THE ROYAL SOCIETY

The health hazards of depleted uranium munitions, part II
Annexe C: Estimate of infant doses from the direct ingestion of soil or dusts containing uranium and depleted uranium

Barry Smith (BGS)

C1 Introduction

It is known that a small number of infants ingest soil at a high rate through a condition called geophagy. However, how much soil is ingested is a deceptively simple but highly relevant question that has led to a substantial discussion in the literature (eg Simon 1998). Some studies considered to be influential (eg Kimborough et al 1984) have been criticised for using ultraconservative soil ingestion rates with little empirical support (Paustenbach et al 1986; Gough 1991). Recent research has been dominated by mass-balance studies of 'conservative tracer elements', ie chemical elements that are present in soil but which are not significantly absorbed by passage through the gut (Calabrese 1989; Davies 1990; van Wijnen et al 1990).

The ingestion of soil and/or dust occurs both within and outside the household environment and it is important to establish, where possible, the concentration of uranium in both environments. Alternatively, a general relationship between indoor dust and outdoor soil contaminant concentrations may have to be assumed.

For example, Keenan et al (1989) and Murphy et al (1989) have reported the proportion of locally derived soil particles in indoor dust to be in the order of 75% to 100%. This estimate was based mainly on a study of land contamination around a series of smelters. However, some studies such as those by Franzen et al (1988) and Steele et al (1990) indicated that in mining communities the proportion was much less than this (typically indoor concentrations were 14% to 15% of soil concentrations). This difference was considered to be due to the surface properties and moisture content of smelter particles, which allowed them to adhere readily to shoes, clothing and pets, and thus to be tracked indoors more easily than other particles.

For uranium and depleted uranium (DU), which may be derived from a variety of sources, it is impossible to suggest one value for the proportion of outdoor-derived dust in the indoor environment. Given the large range of observations and the lack of relevant information, the recommendation of a value of 75% (Keenan et al 1989) would seem appropriate, even though this is almost certainly cautious in many cases.

Three distinct categories of soil ingestion may be considered, and these are discussed below along with suggested quantities of ingested material. From these examples it can be clearly seen that the amount of soil and/or dust ingested varies greatly, and that it is essential that the likely magnitude of geophagic activity is assessed in potentially exposed populations. During surveys of geophagic behaviour, it is essential that great care is exercised to prevent false-negative results being obtained due to cultural taboos associated with this practice (eg being considered to be improper or of lower social status).

C1.1 Inadvertent ingestion of small quantities of soil and dust

It is likely that all members of an exposed population will have intakes by this route, although exposure is likely to be greatest for children under seven years old. Sources of soil and dust are likely to be derived from both outdoors and indoors, and the relative magnitude of exposure will depend greatly on the habits and behaviour of an individual. Despite the wide number of studies, considerable uncertainties still exist in data relating to this activity (eg Simon 1998). This is in part due the difficulty in the methodological use of tracers to estimate such quantities, and also the highly individualistic nature of exposure. Inadvertent soil ingestion rates for studies performed in the USA are given in Tables C1 and C2 and illustrate the uncertainties and typical values determined in such studies. It should be noted that these values are generally slightly higher than those suggested by WHO (20 mg per day; WHO 2001). The use of data based on mass consumed may be inappropriate for such a dense material as DU and its oxides, and correction factors accounting for differences in density may need to be applied.

Table C1. Examples of soil ingestion estimates for children in the USA (mg per day) derived from tracer studies (note that negative values indicate error in mass balance)

Tracer	Davies (1990) n = 101			Calabrese (1989) n = 64		
element	Mean	Median	Range	Mean	Median	Range
Al	39	25	-279 to 904	153	29	-75 to 6837
Si	82	59	-404 to 535	154	40	-53 to 5549
Ti	246	81	-5821 to 6182	218	55	-3069 to 6707

Table C2. Soil ingestion rates for adults (mg per day) derived from tracer experiments (n = 6) (Calabrese et al 1990)

Tracer	Al	Si	Ti
Mean	77	5	377
Standard deviation	65	55	517
Median	57	0.5	211

C1.2 Occasional deliberate consumption of soil and dust (pica)

Most young children indulge in this type of exploratory behaviour for a relatively short time, although there is hardly any quantitative information on the amount of soil deliberately ingested during these activities. This is due in part to the difficulty in separating the occasional consumption of soil from the habitual practice of soil ingestion (geophagy), and from exposures that typically occur during the mouthing of other objects. For a group of 64 US children studied by Calabrese et al (1991) the median soil ingestion rate ranged from 9 to 96 mg per day according to tracer measurements, but one child (a three-and-a-half-year-old girl) ingested much greater quantities (up to 13.6 g per day). Earlier estimates of the amount of soil deliberately

ingested as five grams per day (USEPA, 1984) and ten grmas per day (USEPA, 1989) have generally been based purely on 'judgement'. As this behaviour is by definition occasional, it is unrealistic to use yearly or indeed daily consumption as a quantitative way of expressing occasional exposure. It is more realistic to use an exposure per event. For the purpose of this exercise it is assumed that the event is of one day duration.

