THE ROYAL SOCIETY

The health hazards of depleted uranium munitions, part II
Annexe D: Calculation of generalised limits for radioactivity

Stephanie Haywood (NRPB)

D1 Introduction

Generalised derived limits (GDLs) for ^{234}U, ^{235}U and ^{238}U have been published by NRPB. This note describes the philosophy of GDLs and the assumptions underlying the calculations of GDLs for well-mixed soil and aquatic pathways. The GDLs for ^{238}U for these pathways are given and, for the GDL for well-mixed soil, the relative significance of the exposure pathways is indicated.

GDLs are intended for use as convenient reference levels against which the results of environmental monitoring can be compared. They relate to the annual effective dose limit for members of the public in the UK of 1 mSv. GDLs relate only to possible increases in concentrations of radioactivity resulting from human activities. They are not applicable to natural background radiation.

GDLs are calculated using deliberately cautious assumptions and are based on the assumption that the level of environmental contamination is uniform over a year. For application in the UK, it is recommended that if a measured environmental concentration exceeds about 10% of the GDL 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.

GDLs are calculated using effective dose as defined in ICRP Publication 60 (ICRP, 1990). The values for dose coefficients from inhalation and ingestion assumed for ^{238}U are given in Table D1. The GDLs are based on the dose to the most restrictive age group, taking into account variations in dose coefficients 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). In addition, for GDLs in milk or where the ingestion of milk could be the dominant pathway, calculations are also performed for infants on a milk diet in the first year of life based on dose coefficients for a three month old.

As GDLs relate only to incremental concentrations of radioactivity resulting from human activities, and not to the total concentration measured, some estimate of the ambient levels in the area of interest should be obtained, to subtract from any measured concentrations of radioactivity before comparison with the appropriate GDL.

D2 Methodology for the calculation of GDLs

The GDLs for the exposure pathways considered in this note are calculated for both single and multiple pathways. The GDL for each age group was calculated and the most restrictive of these are presented in Table D2. For single and multiple pathways, three age groups were considered: infants (one year old), children (ten years old) and adults (20 years old). An additional age group

is considered in calculating GDLs for sea-washed pasture and for well-mixed soil, which is unweaned infants in the first year of life (average three months old). For this age group only ingestion of milk was considered.

D2.1 GDLs for single pathways

The GDLs 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

$$GDL_m = \frac{D}{H_e I_m} \qquad (1)$$

where

GDL_m	=	GDL for a particular material (m), and age group exposed (Bq kg^{-1}, or Bq $litre^{-1}$)
D	=	effective dose limit of 10^{-3} Sv $year^{-1}$
H_e	=	dose coefficient for inhalation or ingestion (Sv Bq^{-1})
I_m	=	annual intake of the material (m), by each age group (kg $year^{-1}$ or litres $year^{-1}$).

The dose coefficients (H_e) are given in Table D1 for ^{238}U. The assumed annual intakes are given in Tables D3 and D4, 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).

D2.2 GDLs for multiple pathways

The GDLs for multiple pathways considered in this annexe are for well-mixed soil, freshwater sediments, marine sediments, freshwater and sea-washed pasture. The ingrowth of progeny has been included over a 50-year period for all of these GDLs. The short-lived progeny of ^{238}U (^{234}Th, ^{234}Pa and ^{234m}Pa) are assumed to be in secular equilibrium with the parent.

The exposure pathways considered in the calculation of the multiple pathway GDLs are summarised in Table D5. For each environmental material, the GDL was calculated by summing the contributions from all the significant exposure pathways, as shown in Equation 2:

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

where

GDL_m	=	GDL for the material (m), and exposed age group, summed over all exposure pathways (i) (Bq kg^{-1} or Bq $litre^{-1}$)
GDL_{mi}	=	GDL for the material (m), age group and particular exposure pathway (i) (Bq kg^{-1} or Bq $litre^{-1}$)
n	=	number of exposure pathways considered.

Four major exposure pathways were considered:

- external gamma-irradiation from contaminated materials
- internal exposure from inhalation of resuspended material
- internal exposure from inadvertent ingestion of the material
- internal irradiation from ingestion of foods or drinking water

The GDLs for freshwater also include pathways arising from irrigation of land. This application was modelled as a surface deposit using dynamic food-chain and soil models described in Simmonds et al (1995). The methods for estimating GDLs for the main exposure pathways are outlined below.

