THE ROYAL SOCIETY

The health effects of depleted uranium munitions, Part II
Annexe E: Calculation of generalised limits for chemical toxicity

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E1 Introduction

Generalised derived limits (GDLs) for exposure to depleted uranium (DU) derived on the basis of chemical toxicity (GDLCs) may be calculated in a similar way to those published by the NRPB (NRPB 2000) covering effects due to radioactivity.

This annexe describes the philosophy of such GDLCs and the assumptions underlying the calculations of GDLCs for well-mixed soil and aquatic pathways. The GDLCs for DU for these pathways are given and, for the GDLC for well-mixed soil, the relative significance of different exposure pathways is indicated.

E2 Philosophy of GDLCs

GDLCs are intended for use as convenient reference levels against which the results of environmental monitoring can be compared. They relate to the tolerable daily intake (TDI) values for uranium suggested in the recent WHO report on DU (WHO 2001) for members of the general public (0.5 µg per kg body mass per day). Unlike GDLs derived for radioactive effects, GDLCs relate to exposures to uranium and DU resulting from both human activities and natural background exposures.

GDLs for the chemical toxicity of uranium are calculated using deliberately cautious assumptions and are based on the assumption that the level of environmental contamination is uniform over a year and that exposure results solely from one pathway (eg drinking water). It is perhaps not unreasonable to apply a similar ruling to GDLCs as that applied to GDLs. For example, it is recommended that if a measured environmental concentration exceeds about 10% of the GDLC then the doses should be examined more closely, taking account of site-specific factors and the length of time the measured level is likely to be maintained.

GDLCs are calculated using TDIs from WHO (2001). The values for TDIs from inhalation and ingestion assumed for ^{238}U are given in Table E1. The GDLCs are based on the exposure to the most restrictive age group, taking into account variations in TDI and dietary and other habits with age. The age groups considered are infants (one year old), children (ten years old) and adults (assumed to be 20 years old). TDIs were therefore scaled according to body weight for these ages.

E3 Methodology for the calculation of GDLCs

The GDLCs for the exposure pathways considered in this note are calculated for both single and multiple pathways. The GDLC for each age group was calculated and the most restrictive of

these are presented in Table E2. For single and multiple pathways, three age groups are considered: infants (one year old), children (ten years old) and adults (20 years old).

E3.1 GDLCs for single pathways

The GDLCs for single pathways considered in this annexe are for inhalation of air, and ingestion of locally produced products, including fruit, potatoes and root vegetables, green vegetables and other vegetables, cereals, cattle meat, sheep meat, cattle offal, sheep offal, milk, milk products, marine fish, freshwater fish, crustaceans, molluscs and drinking water. These are calculated using the general formula

$$GDLC_m = \frac{D_c}{I_m} \qquad (1)$$

where

$GDLC_m$	=	GDLC for a particular material (m), and for the age group exposed (mg kg^{-1} or mg per litre)
D_c	=	effective exposure limit for the age group (mg y^{-1})
I_m	=	annual intake of the material (m), by each age group (kg y^{-1} or litres y^{-1}).

The assumed annual intakes are given in Tables E3 and E4, which are considered to be applicable to the critical group (ie those people in the population who are representative of those who receive the highest exposures). These were the same as those used to calculate GDLs for exposures to radioactivity (NRPB 2000).

E3.2 GDLCs for multiple pathways

The GDLCs for multiple pathways considered in this annexe are for well-mixed soil, freshwater sediments, marine sediments, freshwater and sea-washed pasture.

The exposure pathways considered in the calculation of the multiple-pathway GDLCs are summarised in Table E5. For each environmental material, the GDLC was calculated by summing the contributions from all the significant exposure pathways, as shown in Equation 2.

$$\frac{1}{GDLC_m} = \sum_{i=1}^{i=n} \frac{1}{GDLC_{mi}} \qquad (2)$$

where

$GDLC_m$	=	GDLC for the material (m), and the exposed age group, summed over all exposure pathways (i) (mg kg^{-1} or mg l^{-1})
$GDLC_{mi}$	=	GDLC for the material (m), the age group and the particular exposure pathway (i) (mg kg^{-1} or mg l^{-1})
n	=	number of exposure pathways considered.

Five major exposure pathways were considered: well-mixed soil, freshwater sediments, marine sediments, freshwater and sea-washed pasture. Individual components of these pathways were

calculated as follows (see NRPB (2000) for a more in-depth discussion of the basis behind these calculations and associated variables).