C1.3 Geophagia

The term geophagia refers to the persistent and purposeful consumption of soil and/or dust, often in relatively large quantities. It is typically associated with children and pregnant females who may be subject to nutrient deficiencies. Geophagia should be considered as being distinct from pica (see above), which relates to the inadvertent ingestion of soil/dusts when mouthing or eating unusual objects, and should not be considered as only occurring in rural environments. Geophagia has been studied in both the UK and North America within the wider context of pica (eg Cooper 1957; Barltrop 1966; Bicknell 1975; Morgan et al 1988). However, as Lacey (1990) comments 'The body of literature on pica is so fragmented that it is difficult to find a precise summary of the knowns and unknowns about the condition. There is little consistency in defining pica, classifying substances ingested, identifying key characteristics of practitioners, recommending treatment or projecting outcomes'. The fragmentary nature of this information therefore makes it extremely difficult to calculate exposure of populations or individuals via this route. The situation elsewhere is even more complicated, particularly in tribal cultures where geophagy is commonly practised. For example, studies by Geissler et al (1998) indicated that a large proportion of male and female children in Kenya practise geophagy up to the age of 16 years, with an average soil consumption rate of 25 g per day.

The purpose of this annexe is to estimate the radiological doses and chemical exposures that would correspond to such intakes from the ingestion of soil containing ^{238}U.

C2 Methodology

C2.1 Radiological dose

The calculation of dose used the following formula:

D = Actconc x Ding x ingrate

where

D	=	annual effective dose to one-year-old infants (Sv per year) (note: assumption of one-year-old infant is conservative)
Actconc	=	activity concentration in soil (Bq per kg)
Ding	=	ingestion dose coefficient for one-year-old infants (Sv per Bq); the dose coefficient for ingestion for one-year-old infants is 1.2×10^{-7} Sv per Bq, from ICRP (1996)
ingrate	=	soil ingestion rate for infants (pica) (kg per year)

C2.2 Chemical exposure

The calculation of chemical exposure used the following formula:

D = Conc x ingrate

where

D	=	annual exposure (mg per year)
Conc	=	concentration of uranium in soil or dust (mg per kg)
ingrate	=	soil ingestion rate for infants (kg per year)

C3 Results

C3.1 Inadvertent ingestion of small quantities of soil and dust

Concentration of uranium in soil and dust = 100 mg per kg (=124,000 Bq per kg)
(representative of upper uranium concentration in dusts and local soil contamination)
Central estimate: 0.080 g soil per day
Worst-case: 0.200 g soil per day
Radiation dose = 0.0045 and 0.011 mSv per year
Chemical exposure = 3 and 7 mg uranium per year.

C3.2 Occasional deliberate consumption of soil and dust

Concentration of uranium in soil and dust = 10,000 mg per kg (=124,000 Bq per kg)
(representative of occasional consumption of grossly contaminated material such as when playing in an attacked vehicle)
Central estimate: 0.096 g soil per event
Worst case: 13.6 g soil per event
Radiation dose = 0.0015 and 0.209 mSv per event
Chemical exposure = 0.96 and 136 mg uranium per event

C3.3 Geophagia

Concentration of uranium in soil and dust = 1,000 mg per kg (=12,400 Bq per kg)
(representative of habitual consumption of contaminated material in the local environment of a DU attack)
Central estimate: 26 g soil per day
Worst-case: 85 g soil per day
Radiation dose = 14.6 and 47.7 mSv per year
Chemical exposure = 9.5 and 31 g uranium per year

C4 Discussion and conclusions

From the results presented above it is clear that elevated radiation doses and chemical exposures can result from the occasional deliberate and habitual consumption of contaminated soils and dusts. For example, the yearly radiological dose of 1 mSv and the chemical tolerable daily intake (TDI) for an adult or child (approximately 13 and 6 mg per year, respectively; see Annexe E) are both exceeded by an individual practising geophagia (central

estimate and worst-case) or by the one-off deliberate consumption of soil/dust (worst-case, consumption of highly contaminated dusts). The inadvertent ingestion of dusts and soils contaminated to a moderate degree (ie 20 times typical background U values for soil; 100 mg per kg) does not appear to result in a significant chemical or radiological exposure.