D2.2.1 External gamma exposure

External dose is dependent on the energy and frequency of emissions, the properties of the materials, shielding and occupancy. A model (for details see Simmonds et al (1995)) is used to calculate external exposure for GDLs for marine and freshwater sediment, freshwater, well-mixed soil and sea-washed pasture; it calculates effective external dose rates one m above various materials. The occupancies, shielding and physical properties of the materials used to calculate the doses are given in Table D6. The external gamma component of the multiple pathway GDLs is given by Equations 3 and 4.

$$GDL_{ex} = \frac{D}{E} \qquad (3)$$

where

GDL_{ex}	=	GDL for external gamma exposure for each age group (Bq kg^{-1})
D	=	effective dose limit of 10^{-3} Sv $year^{-1}$
E	=	effective dose from external irradiation from a unit concentration of radioactivity in the materials for each age group (Sv $year^{-1}$ per Bq kg^{-1}).

For soils, E is given by

$$E = G\ (F_{ind}\ T_{ind} + F_{out}\ T_{out}) \qquad (4)$$

where

G	=	external effective dose one m above the materials, integrated over one year (Sv $year^{-1}$ per Bq kg^{-1})
F_{ind}	=	fraction of a year spent indoors (dimensionless)
T_{ind}	=	indoor location factor (dimensionless)
F_{out}	=	fraction of a year spent outdoors (dimensionless)
T_{out}	=	outdoor location factor (dimensionless).

The term location factor is defined as the ratio of the dose received in the protected location (indoors or outdoors) to that received outdoors for the period during which the person is in that location. The term location factor therefore describes the shielding offered at a particular location compared with a situation where no shielding is available. For sea-washed pasture, freshwater and marine sediments, E is derived from the product of external effective dose one m above the materials, integrated over one year, and the fraction of the year spent above the materials. The material depths were 0.3 m for both soil and sediments. The bulk densities were 1.5 t m^{-3} for soil and 1.7 t m^{-3} for sediment.

D2.2.2 Inhalation of resuspended materials

Two pathways have been defined for the inhalation of resuspended materials: ambient resuspension, which gives rise to low but persistent levels of resuspended material, and mechanical resuspension by ploughing of agricultural land, which gives rise to enhanced local levels of resuspended material. The mechanical resuspension component of inhalation exposure has been calculated for soils, on the assumption that only adults are exposed. The GDL for inhalation of resuspended materials is given by Equation 5.

$$GDL_{inh} = \frac{D}{(O_{mech} \; L_{mech} + O_{wind} \; L_{wind}) \; H_{e(inh)} \; B} \qquad (5)$$

where

GDL_{inh}	=	GDL for inhalation of resuspended materials (Bq kg^{-1})
D	=	effective dose limit of 10^{-3} Sv y^{-1}
$H_{e(inh)}$	=	dose coefficient for inhalation (Sv Bq^{-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}) (= 1 x 10^{-5} 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}) (= 1 x 10^{-7} kg m^{-3}).

These parameters are given in the Tables D4 and D6.

D2.2.3 Inadvertent ingestion

The third exposure pathway considered is inadvertent ingestion. Inadvertent ingestion as described by equation 6 was included in the calculation of GDLs for marine sediment, freshwater sediment, sea-washed pasture, well-mixed soil and farmland treated with freshwater irrigation.

$$GDL_a = \frac{D}{I_a \; H_{e(ing)} \; O_m} \qquad (6)$$

where

GDL_a	=	GDL for inadvertent ingestion of materials for each age group (Bq kg^{-1})
D	=	effective dose limit of 10^{-3} Sv y^{-1}
I_a	=	inadvertent ingestion rate for each age group (kg h^{-1})
$H_{e(ing)}$	=	dose coefficient for ingestion (Sv Bq^{-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 GDL, 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 D6), and O_m is no longer required.

D2.2.4 Ingestion of food products

The fourth pathway considered is ingestion of foods produced on contaminated soils. GDLs for well-mixed soil, sea-washed pasture and farmland irrigated with fresh water have contributions from food ingestion.