E3.2.1 Inhalation of resuspended material

The inhalation of resuspended material is described by equation 3:

$$GDLC_{inh} = \frac{D_c}{(O_{mech} \; L_{mech} + O_{wind} \; L_{wind}) \; H_{e(inh)} \; B} \qquad (3)$$

where

$GDLC_{inh}$	=	GDL for inhalation of resuspended materials (mg kg^{-1})
D_c	=	exposure limit (mg y^{-1})
B	=	breathing rate (m^3 h^{-1})
O_{mech}	=	occupancy in air containing mechanically disturbed soil (h y^{-1}) (adults only)
L_{mech}	=	concentration of soil in air due to mechanical disturbance (kg m^{-3})
O_{wind}	=	occupancy above materials for ambient resuspension (h y^{-1})
L_{wind}	=	concentration of soil in air due to ambient resuspension (kg m^{-3}).

E3.2.2 Inadvertent ingestion

Inadvertent ingestion as described by Equation 4 was included in the calculation of GDLC for well-mixed soil

$$GDLC_a = \frac{D_c}{I_a \; O_m} \qquad (4)$$

where

$GDLC_a$	=	GDLC for inadvertent ingestion of materials for each age group (mg kg^{-1})
D_c	=	exposure limit (mg y^{-1})
I_a	=	inadvertent ingestion rate for each age group (kg h^{-1})
O_m	=	number of hours per year exposed to the particular material for each age group (h y^{-1}).

In some calculations, for example for the well-mixed soil GDLC, 100% occupancy of the area is assumed and allowance only has to be made for the time spent indoors. In these cases, I_a is replaced by the annual inadvertent ingestion rate (kg y^{-1}), taking into account indoor occupancy (see Table E6) and O_m is no longer required.

E3.2.3 Ingestion of food products

The fourth pathway considered is ingestion of foods produced on contaminated soils. GDLCs for well-mixed soil and sea-washed pasture have contributions from food ingestion.

The GDLCs for foodstuffs (except those associated with animals or animal products) produced on well-mixed soil and sea-washed pasture are given by Equation 5.

$$GDLC_f = \frac{D_c}{I_f \; C_{sf}} \qquad (5)$$

where

$GDLC_f$	=	GDLC for the ingestion of food (f), grown on contaminated soil for each age group (mg kg^{-1} or mg l^{-1}),
D_c	=	exposure limit (mg y^{-1})
I_f	=	food ingestion rate (kg y^{-1} or litres y^{-1})
C_{sf}	=	concentration factor relating the radionuclide concentration in soil to the radionuclide concentration in food (Bq kg^{-1} or Bq l^{-1} in food per Bq kg^{-1} in the soil).

The GDLCs for meat and animal products derived from potentially contaminated soils use concentrations of DU predicted by dynamic food-chain models following deposition of the radionuclides. The modelling approach adopted is described in NRPB (2000).

Ingestion rates for the multiple-pathway GDLCs are given in Table E3. For well-mixed soil, consumption of all agricultural foods is assumed (green and root vegetables, fruit, sheep and cow meat, sheep and cow offal, milk and milk products). For sea-washed pasture, only consumption of animal products was considered (sheep and cow meat, sheep and cow offal, milk and milk products).

E4 Summary of uranium GDLCs

GDLCs for uranium are presented in Table E2. The relative importance of pathways for well-mixed soil GDLCs are summarised in Figure E1, which shows that the dominant exposure pathway associated with DU contamination of soil is the ingestion of food. Other less important exposure pathways were inadvertent ingestion and inhalation of soil, although these were of greater importance for infants and children. Comparison of individual GDLCs indicates the sensitivity of air, drinking water, milk and milk products to contamination from DU. In all of these cases the critical group is children and/or infants.

Figure E1. Reciprocal GDLC values (1/GDLC) for infants, children and adults, emphasising the importance of exposure from drinking water compared with other ingested materials. Note that 1/GDLC values for inhalation in ambient air are between 500,000 and 900,000, whereas for drinking water they are between 47 and 136.