However, the actual level of dose and exposure is highly dependent upon the validity of the central estimate and/or worst case. For example, calculations undertaken in early appraisals of radiological dose resulting from military conflict in Kosovo by the Swedish Radiation Protection Institute (SSI 2000) used maximum daily exposures of 1 g, clearly well below central estimates (about 26 g) described above. Of particular concern, especially under post-conflict situations, are doses and exposures resulting from the practice of geophagy, and those from the occasional deliberate consumption of highly contaminated materials. A further factor likely to greatly influence any resulting dose or toxic effect from the direct ingestion of soil is the bioavailability of DU. These calculations have been made using a conservative approach, assuming a similar bioavailability to uranium dissolved in water. This may not be the case. Alternatively, it can be argued that other factors likely to increase exposures to DU have not been accounted for in these calculations. For example, the high density of DU oxides compared with typical soil suggests that ingestion of apparently similar volumes would result in significantly greater intake rates (based on mass ingested) in the case of grossly contaminated DU dusts.

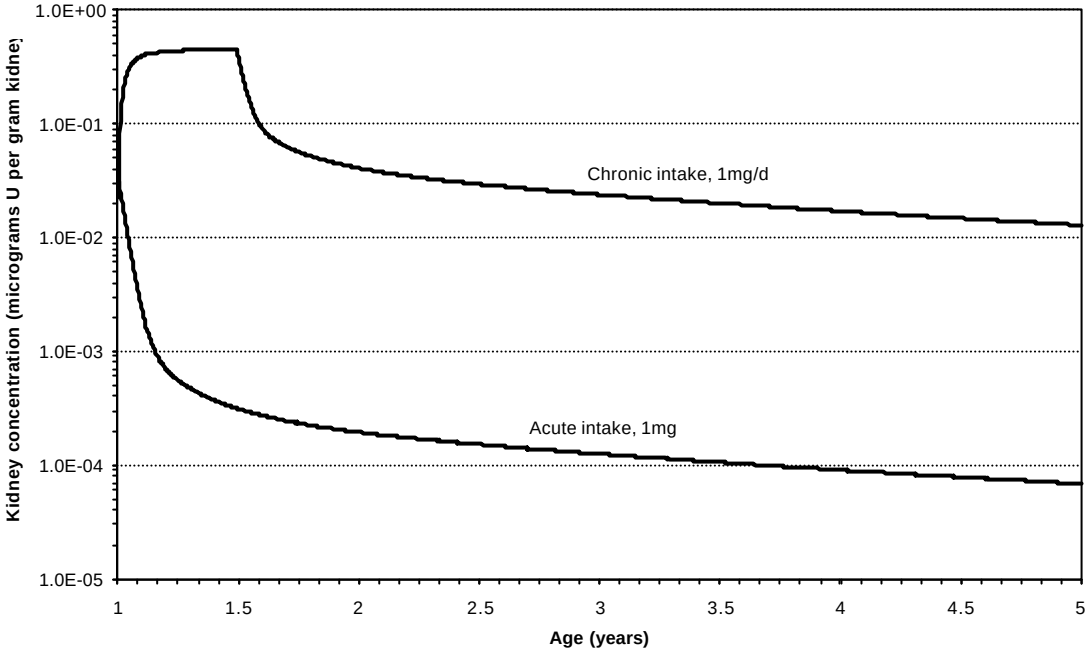
The amount of dust produced and material available on the surface for ingestion are clearly factors that contribute to the likelihood of exposure via the direct ingestion of soils and dusts. Such exposures are therefore likely to be reduced in strafing attacks where a large proportion of DU may end up buried below the earth's surface or where relatively intact penetrators lie on the surface. Conversely, higher exposures via this pathway may be expected from tank battles involving large calibre DU munitions and heavily armoured targets, where more DU is converted to dusts and near-surface DU fragments the surface.

Exposures via the deliberate habitual ingestion of soils and dusts are particularly relevant in developing and tribal societies, and where there may be malnourished individuals, which may enhance the likelihood of geophagic behaviour and any resultant harmful effect (ie some post-conflict situations).

The potential importance of the ingestion of soils and dusts and the particular sensitivity of the young to DU exposure suggest that minimisation of exposure through the removal of gross contamination in the immediate vicinity of penetrator strikes (ie on road surfaces; UNEP 2001) is a beneficial remedial measure.

The levels of uraniujm in the kidney are shown for a one-year-old child following the acute ingestion of 1 mg of DU and for chronic ingestion (daily ingestion of 1 mg DU per day for six months). These values can be scaled for other intakes of DU by ingestion.

Figure C1. Kidney concentration (microgram uranium per gram kidney) following intakes of uranium by a one-year-old infant. The acute intake of 1 mg occurs at age one year; the chronic intake of 365 mg per year occurs for six months then ceases. Changes in biokinetic data are taken into account as the child grows up (courtesy of Katie Davis, NRPB).



