NRPB

Documents of the NRPB

Generalised Derived Constraints for Radioisotopes of Strontium, Ruthenium, Iodine, Caesium, Plutonium, Americium and Curium

Generalised Derived Limits for Radioisotopes of Polonium, Lead, Radium and Uranium

VOLUME 11 NO 2 2000

National Radiological Protection Board
Chilton, Didcot, Oxon OX11 0RQ

The National Radiological Protection Board was created by the Radiological Protection Act 1970. The functions of the Board are to give advice, to conduct research, and to provide technical services in the field of protection against both ionising and non-ionising radiations.

In 1977 the Board received Directions under the Radiological Protection Act which require it to give advice on the acceptability to and the application in the UK, of standards recommended by international or intergovernmental bodies, and to specify emergency reference levels (ERLs) of dose for limiting radiation doses in accident situations.

Documents of the NRPB contain both the formal advice of the Board on standards of protection as well as guidance on their application in practice.

DOCUMENTS OF THE NRPB

Generalised Derived Constraints for Radioisotopes of Strontium, Ruthenium, Iodine, Caesium, Plutonium, Americium and Curium

Generalised Derived Limits for Radioisotopes of Polonium, Lead, Radium and Uranium

VOLUME 11 NO 2 2000

National Radiological Protection Board
Chilton, Didcot, Oxon OX11 0RQ

Contents

GENERALISED DERIVED CONSTRAINTS FOR RADIOISOTOPES OF STRONTIUM, RUTHENIUM, IODINE, CAESIUM, PLUTONIUM, AMERICIUM AND CURIUM

ABSTRACT

The 1990 recommendations of the International Commission on Radiological Protection (ICRP) introduced the concept of the dose constraint and in the NRPB response to the recommendations the concept of a generalised derived constraint (GDC) was introduced. Generalised derived constraints apply to discharges of radionuclides to the environment and are based on the upper value of constraint on effective dose for members of the public of 0.3 mSv y^{-1}. Generalised derived constraints have been calculated for discharges to atmosphere, rivers and sewers for the radiologically significant isotopes of strontium, ruthenium, iodine, caesium, plutonium, americium and curium. The most recent age-dependent dosimetric models were used in the calculations. The GDCs presented here are intended as convenient reference levels against which proposed discharges can be compared. The GDCs for atmospheric discharges can replace previously published generalised derived limits (GDLs) for radionuclide discharges to atmosphere.

Generalised derived constraints are calculated using deliberately cautious assumptions and are in terms of annual discharges, assuming that the releases to the environment are continuous. If a proposed discharge is greater than about 30% of the GDC then the doses should be examined more closely, taking account of site-specific factors.

PREPARED BY J G TITLEY, C A ATTWOOD AND J R SIMMONDS

This advice reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.

INTRODUCTION

1 The publication of the 1990 recommendations of the International Commission on Radiological Protection (ICRP)[1] introduced the concepts of effective dose and dose constraint. NRPB has published guidance on the ICRP recommendations[2] and has considered their implications for public exposure[3]. Previously, NRPB had published generalised derived limits (GDLs) based on the dose limit for members of the public for discharges of radionuclides to the atmosphere and for radionuclides in environmental materials. In considering the implications of the 1990 ICRP recommendations for public exposure NRPB noted that GDLs for environmental materials should still be based on the overall dose limit for members of the public. However, derived quantities for discharges of radionuclides to the environment are clearly related to the current operation of a single controlled source and should therefore be based on the appropriate dose constraint[3]. Generalised derived constraints (GDCs) have therefore been developed for discharges of radioisotopes of seven elements, and they are published here. The GDCs are based on the upper value of the constraint on effective dose for members of the public of 0.3 mSv y^{-1} recommended by NRPB[3]. Revised GDLs for the same radioisotopes have also recently been published by NRPB for a range of environmental materials together with advice on their application[4,5]. The revised GDLs and the new GDCs replace all those published previously[6,7].

2 Generalised derived constraints are intended to be convenient reference quantities against which proposed controlled discharges to the environment can be compared. They are expected to be particularly useful for small (non-nuclear industry) users of radioactive materials discharging low levels of radionuclides to the environment. The GDCs may not be relevant to authorised discharges from nuclear sites where discharges can be greater and the dispersion conditions may be very different from those assumed here; for example, liquid discharges are mainly to the sea not to sewers or small rivers. Generalised derived constraints are related to the dose constraint by a defined model and are calculated such that compliance with the GDC should ensure virtual certainty of compliance with the constraint. They are intended for general application and are based on a generic definition of the discharge location and the receiving environment. The GDC does not replace the requirement on the dischargers of radioactive material to optimise their use of sources or management of practices so that exposures of members of the public are kept as low as reasonably achievable.

3 This report considers three types of discharge of radionuclides to the environment and GDCs are presented for each. The discharges are to atmosphere, rivers and to sewers. Previously[6,7], GDLs for discharge to atmosphere only were presented and these were based on the annual dose limit for members of the public. The GDCs for discharges to atmosphere are based on the dose constraint, rather than the dose limit, and the opportunity has also been taken to review the data and methods used in the calculations leading to some additional differences from those published previously[6,7]. Small users of radioactive materials, such as hospitals and universities, discharge small quantities of radionuclides to the sewerage system or directly to rivers in addition to discharging to atmosphere. Therefore GDCs for discharges to sewers and to rivers have also been determined. The GDCs have been calculated using effective dose as defined in ICRP Publication 60[1]. The latest age-dependent dose coefficients[8] for members of the public were used in the calculations.

4 This document presents GDCs for discharges to atmosphere, rivers and sewers for the radioisotopes of seven elements for which GDLs in environmental materials have already been published[4]. The methods and data used in their calculation are outlined and the important exposure pathways for each GDC are discussed. Advice is also given on when site-specific assessments are required.

BASIS FOR GDCs

5 A dose constraint is the upper bound on the annual effective dose that members of the public may receive from the planned operation of a single controlled source; the dose constraint places an upper bound on the outcome of optimisation studies. The quantity to be compared with the dose constraint is the annual dose to the overall critical group summed over all exposure pathways, arising from the current and future operations of a controlled source[3]. The exposure pathways to be considered include those which are expected to arise in the future from current operations, since these can be influenced by current or future control procedures. It does not include exposures from past discharges, since these cannot be influenced by current or future control procedures. However, account should be taken of any build-up of radioactivity in the environment owing to present and future operation[3]. For proposed controlled sources, NRPB has recommended[2] a maximum dose constraint for public exposure of 0.3 mSv y^{-1}, with the proviso that dose constraints lower than this could be set where such doses are readily achievable. The GDCs presented here are based on this upper value of the dose constraint. They represent the annual discharge of a particular radionuclide by a single mode of discharge which is calculated to give a dose of 0.3 mSv y^{-1} to the critical group. The GDCs are intended for screening purposes to enable the doses from low levels of discharge of radionuclides to the environment to be assessed. In particular, they enable the impact of proposed discharges from small users of radioactive materials, such as hospitals, to be estimated, without necessarily carrying out a full site-specific dose assessment.

6 Generalised derived constraints have been calculated for three modes of discharge: to atmosphere, rivers and sewers. In each case doses are calculated for all relevant exposure pathways and are summed. For discharge to atmosphere the radionuclide is assumed to be discharged as particles, while for discharges to rivers and to sewers the radionuclide is assumed to be discharged in solution. The disposal of solid forms of radioactive waste is outside the scope of this document. For each of the three modes of discharge, cautious assumptions are made about the nature of the discharge and the location of the critical group relative to the discharge point. For example, it has been necessary to adopt generic values for the height of the discharge point for atmospheric releases, the characteristics of the river receiving liquid discharges and the type of sewerage system. The use of cautious assumptions is intended to ensure that compliance with the GDC should also lead to compliance with the dose constraint. Nevertheless, as discussed later, site-specific assessments will be required if a proposed discharge is a significant fraction of the relevant GDC.

7 The GDCs are for continuous discharges of radionuclides to the environment and are for annual discharges, which are assumed to continue for 50 years. They have been calculated assuming that annual average conditions apply. They, therefore, do not apply to uncontrolled or controlled short-term releases nor to releases which vary significantly over the year.

8 The age groups considered in calculating GDCs are infants (1 year old), children (10 years old) and adults (assumed to be 20 years old), taking into account variations in the dose coefficients and dietary and other habits with age. In addition, for radionuclides where the ingestion of milk is likely to be the dominant exposure pathway, calculations are also performed for infants on an all-milk diet in the first year of life based on dose coefficients for a 3 month old. These age groups are the same as those considered in the calculations of GDLs[4] and again the GDCs are based on the dose to the most restrictive age group. The use of the ingestion dose coefficient for a 3 month old, together with a milk intake more applicable to an older infant to represent the first year of life, will lead to a cautious estimate of the GDC. This is particularly the case for radioisotopes where there is a marked reduction in the dose coefficient between 3 and 12 months. It is considered inappropriate to use the 3 month old dose coefficient for intakes of other foods as they are generally only consumed by older infants for whom a lower dose coefficient usually applies. Although data on dose coefficients are available for additional age groups[8], the ages considered here are thought to cover the range and to be adequate for the purposes of calculating GDCs. For calculating the doses from intakes of radionuclides the lifetime of an individual is taken to be 70 years. Although it is slightly shorter than the average lifetime of individuals in the UK, its use is sufficiently cautious because intakes of radionuclides and the resulting risks decrease in old age.

9 The values of the effective dose coefficients for intake by inhalation and ingestion are as described elsewhere[8]. They have been calculated for each age group considered using the most recent age-dependent dosimetric models. Tables 1 and 2 give the values for the effective dose coefficients used here for intake by ingestion and inhalation, respectively. The recommended[8] default absorption types for particulate aerosols are used to select the appropriate inhalation dose coefficients for the GDC calculations.

10 As presented here, GDCs relate the discharge of a single radionuclide from a single mode of discharge to the upper value on the constraint on effective dose for members of the public. In practice, sites are likely to discharge a number of radionuclides by more than one mode and this needs to be taken into account, as outlined later.

GDCs FOR DISCHARGES TO ATMOSPHERE, RIVERS AND SEWERS

11 The general approach and formulae used to calculate the GDCs for discharges to atmosphere, rivers and sewers are given in Appendices A, B and C, respectively, together with the data on occupancy and intakes of air, terrestrial and aquatic foods used in the calculations. These data are generally the same as those used to calculate GDLs[4].

12 The release to atmosphere is assumed to be from a height of 1 m above the ground and the members of the critical group are assumed to live 100 m from the release point, obtaining all of their food from an area 500 m from the release point. Further details of the assumptions adopted are given in Appendix A. Five exposure pathways are considered:

(a) internal irradiation from inhalation of radionuclides in air,
(b) external irradiation from radionuclides in the plume,
(c) external irradiation from radionuclides deposited on the ground,
(d) internal irradiation from inhalation of deposited radionuclides resuspended into the air,
(e) internal irradiation from ingestion of radionuclides in terrestrial foods.

TABLE 1 *Dose coefficients for intake by ingestion*

		Committed effective dose per unit intake (Sv Bq^{-1})			
Nuclide	f_1*	Infant (3 months)	Infant (1 y)	Child (10 y)	Adult (20 y)
^{89}Sr	$3.0\ 10^{-1}$	$3.6\ 10^{-8}$	$1.8\ 10^{-8}$	$5.8\ 10^{-9}$	$2.6\ 10^{-9}$
^{90}Sr	$3.0\ 10^{-1}$	$2.3\ 10^{-7}$	$7.3\ 10^{-8}$	$6.0\ 10^{-8}$	$2.8\ 10^{-8}$
^{103}Ru	$5.0\ 10^{-2}$	$7.1\ 10^{-9}$	$4.6\ 10^{-9}$	$1.5\ 10^{-9}$	$7.3\ 10^{-10}$
^{106}Ru	$5.0\ 10^{-2}$	$8.4\ 10^{-8}$	$4.9\ 10^{-8}$	$1.5\ 10^{-8}$	$7.0\ 10^{-9}$
^{125}I	1.0	$5.2\ 10^{-8}$	$5.7\ 10^{-8}$	$3.1\ 10^{-8}$	$1.5\ 10^{-8}$
^{129}I	1.0	$1.8\ 10^{-7}$	$2.2\ 10^{-7}$	$1.9\ 10^{-7}$	$1.1\ 10^{-7}$
^{131}I	1.0	$1.8\ 10^{-7}$	$1.8\ 10^{-7}$	$5.2\ 10^{-8}$	$2.2\ 10^{-8}$
^{132}I	1.0	$3.0\ 10^{-9}$	$2.4\ 10^{-9}$	$6.2\ 10^{-10}$	$2.9\ 10^{-10}$
^{133}I	1.0	$4.9\ 10^{-8}$	$4.4\ 10^{-8}$	$1.0\ 10^{-8}$	$4.3\ 10^{-9}$
^{134}I	1.0	$1.1\ 10^{-9}$	$7.5\ 10^{-10}$	$2.1\ 10^{-10}$	$1.1\ 10^{-10}$
^{135}I	1.0	$1.0\ 10^{-8}$	$8.9\ 10^{-9}$	$2.2\ 10^{-9}$	$9.3\ 10^{-10}$
^{134}Cs	1.0	$2.6\ 10^{-8}$	$1.6\ 10^{-8}$	$1.4\ 10^{-8}$	$1.9\ 10^{-8}$
^{136}Cs	1.0	$1.5\ 10^{-8}$	$9.5\ 10^{-9}$	$4.4\ 10^{-9}$	$3.0\ 10^{-9}$
^{137}Cs	1.0	$2.1\ 10^{-8}$	$1.2\ 10^{-8}$	$1.0\ 10^{-8}$	$1.3\ 10^{-8}$
^{238}Pu	$5.0\ 10^{-4}$	$4.0\ 10^{-6}$	$4.0\ 10^{-7}$	$2.4\ 10^{-7}$	$2.3\ 10^{-7}$
^{239}Pu	$5.0\ 10^{-4}$	$4.2\ 10^{-6}$	$4.2\ 10^{-7}$	$2.7\ 10^{-7}$	$2.5\ 10^{-7}$
^{240}Pu	$5.0\ 10^{-4}$	$4.2\ 10^{-6}$	$4.2\ 10^{-7}$	$2.7\ 10^{-7}$	$2.5\ 10^{-7}$
^{241}Pu	$5.0\ 10^{-4}$	$5.6\ 10^{-8}$	$5.7\ 10^{-9}$	$5.1\ 10^{-9}$	$4.8\ 10^{-9}$
^{242}Pu	$5.0\ 10^{-4}$	$4.0\ 10^{-6}$	$4.0\ 10^{-7}$	$2.6\ 10^{-7}$	$2.4\ 10^{-7}$
^{241}Am	$5.0\ 10^{-4}$	$3.7\ 10^{-6}$	$3.7\ 10^{-7}$	$2.2\ 10^{-7}$	$2.0\ 10^{-7}$
^{242}Am	$5.0\ 10^{-4}$	$5.0\ 10^{-9}$	$2.2\ 10^{-9}$	$6.4\ 10^{-10}$	$3.0\ 10^{-10}$
^{243}Am	$5.0\ 10^{-4}$	$3.6\ 10^{-6}$	$3.7\ 10^{-7}$	$2.2\ 10^{-7}$	$2.0\ 10^{-7}$
^{242}Cm	$5.0\ 10^{-4}$	$5.9\ 10^{-7}$	$7.6\ 10^{-8}$	$2.4\ 10^{-8}$	$1.2\ 10^{-8}$
^{243}Cm	$5.0\ 10^{-4}$	$3.2\ 10^{-6}$	$3.3\ 10^{-7}$	$1.6\ 10^{-7}$	$1.5\ 10^{-7}$
^{244}Cm	$5.0\ 10^{-4}$	$2.9\ 10^{-6}$	$2.9\ 10^{-7}$	$1.4\ 10^{-7}$	$1.2\ 10^{-7}$

* The gut transfer factors (f_1) for each nuclide given are the same for all age groups with the following exceptions:

Isotopes of Sr	3 month old: $6.0\ 10^{-1}$	1 year old and 10 year old: $4.0\ 10^{-1}$
Isotopes of Ru	3 month old: $1.0\ 10^{-1}$	
Isotopes of Am, Pu, Cm	3 month old: $5.0\ 10^{-3}$	

The doses from each of these exposure pathways are summed to obtain the GDC. For the radionuclides considered in this document equivalent doses to the skin and lens of the eye are not explicitly considered as these doses are less restrictive than the effective dose in determining the GDC. This would not necessarily be the case for some other radionuclides, notably the noble gases for which these doses may need to be considered. In estimating the doses the release is taken to continue for 50 years allowing for any build-up of radionuclides in the environment.

13 Table 3 gives the calculated GDCs for discharges to atmosphere for the 25 radionuclides considered in this document. These values are significantly different from the GDLs for discharge to atmosphere published previously[6,7] and are all more restrictive. This is partly because the dose criterion has changed from 1 mSv y^{-1} to 0.3 mSv y^{-1}. There are

TABLE 2 *Dose coefficients for intake by inhalation*

			Committed effective dose per unit intake (Sv Bq^{-1})		
Nuclide	f_1	Type*	Infant (1 y)	Child (10 y)	Adult (20 y)
^{89}Sr	1.0 10^{-1}	M	2.4 10^{-8}	9.1 10^{-9}	6.1 10^{-9}
^{90}Sr	1.0 10^{-1}	M	1.1 10^{-7}	5.1 10^{-8}	3.6 10^{-8}
^{103}Ru	5.0 10^{-2}	M	8.4 10^{-9}	3.5 10^{-9}	2.4 10^{-9}
^{106}Ru	5.0 10^{-2}	M	1.1 10^{-7}	4.1 10^{-8}	2.8 10^{-8}
^{125}I	1.0	F	2.3 10^{-8}	1.1 10^{-8}	5.1 10^{-9}
^{129}I	1.0	F	8.6 10^{-8}	6.7 10^{-8}	3.6 10^{-8}
^{131}I	1.0	F	7.2 10^{-8}	1.9 10^{-8}	7.4 10^{-9}
^{132}I	1.0	F	9.6 10^{-10}	2.2 10^{-10}	9.4 10^{-11}
^{133}I	1.0	F	1.8 10^{-8}	3.8 10^{-9}	1.5 10^{-9}
^{134}I	1.0	F	3.7 10^{-10}	9.7 10^{-11}	4.5 10^{-11}
^{135}I	1.0	F	3.7 10^{-9}	7.9 10^{-10}	3.2 10^{-10}
^{134}Cs	1.0	F	7.3 10^{-9}	5.3 10^{-9}	6.6 10^{-9}
^{136}Cs	1.0	F	5.2 10^{-9}	2.0 10^{-9}	1.2 10^{-9}
^{137}Cs	1.0	F	5.4 10^{-9}	3.7 10^{-9}	4.6 10^{-9}
^{238}Pu	5.0 10^{-4}	M	7.4 10^{-5}	4.4 10^{-5}	4.6 10^{-5}
^{239}Pu	5.0 10^{-4}	M	7.7 10^{-5}	4.8 10^{-5}	5.0 10^{-5}
^{240}Pu	5.0 10^{-4}	M	7.7 10^{-5}	4.8 10^{-5}	5.0 10^{-5}
^{241}Pu	5.0 10^{-4}	M	9.7 10^{-7}	8.3 10^{-7}	9.0 10^{-7}
^{242}Pu	5.0 10^{-4}	M	7.3 10^{-5}	4.5 10^{-5}	4.8 10^{-5}
^{241}Am	5.0 10^{-4}	M	6.9 10^{-5}	4.0 10^{-5}	4.2 10^{-5}
^{242}Am	5.0 10^{-4}	M	5.9 10^{-8}	2.4 10^{-8}	1.7 10^{-8}
^{243}Am	5.0 10^{-4}	M	6.8 10^{-5}	4.0 10^{-5}	4.1 10^{-5}
^{242}Cm	5.0 10^{-4}	M	1.8 10^{-5}	7.3 10^{-6}	5.2 10^{-6}
^{243}Cm	5.0 10^{-4}	M	6.1 10^{-5}	3.1 10^{-5}	3.1 10^{-5}
^{244}Cm	5.0 10^{-4}	M	5.7 10^{-5}	2.7 10^{-5}	2.7 10^{-5}

* Absorption types M (moderate) and F (fast) describing absorption from the respiratory tract.

also significant differences due to using different assumptions regarding the discharge point and the location of the critical group; further differences occur because of revisions in the dose coefficients and other parameter values used. The change in assumptions on location has also affected the relative contributions of the different exposure pathways to the overall dose, as the predicted concentrations of radionuclides in air used in the calculations have increased more than the predicted concentrations of radionuclides on the ground. Appendix D presents the contributions of the different exposure pathways to the overall dose used in calculating the GDCs. The GDCs are based on the limiting age group which is indicated in Table 3.

14 Generalised derived constraints for discharges to rivers are also given in Table 3. They are again for the most restrictive age group which is indicated in the table. The discharges are assumed to be to a generic river with a flow of 1 m^3 s^{-1}. This flow is relatively low and so will generally result in a cautious estimate of the concentrations of radionuclides in river water and hence radiation doses. Full details of the river characteristics and other data used in the calculations are given in Appendix B. The exposure pathways included in calculating the GDCs are:

(a) internal irradiation from ingestion of radionuclides in drinking water,
(b) internal irradiation from ingestion of radionuclides in freshwater fish,
(c) external irradiation from radionuclides deposited on river sediments,
(d) internal irradiation from inhalation of radionuclides resuspended into the air from sediments,
(e) internal irradiation from ingestion of radionuclides in terrestrial foods grown on irrigated land.

The GDC is based on the sum of doses from all exposure pathways. The relative contributions of the different exposure pathways to the overall dose are given in Appendix D.