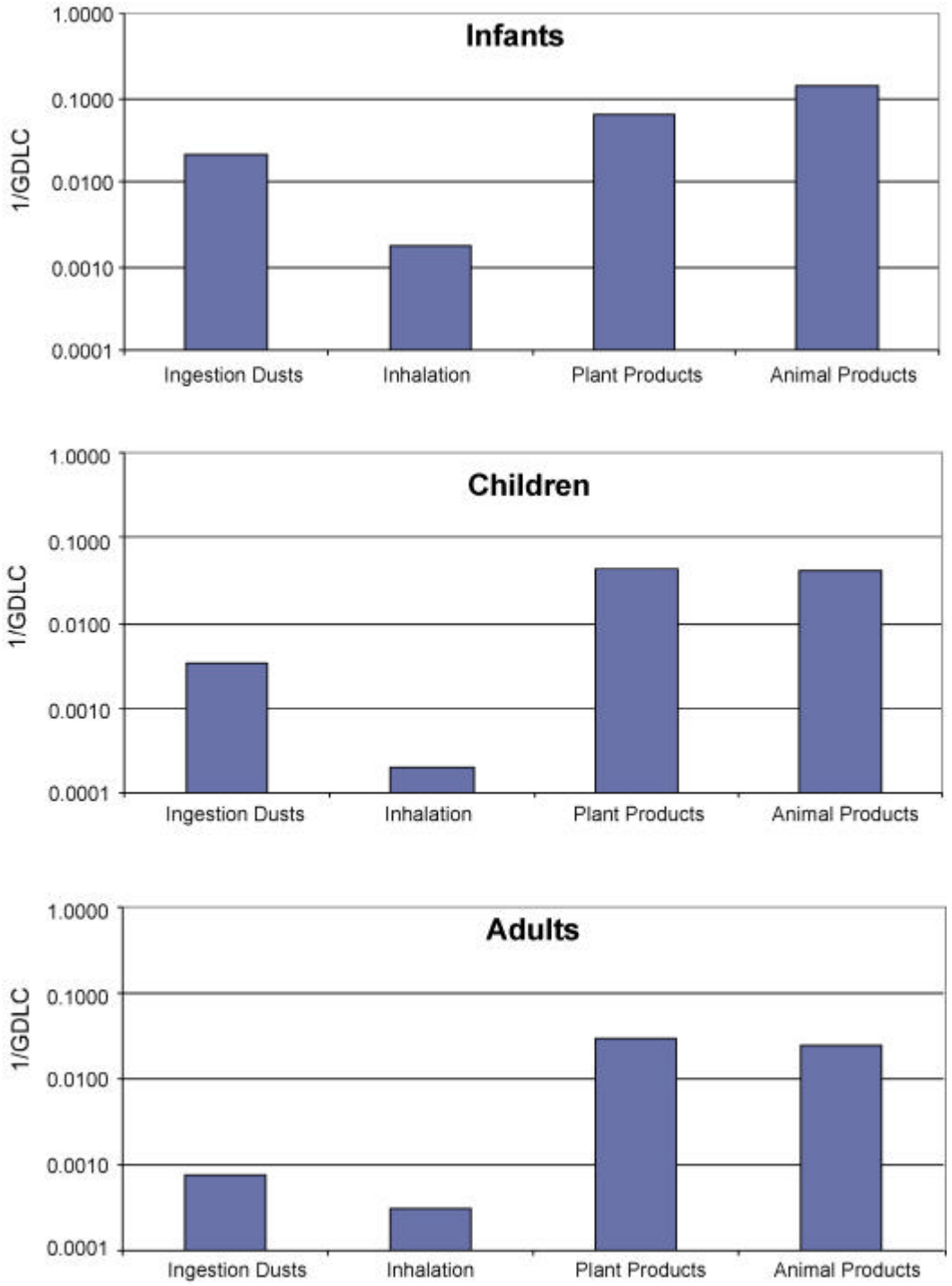

Table E1. TDI coefficients (mg DU per annum) for intake by ingestion and inhalation (based on TDIs from WHO (2001))

	Type	Infant (1 year) 10.5 kg	Child (10 years) 32.5 kg	Adult (20 years) 70 kg
Ingestion	**F**	**1.9**	**5.9**	**12.8**
Ingestion	M	1.9	5.9	12.8
Ingestion	S	1.9	5.9	12.8
Inhalation	**F**	**2.3**	**7.1**	**15.3**
Inhalation	M	2.3	7.1	15.3
Inhalation	S	23	71	153

In calculating GDLCs a conservative approach has been used and Type F behaviour (ie soluble uranium) has been assumed for all exposures.

Where GDLCs relate to exposure from a single environmental exposure route it is important to note that in practice people will be exposed to a variety of materials/pathways, and hence in comparing these levels against environmental measurements it is necessary to take into account all possible sources of contamination to ensure the toxicity limit is not exceeded.