References

Barltrop D (1966). *The prevalence of pica*. American Journal of Diseases of Children **112**, 116–123

Bicknell J (1975). *Pica: a Childhood Symptom*. Butterworths: London

Calabrese E J (1989). *How much soil do young children ingest: an epidemiological study.* Regulatory Toxicology and Pharmacology **10**, 113–123

Calabrese E J, Stanek E J & Gilbert C E (1990). *Adult soil ingestion estimates*. In *Petroleum Contaminated Soils 3, School of Public Health, Environmental Health Sciences Programme* (eds Kostecke P T & Calabrese Lewis E J), pp. 349–356. Lewis: Amherst, USA

Calabrese E J, Stanek E J & Gilbert C E (1991). *Evidence of soil pica behaviour and quantification of soil ingested.* Human and Experimental Toxicology **10**, 245–249

Cooper M (1957) *Pica.* Thomas: Springfield, Illinois, USA

Davies S (1990). *Quantitative estimates of soil ingestion in normal children, between the ages of 2 and 7 years: Population-based estimates using aluminium, silicon and titanium as soil tracer elements.* Archives of Environmental Health **45**, 112–122

Franzen D, Sackman A, Oale R & Chopin M (1988). *Analytical results report for ambient air and residential characterisation at Prospect Square, Park City, Utah*. Report prepared for US EPA Hazardous Site Evaluation Division. USEPA: Washington, USA

Geissler P W, Mwaniki D L, Thiongo F, Michaelsen K F & Friis H (1998). *Geophagy, iron status and anaemia among primary school children in Western Kenya.* Tropical Medicine & International Health **3**(7), 529–534

Gough M (1991). *Human exposures from dioxin in soil – a meeting report.* Journal of Toxicology and Environmental Health **32**, 205–245

ICRP (1996). *Age-dependent doses to members of the public from intake of radionuclides: Part 5. Compilation of ingestion and inhalation dose coefficients.* ICRP Publication 72. Ann. ICRP, **26** (1)

Keenan R E, Sauer M M, Lawrence F H & Crawford D W (1989). *Examination of potential risks from exposure to dioxin in sludge used to reclaim abandoned strip mines*. In *The Risk Assessment of Environmental Hazards: A Text Book of Case Studies* (ed Paustenbauch D J), 935–998. John Wiley: New York

Kimborough R D, Falk H, Stehr P & Fries G (1984). *Health implications of 2,3,7,8-tetrachlorodibenzeno-p-dioxin (TCDD) contamination of residential soil*. Journal of Toxicology and Environmental Health **14**, 47–93

Lacey E P (1990). *Broadening the perspective of pica: literature review*. Public Health Reports **105**, 29–35

Morgan H, Smart G A & Sherlock J C (1988). *Intakes of metals*. The Science of the Total Environment **75**, 71–100

Murphy B L, Toole A P & Bergstrom P D (1989). *Health risk assessment for arsenic contaminated soil.* Environmental Geochemistry and Health **11**, 163–169

Paustenbach D J, Shu H P & Murray F J (1986). *A critical examination of assumptions used in risk assessments of dioxin contaminated soils*. Regulatory Toxicology and Pharmacology **6**, 284–307

Simon S L (1998). *Soil ingestion by humans: a review of history, data, and aetiology with application to risk assessment of radioactively contaminated Soil.* Health Physics **74**(6), 647–672

SSI (2000). *Use of depleted uranium in military conflicts and possible impacts on health and environment.* Swedish Radiation Protection Institute Newsletter **8**,1–8

Steele M J, Beck B D, Murphy B L & Strauss H S (1990). *Assessing the contribution from lead in mining wastes to blood lead.* Regulatory Toxicology and Pharmacology **11**, 158–190

UNEP (2001). *Depleted uranium in Kosovo: post-conflict assessment*. Report of the United Nations Environment Programme Scientific Mission to Kosovo, 5–19 November 2000. UNEP: Geneva

USEPA (1984). *Risk analysis of TCDD Contaminated Soil*. US EPA, Office of Health and Environmental Assessment, Report EPA/620/8–84/031. Washington, DC

USEPA (1989). *Exposure Factors Handbook.* US EPA, Office of Health and Environmental Assessment, Report EPA/600/8–89/043: Washington, DC

van Wijnen J H, Clausing P & Brunekreef B (1990). *Estimated soil ingestion by children.* Environmental Research **51**, 147–162

WHO (2001). *Depleted Uranium: sources, exposure and health effects*. Report WHO/SDE/PHE/01.1, Department of the Protection of the Human Environment. WHO: Geneva