TABLE 3
Generalised derived constraints for releases to atmosphere, rivers and sewers

	Releases to atmosphere		Releases to river		Releases to sewers*	
Nuclide	GDC (Bq y^{-1})	Limiting age group	GDC (Bq y^{-1})	Limiting age group	GDC (Bq y^{-1})	Limiting age group
^{89}Sr	$2\ 10^{12}$	1 y old	$2\ 10^{12}$	1 y old	$6\ 10^{9}$	First year†
^{90}Sr	$1\ 10^{11}$	10 y old	$2\ 10^{11}$	Adult	$3\ 10^{7}$	First year
^{103}Ru	$3\ 10^{12}$	Adult	$9\ 10^{12}$	1 y old	$7\ 10^{8}$	Adult w
^{106}Ru	$4\ 10^{11}$	Adult	$9\ 10^{11}$	1 y old	$2\ 10^{9}$	Adult w
^{125}I	$4\ 10^{10}$	1 y old	$4\ 10^{11}$	10 y old	$4\ 10^{9}$	1 y old
^{129}I	$4\ 10^{9}$	1 y old	$5\ 10^{10}$	10 y old	$8\ 10^{7}$	1 y old
^{131}I	$3\ 10^{10}$	1 y old	$2\ 10^{11}$	1 y old	$8\ 10^{8}$	Adult w
^{132}I	$3\ 10^{13}$	Adult	$2\ 10^{13}$	1 y old	$1\ 10^{8}$	Adult w
^{133}I	$1\ 10^{12}$	1 y old	$8\ 10^{11}$	1 y old	$5\ 10^{8}$	Adult w
^{134}I	$6\ 10^{13}$	Adult	$7\ 10^{13}$	1 y old	$1\ 10^{8}$	Adult w
^{135}I	$1\ 10^{13}$	1 y old	$4\ 10^{12}$	1 y old	$2\ 10^{8}$	Adult w
^{134}Cs	$7\ 10^{10}$	Adult	$1\ 10^{10}$	Adult	$2\ 10^{8}$	Adult
^{136}Cs	$2\ 10^{12}$	Adult	$8\ 10^{10}$	Adult	$1\ 10^{8}$	Adult w
^{137}Cs	$5\ 10^{10}$	Adult	$2\ 10^{10}$	Adult	$1\ 10^{8}$	Adult
^{238}Pu	$3\ 10^{8}$	Adult	$2\ 10^{11}$	Adult	$5\ 10^{8}$	Adult
^{239}Pu	$3\ 10^{8}$	Adult	$2\ 10^{11}$	Adult	$4\ 10^{8}$	Adult
^{240}Pu	$3\ 10^{8}$	Adult	$2\ 10^{11}$	Adult	$4\ 10^{8}$	Adult
^{241}Pu	$2\ 10^{10}$	Adult	$9\ 10^{12}$	Adult	210^{10}	Adult
^{242}Pu	$3\ 10^{8}$	Adult	$2\ 10^{11}$	Adult	$4\ 10^{8}$	Adult
^{241}Am	$3\ 10^{8}$	Adult	$3\ 10^{11}$	Adult	$5\ 10^{8}$	Adult
^{242}Am	$8\ 10^{11}$	10 y old	$3\ 10^{14}$	1 y old	$2\ 10^{10}$	Adult w
^{243}Am	$4\ 10^{8}$	Adult	$2\ 10^{11}$	Adult	$2\ 10^{8}$	Adult
^{242}Cm	$3\ 10^{9}$	10 y old	$4\ 10^{12}$	1 y old	$2\ 10^{10}$	1 y old
^{243}Cm	$5\ 10^{8}$	Adult	$4\ 10^{11}$	Adult	$4\ 10^{8}$	Adult
^{244}Cm	$5\ 10^{8}$	Adult	$5\ 10^{11}$	Adult	$9\ 10^{8}$	Adult

* The GDCs are limited by application of sewage sludge to land except where indicated by w – exposure at the sewage works.

† First year – refers to infants in the first year of life on an all-milk diet.

15 Radionuclides discharged to a sewerage system can give rise to exposures in a number of different ways. If the radionuclide becomes associated with the sewage sludge then exposure could result to the workers at the sewage works; the sludge might also be used for land treatment leading to the transfer of radionuclides to terrestrial foods. In some cases sewage sludge is incinerated or sent to landfill sites. However, if the radionuclide is not transferred to the sludge but remains in the water phase then it would be discharged to a river, giving rise to the same exposure pathways as in the case of a direct discharge to a river. There is little information available on the extent to which radionuclides discharged to sewers would partition between the sludge and the water. A recent study has been carried out to investigate the fate of radionuclides to public sewers[9] and this considers the partitioning of radionuclides and the exposure from different routes of sewage sludge disposal.

16 For simplicity, a cautious approach is taken in calculating GDCs for discharges to sewers. Two distinct possibilities are considered: that all of the radioactivity is transferred to sludge and that all of the activity remains in water. In the former case, two separate situations are considered: firstly, the doses to sewage plant workers are calculated and, secondly, the doses due to the ingestion of radionuclides in foods grown on land treated with sludge are calculated. In the latter case doses are calculated as for discharge to a river. The three exposure scenarios are considered to be mutually exclusive and GDCs have been calculated for all three and the most restrictive taken to be the GDC for this discharge route. Full details of the methods, assumptions and data used in these calculations are given in Appendix C. It is assumed that the discharge goes to a small sewage works serving 500 people. The exposure pathways considered for the sewage plant workers are:

(a) external irradiation from radionuclides in sewage sludge stored in tanks,
(b) internal irradiation from inhalation of radionuclides resuspended from the sludge,
(c) internal irradiation from inadvertent ingestion of radionuclides in the sludge.

The sludge produced by a small works could be used to treat a limited area of land used for raising sheep, beef or dairy cattle. The exposure pathways considered are:

(a) external irradiation from radionuclides in the soil,
(b) internal irradiation from inadvertent ingestion of radionuclides in the soil,
(c) internal irradiation from inhalation of radionuclides resuspended from the soil,
(d) internal irradiation from ingestion of radionuclides in animal products.

The limited area of land treated means that it is not considered feasible for the land to be used for more than one animal product. Doses are therefore calculated for products from each type of animal and the most restrictive taken. The exposure pathways for radionuclides discharged to the river are as described in paragraph 14.

17 Table 3 gives the GDCs for discharges to sewers; the values are the most restrictive from those calculated for the three scenarios considered and the limiting case is indicated in Table 3. The limiting age group is also indicated. In some cases the limiting scenario is the exposure of the workers at the sewage works and in others it results from the treatment of land with sewage sludge. However, the case of discharges from the sewage works to the river is never limiting for the radionuclides considered here. Details of the relative contributions of the different exposure pathways to the overall dose used to calculate the GDCs are given in Appendix D. As discussed in Appendix C, exposure following the treatment of agricultural land with sewage sludge was not considered for short-lived radionuclides (half-life less than about two weeks) as the sludge is stored prior to land treatment and there is a delay between application and food production and consumption leading to radioactive decay.

SITE-SPECIFIC ASSESSMENTS

18 Generalised derived constraints are intended for screening purposes and have been calculated using a set of generic assumptions such that the resultant doses are expected to be overestimated in most circumstances. However, it is possible for underestimation to occur in particular circumstances – for example, where the discharge occurs under different circumstances or if additional exposure pathways are present. It has therefore been recommended that an implied dose of 0.1 mSv y^{-1} is a reasonable level at which to trigger further investigation[3]. This corresponds to about 30% of the GDC for discharges and if this is exceeded then the situation should be examined more closely, taking account of site-specific factors, the source of the activity and the length of time for which the situation is likely to persist. As the GDC is based on the upper value of constraint on effective dose for members of the public, a lower investigation level might also be necessary if a lower dose constraint is considered appropriate for the particular practice of interest; in this case the GDC can simply be scaled by the ratios of the particular dose constraint to the upper value (0.3 mSv y^{-1}).

19 In practice, discharges of more than one radionuclide and from more than one route will occur. Account must be taken of exposures from all radionuclides discharged and this can be done by summing proportions of the relevant GDCs (see the equation below).

$$\sum_i A_i / \mathrm{GDC}_i \leq 1$$

where A_i = discharge rate of radionuclide i in Bq y^{-1},
GDC_i = the GDC for radionuclide i in Bq y^{-1}.

For some sites, direct radiation from a source on site may contribute to the exposure of members of the public. This exposure also needs to be included with that from discharges in comparison with the dose constraint. It is also likely that radionuclides will be discharged from more than one route – for example, discharges to atmosphere and to the sewer system may occur from the same location. In this case the critical group for the different discharge routes is unlikely to be the same and so summing fractions of the GDC is very cautious and is not recommended. If a site-specific dose assessment is required then a more realistic approach could be adopted where account is taken of exposure from all routes using a combination of critical group and average habits[10].

20 A discharge greater than 30% of the GDC does not, of course, necessarily imply that an effective dose of 0.1 mSv y^{-1} will be exceeded. Significantly different radiation doses will result from discharges occurring under different circumstances than those assumed in the generic cases considered here, which have been chosen to give cautious estimates of the resulting doses. For releases to atmosphere, significantly lower concentrations of radionuclides in air or on the ground than those assumed here would arise for discharges from a greater height. In the case of discharges to a river, the characteristics of the river, particularly the volumetric flow rate, have a significant effect on the extent to which the radionuclide is diluted, and hence on doses. In many cases the receiving river is likely to have a higher flow and dilution is likely to be greater than assumed here, but it may also be possible for the dilution to be less. Similarly, for discharges to sewers, cautious assumptions have been made about the size of the treatment plant and hence the degree of dilution that would occur for the radionuclide discharged. Discharges of radionuclides to a smaller sewage treatment works than that assumed are unlikely. However, the size of water body receiving treated effluent may be smaller than that assumed, and in some cases doses from the receiving water body could become limiting. The assumed location of the critical group relative to the discharge point also has a significant effect on the estimated doses. For discharges to atmosphere, doses will generally be lower for groups living further from the discharge point and higher for those living closer. Similarly, for discharges to a river, the location of the drinking water abstraction point relative to the discharge location will have a significant effect on the resulting estimated activity concentrations in water, and hence on doses.

21 If a proposed discharge is a significant fraction of the GDC and worthy of further investigation, then the first factor to consider is the nature of the discharge and the location of the critical group. The information in Appendix D could then be examined to determine which exposure pathways are important and refining the dose calculations for the important pathways could be considered. Care has to be taken, however, as the relative importance of different exposure pathways may change for different discharge assumptions. For example, for discharges to atmosphere, the locations of the critical group and the representative point where members of the group are assumed to obtain their food can affect the relative importance of the doses from ingestion of terrestrial foods and inhalation. In addition, particular pathways may not always be relevant for the situation of interest. For example, river water may not be used for human drinking water supplies. However, the fact that a pathway does not exist at present does not necessarily mean that it will not exist in the future and that it should not be considered. In many circumstances, including site-specific information on the discharge and critical group location may be sufficient to reduce estimated doses to acceptable levels. However, if the estimated doses are still considered significant, then a more rigorous site-specific assessment could be required looking in detail at the exposure pathways and the data used to calculate doses. Factors to be considered in site-specific calculations of GDLs, as discussed elsewhere[5], may also be relevant here.

22 In calculating the GDCs for release to a sewer, the discharge is assumed to be to a small rural sewage works. In many cases – for example, for large hospitals – discharge would be to a larger sewage works perhaps serving 100 000 people. In this case the radionuclides would become dispersed in a greater volume of sewage and hence doses would be expected to be lower. However, there is not always a simple relationship between the size of the sewage works and the resulting doses as additional exposure pathways could arise from land treatment and from incineration of the sludge which may also occur. A recent study[9] has shown that doses from discharges of radionuclides to a large urban works are lower than those from a rural works and indicates that a site-specific study for discharges to a large sewage works would give significantly lower doses than those estimated here. Appendix D presents equations giving an indication of the likely relationship between the GDCs and the actual size of the receiving sewage works for the radionuclides considered in the study.

CONCLUSIONS

23 Generalised derived constraints have been presented in this document for discharges of the most significant radioisotopes of strontium, ruthenium, iodine, caesium, plutonium, americium and curium. Discharges to atmosphere, to rivers and to sewers have been considered. The GDCs are based on an annual effective dose constraint of 0.3 mSv for members of the public and take account of the 1990 recommendations of ICRP, including the definition of effective dose[1]. In each case the GDC is the most restrictive of those calculated for the three age groups considered.

24 If proposed discharges from a particular source exceed about 30% of the GDC then doses to the most exposed group should be examined more closely taking into account site-specific factors.

ACKNOWLEDGEMENTS

25 The calculation of the GDCs was carried out under formal quality assurance procedures. Dr K R Smith and Mr N Green acted as quality assurance managers for the work. Dr B T Wilkins, Ms C A Robinson and Mr C A Fayers also made a valuable contribution to the project.

REFERENCES

1 ICRP. 1990 recommendations of the International Commission on Radiological Protection. ICRP Publication 60. *Ann ICRP*, **21**, Nos 1–3 (1991).

2 NRPB. Statement by NRPB: 1990 recommendations of the International Commission on Radiological Protection. *Doc NRPB*, **4**, No. 1, 1–5 (1993).

3 NRPB. Public exposure: guidance on the 1990 recommendations of ICRP. *Doc NRPB*, **4**, No. 2, 27–41 (1993).

4 NRPB. Revised generalised derived limits for radioisotopes of strontium, ruthenium, iodine, caesium, plutonium, americium and curium. *Doc NRPB*, **9**, No. 1, 1–34 (1998).

5 NRPB. Application of generalised derived limits. *Doc NRPB*, **9**, No. 1, 35–60 (1998).

6 NRPB. Revised generalised derived limits for radioisotopes of strontium, iodine, caesium, plutonium, americium and curium. Chilton, NRPB-GS8 (1987).

7 NRPB. Generalised derived limits for radioisotopes of ruthenium. Chilton, NRPB-GS10 (1989).

8 ICRP. 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**, No. 1 (1996).

9 Titley J G, Carey A D, Crockett G M, *et al.* Investigation of the sources and fate of radioactive discharges to public sewers. London, Environment Agency (to be published).

10 Robinson C A, Mayall A, Attwood C A, *et al.* Critical group doses around nuclear sites in England and Wales. Chilton, NRPB-R271 (DOE/HMIP/RR94/026, MAFF FSD RP 0306) (1994).

Appendix A

PRINCIPLES AND METHODS FOR CALCULATING GDCs FOR DISCHARGES TO ATMOSPHERE

Introduction

Generalised derived constraints (GDCs) are estimates of the amount of activity discharged to the environment, which, if not exceeded, mean that it is are very unlikely that members of the public would receive an effective dose above the maximum values of the dose constraint[1] of 0.3 mSv y^{-1}. The discharges have been related to the dose constraint using cautious environmental modelling and a cautious dose assessment. Atmospheric releases were assumed to continue for 50 years under the same conditions, and the resulting build-up in the environment was modelled. The exposed individuals were assumed to live and produce food close to the discharge point and to have critical group habits and intakes.

Some of the radionuclides considered have very short radioactive half-lives. For these, the dose assessment was limited to exposures that could reasonably occur within a few hours or days of release. Some of the radionuclides considered are likely to have radioactive decay products (progeny) and the ingrowth and decay of these were taken into account when determining the GDCs. Ingrowth of progeny was considered if significant ingrowth is likely to occur in the 50 year discharge period. Some radionuclides, such as ^{106}Ru, ^{137}Cs and ^{243}Am, have progeny with very short radioactive half-lives and were assumed to be in secular equilibrium when the GDCs were determined. Ingrowth of ^{241}Am from ^{241}Pu has been taken into account in the derivation of the GDC for ^{241}Pu.

This appendix is in three parts, the first section describes the environmental modelling performed, the second details the dose assessment and the final part describes the calculation of the GDCs for discharges to atmosphere. The GDCs themselves are given in Table 3 of the main text.

Environmental models

Atmospheric dispersion and deposition modelling

Activity concentrations of each radionuclide in the plume were calculated using a Gaussian plume atmospheric dispersion model[2,3], assuming a 1 m high stack and uniform wind rose. The atmospheric conditions assumed are given in Table A1. A semi-urban environment was modelled assuming 100% occupancy at 100 m from the release point and that all food consumed was produced on land 500 m from the release point. The dry deposition velocities and washout coefficients[4] are given in Table A2. The predicted air concentrations from a continuous release rate of 1 Bq s^{-1} and the resulting deposition rates are given in Table A3.

Foodchain modelling

Activity concentrations in foods resulting from 50 years of continuous atmospheric discharges were predicted using the dynamic foodchain model FARMLAND[5]. It was assumed that activity in the plume deposited on to soil, some activity was directly intercepted by the plants, and that a fraction of the intercepted activity was transferred into the plants. Build-up in soil over 50 years, uptake of activity from soil into plants and the

TABLE A1 *Atmospheric conditions assumed*

Pasquill stability category	Frequency of occurrence (%)
A	1
B	9
C	21
D	50
E	8
F	10
G	2

TABLE A2 *Deposition to ground from the plume*[4]

Factor	Parameter value
Dry deposition velocity ($m\ s^{-1}$)	10^{-3}
Dry deposition velocity (iodine) ($m\ s^{-1}$)	10^{-2}
Washout coefficient (1 μm particles) (s^{-1})	10^{-4}

TABLE A3 *Predicted activity concentration in air and deposition rates per Bq s^{-1} of discharge from a 1 m high stack*

Factor	100 m from stack	500 m from stack
Ground-level air concentration ($Bq\ m^{-3}$)	$8.8\ 10^{-5}$	$4.3\ 10^{-6}$
Deposition rate ($Bq\ m^{-2}\ s^{-1}$)	$9.0\ 10^{-8}$	$4.7\ 10^{-9}$
Deposition rate (iodine) ($Bq\ m^{-2}\ s^{-1}$)	$8.1\ 10^{-7}$	$3.4\ 10^{-8}$

transfer of activity into animal products was modelled. The activity concentrations in food products in the 50th year of discharge were derived using equation A1.

$$A_f = A_{f(u)}\ R_f \qquad \text{(A1)}$$

where A_f = food product activity concentration in the 50th year grown 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}).

$A_{f(u)}$ = food product activity concentration in the 50th year per unit deposition rate (Bq kg^{-1} per Bq $m^{-2}\ s^{-1}$) (Table A4).

R_f = deposition rate to ground of activity from the plume 500 m from the release point (Bq $m^{-2}\ s^{-1}$ per Bq s^{-1}) (Table A3).

Soil, external dose and resuspension modelling

The predicted activity concentrations in soil in the 50th year of continuous deposition from a plume were modelled using the soil model part of the FARMLAND[5] model, allowing for migration down the soil profile. Effective dose rates from external exposure above soil 100 m from the release point were calculated using equation A2.

$$D_{ext} = D_{ext(u)}\ R_n \qquad \text{(A2)}$$

where D_{ext} = external dose rate in the 50th year from deposition of activity 100 m from the point of discharge (Sv y^{-1} per Bq s^{-1}).

$D_{ext(u)}$ = external dose rate in the 50th year per unit deposition rate (Sv y^{-1} per Bq $m^{-2}\ s^{-1}$) (Table A5[6]).

R_n = deposition rate to ground of activity from the plume 100 m from the release point (Bq $m^{-2}\ s^{-1}$ per Bq s^{-1}) (Table A3).

TABLE A4 *Predicted activity concentrations of radionuclides in foods in the 50th year per unit deposition rate*

	50th year activity concentrations in foods per unit deposition rate (Bq kg^{-1} or Bq l^{-1} per Bq m^{-2} s^{-1})									
Nuclide	Domestic fruit	Green and domestic vegetables	Cereals	Potatoes and root vegetables	Cow meat	Cow offal*	Sheep meat	Sheep offal*	Milk	Milk products
^{89}Sr	$1.5\ 10^{4}$	$8.8\ 10^{4}$	$5.0\ 10^{4}$	$8.1\ 10^{2}$	$4.0\ 10^{3}$	$4.0\ 10^{3}$	$5.7\ 10^{3}$	$5.7\ 10^{3}$	$2.0\ 10^{4}$	$2.2\ 10^{5}$
^{90}Sr	$1.3\ 10^{5}$	$6.2\ 10^{5}$	$4.2\ 10^{5}$	$8.8\ 10^{4}$	$3.0\ 10^{4}$	$3.0\ 10^{4}$	$2.2\ 10^{4}$	$2.2\ 10^{4}$	$1.4\ 10^{5}$	$1.5\ 10^{6}$
^{103}Ru	$7.1\ 10^{3}$	$7.7\ 10^{4}$	$4.0\ 10^{3}$	$1.2\ 10^{2}$	$3.1\ 10^{3}$	$3.1\ 10^{3}$	$5.1\ 10^{3}$	$5.1\ 10^{3}$	$2.4\ 10^{1}$	$2.6\ 10^{2}$
^{106}Ru	$8.8\ 10^{3}$	$1.0\ 10^{5}$	$6.1\ 10^{3}$	$9.5\ 10^{2}$	$1.6\ 10^{4}$	$1.6\ 10^{4}$	$2.3\ 10^{4}$	$2.3\ 10^{4}$	$3.0\ 10^{1}$	$3.3\ 10^{2}$
^{125}I	$6.1\ 10^{4}$	$1.0\ 10^{5}$	$3.1\ 10^{5}$	$8.9\ 10^{4}$	$7.5\ 10^{4}$	$7.5\ 10^{4}$	$1.7\ 10^{5}$	$1.7\ 10^{5}$	$1.2\ 10^{5}$	$1.3\ 10^{6}$
^{129}I	$2.8\ 10^{5}$	$1.9\ 10^{5}$	$5.6\ 10^{5}$	$2.1\ 10^{5}$	$2.0\ 10^{5}$	$2.0\ 10^{5}$	$5.2\ 10^{5}$	$5.2\ 10^{5}$	$2.9\ 10^{5}$	$3.2\ 10^{6}$
^{131}I	$3.1\ 10^{4}$	$4.1\ 10^{4}$	$4.2\ 10^{4}$	$1.1\ 10^{4}$	$2.5\ 10^{4}$	$2.5\ 10^{4}$	$3.2\ 10^{4}$	$3.2\ 10^{4}$	$5.8\ 10^{4}$	$6.4\ 10^{5}$
^{132}I	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
^{133}I	$5.3\ 10^{3}$	$6.2\ 10^{3}$	$5.3\ 10^{2}$	$4.7\ 10^{1}$	$1.1\ 10^{3}$	$1.1\ 10^{3}$	$6.9\ 10^{2}$	$6.9\ 10^{2}$	$3.8\ 10^{3}$	$4.2\ 10^{4}$
^{134}I	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
^{135}I	$1.8\ 10^{3}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	$3.1\ 10^{2}$	$3.4\ 10^{3}$
^{134}Cs	$7.2\ 10^{4}$	$1.3\ 10^{5}$	$4.9\ 10^{5}$	$1.4\ 10^{5}$	$7.9\ 10^{5}$	$7.9\ 10^{5}$	$1.5\ 10^{6}$	$1.5\ 10^{6}$	$1.6\ 10^{5}$	$1.8\ 10^{6}$
^{136}Cs	$3.9\ 10^{4}$	$5.6\ 10^{4}$	$8.7\ 10^{4}$	$1.9\ 10^{4}$	$1.4\ 10^{5}$	$1.4\ 10^{5}$	$2.8\ 10^{5}$	$2.8\ 10^{5}$	$6.3\ 10^{4}$	$6.9\ 10^{5}$
^{137}Cs	$7.4\ 10^{4}$	$1.5\ 10^{5}$	$5.2\ 10^{5}$	$1.6\ 10^{5}$	$9.1\ 10^{5}$	$9.1\ 10^{5}$	$1.9\ 10^{6}$	$1.9\ 10^{6}$	$1.8\ 10^{5}$	$2.0\ 10^{6}$
^{238}Pu	$1.0\ 10^{4}$	$1.1\ 10^{5}$	$5.5\ 10^{3}$	$1.2\ 10^{2}$	$4.4\ 10^{3}$	$5.4\ 10^{5}$	$3.6\ 10^{3}$	$2.6\ 10^{5}$	$7.9\ 10^{1}$	$8.7\ 10^{2}$
^{239}Pu	$1.1\ 10^{4}$	$1.1\ 10^{5}$	$5.5\ 10^{3}$	$1.5\ 10^{2}$	$4.5\ 10^{3}$	$5.6\ 10^{5}$	$3.7\ 10^{3}$	$2.6\ 10^{5}$	$8.2\ 10^{1}$	$9.0\ 10^{2}$
^{240}Pu	$1.1\ 10^{4}$	$1.1\ 10^{5}$	$5.5\ 10^{3}$	$1.5\ 10^{2}$	$4.5\ 10^{3}$	$5.6\ 10^{5}$	$3.7\ 10^{3}$	$2.6\ 10^{5}$	$8.2\ 10^{1}$	$9.0\ 10^{2}$
^{241}Pu	$9.5\ 10^{3}$	$1.0\ 10^{5}$	$5.4\ 10^{3}$	$5.9\ 10^{1}$	$3.7\ 10^{3}$	$4.5\ 10^{5}$	$3.3\ 10^{3}$	$2.4\ 10^{5}$	$6.7\ 10^{1}$	$7.4\ 10^{2}$
^{242}Pu	$1.1\ 10^{4}$	$1.1\ 10^{5}$	$5.5\ 10^{3}$	$1.5\ 10^{2}$	$4.5\ 10^{3}$	$5.6\ 10^{5}$	$3.7\ 10^{3}$	$2.6\ 10^{5}$	$8.2\ 10^{1}$	$9.0\ 10^{2}$
^{241}Am	$1.1\ 10^{4}$	$1.1\ 10^{5}$	$5.5\ 10^{3}$	$2.3\ 10^{2}$	$4.7\ 10^{3}$	$5.7\ 10^{5}$	$3.7\ 10^{3}$	$2.7\ 10^{5}$	$8.4\ 10^{1}$	$9.3\ 10^{2}$
^{242}Am	$5.2\ 10^{2}$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
^{243}Am	$1.1\ 10^{4}$	$1.1\ 10^{5}$	$5.6\ 10^{3}$	$2.3\ 10^{2}$	$4.7\ 10^{3}$	$5.8\ 10^{5}$	$3.7\ 10^{3}$	$2.7\ 10^{5}$	$8.5\ 10^{1}$	$9.4\ 10^{2}$
^{242}Cm	$8.5\ 10^{3}$	$9.6\ 10^{4}$	$5.0\ 10^{3}$	$1.3\ 10^{0}$	$5.7\ 10^{2}$	$6.9\ 10^{4}$	$1.1\ 10^{3}$	$7.8\ 10^{4}$	$1.1\ 10^{1}$	$1.2\ 10^{2}$
^{243}Cm	$9.8\ 10^{3}$	$1.1\ 10^{5}$	$5.4\ 10^{3}$	$5.3\ 10^{1}$	$4.2\ 10^{3}$	$5.1\ 10^{5}$	$3.5\ 10^{3}$	$2.5\ 10^{5}$	$7.6\ 10^{1}$	$8.3\ 10^{2}$
^{244}Cm	$9.6\ 10^{3}$	$1.0\ 10^{5}$	$5.4\ 10^{3}$	$4.1\ 10^{1}$	$3.9\ 10^{3}$	$4.8\ 10^{5}$	$3.4\ 10^{3}$	$2.5\ 10^{5}$	$7.1\ 10^{1}$	$7.8\ 10^{2}$