Table E2. GDLC (in mg m^{-3}, mg kg^{-1} or mg per litre DU) for various exposure routes and scenarios

	Infant (one year)	Child (ten years)	Adult (20 years)	Critical group[1]
GDLCs: single-exposure pathways				
Inhalation of air	0.001	0.001	0.002	children aged ten years
Locally grown fruit	0.055	0.12	0.17	infants aged one year
Potatoes and root vegetables	0.043	0.062	0.098	children aged ten years
Green and other locally grown vegetables	0.13	0.17	0.16	infants aged one year
Cereals	0.064	0.079	0.13	children aged ten years
Cattle meat	0.19	0.20	0.29	children aged ten years
Sheep meat	0.64	0.59	0.51	adult
Cow offal	0.70	1.2	1.3	infants aged one year
Sheep offal[2]	0.70	1.2	1.3	infants aged one year
Milk	0.006	0.025	0.053	infants aged one year
Milk products	0.043	0.13	0.21	infants aged one year
Marine fish[3]	0.38	0.30	0.13	children aged ten years
Crustaceans[3]	1.9	1.2	0.64	children aged ten years
Molluscs[3]	1.9	1.2	0.64	children aged ten years
Drinking water	0.007	0.017	0.021	infants aged one year
Freshwater fish[3]	1.9	1.2	0.64	children aged ten years
GDLCs: multiple-exposure pathways				
Well-mixed soil[4]	4.1	10.9	15.7	infants aged one year
Freshwater sediments[4]	1300	1200	5000	infants aged one year
Marine sediments[4]	1300	2000	1300	adult
Fresh water[5]	0.0071	0.015	0.016	infants aged one year
Sea-washed pasture[4]	6.5	22	36	infants aged one year

[1]The GDLCs apply to uniform conditions over a year and are based on the limiting age group. Unless stated otherwise GDLCs for food products are expressed as fresh mass.
[2]Offal refers to cow liver and sheep liver.
[3]The GDLCs for aquatic foodstuffs are for the edible fraction and are expressed as fresh mass.
[4]The GDLCs are expressed as dry mass.
[5]The GDLCs for fresh water include activity in the dissolved and suspended fractions. Unlike GDLs, GDLCs for freshwater do not include contributions from the ingestion of irrigated vegetables (see Table E5).

Table E3. Critical group food intake rates

Food group	Critical group intakes (kg y^{-1})		
	Infant (one year)	Child (ten years)	Adult (20 years)
Drinking water (litres y^{-1})	260	350	600
Freshwater fish	1	5	20
Marine fish	5	20	100
Crustaceans	1	5	20
Molluscs	1	5	20
Domestic fruit	35	50	75
Potatoes and root vegetables	45	95	130
Green and other domestic vegetables[1]	15	35	80
Pig meat	5.5	25	40
Cattle meat	10	30	45
Sheep meat	3.0	10	25
Cattle offal	2.75	5	10
Sheep offal	2.75	5	10
Poultry	5.5	15	30
Milk (litres y^{-1})	320	240	240
Milk products	45	45	60
Cereals	30	75	100

[1]*Intakes summed over green vegetables and other locally grown vegetables including legumes.*

Table E4. Other critical group intake rates

	Infant (one year)	Child (ten years)	Adult (20 years)
Inhalation rate (m^3 y^{-1})	1900	5500	7300
Inadvertent ingestion rate whilst occupying a substrate (kg h^{-1})	$5x10^{-5}$	$1x10^{-5}$	$5x10^{-6}$
Annual inadvertent ingestion rate accounting for indoor occupancy (kg y^{-1}) – for well-mixed soil and irrigated soil	$4.4x10^{-2}$	$1.8x10^{-2}$	$8.3x10^{-3}$

Table E5. Pathways considered for multiple-exposure GDLCs

GDLC	Exposure pathways
Well-mixed soil	Inadvertent ingestion of well-mixed soil Inhalation of resuspended well-mixed soil Ingestion of plant products from well-mixed soil Ingestion of animal products from well-mixed soil
Marine and freshwater sediments	Inadvertent ingestion of sediment Inhalation of resuspended sediment
Fresh water	*Aquatic exposure pathways* Ingestion of river water Ingestion of freshwater fish Inhalation of resuspended shoreline sediment
Sea-washed pasture	Inadvertent ingestion of soil Inhalation of resuspended soil Ingestion of animal products from sea-washed pasture

Table E6. Occupancies

	Occupancy (h y^{-1}) Infant (one year)	Child (ten years)	Adult (20 years)
Marine sediment	30	300	2000
Freshwater sediment	30	500	500
Sea-washed pasture	30	300	2000
Contaminated land (well-mixed soil and irrigated soil)			
External exposure	Occupancy (%)		
Indoor	90	80	50
Outdoor	10	20	50
Inhalation	Occupancy (h y^{-1})		
Mechanical dust			300
Ambient dust	8760	8760	8760

References

NRPB (2000). *Generalised derived limits for radioisotopes of polonium, lead, radium and uranium*. Documents of the NRPB, Vol 11, No 2

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, Switzerland