air concentration.

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