* Offal refers to liver for sheep or cow.

TABLE A5
Predicted external dose rates from deposited activity, resuspended activity concentrations in air in the 50th year per unit deposition rate and effective dose from the plume per unit discharge

Nuclide	Effective dose rate above undisturbed soil per unit deposition rate ($Sv\ y^{-1}$ per $Bq\ m^{-2}\ s^{-1}$)	Resuspended activity concentration in air per unit deposition rate ($Bq\ m^{-3}$ per $Bq\ m^{-2}\ s^{-1}$)	Effective dose from the plume per unit discharge ($Sv\ y^{-1}$ per $Bq\ s^{-1}$)
^{89}Sr	$9.7\ 10^{-6}$	$3.9\ 10^{-1}$	$7.4\ 10^{-16}$
^{90}Sr	$4.0\ 10^{-8}$	$9.2\ 10^{-1}$	0.0
^{103}Ru	$4.4\ 10^{-2}$	$3.6\ 10^{-1}$	$4.4\ 10^{-12}$
^{106}Ru	$1.6\ 10^{-1}$	$5.9\ 10^{-1}$	$1.9\ 10^{-12}$
^{125}I	$9.3\ 10^{-4}$	$4.0\ 10^{-1}$	$2.4\ 10^{-13}$
^{129}I	$1.5\ 10^{-2}$	$1.0\ 10^{0}$	$1.6\ 10^{-13}$
^{131}I	$7.4\ 10^{-3}$	$2.0\ 10^{-1}$	$3.3\ 10^{-12}$
^{132}I	$5.2\ 10^{-4}$	$9.2\ 10^{-6}$	$1.9\ 10^{-11}$
^{133}I	$1.3\ 10^{-3}$	$3.2\ 10^{-2}$	$5.1\ 10^{-12}$
^{134}I	$2.3\ 10^{-4}$	$3.0\ 10^{-11}$	$2.1\ 10^{-11}$
^{135}I	$1.2\ 10^{-3}$	$2.5\ 10^{-3}$	$1.3\ 10^{-11}$
^{134}Cs	$2.1\ 10^{0}$	$6.7\ 10^{-1}$	$1.4\ 10^{-11}$
^{136}Cs	$6.7\ 10^{-2}$	$2.5\ 10^{-1}$	$1.9\ 10^{-11}$
^{137}Cs	$3.4\ 10^{0}$	$9.3\ 10^{-1}$	$5.1\ 10^{-12}$
^{238}Pu	$1.6\ 10^{-4}$	$9.8\ 10^{-1}$	$4.0\ 10^{-15}$
^{239}Pu	$3.4\ 10^{-4}$	$1.0\ 10^{0}$	$6.1\ 10^{-12}$
^{240}Pu	$2.1\ 10^{-4}$	$1.0\ 10^{0}$	$4.0\ 10^{-15}$
^{241}Pu	$6.8\ 10^{-4}$	$8.6\ 10^{-1}$	$2.0\ 10^{-17}$
^{242}Pu	$4.7\ 10^{-3}$	$1.0\ 10^{0}$	$8.9\ 10^{-15}$
^{241}Am	$6.3\ 10^{-2}$	$1.0\ 10^{0}$	$5.8\ 10^{-12}$
^{242}Am	$1.9\ 10^{-5}$	$2.1\ 10^{-2}$	$1.6\ 10^{-13}$
^{243}Am	$1.3\ 10^{0}$	$1.0\ 10^{0}$	$6.3\ 10^{-13}$
^{242}Cm	$2.6\ 10^{-5}$	$5.1\ 10^{-1}$	$4.6\ 10^{-15}$
^{243}Cm	$6.1\ 10^{-1}$	$9.2\ 10^{-1}$	$1.3\ 10^{-12}$
^{244}Cm	$9.6\ 10^{-4}$	$8.9\ 10^{-1}$	$5.8\ 10^{-15}$

Resuspension of deposited activity was modelled using a time-dependent resuspension model[4]; the ground-level air concentrations from resuspension at 100 m from the point of release were calculated using equation A3.

$$A_{res} = A_{res(u)}\, R_n \qquad \text{(A3)}$$

where A_{res} = activity concentration from resuspension of activity deposited 100 m from the point of discharge in the 50th year ($Bq\ m^{-3}$ per $Bq\ s^{-1}$),

$A_{res(u)}$ = activity concentration from resuspension of activity per unit deposition rate in the 50th year of discharge ($Bq\ m^{-3}$ per $Bq\ m^{-2}\ s^{-1}$) (Table A5),

R_n = deposition rate to ground of activity from the plume 100 m from the release point ($Bq\ m^{-2}\ s^{-1}$ per $Bq\ s^{-1}$) (Table A3).

Effective dose rates from the plume 100 m from the point of release were modelled using a semi-infinite cloud model. The dose rates are given in Table A5.

Dose calculations

Five exposure pathways were considered for the GDC for discharges to atmosphere: external exposure to the plume and from activity deposited on to the soil, internal exposure from inhalation of the plume and resuspended activity, and ingestion of foods produced on land contaminated by activity from the plume. The age groups considered in the dose calculations were infants in the first year of life on an all-milk diet, 1 year old infants, 10 year old children and adults.

Inhalation doses

Effective doses to each age group from inhalation of the plume and resuspended activity were calculated using equations A4 and A5, respectively.

$$D_{ip} = A_a B D_{inh} \quad \text{(A4)}$$

$$D_{ires} = A_{res} B D_{inh} \quad \text{(A5)}$$

where D_{ip} = effective dose from inhalation of the plume 100 m from the point of discharge ($Sv\ y^{-1}$ per $Bq\ s^{-1}$),

D_{ires} = effective dose from inhalation of resuspended activity deposited 100 m from the point of discharge ($Sv\ y^{-1}$ per $Bq\ s^{-1}$),

A_a = activity concentration in the plume 100 m from the point of discharge ($Bq\ m^{-3}$ per $Bq\ s^{-1}$) (Table A3),

A_{res} = activity concentration from resuspension of activity deposited 100 m from the point of discharge in the 50th year ($Bq\ m^{-3}$ per $Bq\ s^{-1}$) (equation A3),

B = breathing rate ($m^3\ y^{-1}$) (Table A6),

D_{inh} = inhalation dose coefficient ($Sv\ Bq^{-1}$) (Table 2 of the main text).

An occupancy of 100% was assumed 100 m from the point of release.

TABLE A6 *Critical group inhalation rates and food ingestion rates*[7]

	Age group		
	1 y	10 y	Adult
Breathing rate ($m^3\ y^{-1}$)	1900	5500	7300
Food intake rates ($kg\ y^{-1}$ or $l\ y^{-1}$)			
Domestic fruit	35	50	75
Green and domestic vegetables	15	35	80
Cereals	30	75	100
Potatoes and root vegetables	45	95	130
Cow meat	10	30	45
Cow offal	2.75	5	10
Sheep meat	3	10	25
Sheep offal	2.75	5	10
Milk*	320	240	240
Milk products	45	45	60

* Milk intake of 350 $l\ y^{-1}$ assumed for unweaned infants in the first year of life.

External exposure

Effective doses to each age group from external exposure from activity deposited over 50 years on to soil from the plume were calculated using equation A6.

$$D_{dep} = D_{ext}\,(F_{ind}\,T_{ind} + F_{out}\,T_{out}) \qquad \text{(A6)}$$

where D_{dep} = effective dose from external irradiation from soil contaminated by deposition from the plume, in the 50th year 100 m from the point of release (Sv y^{-1} per Bq s^{-1}),

D_{ext} = external dose rate in the 50th year from deposition of activity 100 m from the point of discharge (Sv y^{-1} per Bq s^{-1}) (equation A2),

F_{ind} = fraction of year spent indoors (Table A7),

T_{ind} = indoor location factor,

F_{out} = fraction of year spent outdoors (Table A7),

T_{out} = outdoor location factor.

TABLE A7
Occupancies associated with external exposure from deposited activity[7]

	Occupancy (fraction of year)		
	Age group		
	1 y	10 y	Adult
Indoors	0.9	0.8	0.5
Outdoors	0.1	0.2	0.5

The location factor is defined as the ratio of dose received in the protected location (indoors or outdoors) to that received outdoors over undisturbed soil for the period during which the exposed person is in the location. The location factor therefore describes the shielding offered at a particular location compared with the situation where no shielding is available. The indoor and outdoor location factors are 0.1 and 1.0, respectively[4]. The age-dependent occupancies are given in Table A7.

Effective doses from external exposure to the plume 100 m from the point of discharge were estimated using the dose rates given in Table A5. Exposure to the plume was assumed to be independent of location factor and age.

Ingestion of foods

Ingestion doses to each age group from foods produced 500 m from the point of discharge were calculated using equation A7.

$$D_{food} = \Sigma_f\, A_f\, I_f\, D_{ing} \qquad \text{(A7)}$$

where D_{food} = effective dose (summed over all foods) from foods produced 500 m from the point of discharge (Sv y^{-1} per Bq s^{-1}),

A_f = activity concentrations in each food produced 500 m from the point of discharge (Bq kg^{-1} per Bq s^{-1}) (equation A1),

I_f = ingestion rate of each food (kg y^{-1}) (Table A6),

D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

Total dose

The total effective dose per unit discharge rate for each age group from each radionuclide was calculated by summing the dose estimates from the five exposure pathways described above using equation A8.

$$D_{tot} = D_{food} + D_{dep} + D_{extp} + D_{ip} + D_{ires} \quad \text{(A8)}$$

where D_{tot} = total effective dose per unit discharge rate (Sv y^{-1} per Bq s^{-1}),
D_{extp} = effective external dose per unit discharge rate from the plume (Sv y^{-1} per Bq s^{-1}) (Table A5).

The total dose to infants in the first year of life was calculated from doses to 3 month olds from ingestion of milk and only summed with inhalation doses and external doses to 1 year olds.

Calculation of GDCs for discharges to atmosphere

The GDCs for each age group and radionuclide were calculated using equation A9.

$$\text{GDC} = T\,\text{Dose Constraint}/D_{tot} \quad \text{(A9)}$$

where GDC = GDC for atmospheric discharges (Bq y^{-1}),
T = conversion factor from seconds to years (s y^{-1}).

The dose constraint used was 0.3 mSv y^{-1}, which was the maximum dose constraint recommended by NRPB[1]. The most restrictive GDC for each radionuclide is presented in Table 3 of the main text.

REFERENCES

1 NRPB. Public exposure: guidance on the 1990 recommendations of ICRP. *Doc NRPB*, **4**, 2, 27–41 (1993).
2 Clarke R H. A model for short and medium range dispersion of radionuclides released to the atmosphere. First report of a Working Group on Atmospheric Dispersion. Chilton, NRPB-R91 (1979).
3 Jones J A. ESCLOUD: a computer program to calculate the air concentration, deposition rate and external dose rate from a continuous discharge of radioactive material to atmosphere. Chilton, NRPB-R101 (1980).
4 Simmonds J R, Lawson G and Mayall A. Methodology for assessing the radiological consequences of routine releases of radionuclides to the environment. Luxembourg, EC, EUR15760 (1995).
5 Brown J and Simmonds J R. FARMLAND: a dynamic model for the transfer of radionuclides through terrestrial foodchains. Chilton NRPB-R273 (1995).
6 Carey A D, Jones J A and Mobbs S F. GRANIS: a model for the assessment of external photon irradiation from contaminated media of finite lateral extent. Chilton, NRPB (to be published).
7 Robinson C A. Generalised habit data for radiological assessments. Chilton, NRPB-M636 (1996).

Appendix B

PRINCIPLES AND METHODS FOR CALCULATING GDCs FOR DISCHARGES TO RIVERS

Introduction

Generalised derived constraints (GDCs) for rivers are estimates of the amount of activity discharged to rivers, which, if not exceeded, mean that it is very unlikely that members of the public would receive an effective dose above the maximum dose constraint[1] of 0.3 mSv y^{-1}. The discharges have been related to the dose constraint using cautious environmental modelling and dose assessment. Discharges were assumed to continue for 50 years to a river of low volumetric flow, and the resulting build-up in the environment was modelled. Doses were calculated for individuals who spend time on the river bank, drink water and eat fish from the river, and produce and consume vegetables, grain and potatoes on land irrigated by the river water. Critical group habits and critical intakes of foods[2] produced within the river catchment were used.

Some of the radionuclides considered have very short radioactive half-lives. For these, the dose assessment was limited to exposures that could reasonably occur within a few hours or days of release. Some of the radionuclides considered are likely to have radioactive decay products (progeny) and the ingrowth and decay of these were taken into account when determining the GDCs. Ingrowth of progeny was considered if significant ingrowth is likely to occur in the 50 year discharge period. Some radionuclides, such as ^{106}Ru, ^{137}Cs and ^{243}Am, have progeny with very short radioactive half-lives which were assumed to be in secular equilibrium when the GDCs were determined. Ingrowth of ^{241}Am from ^{241}Pu has been taken into account in the derivation of the GDC for ^{241}Pu.

This appendix is in three parts, the first section describes the environmental modelling performed, the second details the dose assessment and the final part describes the calculation of the GDCs for discharges to rivers. The GDCs themselves are given in Table 3 of the main text.

Environmental models

River dispersion modelling

Activity concentrations of each radionuclide released into the river were calculated using a compartmental model[3]. A single compartment is defined, into which the activity was discharged. Four main processes are modelled, downstream transport of radionuclides in solution and in association with suspended sediment, sedimentation of radionuclides to the river bed and downstream transport of radionuclides in bed sediment. The river compartment was defined using the parameters given in Table B1. The river was considered to have properties similar to those of small rivers in eastern England, ie slow flowing, relatively low average flows (0.25 to 5 m^3 s^{-1}) sustained by groundwater during dry spells and used for irrigation and public supply[4].

The partitioning of radionuclides between the solution and solid phases and the concentration in freshwater fish are defined by the parameters given in Table B2, and the resulting activity concentrations for unit discharges are shown in Table B3. It was assumed that the activity concentrations in bed sediments attained equilibrium with the discharges by the 50th year.

Characteristic	Parameter value
River section	
Length (m)	500
Width (m)	5
Water depth (m)	1
Water volume (m^3)	2500
Bed sediment depth (m)	0.3
Dry sediment density (kg m^{-3})	1500
River suspended sediment load (kg m^{-3})	0.04
River water flows	
Velocity (m s^{-1})	0.2
Volumetric flow (m^3 s^{-1})	1
Bed sediment flow	
Velocity (m s^{-1})	0.000 031 7
Volumetric flow (m^3 s^{-1})	0.000 047 6

TABLE B1
Assumed river characteristics

Element	Distribution coefficient, K_d (Bq kg^{-1} per Bq l^{-1})	Sedimentation factor, k' (m^{-1})	Fish concentration factor (Bq t^{-1} per Bq m^{-3})
Sr	$2\ 10^3$	$7.9\ 10^{-6}$	$6.0\ 10^1$
Ru	$7\ 10^3$	$1\ 10^{-5}$	$1.0\ 10^1$
I	$3\ 10^2$	0	$2.0\ 10^1$
Cs	$2\ 10^3$	$8.5\ 10^{-5}$	$2.0\ 10^3$
Pu	$1\ 10^5$	$1.8\ 10^{-4}$	$3.5\ 10^0$
Am	$4\ 10^5$	$1.1\ 10^{-4}$	$2.5\ 10^1$
Cm	$4\ 10^5$	$1\ 10^{-5}$	$2.5\ 10^1$

TABLE B2
Element-dependent sediment water distribution coefficients, sedimentation factors and fish concentration factors for freshwater[3]

At an irrigation rate[5] of 0.1 m^3 per m^2 y^{-1}, applied over a dry period of four weeks in summer, a few per cent of the river flow is sufficient to irrigate enough land to provide vegetables, cereals and potatoes for up to 2000 individuals and to provide for the water needs of several thousand individuals.

Foodchain modelling

Concentrations in freshwater fish resulting from the discharges of radionuclides were predicted using the element-dependent equilibrium transfers given in Table B2. Concentrations in terrestrial foods from irrigation with the river water were predicted using the dynamic foodchain model FARMLAND[6] and are given in Table B4. It was assumed that some activity in the irrigated water was deposited directly on to soil, except for a fraction that was intercepted by plants and some of the intercepted activity was transferred into the plant. Build-up in soil over 50 years and the uptake into plants from soil were modelled. The activity concentrations in food products in the 50th year of discharge for an irrigation rate[5] of 0.1 m^3 per m^2 y^{-1} were derived using equation B1.

TABLE B3
Predicted activity concentrations of radionuclides in river water and sediments in the 50th year of discharge

	50th year activity concentrations per Bq s^{-1} discharged		
Nuclide	Filtered water (Bq m^{-3})	Suspended sediment (Bq kg^{-1})	Bed sediment (Bq kg^{-1})
^{89}Sr	$9.3\ 10^{-1}$	$1.9\ 10^{0}$	$1.2\ 10^{-3}$
^{90}Sr	$9.2\ 10^{-1}$	$1.8\ 10^{0}$	$5.4\ 10^{-2}$
^{103}Ru	$7.8\ 10^{-1}$	$5.5\ 10^{0}$	$3.6\ 10^{-3}$
^{106}Ru	$7.8\ 10^{-1}$	$5.5\ 10^{0}$	$5.2\ 10^{-2}$
^{125}I	$9.9\ 10^{-1}$	$3.0\ 10^{-1}$	0.0
^{129}I	$9.9\ 10^{-1}$	$3.0\ 10^{-1}$	0.0
^{131}I	$9.9\ 10^{-1}$	$3.0\ 10^{-1}$	0.0
^{132}I	$8.2\ 10^{-1}$	$2.5\ 10^{-1}$	0.0
^{133}I	$9.7\ 10^{-1}$	$2.9\ 10^{-1}$	0.0
^{134}I	$6.4\ 10^{-1}$	$1.9\ 10^{-1}$	0.0
^{135}I	$9.2\ 10^{-1}$	$2.8\ 10^{-1}$	0.0
^{134}Cs	$9.2\ 10^{-1}$	$1.9\ 10^{0}$	$3.8\ 10^{-2}$
^{136}Cs	$9.2\ 10^{-1}$	$1.8\ 10^{0}$	$4.1\ 10^{-3}$
^{137}Cs	$8.9\ 10^{-1}$	$1.9\ 10^{0}$	$5.6\ 10^{-1}$
^{238}Pu	$1.9\ 10^{-1}$	$1.9\ 10^{1}$	$9.4\ 10^{-1}$
^{239}Pu	$1.8\ 10^{-1}$	$1.8\ 10^{1}$	$1.2\ 10^{0}$
^{240}Pu	$1.9\ 10^{-1}$	$1.9\ 10^{1}$	$9.4\ 10^{-1}$
^{241}Pu	$1.9\ 10^{-1}$	$1.9\ 10^{1}$	$9.2\ 10^{-1}$
^{242}Pu	$1.9\ 10^{-1}$	$1.9\ 10^{1}$	$9.4\ 10^{-1}$
^{241}Am	$5.6\ 10^{-2}$	$2.2\ 10^{1}$	$6.9\ 10^{-1}$
^{242}Am	$5.4\ 10^{-2}$	$2.2\ 10^{1}$	$3.5\ 10^{-3}$
^{243}Am	$5.6\ 10^{-2}$	$2.2\ 10^{1}$	$6.9\ 10^{-1}$
^{242}Cm	$5.9\ 10^{-2}$	$2.3\ 10^{1}$	$3.7\ 10^{-2}$
^{243}Cm	$5.9\ 10^{-2}$	$2.3\ 10^{1}$	$6.5\ 10^{-2}$
^{244}Cm	$5.9\ 10^{-2}$	$2.3\ 10^{1}$	$6.4\ 10^{-2}$

$$A_f = A_{f(u)}\, I_{app}\, [R_{fil} + (R_{sus}\, S)] \qquad \text{(B1)}$$

where A_f = activity concentrations in food products in the 50th year grown on land irrigated by the river 500 m downstream of the point of discharge (Bq kg^{-1} per Bq s^{-1}).