The GDLs for each foodstuff produced on well-mixed soil and sea-washed pasture are given by Equation 7:

$$GDL_f = \frac{D}{I_f \quad H_{e(ing)} \quad C_{sf}} \qquad (7)$$

where

GDL_f	=	GDL for the ingestion of food (f), grown on contaminated soil for each age group (Bq kg^{-1} or Bq l^{-1}),
D	=	effective dose limit of 10^{-3} Sv y^{-1}
I_f	=	food ingestion rate (kg y^{-1} or litre y^{-1})
$H_{e(ing)}$	=	dose coefficient for ingestion (Sv Bq^{-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 GDLs for foodstuffs derived from land irrigated with fresh water used concentrations of radioactivity predicted by dynamic food-chain models following deposition of the radionuclides. The modelling approach adopted is described in NRPB (2000).

The ingestion rates for the multiple pathway GDLs are given in Table D3. For the freshwater GDL, in which arable land is irrigated, the ingestion of green and root vegetables and cereals was considered. For well-mixed soil, the 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).

D2.2.5 Exposure from freshwater pathways

The GDL for fresh water (expressed as whole water, covering both dissolved and suspended fractions) has the following method of derivation. The GDL is divided into two main components: exposure associated with aquatic exposure pathways and exposure due to irrigation. Exposure due to irrigation was modelled using the pathways described above. The GDLs from aquatic exposure pathways were derived from the GDLs calculated for each exposure pathway, using Equation 8:

$$GDL_{fwaq} = \frac{GDL_{aqex}}{C_f} \qquad (8)$$

where

GDL_{fwaq}	=	GDL for dissolved fraction of, or filtered, freshwater (Bq l^{-1})
GDL_{aqex}	=	GDL for the aquatic exposure pathways: ingestion of freshwater fish, inhalation of and external exposure from shoreline sediment (Bq kg^{-1})

C_f = concentration factor between environmental material or fish and filtered freshwater (Bq kg^{-1} per Bq l^{-1}). For uranium this concentration factor is 1 x10^1 Bq kg^{-1} per Bq l^{-1}.

For the pathways associated with sediment (external exposure and inhalation), the concentration factor used was the element-dependent sediment water distribution coefficient (K_d). For the GDL associated with the consumption of fish, the element-dependent freshwater fish concentration factor was used. The GDL for freshwater expressed in terms of unfiltered water (ie dissolved and solid phase) was derived using Equation 9:

$$GDL_{fwater} = GDL_{fwaq} (1 + K_d S) \quad (9)$$

where

GDL_{fwater} = GDL for freshwater (dissolved and suspended fraction) (Bq l^{-1}),per litre)

K_d = freshwater sediment water distribution coefficient (Bq kg^{-1} per Bq l^{-1}). For uranium this distribution coefficient is 5 x 10^1 Bq kg^{-1} per Bq l^{-1}

S = freshwater suspended sediment load (kg l^{-1}).

D3 Summary of uranium GDLs

GDLs for uranium are presented in Table D2. The relative importance of pathways for well-mixed soil GDLs are summarised in Fig. D1, 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 GDLs indicates the sensitivity of air, drinking water and milk to contamination from DU. In all of these cases the critical group is children and/or infants (including those in the first year of life).

Table D1 Dose coefficients for intake by ingestion and inhalation for ^{238}U

Nuclide	f_1 (for three month old infant)	f_1 (other ages)	Type[1]	Committed effective dose per unit intake (Sv Bq^{-1})[2]			
				Infant (three months)	Infant (one year)	Child (ten years)	Adult (20 years)
Ingestion	4.0 x 10^{-2}	2.0 x 10^{-2}		3.40 x 10^{-7}	1.20 x 10^{-7}	6.80 x 10^{-8}	4.50 x 10^{-8}
Inhalation		2.0 x 10^{-2}	M		9.40 x 10^{-6}	4.00 x 10^{-6}	2.90 x 10^{-6}

[1]Absorption type M (moderate) describing absorption from the respiratory tract.
[2]The age groups for dose coefficients given in Tables D1 and D2 are those given in ICRP (1996).