$A_{f(u)}$ = activity concentrations in food products in the 50th year per unit deposition rate (Bq kg^{-1} per Bq m^{-2} y^{-1}) (Table B4).

I_{app} = irrigation water application rate (m^3 per m^2 y^{-1}).

R_{fil} = activity concentration in filtered river water per unit discharge (Bq m^{-3} per Bq s^{-1}) (Table B3).

R_{sus} = activity concentration in river suspended sediment per unit discharge (Bq kg^{-1} per Bq s^{-1}) (Table B3).

S = suspended sediment load (kg m^{-3}) (Table B1).

Dose calculations

Five exposure pathways were considered for the GDC for discharges to rivers: external exposure to river bed sediments and internal exposure from inhalation of resuspended river bed sediments, and ingestion of freshwater fish, drinking water, and foods produced

TABLE B4
Predicted activity concentrations of radionuclides in foods in the 50th year per unit deposition rate (from irrigation)

	50th year activity concentrations in foods from a surface deposit of irrigation water ($Bq\ kg^{-1}$ per $Bq\ m^{-2}\ y^{-1}$)		
Nuclide	Green and domestic vegetables	Potatoes and root vegetables	Cereals
^{89}Sr	$8.5\ 10^{-3}$	$5.4\ 10^{-5}$	$4.8\ 10^{-3}$
^{90}Sr	$2.7\ 10^{-2}$	$3.0\ 10^{-4}$	$1.8\ 10^{-2}$
^{103}Ru	$2.5\ 10^{-3}$	$1.3\ 10^{-4}$	$3.7\ 10^{-6}$
^{106}Ru	$9.8\ 10^{-3}$	$2.0\ 10^{-5}$	$5.4\ 10^{-4}$
^{125}I	$9.9\ 10^{-3}$	$7.1\ 10^{-3}$	$3.0\ 10^{-2}$
^{129}I	$1.5\ 10^{-2}$	$1.2\ 10^{-2}$	$5.0\ 10^{-2}$
^{131}I	$1.3\ 10^{-3}$	$1.3\ 10^{-3}$	$3.5\ 10^{-4}$
^{132}I	0.0	0.0	0.0
^{133}I	$2.0\ 10^{-4}$	$1.7\ 10^{-5}$	$1.5\ 10^{-6}$
^{134}I	0.0	0.0	0.0
^{135}I	0.0	0.0	0.0
^{134}Cs	$1.3\ 10^{-2}$	$1.1\ 10^{-2}$	$4.7\ 10^{-2}$
^{136}Cs	$1.8\ 10^{-3}$	$2.8\ 10^{-3}$	$5.9\ 10^{-4}$
^{137}Cs	$1.3\ 10^{-2}$	$1.2\ 10^{-2}$	$4.9\ 10^{-2}$
^{238}Pu	$1.0\ 10^{-2}$	$3.6\ 10^{-7}$	$5.2\ 10^{-4}$
^{239}Pu	$1.0\ 10^{-2}$	$4.1\ 10^{-7}$	$5.2\ 10^{-4}$
^{240}Pu	$1.0\ 10^{-2}$	$4.1\ 10^{-7}$	$5.2\ 10^{-4}$
^{241}Pu	$1.0\ 10^{-2}$	$2.2\ 10^{-7}$	$5.2\ 10^{-4}$
^{242}Pu	$1.0\ 10^{-2}$	$4.1\ 10^{-7}$	$5.2\ 10^{-4}$
^{241}Am	$1.0\ 10^{-2}$	$6.4\ 10^{-7}$	$5.2\ 10^{-4}$
^{242}Am	0.0	0.0	0.0
^{243}Am	$1.0\ 10^{-2}$	$6.6\ 10^{-7}$	$5.2\ 10^{-4}$
^{242}Cm	$9.3\ 10^{-3}$	$4.9\ 10^{-8}$	$4.8\ 10^{-4}$
^{243}Cm	$1.0\ 10^{-2}$	$1.7\ 10^{-7}$	$5.2\ 10^{-4}$
^{244}Cm	$1.0\ 10^{-2}$	$1.5\ 10^{-7}$	$5.2\ 10^{-4}$

on land irrigated with river water. The age groups considered in the dose calculations were 1 year old infants, 10 year old children and adults.

External dose from bed sediments

Effective doses to each age group from external exposure to well-mixed river bed sediment 500 m downstream of the discharge point were calculated using equation B2.

$$D_{RB,ext} = D_{ext(u)}\ R_B\ O \qquad (B2)$$

where $D_{RB,ext}$ = external dose above well-mixed sediment in the 50th year of discharge 500 m downstream from the discharge point ($Sv\ y^{-1}$ per $Bq\ s^{-1}$).

$D_{ext(u)}$ = external dose rate above well-mixed sediment per unit activity concentration[7] ($Sv\ h^{-1}$ per $Bq\ kg^{-1}$) (Table B5).

R_B = activity concentration in river bed sediment from a unit discharge rate to a river flowing at 1 $m^3\ s^{-1}$, 500 m downstream from the release point ($Bq\ kg^{-1}$ per $Bq\ s^{-1}$) (Table B3).

O = occupancy of river bank sediment[2] ($h\ y^{-1}$) (Table B6).

TABLE B5
Predicted external dose rates above well-mixed sediment per unit activity concentration

Nuclide	Effective dose rate (Sv h^{-1} per Bq kg^{-1})
^{89}Sr	1.5 10^{-14}
^{90}Sr	1.4 10^{-18}
^{103}Ru	7.8 10^{-11}
^{106}Ru	3.5 10^{-11}
^{125}I	3.1 10^{-13}
^{129}I	2.5 10^{-13}
^{131}I	6.1 10^{-11}
^{132}I	4.0 10^{-10}
^{133}I	1.0 10^{-10}
^{134}I	4.7 10^{-10}
^{135}I	2.9 10^{-10}
^{134}Cs	2.7 10^{-10}
^{136}Cs	3.8 10^{-10}
^{137}Cs	9.8 10^{-11}
^{238}Pu	2.9 10^{-15}
^{239}Pu	6.4 10^{-15}
^{240}Pu	3.8 10^{-15}
^{241}Pu	1.5 10^{-16}
^{242}Pu	9.8 10^{-14}
^{241}Am	1.1 10^{-12}
^{242}Am	1.2 10^{-12}
^{243}Am	2.3 10^{-11}
^{242}Cm	4.6 10^{-15}
^{243}Cm	1.5 10^{-11}
^{244}Cm	3.1 10^{-14}

Doses from inhalation of resuspended bed sediment

Effective doses to each age group from inhalation of resuspended river bed sediments were calculated using equation B3.

$$D_{RB,inh} = R_B \, B \, L \, D_{inh} \, O_{frac} \qquad \text{(B3)}$$

where $D_{RB,inh}$ = effective dose from inhalation of resuspended river bed sediment (Sv y^{-1} per Bq s^{-1}),
B = breathing rate (m^3 y^{-1}) (Table B6),
L = concentration of suspended sediment in air (kg m^{-3}),
D_{inh} = inhalation dose coefficient (Sv Bq^{-1}) (Table 2 of the main text),
O_{frac} = fraction of the year spent occupying sediment[2] (dimensionless) (Table B6).

The concentration of suspended sediment in air[3] used was 10^{-7} kg m^{-3}.

Dose from ingestion of water

Doses to each age group from ingestion of filtered river water abstracted 500 m downstream of the discharge point were calculated using equation B4.

TABLE B6 *Critical group habits*[2]

	Age group		
	1 y	10 y	Adult
Occupancy of sediment (h y^{-1})	30	500	500
Intake rates			
Breathing rate (m^3 y^{-1})	1900	5500	7300
Drinking water (m^3 y^{-1})	0.26	0.35	0.60
Freshwater fish (t y^{-1})	0.001	0.005	0.02
Green vegetables (kg y^{-1})	15	35	80
Cereals (kg y^{-1})	30	75	100
Potatoes and root vegetables (kg y^{-1})	45	95	130

$$D_{water} = R_{fil}\, I_{water}\, D_{ing} \tag{B4}$$

where D_{water} = effective dose from drinking filtered river water 500 m downstream of the point of discharge (Sv y^{-1} per Bq s^{-1}).
R_{fil} = activity concentrations in filtered river water 500 m downstream of the point of discharge (Bq m^{-3} per Bq s^{-1}) (Table B3).
I_{water} = ingestion rate of water[2] (m^{-3} y^{-1}) (Table B6).
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

Dose from ingestion of freshwater fish

Ingestion doses to each age group from freshwater fish caught 500 m downstream from the point of discharge were calculated using equation B5.

$$D_{fish} = R_{fil}\, I_{fish}\, C_{fish}\, D_{ing} \tag{B5}$$

where D_{fish} = effective dose from ingestion of freshwater fish caught 500 m downstream of the point of discharge (Sv y^{-1} per Bq s^{-1}).
R_{fil} = activity concentrations in the filtered fraction of river water 500 m downstream from the point of discharge (Bq m^{-3} per Bq s^{-1}) (Table B3).
I_{fish} = ingestion rate of freshwater fish[2] (t y^{-1}) (Table B6).
C_{fish} = concentration factor for freshwater fish (Bq t^{-1} per Bq m^{-3}) (Table B2).
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

Dose from ingestion of foods

Ingestion doses to each age group from foods produced on land irrigated with river water downstream from the discharge were calculated using equation B6.

$$D_{food} = \textstyle\sum_f A_f\, I_f\, D_{ing} \tag{B6}$$

where D_{food} = effective dose summed over all foods produced on land irrigated with river water abstracted 500 m downstream from the point of discharge (Sv y^{-1} per Bq s^{-1}).
A_f = activity concentrations in each food after irrigation with river water (Bq kg^{-1} per Bq s^{-1}) (equation B1).
I_f = ingestion rate of each food (kg y^{-1}) (Table B6).
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

Total dose

The total effective dose per unit discharge rate for each age group from each radionuclide was calculated by summing the dose estimates from the five exposure pathways described above using equation B7.

$$D_{tot} = D_{food} + D_{fish} + D_{water} + D_{RB,inh} + D_{RB,ext} \quad \text{(B7)}$$

where D_{tot} = total effective dose per unit discharge rate (Sv y^{-1} per Bq s^{-1}).

Calculation of GDCs

The GDC for each age group and each radionuclide were calculated using equation B8.

$$\text{GDC} = T \text{ Dose Constraint}/D_{tot} \quad \text{(B8)}$$

where GDC = GDC for river discharges (Bq y^{-1}).
T = conversion factor from seconds to years (s y^{-1}).

The dose constraint used was 0.3 mSv y^{-1} which was the maximum dose constraint recommended by NRPB[1]. The most restrictive GDC for each radionuclide is presented in Table 3 of the main text.

REFERENCES

1 NRPB. Public exposure: guidance on the 1990 recommendations of ICRP. *Doc NRPB*, **4**, 2, 27–41 (1993).

2 Robinson C A. Generalised habit data for radiological assessments. Chilton, NRPB-M636 (1996).

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

4 Institute of Hydrology and British Geological Survey. Hydrological data United Kingdom 1993 year book. An account of rainfall, river flows, groundwater levels and river water quality, January to December 1993. Wallingford, NERC (1994).

5 MAFF. Survey of irrigation of outdoor crops in 1990, England and Wales. Guildford, Government Statistical Service, MAFF Stats 157 (1990).

6 Brown J and Simmonds J R. FARMLAND: a dynamic model for the transfer of radionuclides through terrestrial foodchains. Chilton, NRPB-R273 (1995).

7 Carey A D, Jones J A and Mobbs S F. GRANIS: a model for the assessment of external photon irradiation from contaminated media of finite lateral extent. Chilton, NRPB (to be published).

Appendix C

PRINCIPLES AND METHODS FOR CALCULATING GDCs FOR DISCHARGES TO SEWERS

Introduction

Generalised derived constraints (GDCs) for sewers are estimates of the amount of activity discharged to sewers, which, if not exceeded, mean that it is very unlikely that sewage plant workers or members of the public would receive an effective dose above the maximum dose constraint[1] of 0.3 mSv y^{-1}. The discharges have been related to the dose constraint using cautious models for radionuclide transport and dose assessment. The sewage collection and treatment system used was assumed to serve a small rural community, and was characterised by low volumetric effluent flow. The effluent is treated at the works to remove suspended solids and biochemical oxygen demand through primary and secondary treatment of liquid and solid phases. Treated effluents are then assumed to be discharged to a river of low volumetric flow, and treated sludges applied to nearby farmland. Discharges of radionuclides to sewers were assumed to continue for 50 years under the same conditions, and the resulting build-up in the river and farmland environments were modelled.

The calculations accounted for three separate exposure groups as follows:

(a) sewage plant workers who were considered to spend a working year at the sewage works, and were exposed to sludges and effluents,

(b) members of the public who were exposed to river water that has received treated effluent, as described in Appendix B,

(c) the third group was assumed to live on land treated repeatedly with sewage sludge and to consume animal products produced from the treated land – foods consumed were assumed to have been produced within either the river catchment or on treated farmland, intakes were assumed to be at critical group levels.

Some of the radionuclides considered have very short radioactive half-lives. For these, the dose assessment was limited to exposures that could reasonably occur within a few hours or days of release. Some of the radionuclides considered are likely to have radioactive decay products (progeny) and the ingrowth and decay of these radionuclides were taken into account when determining the GDCs. Ingrowth of progeny was considered if significant ingrowth is likely to occur in the 50 year discharge period. Some radionuclides, such as ^{106}Ru, ^{137}Cs and ^{243}Am, have progeny with very short radioactive half-lives which were assumed to be in secular equilibrium when the GDCs were determined. Ingrowth of ^{241}Am from ^{241}Pu has been taken into account in the derivation of the GDC for ^{241}Pu.

This appendix is in three parts, the first section describes the environmental modelling performed, the second details the dose assessment and the final part describes the calculation of the GDCs for discharges to sewers. The GDCs themselves are given in Table 3 of the main text.

Environmental models

Sewage transport and treatment modelling

Activity concentrations of each radionuclide released into effluent in the sewerage system were calculated using the simple dilution approach that is applied in river modelling[2], using estimates of effluent flow. The volume of effluent flow was derived from *per caput* water usage combined with information on the sizes of community served by small rural sewage works[3]. Disposed activity is assumed to be discharged continuously into the raw sewage effluent and to flow in pipes to the sewage treatment works. The main processes considered were dilution of activity in the effluent, collection of effluent in settling tanks at the sewage works, separation of suspended solids from the liquid effluent and treatment of liquid effluent and sludges. Instant transport from the disposal point to the sewage treatment works was assumed; radioactive decay during transport and treatment was not considered. Radionuclide partitioning between the solution and solid phases was not modelled because of the lack of reliable information on the behaviour of the elements of interest in sewage effluent and because, on disposal, the treated effluent still contains suspended solids and the treated sludges still contain a high level of water. The GDCs were therefore calculated using the conservative assumption that all the disposed activity remained 100% with the effluent or 100% with the sludge. The most restrictive GDC calculated using the two assumptions was then adopted.

The largest influence on activity concentrations in sewage effluents and sludges will be the total flow of effluent, which depends on the size of the works, which in turn is dependent on the population served. Small effluent flows will result in higher activity concentrations and potentially higher individual doses. Statistics for sewage treatment works in the Thames Water region[3] show that approximately 30% of the total number of sewage works serve populations of less than about one thousand. Given the relatively large number of small sewage works it is reasonable that some disposers of radioactive materials may be served by small rural sewage works.

The sewage works size, effluent characteristics, treatment processes and timescales are shown in Table C1, and the modelled activity concentrations in the effluent and sludges are shown in Table C2.

Modelling disposal of sewage effluent

Treated sewage effluents are normally discharged into water bodies such as rivers or estuaries. The GDC for sewers was calculated assuming the effluents were discharged into a small rural river with the same characteristics and exposure pathways as those used for the river GDC, which is described in Appendix B. The effect of radioactive decay on the radionuclides being disposed to river was taken into account, using the treatment times for the liquid phase of the effluent given in Table C1.

Modelling disposal of sewage sludge

In the UK, treated sludges may be disposed of by several routes, depending on the size and location of the sewage works. The main disposal routes for treated sludges are disposal to sea, to farmland, to landfill and to incinerators. Approximately 50% of treated sludges are currently disposed of to land and this proportion may increase because disposals of sludge to sea ceased in 1998, and landfilling is becoming more expensive. For the same reasons, the use of incinerators for sludges from large urban sewage works is also due to increase. In radiological protection terms, the discharge of radionuclides to small sewage treatment works is likely to be the most significant because the effluent volumes are small, giving

TABLE C1 *Sewage effluent, flows and treatment times assumed*

Characteristic	Parameter value
Raw effluent	
Suspended sediment load (%)	0.05
Volumetric flow ($m^3 s^{-1}$)	0.000 695
Treatment works	
Population served	500
Dry sludge production ($kg\ y^{-1}$)	10 000
Liquid effluent treatment times (h)	
Primary settlement	4
Biological filtration	7
Final settlement	4
Total time	15
Solid sludge treatment times (h)	
Primary settlement	4
Pasteurisation	2
Digestion	300
Storage	350
Total time	656
Treated sludge	
Solid content (%)	5

TABLE C2 *Predicted activity concentrations of radionuclides in sewage effluent and sludges in the 50th year of discharge*

Sewage material	50th year activity concentrations per unit discharge ($Bq\ kg^{-1}$ per $Bq\ s^{-1}$)*
Raw effluent arriving at works	1.44
Sludges during treatment	144
Treated effluent at disposal	1.44
Treated sludge at disposal	144†

* It is assumed that 1 kg is equal to 1 litre of sewage.

† The radionuclides ^{131}I, ^{132}I, ^{133}I, ^{134}I, ^{135}I, ^{136}Cs and ^{242}Am will undergo significant radioactive decay during sludge treatment and storage and were not considered for application to land.

less dilution. The most significant disposal route for sludge from small and medium rural sewage works is treatment of land[3]. In addition, one area of land may be treated repeatedly with sludge from the same works, potentially allowing build-up in soil. In small rural sewage works, sludges may be stored in batches before being applied to land. The sludge processing and storage times given in Table C1 were used to calculate radioactive decay of short half-life radionuclides.

Foodchain modelling

For disposals of sewage sludge, only animal products were considered because of the restrictions on the application of sewage sludge on land use to produce foods that may be eaten raw[4]. The sewage works considered produced enough sludge to treat a few tens of hectares of pasture land, sufficient for ten cows or sheep. Conditioning of the soil was assumed to occur annually in early spring, approximately one month before grazing animals were allowed on to the pasture. It was assumed that application was directly on to permanent pasture and that the grass grew after the application and before animals were allowed on to it. Therefore, there would be no direct contamination of the grass by radionuclides in the sludge. The dynamic foodchain model FARMLAND[5] was used to predict the activity concentrations in cow meat and offal, milk, and sheep meat and offal from annual applications over 50 years per unit deposit (equation C1). The activity concentrations were scaled by the application rate of sewage sludge[6] which was assumed to be 8 kg m^{-2} y^{-1}.

$$A_f = A_{f(u)}\, SL_{app}\, SL_{conc} \qquad (C1)$$

where A_f = food product activity concentration in the 50th year grown on land treated with sewage sludge (Bq kg^{-1} per Bq s^{-1}),

$A_{f(u)}$ = food product activity concentration in the 50th year per unit deposition rate (Bq kg^{-1} per Bq m^{-2} y^{-1}) (Table C3),

SL_{app} = sewage sludge application rate (kg m^{-2} y^{-1}),

SL_{conc} = sewage sludge activity concentration per unit discharge (Bq kg^{-1} per Bq s^{-1}) (Table C2).

The foodchain modelling used for treated sewage effluent disposal to a river is as described in Appendix B.

Modelling sludge application to soil and external dose

The predicted soil concentrations from application of sewage sludge at 8 kg m^{-2} y^{-1} were modelled using the soil module of FARMLAND[5], which allows for migration down

TABLE C3
Predicted activity concentrations in foods from 50 years of surface deposition (sewage sludge application to land)

	Activity concentration in foods from 50 years of application of sewage sludge at unit rate (Bq kg^{-1} or Bq l^{-1} per Bq m^{-2} y^{-1})				
Nuclide	Cow meat	Cow offal*	Milk	Sheep meat	Sheep offal*
^{89}Sr	2.2 10^{-5}	2.2 10^{-5}	1.1 10^{-4}	2.4 10^{-5}	2.4 10^{-5}
^{90}Sr	7.2 10^{-4}	7.2 10^{-4}	3.4 10^{-3}	4.7 10^{-4}	4.7 10^{-4}
^{103}Ru	1.5 10^{-6}	1.5 10^{-6}	1.2 10^{-8}	4.3 10^{-6}	4.3 10^{-6}
^{106}Ru	4.7 10^{-5}	4.7 10^{-5}	8.8 10^{-8}	1.0 10^{-4}	1.0 10^{-4}
^{125}I	7.4 10^{-5}	7.4 10^{-5}	1.2 10^{-4}	2.4 10^{-4}	2.4 10^{-4}
^{129}I	9.9 10^{-4}	9.9 10^{-4}	1.5 10^{-3}	8.3 10^{-3}	8.3 10^{-3}
^{134}Cs	4.6 10^{-3}	4.6 10^{-3}	9.2 10^{-4}	1.0 10^{-2}	1.0 10^{-2}
^{137}Cs	8.3 10^{-3}	8.3 10^{-3}	1.6 10^{-3}	2.3 10^{-2}	2.3 10^{-2}
^{238}Pu	2.0 10^{-5}	2.4 10^{-3}	1.4 10^{-6}	3.5 10^{-5}	2.5 10^{-3}
^{239}Pu	2.1 10^{-5}	2.6 10^{-3}	1.5 10^{-6}	3.7 10^{-5}	2.6 10^{-3}
^{240}Pu	2.1 10^{-5}	2.5 10^{-3}	1.5 10^{-6}	3.7 10^{-5}	2.6 10^{-3}
^{241}Pu	1.4 10^{-5}	1.8 10^{-3}	1.0 10^{-6}	2.9 10^{-5}	2.1 10^{-3}
^{242}Pu	2.1 10^{-5}	2.6 10^{-3}	1.5 10^{-6}	3.7 10^{-5}	2.6 10^{-3}
^{241}Am	2.6 10^{-5}	3.1 10^{-3}	1.9 10^{-6}	3.8 10^{-5}	2.7 10^{-3}
^{243}Am	2.6 10^{-5}	3.2 10^{-3}	1.9 10^{-6}	3.8 10^{-5}	2.8 10^{-3}
^{242}Cm	4.6 10^{-7}	5.5 10^{-5}	3.3 10^{-8}	2.2 10^{-6}	1.6 10^{-4}
^{243}Cm	2.1 10^{-5}	2.5 10^{-3}	1.5 10^{-6}	3.4 10^{-5}	2.4 10^{-3}
^{244}Cm	1.9 10^{-5}	2.3 10^{-3}	1.3 10^{-6}	3.2 10^{-5}	2.3 10^{-3}

* Offal refers to liver for sheep or cow.

the soil profile. Soil activity concentrations in the top 1 cm of the soil were calculated using equation C2. Effective dose rates from per unit discharge for external exposure above soil were derived using an external dose model[7] and were calculated using equation C3.

$$A_s = A_{s(u)}\, SL_{app}\, SL_{conc} \quad \text{(C2)}$$

$$D_{ext} = D_{ext(u)}\, SL_{app}\, SL_{conc} / T \quad \text{(C3)}$$

where A_s = activity concentration in the top 1 cm of soil after 50 years of treatment with sewage sludge (Bq kg^{-1} per Bq s^{-1}).
$A_{s(u)}$ = activity concentration in the top 1 cm of soil per unit deposit after 50 years (Bq kg^{-1} per Bq m^{-2} y^{-1}) (Table C4).
D_{ext} = external dose rate in year 50 from application of sewage sludge to land per unit discharge (Sv y^{-1} per Bq s^{-1}).
$D_{ext(u)}$ = external dose rate in year 50 per unit deposition rate (Sv y^{-1} per Bq m^{-2} s^{-1}) (Table C4[7]).
T = number of seconds in a year.

Dose calculations

Doses to three separate exposed groups were performed for the sewer GDC: to workers at the sewage treatment works, to groups exposed to discharges of treated sewage effluent to river and to groups exposed to farmland treated with sewage sludge. Critical group food intakes and habits[8] were used.

Exposure of sewage plant workers

Sewage plant workers were assumed to spend an entire working year at the sewage works. The exposure pathways (adults only) were: inadvertent ingestion of sewage effluent, inhalation of resuspended sewage effluent and external exposure to tanks containing effluents and sludges.

Doses from inhalation of resuspended sewage sludge

Effective doses from inhalation of resuspended sewage sludge at an air concentration of 10^{-7} kg m^{-3} (of sludge[9]) were calculated using equation C4.

$$D_{tw,inh} = SL_{conc}\, B\, L\, D_{inh}\, O \quad \text{(C4)}$$

where $D_{tw,inh}$ = effective dose from inhalation of resuspended of sewage sludge at the sewage treatment works (Sv y^{-1} per Bq s^{-1}).
B = breathing rate (m^3 h^{-1}) (Table C5).
L = concentration of suspended sludge in air (kg m^{-3}).
D_{inh} = inhalation dose coefficient (Sv Bq^{-1}) (Table 2 of the main text).
O = occupancy of sewage works (h y^{-1}) (Table C5).

Doses from inadvertent ingestion of sewage sludge

Effective doses from inadvertent ingestion of sewage sludge were calculated using equation C5.

TABLE C4 *Predicted activity concentrations and external dose rates in the 50th year above undisturbed soil per unit deposit and external dose rates above well-mixed sewage sludge in tanks per unit activity concentration*

Nuclide	50th year activity concentrations in soil per unit deposit ($Bq\,kg^{-1}$ per $Bq\,m^{-2}\,y^{-1}$)	50th year effective external dose rate 1 m above soil per unit deposit ($Sv\,y^{-1}$ per $Bq\,m^{-2}\,s^{-1}$)	Effective external dose rate 1 m above sludge in tanks ($Sv\,h^{-1}$ per $Bq\,kg^{-1}$)
^{89}Sr	$1.5\ 10^{-2}$	$9.7\ 10^{-6}$	$1.8\ 10^{-14}$
^{90}Sr	$1.6\ 10^{-1}$	$4.0\ 10^{-8}$	$6.7\ 10^{-18}$
^{103}Ru	$1.2\ 10^{-2}$	$4.4\ 10^{-2}$	$9.8\ 10^{-11}$
^{106}Ru	$8.6\ 10^{-2}$	$1.6\ 10^{-1}$	$4.3\ 10^{-11}$
^{125}I	$1.8\ 10^{-2}$	$9.3\ 10^{-4}$	$1.7\ 10^{-12}$
^{129}I	$3.3\ 10^{-1}$	$1.5\ 10^{-2}$	$1.4\ 10^{-12}$
^{131}I	-	-	$8.1\ 10^{-11}$
^{132}I	-	-	$4.8\ 10^{-10}$
^{133}I	-	-	$1.3\ 10^{-10}$
^{134}I	-	-	$5.6\ 10^{-10}$
^{135}I	-	-	$3.5\ 10^{-10}$
^{134}Cs	$1.4\ 10^{-1}$	$2.1\ 10^{0}$	$3.3\ 10^{-10}$
^{136}Cs	-	-	$4.6\ 10^{-10}$
^{137}Cs	$3.0\ 10^{-1}$	$3.4\ 10^{0}$	$1.2\ 10^{-10}$
^{238}Pu	$3.2\ 10^{-1}$	$1.6\ 10^{-4}$	$1.3\ 10^{-14}$
^{239}Pu	$3.3\ 10^{-1}$	$3.4\ 10^{-4}$	$1.5\ 10^{-14}$
^{240}Pu	$3.3\ 10^{-1}$	$2.1\ 10^{-4}$	$1.4\ 10^{-14}$
^{241}Pu	$2.8\ 10^{-1}$	$6.8\ 10^{-4}$	$3.8\ 10^{-16}$
^{242}Pu	$3.3\ 10^{-1}$	$4.7\ 10^{-3}$	$1.4\ 10^{-13}$
^{241}Am	$3.3\ 10^{-1}$	$6.3\ 10^{-2}$	$4.4\ 10^{-12}$
^{242}Am	-	-	$3.3\ 10^{-12}$
^{243}Am	$3.3\ 10^{-1}$	$1.3\ 10^{0}$	$5.0\ 10^{-11}$
^{242}Cm	$4.5\ 10^{-2}$	$2.6\ 10^{-5}$	$1.7\ 10^{-14}$
^{243}Cm	$3.0\ 10^{-1}$	$6.1\ 10^{-1}$	$2.9\ 10^{-11}$
^{244}Cm	$2.9\ 10^{-1}$	$9.6\ 10^{-4}$	$5.0\ 10^{-14}$

TABLE C5 *Critical group habits for exposure to sewer discharges*[8]

	Age group		
	1 y	10 y	Adult
Occupancy of sewage works ($h\,y^{-1}$)	-	-	2000
Occupancy above sludge tanks ($h\,y^{-1}$)	-	-	1000
Intake rates			
Breathing rate at works ($m^3\,h^{-1}$)	-	-	0.83
Breathing rate ($m^3\,y^{-1}$)	1900	5500	7300
Sewage sludge inadvertent ingestion ($kg\,h^{-1}$)	-	-	0.000 005
Soil inadvertent ingestion ($kg\,y^{-1}$)	0.044	0.018	0.008 3
Food consumption rates ($kg\,y^{-1}$ or $l\,y^{-1}$)			
Milk*	320	240	240
Cow meat	10	30	45
Cow offal	2.8	5	10
Sheep meat	3.0	10	25
Sheep offal	2.8	5	10

* Milk intake of 350 $l\,y^{-1}$ assumed for unweaned infants in the first year of life.

$$D_{tw,inad} = SL_{conc} \, I_{inad} \, D_{ing} \, O_{tank} \qquad (C5)$$

where $D_{tw,inad}$ = effective dose from inadvertent ingestion of sewage sludge (Sv y^{-1} per Bq s^{-1}),
I_{inad} = inadvertent ingestion rate of sewage sludge (kg h^{-1}) (Table C5),
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text),
O_{tank} = occupancy above sewage sludge tanks (h y^{-1}) (Table C5).

Doses from exposure to sludge tanks

Effective doses from external exposure to tanks containing sewage sludge were calculated using equation C6.

$$D_{tw,ext} = D_{tw,ext(u)} \, SL_{conc} \, O_{tank} \qquad (C6)$$

where $D_{tw,ext}$ = external dose at sewage works from tanks of well-mixed sludge in the 50th year of discharge (Sv y^{-1} per Bq s^{-1}),
$D_{tw,ext(u)}$ = external dose rate above tanks containing well-mixed sludge per unit activity concentration (Sv h^{-1} per Bq kg^{-1}) (Table C4).

Total dose at sewage works

The total effective dose to sewage plant workers was calculated by summing the dose estimates from the three exposure pathways using equation C7.

$$D_{tw,tot} = D_{tw,inad} + D_{tw,inh} + D_{tw,ext} \qquad (C7)$$

where $D_{tw,tot}$ = total effective dose per unit discharge rate to sewage plant workers (Sv y^{-1} per Bq s^{-1}).

Exposure to farmland treated with sewage sludge

Four exposure pathways were considered for the disposal of treated sewage sludge applied to land: external exposure to soil treated with sludge, internal exposure from inhalation of resuspended soil, inadvertent ingestion of soil and ingestion of foods produced on land treated with sewage sludge. The age groups considered in the dose calculations were infants in the first year of life on an all-milk diet, 1 year olds, 10 year olds and adults.

External exposure to treated soil

Effective doses to each age group from external exposure to land treated with sewage sludge were calculated using equation C8.

$$D_{occ,ext} = D_{ext} \, (F_{ind} \, T_{ind} + F_{out} \, T_{out}) \qquad (C8)$$

where $D_{occ,ext}$ = effective dose in the 50th year of discharge arising from external irradiation from soil allowing for occupancy over land treated with sewage sludge (Sv y^{-1} per Bq s^{-1}),
D_{ext} = external dose rate in the 50th year per unit discharge (Sv y^{-1} per Bq s^{-1}) (equation C3),
F_{ind} = fraction of a year spent indoors,
T_{ind} = indoor location factor,
F_{out} = fraction of a year spent outdoors,
T_{out} = outdoor location factor.

The term location factor is defined as the ratio of dose received in the protected location (indoors or outdoors) to that received outdoors over undisturbed soil for the period during which the exposed person is in the location. The term location factor therefore describes the shielding offered at a particular location compared with the situation where no shielding is available. The indoor and outdoor location factors used are 0.1 and 1.0, respectively[2]. The age-dependent indoor and outdoor occupancies are given in Table A7 of Appendix A.

Internal exposure to treated soil

Effective doses to each age group from inhalation and inadvertent ingestion of soil from the top 1 cm of the soil profile were calculated using equations C9 and C10, respectively.

$$D_{inh} = A_s \, B \, L \, D_{inh} \quad (C9)$$

$$D_{inad} = A_s \, I_{s,inad} \, D_{ing} \quad (C10)$$

where D_{inh} = effective doses from inhalation of resuspended soil from the top 1 cm after treatment with sewage sludge for 50 years (Sv y^{-1} per Bq s^{-1}),
D_{inad} = effective doses from inadvertent ingestion of soil from the top 1 cm after treatment with sewage sludge for 50 years (Sv y^{-1} per Bq s^{-1}),
B = breathing rate (m^3 y^{-1}) (Table C5),
L = concentration of suspended soil in air (kg m^{-3}),
$I_{s,inad}$ = inadvertent ingestion rate of soil (kg y^{-1}) (Table C5),
D_{inh} = inhalation dose coefficient (Sv Bq^{-1}) (Table 2 of the main text),
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

The concentration of suspended soil in air[2] assumed was 10^{-7} kg m^{-3}.

Doses from ingestion of foods

Ingestion doses to each age group from foods produced on land treated with sewage sludge were calculated using equation C11.

$$D_{food} = A_f \, I_f \, D_{ing} \quad (C11)$$

where D_{food} = effective dose from each food produced on land treated with sewage sludge for 50 years (Sv y^{-1} per Bq s^{-1}),
A_f = activity concentrations in each food after treatment with sewage sludge (Bq kg^{-1} per Bq s^{-1}) (equation C1),
I_f = ingestion rate of each food (kg y^{-1}) (Table C5),
D_{ing} = ingestion dose coefficient (Sv Bq^{-1}) (Table 1 of the main text).

Three different food types were considered: milk, beef products (beef and offal) and sheep products (mutton and offal). The area of land that could be treated with sewage sludge was small, therefore only one food type was considered to be produced and consumed. The food type that gave rise to the maximum dose was used.

Total dose

The total effective dose per unit discharge rate from land application pathways for each age group from each radionuclide was calculated by summing the dose estimates from the four exposure pathways described above using equation C12.

$$D_{sl,tot} = D_{food} + D_{inh} + D_{occ,ext} + D_{inad} \qquad (C12)$$

where $D_{sl,tot}$ = total effective dose from treated land per unit discharge rate (Sv y^{-1} per Bq s^{-1}).

Exposure to treated effluent discharged to a river

Exposure to treated effluent discharged to a river considered five exposure pathways. The dose calculation is as described in Appendix B.

Calculation of GDCs for discharges to sewers

The GDC for disposals to sewers was calculated by considering which of the three exposed groups (workers at the sewage treatment works, groups exposed to discharges of treated sewage effluent to river and groups exposed to farmland treated with sewage sludge) would receive the highest dose.

The GDC for workers at the sewage treatment works was calculated using equation C13 and the GDC for sludge disposal was calculated using equation C14. The GDC for rivers was calculated as described in Appendix B.

$$GDC_{tw} = T \text{ Dose Constraint}/D_{tw,tot} \qquad (C13)$$

$$GDC_{sl} = T \text{ Dose Constraint}/D_{sl,tot} \qquad (C14)$$

where GDC_{tw} = GDC for sewer workers at the treatment works (Bq y^{-1}),
GDC_{sl} = GDC for sludge applied to land (Bq y^{-1}),
T = conversion factor from seconds to years (s y^{-1}).

The dose constraint is 0.3 mSv y^{-1}, the maximum recommended by NRPB[1].

The overall GDC (Bq y^{-1}) for discharges to sewers was then taken to be the minimum of GDC_{tw}, GDC_{sl} and the GDC for discharges to rivers (Appendix B). The most restrictive GDC for discharges to sewers for each radionuclide is presented in Table 3 of the main text and the limiting case is indicated.

REFERENCES

1 NRPB. Public exposure: guidance on the 1990 recommendations of ICRP. *Doc NRPB*, **4**, 2, 27–41 (1993).

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

3 Sinnott C. Thames Water Statistics 1978. Reading, Thames Water (1978).

4 Code of practice for agricultural use of sewage sludge. London, HMSO (1993).

5 Brown J and Simmonds J R. FARMLAND: a dynamic model for the transfer of radionuclides through terrestrial foodchains. Chilton, NRPB-R273 (1995).

6 WRC. The agricultural value of sewage sludge. A farmer's guide. Guidance leaflet produced by WRC, ADAs and MAFF. Medmenham, Water Research Centre.

7 Carey A D, Jones J A and Mobbs S F. GRANIS: a model for the assessment of external photon irradiation from contaminated media of finite lateral extent. Chilton, NRPB (to be published).

8 Robinson CA. Generalised habit data for radiological assessments. Chilton, NRPB-M636 (1996).

9 Northrop R, Carnow B, Wadden R, *et al.* Health effects of aerosols emitted from an activated sludge plant. IN *Waste Water Aerosols and Disease*. Proceedings of a symposium. Cincinnati, Environmental Protection Agency. Publication EPA-600/9-80-028 (1980).

Appendix D

IMPORTANT EXPOSURE PATHWAYS FOR GDCs

Introduction

Details of the limiting exposure pathways and age groups for the generalised derived constraints (GDCs) presented in the main text are discussed in this appendix in the light of the models and data used. In addition, the differences between the GDCs and the GDLs published previously for atmospheric discharges are discussed.

GDCs for discharges to atmosphere

The GDCs for discharges to atmosphere considered exposure of infants (1 year old), children (10 years old), and adults. Infants in the first year of life (3 months old) whose diet was assumed to consist entirely of milk were also considered. Table 3 of the main text indicates the limiting age group for each radionuclide and these are discussed here. The dominant pathways for the GDCs for atmospheric discharges vary, depending on radionuclide, and are shown in Table D1. For all the actinides, plume inhalation is the dominant exposure pathway contributing more than 90% of the dose. Adults are the limiting age group in most cases. Although the inhalation dose coefficients for adults are the lowest of the age groups, this is offset by the higher breathing rate of adults. For the isotopes of caesium and ruthenium, together with ^{132}I and ^{134}I, the main doses are from external irradiation from deposited activity. For ^{106}Ru, inhalation of the plume is also significant. Adults are the limiting age group in these cases, because they are assumed to spend the greatest amount of time outdoors above deposited activity. For ^{89}Sr, ^{125}I, ^{129}I and ^{131}I, milk and milk products contribute the majority of the dose. One year old children are the limiting age group. Despite being the highest milk consumers, infants in the first year of life on an all-milk diet are not the limiting age group for these radionuclides because the diet does not include milk products. Consumption of milk, milk products and inhalation of the plume are the main pathways for the ^{133}I GDC, whilst, for ^{135}I, inhalation of the plume is the main pathway. One year old children are the limiting age group for both isotopes.

It should be noted that the situation modelled in determining the GDCs was fairly cautious but realistic. If the conditions were different to those modelled, eg a different stack height, or the critical group was located in a different place, the limiting age groups and pathways may change. A different stack height to that considered for the GDC would result in different air concentrations at various points away from the stack. The location of the critical group relative to the emission point, and where the group's food is grown are important. Differences in these distances can affect the relative importance of the exposure pathways. These factors should be borne in mind when applying the GDCs.

Differences between the GDCs and the GDLs for atmospheric discharges published previously

Differences between the GDCs presented in Table 3 of the main text and the GDLs for atmospheric discharges published in NRPB-GS8[1] and NRPB-GS10[2] are likely to be of interest to those involved in controlling the discharges of activity. The GDCs are generally more restrictive than the GDLs for atmospheric discharges published previously by a factor of between about 4 and 38 depending on the radionuclide. The differences can be explained mainly by two factors which will affect all the GDCs.

TABLE D1
*Contributions of exposure pathways to the GDC for discharges to atmosphere**

Nuclide	Limiting age group	Plume inhalation	External from deposited activity	Consumption of foods
^{89}Sr	1 y old	71%	-	29% - milk and milk products
^{90}Sr	10 y old	34%	-	66% - cereals, milk and milk products
^{103}Ru	Adult	41%	58%	-
^{106}Ru	Adult	69%	30%	-
^{125}I	1 y old	2%	-	98% - milk and milk products
^{129}I	1 y old	1%	-	99% - milk and milk products
^{131}I	1 y old	4%	-	96% - milk and milk products
^{132}I	Adult	19%	75%	-
^{133}I	1 y old	36%	2%	61% - milk and milk products
^{134}I	Adult	19%	67%	-
^{135}I	1 y old	68%	20%	10% - milk and milk products
^{134}Cs	Adult	3%	81%	15% - all foods
^{136}Cs	Adult	14%	61%	25% - milk and milk products
^{137}Cs	Adult	2%	87%	11% - all foods
^{238}Pu	Adult	100%	-	-
^{239}Pu	Adult	100%	-	-
^{240}Pu	Adult	100%	-	-
^{241}Pu	Adult	100%	-	-
^{242}Pu	Adult	100%	-	-
^{241}Am	Adult	100%	-	-
^{242}Am	10 y old	100%	-	-
^{243}Am	Adult	100%	-	-
^{242}Cm	10 y old	100%	-	-
^{243}Cm	Adult	100%	-	-
^{244}Cm	Adult	100%	-	-

* External irradiation from the plume contributes 6% to the GDC for ^{132}I, 14% to the GDC for ^{134}I and 1% to the GDC for ^{135}I.

(a) The dose constraint[3] used in the calculations is 0.3 mSv y^{-1}, whereas the GDLs for atmospheric discharges published previously were calculated using the public dose limit of 1 mSv y^{-1}. This will make the GDCs more restrictive than the GDLs by a factor of three.

(b) The GDCs assume a ground-level release, whereas the GDLs published previously were based on a stack 15 m high. The lower release height gives rise to air concentrations 15 times higher at 100 m and 2.4 times higher at 500 m from the stack.

In addition, the dose coefficients for ingestion and inhalation have been revised[4] and the critical group intake rates of various materials have been updated[5]. Further, environmental models for predicting external dose above contaminated media[6], models for ground deposition and resuspension of activity[7] and models for transfer of radionuclides through the foodchain[8] have been revised, and location factors for shielding by buildings have been used which reduce the doses.

The extent to which the GDCs are more restrictive is dependent on the radionuclide. For example, the GDCs for the actinides are more restrictive than the GDLs for discharges to atmosphere published previously[1,2] by factors of between 15 and 20. Inhalation of the plume is the dominant pathway for most of the actinides – the GDCs are influenced by higher activity concentrations in air and the more recent, lower, inhalation dose coefficients. Where external dose from deposited activity is important, such as for isotopes of caesium and ruthenium, the GDCs are more restrictive than the previous GDLs for atmospheric discharges[1,2] by factors of between four and seven, influenced by the higher activity concentrations in air and the reduction in external dose from the introduction of location factors. The GDCs for ^{132}I and ^{134}I are also dominated by external dose from deposited activity; in this case the GDCs are more restrictive by factors of 17 and 21, the latter being influenced by an increased deposition rate for iodine. Where food products are important, for isotopes such as ^{125}I, ^{129}I and ^{131}I and isotopes of strontium, the GDCs are more restrictive than the previous GDLs by factors of four to seven.

GDCs for discharges to rivers

The GDCs for discharges to rivers were calculated for 25 radionuclides for three age groups, infants (1 year old), children (10 year old) and adults. Table 3 of the main text indicates the limiting age group for each radionuclide and these are discussed here. The dominant pathways for the GDCs for discharges to rivers vary, depending on the radionuclide. The important pathways are shown in Table D2. The drinking water pathways contribute significantly to the GDC for all radioisotopes except those of caesium. Freshwater fish intakes dominate the GDC for isotopes of caesium, and irrigation of terrestrial foods is important for ^{90}Sr, ^{125}I, ^{129}I and the actinides. Doses from consumption of animal products were not considered, because land used to raise animals is not normally irrigated. External exposure from swimming in river water was not considered – this pathway does not contribute significantly to the overall dose.

GDCs for discharges to sewers

The GDCs for discharges to sewers were calculated for 25 radionuclides for four age groups, infants (3 months old and 1 year old), children (10 year old) and adults. The diet of infants in the first year of life (3 months old) was assumed to consist entirely of milk. Table 3 of the main text indicates the limiting age group for each radionuclide and these are discussed here. The GDC for discharges to sewers differs from the GDC for atmosphere and river because of the nature of sewage treatment and disposal. Raw incoming effluent is comprised of water and suspended solids. During treatment the water and suspended solids are physically separated and are disposed of in different ways. Three distinct exposed groups are considered, those exposed during sewage treatment, effluent disposal to inland water courses, and sludge disposal to farmland.