Table D2. GDLs for ^{238}U (Bq kg^{-1}) (NRPB, 2000)

	GDL Single	Critical group[1]
Inhalation of air	0.05	children aged ten years
Locally grown fruit	200	infants aged one year
Potatoes and root vegetables	200	children aged ten years
Green and other locally grown vegetables	300	adults
Cereals	200	children aged ten years
Cattle meat	500	children aged ten years
Sheep meat	900	adults
Offal[2]	1000	adults
Milk	8	infants under one year on all milk diet
Milk products	200	infants aged one year
Marine fish[3]	200	adults
Crustaceans[3]	1000	adults
Molluscs[3]	1000	adults
Drinking water	30	infants aged one year
Freshwater fish[3]	1000	adults
	Multiple	
Well-mixed soil[4]	20000	infants aged one year
Freshwater sediments[4]	400000	children aged ten years
Marine sediments[4]	100000	adults
Fresh water[5]	20	adults
Sea-washed pasture[4]	20000	infants under one year on all milk diet

[1]The GDLs apply to uniform conditions over a year and are based on the limiting age group. Unless stated otherwise, GDLs for food products are expressed as fresh mass.
[2]Offal refers to cow liver and sheep liver.
[3]The GDLs for aquatic foodstuffs are for the edible fraction and are expressed as fresh mass.
[4]The GDLs are expressed as dry mass.
[5]The GDLs for fresh water include activity in the dissolved and suspended fractions.

Table D3. 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
Home fruit	35	50	75
Potatoes and root vegetables	45	95	130
Green and other locally grown vegetables[1]	15	35	80
Pig meat	5.5	25	40
Cattle meat	10	30	45
Sheep meat	3.0	10	25
Offal	5.5	10	20
Poultry	5.5	15	30
Milk[2] (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.
[2]The GDL for milk, consumed by infants in the first year of life, assumes a milk intake of 350 litres y^{-1}.

Table D4. 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})	5×10^{-5}	1×10^{-5}	5×10^{-6}
Annual inadvertent ingestion rate accounting for indoor occupancy (kg y^{-1}) – for well-mixed soil and irrigated soil	4.4×10^{-2}	1.8×10^{-2}	8.3×10^{-3}

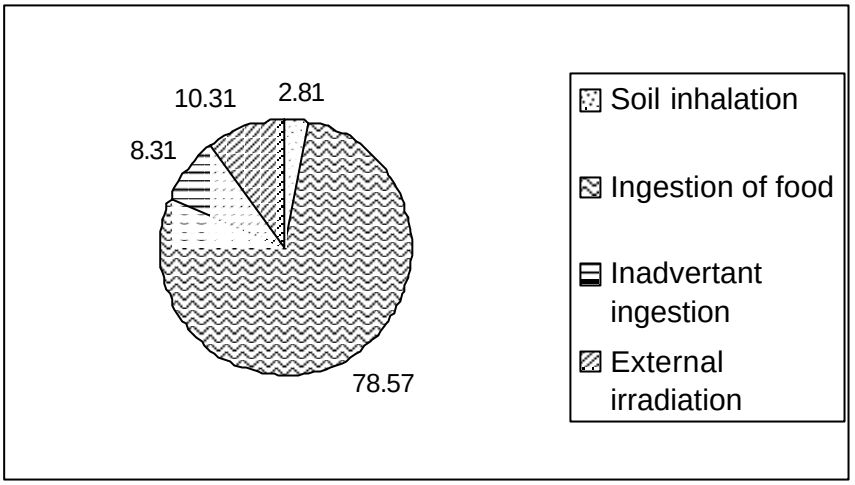
Table D5 Pathways considered for multiple-exposure GDLs

	Exposure pathways
Well-mixed soil	External exposure from 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	External exposure from sediment Inadvertent ingestion of sediment Inhalation of resuspended sediment
Fresh water	*Aquatic exposure pathways* Ingestion of river water Ingestion of freshwater fish External exposure from shoreline sediment Inhalation of resuspended shoreline sediment *Exposure pathways from soil irrigation* External exposure from irrigated soil Inadvertent ingestion of irrigated soil Inhalation of resuspended irrigated soil Ingestion of plant products from irrigated soil
Sea-washed pasture	External exposure from sea-washed pasture Inadvertent ingestion of soil Inhalation of resuspended soil Ingestion of animal products from sea-washed pasture

Table D6. Occupancies

	Infant (one year)	Child (ten years)	Adult (20 years)
	Occupancy (h y^{-1})		
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
Shielding factors (external)			
Indoor	0.1	0.1	0.1

Figure D1. Well-mixed soil: percentage breakdown of GDLs by exposure pathway.



References

ICRP (1990). *Recommendations of the International Commission of Radiological Protection*. ICRP Publication 60. Ann ICRP **21** (1–3)

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)

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

Simmonds J R, Lawson, G & Mayall A (1995). *Methodology for assessing the radiological consequences of routine releases of radionuclides to the environment.* EUR15760 EN. EC: Luxembourg