The GDC for sewers disposal is limited either by exposure at the works or by disposal of sludge to land. Exposures from effluent disposal to inland river courses do not contribute to the GDC for any radionuclides. The dominant pathways for the GDCs for sewers discharge vary, depending on the radionuclide.

For isotopes of iodine with short radioactive half-lives, the isotopes of ruthenium, ^{136}Cs and ^{242}Am, exposures at the sewage works are limiting. This is because these radionuclides would undergo significant radioactive decay during collection treatment and storage before application to land. Exposures to these radionuclides at the works would therefore be more important and external dose from sludge in tanks is predicted to be the main exposure pathway.

TABLE D2
Contributions of exposure pathways to the GDC for discharges to rivers

Nuclide	Limiting age group	Drinking water	Fish ingestion	Inhalation of bank sediments	External from bank sediments	Consumption of terrestrial foods*
^{89}Sr	1 y old	74%	17%	-	-	8%
^{90}Sr	Adult	27%	54%	-	-	19%
^{103}Ru	1 y old	93%	4%	-	1%	2%
^{106}Ru	1 y old	89%	3%	-	1%	7%
^{125}I	10 y old	45%	13%	-	-	42%
^{129}I	Adult	34%	22%	-	-	44%
^{131}I	1 y old	90%	7%	-	-	3%
^{132}I	1 y old	93%	7%	-	-	-
^{133}I	1 y old	93%	7%	-	-	-
^{134}I	1 y old	93%	7%	-	-	-
^{135}I	1 y old	93%	7%	-	-	-
^{134}Cs	Adult	1%	96%	-	1%	2%
^{136}Cs	Adult	1%	98%	-	1%	-
^{137}Cs	Adult	1%	91%	-	6%	2%
^{238}Pu	Adult	52%	6%	4%	-	38%
^{239}Pu	Adult	52%	6%	5%	-	37%
^{240}Pu	Adult	52%	6%	4%	-	38%
^{241}Pu	Adult	53%	6%	3%	-	38%
^{242}Pu	Adult	52%	6%	4%	-	38%
^{241}Am	Adult	22%	18%	4%	1%	54%
^{242}Am	1 y old	91%	9%	-	-	-
^{243}Am	Adult	18%	15%	3%	21%	43%
^{242}Cm	1 y old	48%	4%	-	-	48%
^{243}Cm	Adult	23%	19%	-	2%	56%
^{244}Cm	Adult	23%	19%	-	-	57%

* The terrestrial foods considered were cereals, green vegetables and root vegetables and were assumed to be irrigated with river water.

The remaining radionuclides were limited by disposal of sludge to land. The contributions of the exposure pathways to the GDC are shown in Table D3. In general, adults are the limiting age group for most of the radionuclides, 3 month olds are limiting for isotopes of strontium and 1 year olds are the limiting age for isotopes of iodine because of milk intakes. Inhalation of soil is important for the majority of the actinides, and external dose from soil is important for isotopes of caesium.

Effects of different sizes of sewage treatment works on the GDC for discharges to sewers

The GDCs for discharges to sewers were calculated making the cautious assumption that discharges occurred to a small rural sewage works serving a population of 500. Many disposers may discharge to larger works. Sewage works size is controlled by the population served which affects the amount of sewage effluent produced. If the population is larger then the quantity of effluent is larger, dilution of disposed radionuclides is higher and, as a result, the predicted doses are lower. In the simplest terms, increasing works size

TABLE D3
Contributions of exposure pathways to the GDC for discharges to sewers from treatment of land with sewage sludge

Nuclide	Limiting age group	External dose from soil	Inadvertent ingestion of soil	Inhalation of soil	Consumption of foods
^{89}Sr	3 month old	-	-	-	99% - milk
^{90}Sr	3 month old	-	-	-	100% - milk
^{125}I	1 y old	-	2%	-	98% - milk
^{129}I	1 y old	-	3%	-	97% - milk
^{134}Cs	Adult	85%	-	-	15% - sheep meat and offal
^{137}Cs	Adult	85%	-	-	15% - sheep meat and offal
^{238}Pu	Adult	-	3%	62%	35% - sheep meat and offal
^{239}Pu	Adult	-	3%	62%	35% - sheep meat and offal
^{240}Pu	Adult	-	3%	62%	35% - sheep meat and offal
^{241}Pu*	Adult	4%	3%	59%	34% - sheep meat and offal
^{242}Pu	Adult	-	3%	62%	35% - sheep meat and offal
^{241}Am	Adult	6%	3%	55%	36% - cow meat and offal
^{243}Am	Adult	56%	1%	25%	17% - cow meat and offal
^{242}Cm	1 y old	-	45%	45%	10% - sheep meat and offal
^{243}Cm	Adult	49%	2%	31%	18% - cow meat and offal
^{244}Cm	Adult	-	3%	64%	32% - sheep meat and offal

* The contribution from ^{241}Am ingrowth is assumed to have only a small effect on the pathway contribution.

will reduce the activity concentrations of radionuclides in proportion. However, there are three additional factors which may influence the predicted doses and become important as the sewage works size increases.

In order to allow use of the GDCs where discharges may occur to larger works, scaling factors have been derived for use with the GDCs for each of the radionuclides. For sewage works serving a population of up to 50 000, the GDCs for discharges to sewers in Table 3 of the main text may be scaled using equations D1 to D4 (provided incineration of sewage sludge is not carried out).

$$GDC_{gp1} = GDC \times W_{pe}/500 \quad (D1)$$

$$GDC_{gp2} = GDC \times W_{pe} \times 0.4/500 \quad (D2)$$

For sewage works serving a population of more than 50 000 the GDCs for discharges to sewers given in Table 3 of the main text may be scaled as follows (provided incineration of sewage sludge is not carried out).

$$GDC_{gp1} = GDC \times 100 \quad (D3)$$

$$GDC_{gp2} = GDC \times 40 \quad (D4)$$

where GDC_{gp1} = GDC for group 1 radionuclide for different sized sewage works (Bq y^{-1}) (see Table D4),

GDC_{gp2} = GDC for group 2 radionuclide for different sized sewage works (Bq y^{-1}) (see Table D4),

W_{pe} = population served by the sewage works,

GDC = generalised derived constraint for sewers for radionuclide discharged (Bq y^{-1}) (Table 3 of the main text).

Group number	Nuclides
1	^{89}Sr, ^{90}Sr, ^{103}Ru, ^{106}Ru, ^{131}I, ^{132}I, ^{133}I, ^{134}I, ^{135}I, ^{136}Cs, ^{242}Am and ^{242}Cm
2	^{125}I, ^{129}I, ^{134}Cs, ^{137}Cs, ^{238}Pu, ^{239}Pu, ^{240}Pu, ^{241}Pu, ^{242}Pu, ^{241}Am, ^{243}Am, ^{243}Cm and ^{244}Cm

TABLE D4 *Grouping of radionuclides for use with equations for scaling the GDC for sewers*

If incineration of sewage sludge occurs at the works, the above scaling does not apply. This approach to scaling the GDCs must be used with caution because it is intended only to give an indication of the effects of the size of sewage works on the GDC.

REFERENCES

1 NRPB. Revised generalised derived limits for radioisotopes of strontium, iodine, caesium, plutonium, americium and curium. Chilton, NRPB-GS8 (1987).

2 NRPB. Revised generalised derived limits for radioisotopes of ruthenium. Chilton, NRPB-GS10 (1989).

3 NRPB. Public exposure: guidance on the 1990 recommendations of ICRP. *Doc NRPB*, **4**, 2, 27–41 (1993).

4 ICRP. 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**, No. 1 (1996).

5 Robinson C A. Generalised habit data for radiological assessments. Chilton, NRPB-M636 (1996).

6 Carey A D, Jones J A and Mobbs S F. GRANIS: a model for the assessment of external photon irradiation from contaminated media of finite lateral extent. Chilton, NRPB (to be published).

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

8 Brown J and Simmonds J R. FARMLAND: a dynamic model for the transfer of radionuclides through terrestrial foodchains. Chilton, NRPB-R273 (1995).

GENERALISED DERIVED LIMITS FOR RADIOISOTOPES OF POLONIUM, LEAD, RADIUM AND URANIUM

ABSTRACT

Generalised derived limits (GDLs) are intended for use as convenient reference levels against which the results of environmental monitoring can be compared. Generalised derived limits have been calculated in various environmental materials for the radiologically significant isotopes of polonium, lead, radium and uranium, derived from the annual effective dose limit of 1 mSv. The most recent age-dependent dosimetric models have been used and the methods are as used in calculating GDLs for radioisotopes of other elements, such as strontium, published previously. The radioisotopes of polonium, lead, radium and uranium are all found naturally in the environment and the GDLs relate only to possible increases in activity concentrations resulting from human activities.

Generalised derived limits are calculated using deliberately cautious assumptions and are based on the assumption that the level of environmental contamination is uniform over a year. 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 for which the measured level is likely to be maintained.

PREPARED BY M P HARVEY, J G TITLEY AND J R SIMMONDS

INTRODUCTION

1 Derived limits (DLs) are convenient reference levels against which the results of monitoring can be compared; they may be set for such quantities as dose rate in a workplace, or contamination of air or other environmental materials. They are related to the primary dose criteria by a defined model and are calculated such that compliance with them would ensure virtual certainty of compliance with the appropriate dose criteria. Generalised derived limits (GDLs) are intended for general application, as opposed to DLs which are developed for specific situations for defined groups of individuals; GDLs are directly measurable quantities, such as concentrations in environmental materials (eg milk and other foods, grass and soil), and are calculated for single radionuclides. NRPB has previously published GDLs for radioisotopes of a range of elements[1] together with guidance on their application[2].

2 Measured values may include contributions from a number of sources and from past operations. As discussed elsewhere[3], the dose limit for members of the public covers public exposures from controlled sources and NRPB recommends that exposures arising from past controlled releases should also be included in any comparison with the dose limit. This recommendation was accepted by the government in the White Paper on radioactive waste management policy[4]. Therefore, it is appropriate for doses resulting from measurements to be compared with the overall dose limit for members of the public[3] of 1 mSv y^{-1} and this is the basis for the GDLs presented here. Where appropriate, GDLs are also estimated so that the annual equivalent dose to the lens of the eye and the skin does not exceed the recommended dose limits for members of the public, of 15 and 50 mSv, respectively[3]. However, these organ-specific dose limits are rarely limiting in determining GDLs in environmental materials. Derived quantities for discharges of radionuclides to the environment are clearly related to the current operation of a single controlled source and should therefore be based on the appropriate dose constraint[3]. Generalised derived constraints[3] (GDCs) have therefore been developed[5] for discharges of radionuclides to the environment based on the upper value of the constraint on effective dose for members of the public of 0.3 mSv y^{-1} recommended by NRPB[3]. Generalised derived constraints will also be calculated for the radioisotopes considered here.

3 This report contains values of GDLs for a range of environmental materials for radioisotopes of four naturally occurring elements. The GDLs have been calculated using effective dose as defined in ICRP Publication 60[6]. The values for dose coefficients from inhalation and ingestion are as given elsewhere[7]. The methods used to calculate the GDLs are as used for previous GDL calculations[1]. An earlier report[2] gave more detailed practical guidance on the application of GDLs and their comparison with measurements. In future, further reports will give GDLs for radioisotopes of additional elements and also GDCs for discharges into the environment.

BASIS FOR GDLs

4 Generalised derived limits are intended for general application as environmental reference levels. They can be used as simple screening values for low levels of radionuclides in the environment and are calculated using a set of standardised and deliberately cautious assumptions concerning the habits of the hypothetically exposed group. The GDLs are based on the assumption that the level of environmental contamination

is reasonably uniform over a year and they do not relate to transient conditions. For example, they should not be used in connection with single, short-term releases of radionuclides into the environment.

5 As outlined above and discussed elsewhere[3], GDLs are based on an effective dose limit of 1 mSv y^{-1}. The supplementary limits on the lens of the eye and the skin were also considered in calculating GDLs but, for the radioisotopes and GDLs included in this document, their values were never limiting so only the effective dose was relevant.

6 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. As previously[1], the age groups considered are infants (1 year old), children (10 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 an all-milk diet in the first year of life based on dose coefficients for a 3 month old. For some elements enhanced absorption at this stage of development leads to more restrictive GDLs. The use of the ingestion dose coefficient for a 3 month old, together with a milk intake more applicable to an older infant to represent the first year of life, will lead to a cautious estimate of the GDL. This is particularly the case for radioisotopes where there is a marked reduction in the dose coefficient between 3 and 12 months. It is considered inappropriate to use the dose coefficient for a 3 month old for intakes of other foods as they are generally only consumed by older infants for whom a lower dose coefficient usually applies. Although data on dose coefficients are available for additional age groups[7], the ages considered here are thought to cover the range and to be adequate for the purposes of calculating GDLs. For calculating doses from intakes of radionuclides the lifetime of an individual member of the public is taken to be 70 years. Although this is slightly shorter than the average lifetime of individuals in the UK, its use is sufficiently cautious because intakes of foods and risks decrease in old age.

7 The values of the effective dose coefficients for intake by inhalation and ingestion are as described elsewhere[7]. They have been calculated for each age group considered using the most recent age-dependent dosimetric models. Tables 1 and 2 give the values for the effective dose coefficients used in this document for intake by ingestion and inhalation, respectively. The recommended[7] default absorption types for particulate aerosols were used to select the appropriate inhalation dose coefficients for the GDL calculations.

8 The elements considered here all occur naturally in the environment but enhanced levels can be found in the environment resulting from human activity. The annual dose limit for members of the public does not apply to natural background radiation but only to exposures from controlled sources. Therefore, the GDLs presented here relate only to possible incremental activity concentrations resulting from human activities, and not the total concentration measured. It is therefore necessary to have some estimate of the ambient levels in the area of interest to subtract from any measured activity concentrations before comparison with the appropriate GDL.

9 As presented here, GDLs relate the concentration of a single radionuclide in a single environmental material to the dose limit for members of the public. In practice, people are likely to be exposed to a number of radionuclides in a variety of materials. In comparing environmental measurements with GDLs it is therefore necessary to take account of all possible sources of contamination to ensure that the appropriate dose limit is not exceeded, as discussed later.

TABLE 1 *Dose coefficients for intake by ingestion*

Nuclide	f_1*	Committed effective dose per unit intake (Sv Bq^{-1}) Infant (3 months)	Infant (1 y)	Child (10 y)	Adult (20 y)
^{210}Po	5.0 10^{-1}	2.6 10^{-5}	8.8 10^{-6}	2.6 10^{-6}	1.2 10^{-6}
^{210}Pb	2.0 10^{-1}	8.4 10^{-6}	3.6 10^{-6}	1.9 10^{-6}	6.9 10^{-7}
^{226}Ra	2.0 10^{-1}	4.7 10^{-6}	9.6 10^{-7}	8.0 10^{-7}	2.8 10^{-7}
^{234}U	2.0 10^{-2}	3.7 10^{-7}	1.3 10^{-7}	7.4 10^{-8}	4.9 10^{-8}
^{235}U	2.0 10^{-2}	3.5 10^{-7}	1.3 10^{-7}	7.1 10^{-8}	4.7 10^{-8}
^{238}U	2.0 10^{-2}	3.4 10^{-7}	1.2 10^{-7}	6.8 10^{-8}	4.5 10^{-8}

* The gut transfer factors (f_1) for each nuclide given are the same for all age groups with the following exceptions:

Isotopes of Po	3 month old: 1.0 10^{0}	
Isotopes of Pb	3 month old: 6.0 10^{-1}	1 year old and 10 year old: 4.0 10^{-1}
Isotopes of Ra	3 month old: 6.0 10^{-1}	1 year old and 10 year old: 4.0 10^{-1}
Isotopes of U	3 month old: 4.0 10^{-2}	

TABLE 2 *Dose coefficients for intake by inhalation*

Nuclide	f_1	Type*	Committed effective dose per unit intake (Sv Bq^{-1}) Infant (1 y)	Child (10 y)	Adult (20 y)
^{210}Po	1.0 10^{-1}	M	1.1 10^{-5}	4.6 10^{-6}	3.3 10^{-6}
^{210}Pb	1.0 10^{-1}	M	3.7 10^{-6}	1.5 10^{-6}	1.1 10^{-6}
^{226}Ra	1.0 10^{-1}	M	1.1 10^{-5}	4.9 10^{-6}	3.5 10^{-6}
^{234}U	2.0 10^{-2}	M	1.1 10^{-5}	4.8 10^{-6}	3.5 10^{-6}
^{235}U	2.0 10^{-2}	M	1.0 10^{-5}	4.3 10^{-6}	3.1 10^{-6}
^{238}U	2.0 10^{-2}	M	9.4 10^{-6}	4.0 10^{-6}	2.9 10^{-6}

* Absorption type M (moderate) describing absorption from the respiratory tract.

VALUES OF GDLs

10 The general approach and formulae used to calculate the GDLs are given in Appendix A. The principles and methods of calculation are generally the same as used previously[1]. The data on occupancy and rates of intake of air, water, terrestrial and aquatic foods used to calculate GDLs are presented in Appendix B; the intake data for foods are based on a number of national surveys[8]. Account has been taken of the reduction in external irradiation doses during the time spent indoors; the factors and occupancies adopted are given in Appendix B together with details of the environmental models used in the calculation of GDLs. Appendix C discusses the limiting age groups and important exposure pathways for relevant GDLs.

11 Generalised derived limits for terrestrial foods and other terrestrial and aquatic materials are given in Tables 3, 4 and 5, respectively. In each case the GDL is based on the most restrictive age group, which is indicated. Generalised derived limits are not presented for grass for these radionuclides as foods derived from grazing animals are not important contributors to dose. For GDLs for well-mixed soil, sea washed pasture, marine and fresh-water sediments, sewage sludge and freshwater, the ingrowth of ^{210}Po is included in the GDLs for ^{210}Pb. For these GDLs the ingrowth of ^{210}Po and ^{210}Pb is also included in the GDLs for ^{226}Ra. Short-lived progeny for all radionuclides are assumed to be in secular equilibrium.

TABLE 3
Generalised derived limits for terrestrial foods

Foodstuff*	Generalised derived limit† (Bq kg^{-1}) ^{210}Po	^{210}Pb	^{226}Ra	^{234}U	^{235}U	^{238}U
Domestic fruit	$3\ 10^{0}$ i	$8\ 10^{0}$ i	$3\ 10^{1}$ c	$2\ 10^{2}$ i	$2\ 10^{2}$ i	$2\ 10^{2}$ i
Potatoes and other root vegetables	$3\ 10^{0}$ i	$6\ 10^{0}$ c	$1\ 10^{1}$ c	$1\ 10^{2}$ c	$1\ 10^{2}$ c	$2\ 10^{2}$ c
Green and other domestic vegetables	$8\ 10^{0}$ i	$2\ 10^{1}$ c	$4\ 10^{1}$ c	$3\ 10^{2}$	$3\ 10^{2}$	$3\ 10^{2}$
Pig meat	$2\ 10^{1}$ c	$2\ 10^{1}$ c	$5\ 10^{1}$ c	$5\ 10^{2}$	$5\ 10^{2}$	$6\ 10^{2}$
Cow meat	$1\ 10^{1}$ i	$2\ 10^{1}$ c	$4\ 10^{1}$ c	$5\ 10^{2}$ c	$5\ 10^{2}$ c	$5\ 10^{2}$ c
Sheep meat	$3\ 10^{1}$	$5\ 10^{1}$ c	$1\ 10^{2}$ c	$8\ 10^{2}$	$9\ 10^{2}$	$9\ 10^{2}$
Offal‡	$2\ 10^{1}$ i	$5\ 10^{1}$ i	$1\ 10^{2}$ c	$1\ 10^{3}$	$1\ 10^{3}$	$1\ 10^{3}$
Poultry	$2\ 10^{1}$ i	$4\ 10^{1}$ c	$8\ 10^{1}$ c	$7\ 10^{2}$	$7\ 10^{2}$	$7\ 10^{2}$
Milk§ (Bq l^{-1})	$1\ 10^{-1}$	$3\ 10^{-1}$	$6\ 10^{-1}$	$8\ 10^{0}$	$8\ 10^{0}$	$8\ 10^{0}$
Milk products	$3\ 10^{0}$ i	$6\ 10^{0}$ i	$2\ 10^{1}$ i	$2\ 10^{2}$ i	$2\ 10^{2}$ i	$2\ 10^{2}$ i
Eggs	$8\ 10^{0}$ i	$2\ 10^{1}$ i	$6\ 10^{1}$ c	$5\ 10^{2}$ i	$5\ 10^{2}$ i	$6\ 10^{2}$ i
Cereals	$4\ 10^{0}$ i	$7\ 10^{0}$ c	$2\ 10^{1}$ c	$2\ 10^{2}$ c	$2\ 10^{2}$ c	$2\ 10^{2}$ c

* The GDLs for food products are expressed as fresh mass.

† The GDLs apply to uniform conditions over a year and are based on the limiting age group, which for all foods (except milk) is for adults unless indicated by

i infants aged 1 year c children aged 10 years

‡ Offal refers to cow liver and sheep liver.

§ For milk the limiting age group is for infants in the first year of life (age 3 months).

TABLE 4
Generalised derived limits for the terrestrial environment

Material	Generalised derived limit* (Bq kg^{-1}) ^{210}Po	^{210}Pb	^{226}Ra	^{234}U	^{235}U	^{238}U
Air (Bq m^{-3})†	$4\ 10^{-2}$ c	$1\ 10^{-1}$ c	$4\ 10^{-2}$ c	$4\ 10^{-2}$ c	$4\ 10^{-2}$ c	$5\ 10^{-2}$ c
Well-mixed soil‡	$1\ 10^{2}$ i	$8\ 10^{1}$ i	$1\ 10^{2}$ i	$2\ 10^{4}$ i	$7\ 10^{3}$	$2\ 10^{4}$ i
Sewage sludge§	$8\ 10^{2}$ i	$8\ 10^{1}$ i	$3\ 10^{2}$ i	$8\ 10^{3}$ i	$4\ 10^{3}$	$8\ 10^{3}$ i
Sea washed pasture‡	$2\ 10^{2}$ i	$1\ 10^{2}$ i	$2\ 10^{2}$ i	$2\ 10^{4}$ f	$2\ 10^{4}$	$2\ 10^{4}$ f

* The GDLs apply to uniform conditions over a year and are based on the limiting age group, which is for adults except where indicated by

f infants in the first year of life on an all-milk diet i infants aged 1 year c children aged 10 years

† The GDLs for air are based on the inhalation pathway only.

‡ The GDL for ^{210}Pb includes the ingrowth of ^{210}Po.
The GDL for ^{226}Ra includes the maximum ingrowth of ^{210}Pb and ^{210}Po over 50 years.
The GDLs are expressed as dry mass.

§ The GDL for sewage sludge, when applied to land for ^{210}Pb, includes the ingrowth of ^{210}Po over a 50 year period.
The GDL for sewage sludge, when applied to land for ^{226}Ra, includes the ingrowth of ^{210}Pb and ^{210}Po over a 50 year period.

TABLE 5
Generalised derived limits for the aquatic environment

	Generalised derived limit* (Bq kg^{-1})					
Material	^{210}Po	^{210}Pb	^{226}Ra	^{234}U	^{235}U	^{238}U
Marine fish†	$8\ 10^{0}$	$1\ 10^{1}$	$4\ 10^{1}$	$2\ 10^{2}$	$2\ 10^{2}$	$2\ 10^{2}$
Freshwater fish†	$4\ 10^{1}$	$7\ 10^{1}$	$2\ 10^{2}$	$1\ 10^{3}$	$1\ 10^{3}$	$1\ 10^{3}$
Crustaceans†	$4\ 10^{1}$	$7\ 10^{1}$	$2\ 10^{2}$	$1\ 10^{3}$	$1\ 10^{3}$	$1\ 10^{3}$
Molluscs†	$4\ 10^{1}$	$7\ 10^{1}$	$2\ 10^{2}$	$1\ 10^{3}$	$1\ 10^{3}$	$1\ 10^{3}$
Freshwater sediment‡	$8\ 10^{4}$ i	$4\ 10^{4}$ c	$6\ 10^{3}$ c	$2\ 10^{6}$ c	$1\ 10^{5}$ c	$4\ 10^{5}$ c
Marine sediment‡	$8\ 10^{4}$ i	$5\ 10^{4}$	$2\ 10^{3}$	$9\ 10^{5}$	$2\ 10^{4}$	$1\ 10^{5}$
Freshwater§ (Bq l^{-1})	$3\ 10^{-1}$ i	$3\ 10^{-1}$	$2\ 10^{0}$ c	$2\ 10^{1}$	$2\ 10^{1}$	$2\ 10^{1}$
Drinking water (Bq l^{-1})	$4\ 10^{-1}$ i	$1\ 10^{0}$ i	$4\ 10^{0}$ c	$3\ 10^{1}$ i	$3\ 10^{1}$ i	$3\ 10^{1}$ i

* The GDLs apply to uniform conditions over a year and are based on the limiting age group, which is for adults, except where indicated by:

i infants aged 1 year c children aged 10 years

† The GDLs for aquatic foodstuffs are for the edible fraction and are expressed as fresh mass.

‡ The GDL for ^{210}Pb includes the ingrowth of 100% of ^{210}Po.
The GDL for ^{226}Ra includes the maximum ingrowth of ^{210}Pb and ^{210}Po over 50 years.
The GDLs for sediment are expressed as dry mass.

§ The GDLs for freshwater include activity in the dissolved and suspended fractions.
The GDL for ^{210}Pb for freshwater includes the ingrowth of ^{210}Po from food pathways.
The GDL for ^{226}Ra for freshwater includes the ingrowth of ^{210}Pb and ^{210}Po from food pathways.

INVESTIGATION LEVELS AND SITE-SPECIFIC ASSESSMENTS

12 Generalised derived limits are intended for screening purposes and have been calculated in such a way that the resultant doses are expected to be overestimated in most circumstances. However, it is possible that some underestimation may occur under particular conditions – for example, where additional pathways are possible. It has therefore been recommended that an implied dose of 0.1 mSv y^{-1} is a reasonable level at which to trigger further investigation[3]. This corresponds to 10% of the GDL for environmental materials and if this is exceeded the situation should be examined more closely, taking account of site-specific factors, the source of the activity, and the length of time for which the situation is likely to persist. A single measurement in excess of 10% of the GDL does not, of course, necessarily imply that the effective dose of 0.1 mSv y^{-1} will be exceeded. Factors to be considered in site-specific calculations are discussed elsewhere[2], where advice is also given on the interpretation of environmental measurements for comparison with GDLs and how the GDLs should be applied in particular situations.

13 In practice, people will be exposed to more than one radionuclide and from more than one environmental medium. Account must be taken of exposures from all relevant exposure pathways and radionuclides that contribute significantly to the total effective dose for comparison with the dose limit. When interpreting the results of environmental measurements, therefore, it is necessary to give due consideration to all relevant modes of exposure. This can be done by summing proportions of the relevant GDLs or, if

necessary, the doses from each route and radionuclide can be calculated and the sum compared with the dose limit. For example, in a particular area both green vegetables and root crops could be grown and found to contain ^{210}Pb, ^{210}Po and ^{226}Ra. The measured concentrations can be expressed as a percentage of the relevant GDL and the six resulting percentages summed. If this sum exceeds 10% then further investigation is required.

CONCLUSIONS

14 Generalised derived limits for the most significant radioisotopes of polonium, lead, radium and uranium are presented in this document. They are based on an annual effective dose limit for members of the public of 1 mSv and take account of the 1990 recommendations of ICRP, including the definition of effective dose[6]. Values are specified for a range of materials from the terrestrial and aquatic environments. In each case the GDL presented is the most restrictive of those calculated for the age groups considered.

15 If environmental contamination exceeds about 10% of the GDL the doses to the most exposed group should be examined more closely, taking into account site-specific factors and the likely duration of the situation.

ACKNOWLEDGEMENTS

16 The calculation of GDLs was carried out under formal quality assurance, QA, procedures. Mr N Green and Dr K R Smith acted as QA managers for the work. Dr B T Wilkins and Mr C A Fayers also made a valuable contribution to the project.

REFERENCES

1 NRPB. Revised generalised derived limits for radioisotopes of strontium, iodine, caesium, plutonium, americium and curium. *Doc NRPB*, **9**, No. 1, 1–34 (1998).

2 NRPB. Application of generalised derived limits. *Doc NRPB*, **9**, No. 1, 35–60 (1998).

3 NRPB. Public exposure: guidance on the 1990 recommendations of ICRP. *Doc NRPB*, **4**, No. 2, 27–41 (1993).

4 White Paper: Review of radioactive waste management policy. London, HMSO, Cm 2919 (1995).

5 NRPB. Generalised derived constraints for radioisotopes of strontium, ruthenium, iodine, plutonium, americium and curium. *Doc NRPB*, **11**, No.2, 1–42 (2000).

6 ICRP. 1990 recommendations of the International Commission on Radiological Protection. ICRP Publication 60. *Ann ICRP*, **21**, Nos 1–3 (1991).

7 ICRP. 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**, No. 1 (1996).

8 Byrom J, Robinson C A, Simmonds J R, *et al.* Food consumption rates for use in generalised radiological dose assessments. *J Radiol Prot*, **15**, No. 4, 335–41 (1995).

Appendix A

PRINCIPLES AND METHODS OF CALCULATING GDLs FOR ENVIRONMENTAL MATERIALS

Introduction

Generalised derived limits (GDLs) have been calculated for eleven materials which are important for, and relevant to, monitoring and control in the aquatic and terrestrial environments. The eleven GDLs can be divided into two groups, GDLs for materials which give rise to doses over a single exposure pathway and GDLs for materials which give rise to doses over multiple exposure pathways. Five environmental materials are considered to give rise to doses over a single exposure pathway: air, terrestrial and marine foods, drinking water and freshwater fish. Six environmental materials are considered to give rise to doses over multiple exposure pathways: well-mixed soil, sea washed pasture, marine and freshwater sediments, freshwater and sewage sludge. The GDLs are presented for a total of six radionuclides.

Some of the radionuclides considered are likely to have radioactive decay products (progeny) and these may need to be taken into account when determining GDLs. Progeny ingrowth only needs to be considered explicitly if sufficient time is likely to elapse for ingrowth to occur. For the materials which give rise to doses over a single exposure pathway, the ingestion or inhalation can occur without a significant delay and so progeny ingrowth does not need to be considered explicitly. However, for materials which give rise to doses over multiple exposure pathways, such as soil and sediments, exposure may continue to occur some time into the future; in these cases ingrowth of longer lived progeny may need to be considered explicitly.

GDLs for materials which give rise to doses over a single exposure pathway

This group comprises GDLs for air, terrestrial foods, marine foods, drinking water and freshwater fish. The GDLs for three age groups, infants (1 year old), children (10 years old) and adults (20 years old), were calculated and the most restrictive of these are presented in Tables 3, 4 and 5 of the main text. An additional age group is considered in calculating GDLs for milk, unweaned infants in the first year of life (3 months old). The GDLs for single exposure pathways, ingestion or inhalation, are calculated using equation A1.

$$\mathrm{GDL_m} = \frac{D}{H_e\, I_m} \qquad \text{(A1)}$$

where $\mathrm{GDL_m}$ = GDL for a particular material (m), and age group exposed (Bq kg^{-1}, Bq l^{-1} or Bq m^{-3}),

D = effective dose limit of 10^{-3} Sv y^{-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 y^{-1}, l y^{-1} or m^3 y^{-1}).

GDLs for materials which give rise to doses over multiple exposure pathways

The GDLs which fall into this group are well-mixed soil, marine and freshwater sediments, sea washed pasture, freshwater and sewage sludge. The ingrowth of progeny has been included over a 50 year period for all of these GDLs. The radionuclides considered for ingrowth of progeny were ^{210}Pb, ^{226}Ra, ^{235}U and ^{238}U. For ^{235}U and ^{238}U all the short-lived progeny (^{235}U includes ^{231}Th; ^{238}U includes ^{234}Th, ^{234}Pa and ^{234m}Pa) were assumed to exist in secular equilibrium with the parent. For ^{210}Pb the short-lived progeny ^{210}Bi was assumed to exist in secular equilibrium for all pathways. However, the second progeny of ^{210}Pb, ^{210}Po, was assumed to be in secular equilibrium for well-mixed soil, sediment and sea washed pasture only. For exposure at the sewage works, no ingrowth of ^{210}Po was assumed owing to the relatively short timescales involved. For the pathway where sewage sludge was applied to land, the maximum ingrowth of ^{210}Po was considered over a 50 year period, assuming ^{210}Po was supported by ^{210}Pb. For the freshwater GDL the contribution from ^{210}Po was taken into account in irrigated food as a result of ingrowth. For ^{226}Ra the short-lived progeny were assumed to exist in secular equilibrium for all GDLs (^{222}Rn, ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po). Radon was included in the decay chain as it is assumed to be contained within the environmental media rather than be released to atmosphere. The ingrowth of the longer lived progeny of ^{226}Ra (^{210}Pb and ^{210}Po) is considered for the following GDLs. For well-mixed soil, sediments and sea washed pasture the maximum ingrowth of ^{210}Pb and ^{210}Po was considered for a 50 year period for a given age group. The largest dose or minimum GDL which occurred between the first year and the 50th year was used. For exposure at the sewage works, no ingrowth of ^{210}Pb and ^{210}Po was assumed. For the pathway where sewage sludge was applied to land, the maximum ingrowth of ^{210}Pb and ^{210}Po was considered over a 50 year period. For the freshwater GDLs the contribution from ^{210}Pb and ^{210}Po was considered in irrigated food as a result of ingrowth.

The exposure pathways considered in the calculation of multiple exposure GDLs are summarised in Table A1. The GDLs for three age groups, infants (1 year old), children (10 years old) and adults (20 years old), were calculated and the most restrictive of these are presented in Tables 4 and 5 of the main text. An additional age group is considered in calculating GDLs for sea washed pasture, unweaned infants in the first year of life (3 months old). For each environmental material, the GDL was calculated by summing the contributions from all the significant exposure pathways; it is given by equation A2.

$$\frac{1}{\mathrm{GDL_m}} = \sum_{i=1}^{i=n} \frac{1}{\mathrm{GDL}_{\mathrm{m}\,i}} \qquad \text{(A2)}$$

where $\mathrm{GDL_m}$ = GDL for the material (m), and exposed age group, summed over all exposure pathways (i) (Bq kg^{-1} or Bq l^{-1}),

$\mathrm{GDL}_{\mathrm{m}\,i}$ = GDL for the material (m), age group and particular exposure pathway (i) (Bq kg^{-1} or Bq l^{-1}),

n = number of exposure pathways considered.

Four major types of 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, and internal irradiation from

TABLE A1
Pathways considered for multiple exposure GDLs

GDL	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
Freshwater	*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
Sewage sludge	*Exposure at sewage works* External exposure from sludge tanks Inhalation of resuspended sewage sludge Inadvertent ingestion of sewage sludge *Exposure pathways associated with soil conditioning of soil with sewage sludge* External exposure from conditioned soil Inadvertent ingestion of conditioned soil Inhalation of resuspended conditioned soil Ingestion of cereal products from conditioned soil Ingestion of animal products from conditioned 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

ingestion of foods or drinking water. The GDLs for sewage sludge and freshwater include pathways arising from conditioning and irrigation of land, respectively. These applications were modelled as a surface deposit using dynamic foodchain and soil models, as outlined in Appendix B. The methods for estimating GDLs for the main exposure pathways are outlined below.

External gamma exposure

External dose is dependent on the energy and frequency of emissions, the properties of the materials, shielding and occupancy. The external dose model and effective external dose rates 1 m above various materials, together with occupancies, shielding and physical properties of the materials, are described in Appendix B. The external gamma component of the multiple pathway GDLs is given by equations A3 and A4.

$$\mathrm{GDL_{ex}} = \frac{D}{E} \tag{A3}$$

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

For soils, E is given by

$$E = G\,(F_{\mathrm{ind}}\,T_{\mathrm{ind}} + F_{\mathrm{out}}\,T_{\mathrm{out}}) \tag{A4}$$

where G = external effective dose 1 m above the materials, integrated over 1 year (Sv y^{-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 over undisturbed pasture 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, sewage sludge in tanks, freshwater and marine sediments, E is derived from the product of external effective dose 1 m above the materials, integrated over 1 year, and the fraction of the year spent above the materials.

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 A5.

$$\mathrm{GDL_{inh}} = \frac{D}{(O_{\mathrm{mech}}\,L_{\mathrm{mech}} + O_{\mathrm{wind}}\,L_{\mathrm{wind}})\,H_{\mathrm{e(inh)}}\,B} \tag{A5}$$

where $\mathrm{GDL_{inh}}$ = GDL for inhalation of resuspended materials (Bq kg^{-1}),
D = effective dose limit of 10^{-3} Sv y^{-1},
$H_{\mathrm{e(inh)}}$ = 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}),
O_{wind} = occupancy above materials for ambient resuspension (h y^{-1}),
L_{wind} = concentration in air due to ambient resuspension (kg m^{-3}).

Inadvertent ingestion

The third exposure pathway considered was inadvertent ingestion. Inadvertent ingestion, as described by equation A6, was included in the calculation of GDLs for marine and freshwater sediments, sea washed pasture, well-mixed soil and farmland treated with sewage sludge and freshwater irrigation.

$$\mathrm{GDL_a} = \frac{D}{I_a \, H_{e(ing)} \, O_m} \tag{A6}$$

where $\mathrm{GDL_a}$ = 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 cases, eg well-mixed soil, 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 Appendix B) and O_m is no longer required.

Ingestion of food products

The fourth pathway considered was ingestion of foods produced on contaminated soils. The GDLs for well-mixed soil, sea washed pasture and farmland treated with sewage sludge and irrigated with freshwater have contributions from food ingestion.

The GDLs for each foodstuff produced on well-mixed soil and sea washed pasture are given by equation A7.

$$\mathrm{GDL_f} = \frac{D}{I_f \, H_{e(ing)} \, C_{sf}} \tag{A7}$$

where $\mathrm{GDL_f}$ = 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 l y^{-1}),
$H_{e(ing)}$ = dose coefficient for ingestion (Sv Bq^{-1}),
C_{sf} = concentration factor relating the radionuclide activity concentration in soil to the radionuclide activity 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 treated with sewage sludge or irrigated with freshwater used activity concentrations predicted by dynamic foodchain models following deposition of the radionuclides. The modelling approach adopted is described in Appendix B.

Aquatic exposure from freshwater

The GDL for freshwater (expressed as whole water, for both dissolved and suspended fractions) had a unique 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 as described in Appendix B. The GDLs from aquatic exposure pathways were derived from the GDLs calculated for each exposure pathway using equation A8.

$$\mathrm{GDL_{fwaq}} = \frac{\mathrm{GDL_{aqex}}}{C_\mathrm{f}} \tag{A8}$$

where $\mathrm{GDL_{fwaq}}$ = GDL for dissolved fraction of, or filtered, freshwater (Bq l^{-1}),
$\mathrm{GDL_{aqex}}$ = 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 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. These values are given in Table B7. The GDL for freshwater expressed in terms of unfiltered water (ie dissolved and solid phase) was derived using equation A9.

$$\mathrm{GDL_{fwater}} = \mathrm{GDL_{fwaq}}\,(1 + K_\mathrm{d}\,S) \tag{A9}$$

where $\mathrm{GDL_{fwater}}$ = GDL for freshwater (dissolved and suspended fraction) (Bq l^{-1}),
K_d = freshwater sediment water distribution coefficient (Bq kg^{-1} per Bq l^{-1}),
S = freshwater suspended sediment load (kg l^{-1}).

Appendix B

ENVIRONMENTAL MODELS AND HABIT DATA

Habit data

Generalised habit data for radiological protection purposes were reviewed and updated for use in the most recent publication on generalised derived limits (GDLs)[1]. The revised habit data are discussed in detail elsewhere[2], but the main developments are outlined here for ease of reference. The habit data used to calculate GDLs are those considered appropriate for critical groups, ie those people in the population who are representative of those who receive the highest radiation exposures. The terrestrial food ingestion rates given in Table B1 were revised to take account of national surveys of diet and have been agreed by the Ministry of Agriculture, Fisheries and Food and NRPB[3]. The 97.5th percentile of the national distribution of intake has been used to represent the critical group habits. Generalised critical group intakes of marine foods, and occupancies of intertidal areas, beaches and river banks, are based on a review of site-specific surveys conducted by MAFF[4] and on behalf of Her Majesty's Inspectorate of Pollution[5] (now the Environment Agency). These data are given in Tables B2 and B3 and are discussed further elsewhere[2]. A 2000 h y^{-1} occupancy for adults was assumed for the sewage works and represents a working year. An effective occupancy of 1000 h y^{-1} was assumed for plant operators close enough to sewage tanks to receive an external dose.

Inhalation rates were revised to be consistent with the revision of the ICRP model of the respiratory tract[6]. Table B4 gives the inhalation and water intake rates used in the calculations.

Inadvertent ingestion rates of soil and sediment have been derived and are presented in Table B5. Annual critical ingestion rates for soil and sediments are given which take

TABLE B1 *Critical group food intake rates*

Food group	Critical group intakes (kg y^{-1})		
	Infant (1 y)	Child (10 y)	Adult (20 y)
Domestic fruit	35	50	75
Potatoes and root vegetables	45	95	130
Green and other domestic vegetables*	15	35	80
Pig meat	5.5	25	40
Cow meat	10	30	45
Sheep meat	3.0	10	25
Offal†	5.5	10	20
Poultry	5.5	15	30
Milk‡ (l y^{-1})	320	240	240
Milk products	45	45	60
Eggs	15	20	25
Cereals	30	75	100

* Intakes summed over green vegetables and other domestic vegetables including legumes.
† Offal refers to cow liver and sheep liver.
‡ The GDL for milk, consumed by infants in the first year of life, assumed a milk intake of 350 l y^{-1}.

TABLE B2 *Critical group intake rates of aquatic foods*

Food group	Critical group intakes (kg y^{-1}) Infant (1 y)	Child (10 y)	Adult (20 y)
Freshwater fish	1	5	20
Marine fish	5	20	100
Crustaceans	1	5	20
Molluscs	1	5	20

TABLE B3 *Occupancies above marine and freshwater sediment and sea washed pasture*

Substrate	Occupancy (h y^{-1}) Infant (1 y)	Child (10 y)	Adult (20 y)
Marine sediment	30	300	2000
Freshwater sediment	30	500	500
Sea washed pasture	30	300	2000

TABLE B4 *Critical group inhalation and water intake rates*

	Infant(1 y)	Child(10 y)	Adult (20 y)
Inhalation rate (m^3 y^{-1})	1900	5500	7300
Drinking water (l y^{-1})	260	350	600

TABLE B5 *Critical group inadvertent ingestion rates*

	Infant (1 y)	Child (10 y)	Adult (20 y)
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})	$4.4\ 10^{-2}$	$1.8\ 10^{-2}$	$8.3\ 10^{-3}$

TABLE B6 *Occupancies associated with external exposure from contaminated farmland*

	Occupancy (%) Infant (1 y)	Child (10 y)	Adult (20 y)
Indoor	90	80	50
Outdoor	10	20	50

account of time spent outdoors during the course of the year. Hourly inadvertent ingestion rates are also given for use with an occupancy value for time spent on an area of soil or sediment. For example, the hourly ingestion rate (kg h^{-1}) was used in conjunction with occupancy (h y^{-1}) on intertidal sediment. The adult inadvertent ingestion rates were assumed to apply also to people working at a sewage treatment works.

The proportion of time spent indoors and outdoors is necessary for the calculation of external dose in order to account for the shielding effect of buildings. These proportions are given in Table B6, and are discussed in more detail elsewhere[2].

For the pathways associated with inhalation the activity concentrations in air are assumed to be the same indoors as those outdoors and are therefore not affected by indoor occupancy. For inhalation of resuspended material, breathing rates were combined with occupancies above various media. Adults were assumed to receive an additional inhalation dose due to mechanical resuspension of soil. An exposure time of 300 h y^{-1} for ploughing was assumed for this purpose.

Environmental models

Equilibrium transfer factors for terrestrial foods

Simple equilibrium foodchain transfer models were used to determine the concentration of radionuclides in foods for the GDLs for well-mixed soil and sea washed pasture. Concentration factors relating the radionuclide activity concentration in soil to radionuclide activity concentration in plant and animal foodstuffs were calculated using equations B1 and B2, respectively.

$$C_{sf} = \frac{A_p}{A_s} \quad \text{(B1)}$$

$$C_{sf} = C_{f(p-a)} \left(C_{f(s-p)} I_p + I_s \right) \quad \text{(B2)}$$

where C_{sf} = concentration factor relating the activity concentration in the food to the activity concentration in the soil (Bq kg^{-1} or Bq l^{-1} per Bq kg^{-1} dry mass soil),

A_p = activity concentration in the plant (Bq kg^{-1} fresh mass),

A_s = activity concentration in the soil (Bq kg^{-1} dry mass),

$C_{f(s-p)}$ = equilibrium concentration factor relating the activity concentration in food crops to the activity concentration in soil (Bq kg^{-1} fresh mass plant per Bq kg^{-1} dry mass soil),

$C_{f(p-a)}$ = equilibrium concentration factor for the transfer of activity to animal products arising from a daily intake of activity in the animal diet (Bq kg^{-1} or Bq l^{-1} per Bq d^{-1}),

I_p = animal food intake (kg d^{-1} fresh mass),

I_s = intake of soil by cattle or sheep (kg d^{-1} dry mass).

The element-dependent equilibrium concentration factors between soil and plant, and between animal diet and animal products, were taken from NRPB-R273[7] and are given in Table B7. The intakes of food and soil by grazing animals were 1.5 kg d^{-1} and 0.3 kg d^{-1}, respectively, for sheep and 13 kg d^{-1} of food and 0.52 kg d^{-1} of soil by cattle[7].

Aquatic environment distribution and transfer coefficients

Element-dependent freshwater to sediment distribution coefficients and fish concentration factors used in the derivation of the freshwater GDL are given in Table B7.

External exposure model

External exposure pathways were included in the GDLs for well-mixed soil, sea washed pasture, marine and freshwater sediments, freshwater and sewage sludge. Doses from external irradiation were estimated using an external dose model[8], which predicts the effective dose rate 1 m above an infinite area of contaminated material. External irradiation was modelled for a unit activity concentration of each radionuclide well mixed to a depth of 0.3 m in soil, sea washed pasture, and marine and freshwater sediments. External irradiation was also calculated for sewage sludge tanks, containing uniformly contaminated sludge to a depth of 1 m. The physical properties assumed for each material are summarised

TABLE B7
Element-dependent factors

	Element			
	Po	Pb	Ra	U
Food type	Concentration factor from soil to plant ($Bq\ kg^{-1}$ food per $Bq\ kg^{-1}$ soil)			
Domestic fruit	$2\ 10^{-4}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-3}$
Potatoes and root vegetables	$2\ 10^{-4}$	$1\ 10^{-2}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Green vegetables	$2\ 10^{-4}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-3}$
Cereals	$2\ 10^{-4}$	$1\ 10^{-2}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Pasture	$2\ 10^{-4}$	$1\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-3}$
Animal product	Element-dependent equilibrium factors for uptake of activity from animal intakes to animal products ($Bq\ kg^{-1}$ or $Bq\ l^{-1}$ food per $Bq\ d^{-1}$ animal intake)			
Cow meat	$3\ 10^{-3}$	$1\ 10^{-3}$	$5\ 10^{-4}$	$2\ 10^{-4}$
Sheep meat	$5\ 10^{-2}$	$1\ 10^{-2}$	$5\ 10^{-3}$	$2\ 10^{-3}$
Cow offal	$8\ 10^{-2}$	$2\ 10^{-3}$	$5\ 10^{-4}$	$2\ 10^{-4}$
Sheep offal	$6\ 10^{-1}$	$2\ 10^{-2}$	$5\ 10^{-3}$	$2\ 10^{-3}$
Milk	$1\ 10^{-4}$	$3\ 10^{-4}$	$4\ 10^{-4}$	$6\ 10^{-4}$
Milk products	$1.1\ 10^{-3}$	$3.3\ 10^{-3}$	$4.4\ 10^{-3}$	$6.6\ 10^{-3}$
	Element-dependent fish concentration factors and sediment water distribution coefficients for freshwater ($Bq\ kg^{-1}$ per $Bq\ l^{-1}$)			
Fish	$5.0\ 10^{1}$	$3.0\ 10^{2}$	$5.0\ 10^{1}$	$1\ 10^{1}$
Sediment	$1.0\ 10^{4}$	$1.0\ 10^{4}$	$5.0\ 10^{2}$	$5\ 10^{1}$

in Table B8. The external doses per unit activity concentration in well-mixed materials integrated over 1 year are shown in Table B9. External irradiation of individuals will be influenced by the degree of shielding. For the well-mixed soil GDL, individuals were assumed to spend time inside buildings as indicated in Table B6. Location factors for the reduction in gamma doses to people indoors and outdoors were assumed to be 0.1 and 1.0, respectively[2].

Resuspension model

Inhalation of resuspended materials is included as a pathway in GDLs for well-mixed soil, sea washed pasture, marine and freshwater sediments, sewage sludge and freshwater. Inhalation of resuspended materials used a dust loading approach throughout. Resuspension of materials was assumed to occur by two processes, wind driven resuspension and mechanical disturbance. Wind driven resuspension was assumed for soils and sediments. All age groups were assumed to be exposed continuously to an airborne dust concentration[9] of $10^{-7}\ kg\ m^{-3}$. Resuspension of sewage sludge as liquid droplets from stirring processes assumed an air concentration[10] of $10^{-7}\ kg\ m^{-3}$. Mechanical resuspension of soil was assumed to occur during ploughing, and was therefore included in the GDLs for well-mixed soil, conditioning of soil with sewage sludge and irrigation of land with freshwater. Adults only were assumed to be exposed for $300\ h\ y^{-1}$ at an airborne dust concentration[9] of $10^{-5}\ kg\ m^{-3}$.

Characteristic	Soil	Sediments	Sewage sludge
Depth (m)	0.3	0.3	1.0
Dry bulk density (kg m^{-3})	1250	1500	50
Wet bulk density (kg m^{-3})	1500	1700	1000

TABLE B8 *Depth and density assumed for the generic soil, sediments and sewage sludge*

	Effective gamma dose rates (Sv y^{-1} per Bq kg^{-1})		
Parent nuclide	Well-mixed soil	Sediments	Sewage sludge in tanks
^{210}Po	5.6 10^{-12}	6.1 10^{-12}	7.2 10^{-12}
^{210}Pb	5.3 10^{-10}	4.9 10^{-10}	2.7 10^{-9}
^{226}Ra	2.5 10^{-6}	2.8 10^{-6}	3.4 10^{-6}
^{234}U	8.3 10^{-11}	8.1 10^{-11}	2.7 10^{-10}
^{235}U	1.6 10^{-7}	1.7 10^{-7}	3.3 10^{-7}
^{238}U	3.5 10^{-8}	3.7 10^{-8}	5.5 10^{-8}

TABLE B9 *Integrated effective gamma dose rates per unit activity concentration above well-mixed soil, sediments and sewage sludge*

Treatment of agricultural land

Conditioning with sewage sludge

Sewage sludge can be applied to agricultural land as a soil conditioner. This gives rise to possible routes of exposure to man, and therefore needs to be considered in the derivation of the GDL for sewage sludge. The sewage sludge GDL considered the conditioning of pasture and arable land used for cereals, and resulting exposure from treated soil and ingestion of animal products and crops. Conditioning of pasture was assumed to occur annually in early spring, approximately 1 month before grazing animals were allowed on to the pasture. It was further assumed that the grass grew after the application, and that there was no direct contamination of the grass by radionuclides in the sludge. For cereals, it was assumed that sewage sludge was applied to bare soil, and ploughed in before seeding. For both pasture and cereals it was assumed that the agricultural land was treated every year for 50 years with sewage sludge from the same source. The dynamic foodchain model FARMLAND[7] was used to predict the activity concentrations in cereals, cow meat and offal, milk, and sheep meat and offal in the 50th year, per unit deposit (Table B10). The activity concentrations in the animal and plant products were scaled by the application rate of sewage sludge using equation B3.

$$A_f = A_{f(u)} R_s \qquad \text{(B3)}$$

where A_f = food product activity concentration in the 50th year from conditioning of farmland with sewage sludge (Bq kg^{-1} per Bq kg^{-1} of sludge),

$A_{f(u)}$ = food product activity concentration in the 50th year per unit deposition (Bq kg^{-1} per Bq m^{-2} y^{-1}) (Table B10),

R_s = soil conditioning rate with sewage sludge (kg m^{-2} y^{-1}).

The conditioning rate for sewage sludge[11] was assumed to be 8 kg m^{-2} y^{-1} and the sewage sludge activity concentration was 1 Bq kg^{-1}.

TABLE B10 *Activity concentrations in foods for a surface deposit predicted for the 50th year by the foodchain model (sewage sludge application to land)*

Nuclide	50th year activity concentration in foods from a surface deposit of sewage sludge ($Bq\ kg^{-1}$ or $Bq\ l^{-1}$ per $Bq\ m^{-2}\ y^{-1}$)					
	Cereals	Cow meat	Cow offal*	Milk	Sheep meat	Sheep offal*
^{210}Po	$2.3\ 10^{-7}$	$4.0\ 10^{-5}$	$1.1\ 10^{-3}$	$1.7\ 10^{-6}$	$3.4\ 10^{-4}$	$4.1\ 10^{-3}$
^{210}Pb	$4.9\ 10^{-4}$	$3.5\ 10^{-4}$	$7.1\ 10^{-4}$	$1.3\ 10^{-4}$	$5.2\ 10^{-4}$	$1.0\ 10^{-3}$
^{226}Ra	$9.3\ 10^{-5}$	$2.8\ 10^{-4}$	$2.8\ 10^{-4}$	$2.3\ 10^{-4}$	$5.9\ 10^{-4}$	$5.9\ 10^{-4}$
^{234}U	$9.4\ 10^{-5}$	$3.7\ 10^{-5}$	$3.7\ 10^{-5}$	$1.1\ 10^{-4}$	$2.0\ 10^{-4}$	$2.0\ 10^{-4}$
^{235}U	$9.4\ 10^{-5}$	$3.7\ 10^{-5}$	$3.7\ 10^{-5}$	$1.1\ 10^{-4}$	$2.0\ 10^{-4}$	$2.0\ 10^{-4}$
^{238}U	$9.4\ 10^{-5}$	$3.7\ 10^{-5}$	$3.7\ 10^{-5}$	$1.1\ 10^{-4}$	$2.0\ 10^{-4}$	$2.0\ 10^{-4}$

* Offal refers to cow liver or sheep liver.

Soil activity concentrations from surface deposition were estimated by use of the soil part of the FARMLAND model[7]. The following assumptions were made. For exposure from inhalation of ambient resuspended soil and inadvertent ingestion of soil only the top 0.01 m of the soil profile was involved, while for inhalation of mechanically resuspended soil the top 0.3 m of the soil was subject to resuspension. Activity concentrations in the top 0.01 m of soil were obtained for surface deposition for 50 years on to an undisturbed soil profile. Activity concentrations in the top 0.3 m of the soil were obtained for surface deposition for 50 years on to well-mixed soil. External doses from conditioned soil were modelled for the exposed group occupying undisturbed soil contaminated by surface deposition of radionuclides in sewage sludge.

Activity concentrations in the soil and external doses per unit deposit are given in Table B11. The activity concentrations in the soil and external doses were scaled by the application rate of sewage sludge using equations B4 and B5.

$$S_a = S_{a(u)}\, R_s \qquad \text{(B4)}$$

$$D_{ext} = D_{ext(u)}\, R_s \qquad \text{(B5)}$$

where S_a = soil activity concentration in the 50th year from conditioning of farmland with sewage sludge ($Bq\ kg^{-1}$ per $Bq\ kg^{-1}$ of sludge),

$S_{a(u)}$ = soil activity concentration in the 50th year per unit deposition ($Bq\ kg^{-1}$ per $Bq\ m^{-2}\ y^{-1}$),

D_{ext} = external dose in the 50th year from conditioning of farmland with sewage sludge ($Sv\ y^{-1}$ per $Bq\ kg^{-1}$ of sludge),

$D_{ext(u)}$ = external dose in the 50th year per unit deposition ($Sv\ y^{-1}$ per $Bq\ m^{-2}\ y^{-1}$),

R_s = soil conditioning rate with sewage sludge ($kg\ m^{-2}\ y^{-1}$).

Irrigation with freshwater

Freshwater can be applied to agricultural land for irrigation, and this route therefore needs to be considered in the derivation of the GDL for freshwater. The pathways considered were due to irrigation of vegetables and cereals only, and included exposure from the treated soil. It was assumed that irrigation occurred over the 120 day period of crop growth up to harvest, and that irrigation occurred every year for 50 years using freshwater from the same source. The dynamic foodchain model FARMLAND[7] was used

TABLE B11 *Activity concentrations and external dose rates in the 50th year above soil per unit deposit*

Nuclide	50th year activity concentration ($Bq\ kg^{-1}$ per $Bq\ m^{-2}\ y^{-1}$) In top 0.3 m of well-mixed soil	In top 0.01 m of undisturbed soil	Effective dose rate ($Sv\ y^{-1}$ per $Bq\ m^{-2}\ y^{-1}$) Above well-mixed soil	Above undisturbed soil
^{210}Po	$1.5\ 10^{-3}$	$3.9\ 10^{-2}$	$1.8\ 10^{-14}$	$8.9\ 10^{-14}$
^{210}Pb	$6.0\ 10^{-2}$	$2.9\ 10^{-1}$	$3.2\ 10^{-11}$	$1.2\ 10^{-10}$
^{226}Ra	$1.1\ 10^{-1}$	$3.2\ 10^{-1}$	$2.8\ 10^{-7}$	$5.2\ 10^{-7}$
^{234}U	$1.1\ 10^{-1}$	$3.3\ 10^{-1}$	$9.3\ 10^{-12}$	$2.5\ 10^{-11}$
^{235}U	$1.1\ 10^{-1}$	$3.3\ 10^{-1}$	$1.8\ 10^{-8}$	$4.4\ 10^{-8}$
^{238}U	$1.1\ 10^{-1}$	$3.2\ 10^{-1}$	$4.2\ 10^{-9}$	$8.0\ 10^{-9}$

TABLE B12 *Activity concentrations in foods for a surface deposit predicted for the 50th year by the foodchain model per unit deposit (for irrigation)*

Nuclide	50th year activity concentration in foods from a surface deposit of irrigation water ($Bq\ kg^{-1}$ per $Bq\ m^{-2}\ y^{-1}$) Green vegetables	Root vegetables	Cereals
^{210}Po	$1.1\ 10^{-2}$	$9.3\ 10^{-3}$	$3.9\ 10^{-2}$
$^{210}Pb^{*}$	$1.2\ 10^{-2}$	$1.0\ 10^{-4}$	$1.1\ 10^{-2}$
$^{226}Ra^{\dagger}$	$1.2\ 10^{-2}$	$1.4\ 10^{-4}$	$7.9\ 10^{-3}$
^{234}U	$1.0\ 10^{-2}$	$8.2\ 10^{-6}$	$6.1\ 10^{-4}$
^{235}U	$1.0\ 10^{-2}$	$8.2\ 10^{-6}$	$6.1\ 10^{-4}$
^{238}U	$1.0\ 10^{-2}$	$8.2\ 10^{-6}$	$6.1\ 10^{-4}$

* Includes ingrowth of ^{210}Po.
† Includes ingrowth of ^{210}Pb and ^{210}Po.

to predict the activity concentrations in root vegetables, green vegetables and cereals in the 50th year per unit deposit on to the soil (Table B12). The activity concentrations in the plant products per unit deposition were scaled by the application rate of freshwater using equation B3, with the substitution of sewage sludge parameters by a freshwater unit activity concentration and application rate[12], assumed to be 1 $Bq\ l^{-1}$ and 100 $kg\ m^{-2}\ y^{-1}$, respectively.

Soil activity concentrations from surface deposition were estimated by use of the soil part of the FARMLAND model[7]. In this case, the following assumptions were made. For exposure from inadvertent ingestion of soil and inhalation of both ambient and mechanically resuspended soil the top 0.3 m of the soil was involved. Activity concentrations in the top 0.3 m of the soil were obtained for surface deposition for 50 years on to well-mixed soil. External doses from conditioned soil were modelled for the exposed group occupying well-mixed soil contaminated by surface deposition of radionuclides in freshwater.

Activity concentrations in the soil and external doses per unit deposit are given in Table B11. The activity concentrations in the soil and external doses per unit deposition were scaled by the application rate of freshwater using equations B4 and B5, with the substitution of sewage sludge parameters by the freshwater unit activity concentration and application rates given above.

REFERENCES

1 NRPB. Revised generalised derived limits for radioisotopes of strontium, iodine, caesium, plutonium, americium and curium. *Doc NRPB*, **9**, No.1, 1-34 (1998).

2 Robinson C A. Generalised habit data for radiological assessments. Chilton, NRPB-M636 (1996).

3 Byrom J, Robinson C A, Simmonds J R, *et al.* Food consumption rates for use in generalised radiological dose assessments. *J Radiol Prot*, **15**, No. 4, 335–41 (1995).

4 MAFF DFR. Lowestoft. Personal communications (1992–1994).

5 Research Surveys of Great Britain Ltd. Use of the Cumbrian coastal area. London, Department of the Environment, DOE/HMIP/RR/91/057 (1991).

6 ICRP. Human respiratory tract model of radiological protection. ICRP Publication 66. *Ann ICRP*, **24**, Nos 1-3 (1994).

7 Brown J and Simmonds J R. FARMLAND: a dynamic model for the transfer of radionuclides through terrestrial foodchains. Chilton, NRPB-R273 (1995).

8 Carey A D, Jones J A and Mobbs S F. GRANIS: a model for the assessment of external photon irradiation from contaminated media of infinite lateral extent. Chilton, NRPB (to be published).

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

10 Northrop R, Carnow B, Wadden R, *et al.* Health effects of aerosols emitted from an activated sludge plant. IN *Waste Water Aerosols and Disease*. Proceedings of a symposium. Cincinnati, Environmental Protection Agency, Publication EPA-600/9-80-028 (1980).

11 WRC. The agricultural value of sewage sludge. A farmers' guide. Guidance leaflet produced by WRC, ADAS and MAFF. Medmenham, Water Research Centre.

12 MAFF. Survey of irrigation of outdoor crops in 1990. England and Wales. Guildford, Government Statistical Service, MAFF Stats 157 (1991).

Appendix C

IMPORTANT EXPOSURE PATHWAYS FOR GDLs

Introduction

Details of the limiting exposure pathways and age groups for the generalised derived limits (GDLs) presented in the main text are discussed in this appendix in the light of habit and environmental data used in the calculations. Six figures are included in this appendix, which give the percentage pathway contributions for the multiple exposure pathway GDLs. This information will be of use if action is requested because the screening level (10% of the GDL) is exceeded, as discussed elsewhere*.

Single exposure pathway GDLs

Inhalation of air

For GDLs for air 10 year old children are the limiting group for all radionuclides as the dose coefficients for intake by inhalation are greater for children than for adults, even though the breathing rate is greater for adults.

Terrestrial foods

The GDLs for terrestrial foods were calculated for the six radionuclides for the three main age groups, infants (1 year old), children (10 years old), and adults (assumed to be 20 years old). An additional age group was considered for the GDL for milk to take account of infants in the first year of life whose diet was assumed to consist entirely of milk (3 months old). Table 3 of the main text indicates the limiting age group for each terrestrial food GDL and a number of trends are worthy of discussion. Infants in the first year of life always constitute the limiting group for the ingestion of milk. The reasons for this are two-fold. For all radionuclides dose coefficients for ingestion by 3 month old infants are higher than the corresponding values for 1 year olds to take account of the higher gut transfer factor appropriate for infants on an all-milk diet. The milk intake rate of 350 l y^{-1} for infants in the first year of life is also the highest. For other foods infants or children are often the limiting age group despite their lower food intakes which are offset by higher dose coefficients for ingestion.

Drinking water

Infants (1 year old) are the limiting group for all radionuclides except for ^{226}Ra, where children (10 years old) are more limiting. Although the drinking water intakes of infants (260 l y^{-1}) and children (350 l y^{-1}) are considerably less than that for adults (600 l y^{-1}), this is offset by higher child and infant dose coefficients for ingestion.

Aquatic foods

GDLs for marine fish, crustaceans, molluscs and freshwater fish are limited by the adult age group for all radionuclides. This is a function of the higher adult critical group intakes of these foods, as shown in Table B2.

---

* NRPB. Application of generalised derived limits. *Doc NRPB*, **9**, No. 1, 35–60 (1998).

Multiple exposure pathway GDLs

Well-mixed soil

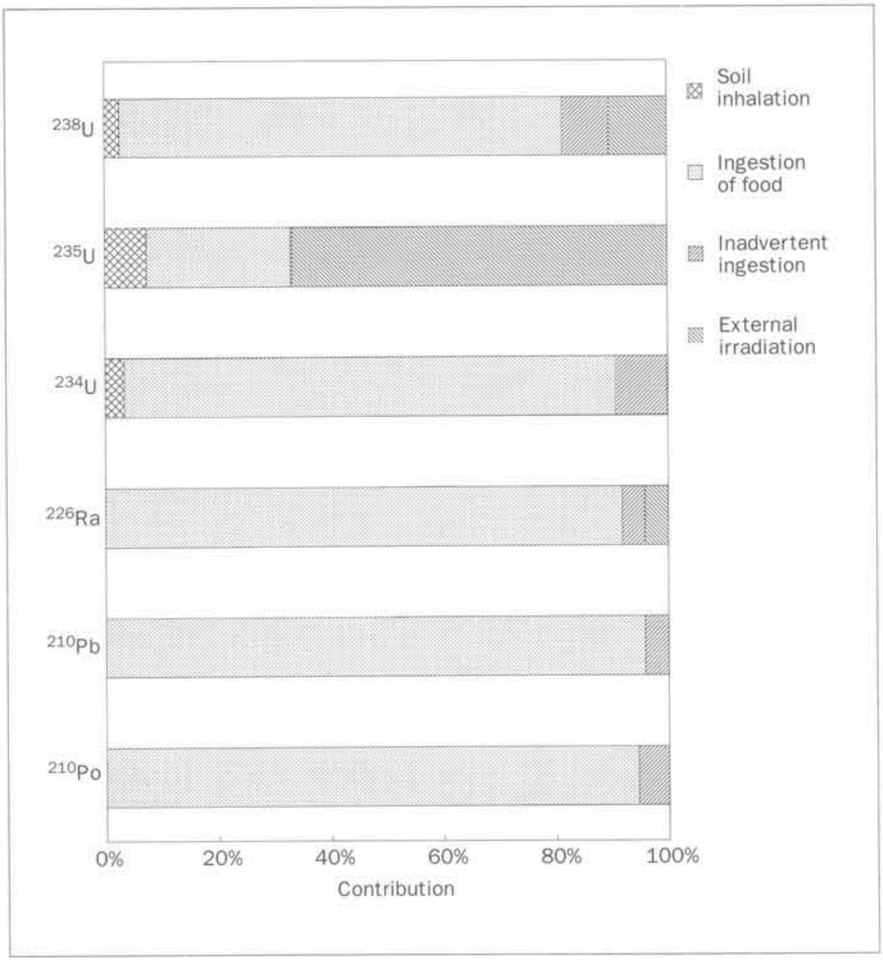
This GDL applies to deposits of radionuclides in soil well mixed to a depth of 0.3 m by natural weathering or farming activities.

The dominant pathways in the GDLs for well-mixed soil are illustrated in Figure C1 and vary depending on radionuclide. Ingestion of foods contributes between 79% and 96% of the GDLs for all radionuclides except ^{235}U, and is limited by the infant (1 year old) age group. External irradiation accounts for 67% of the GDL for ^{235}U, and the adult age group is limiting for this radionuclide. For ^{226}Ra the GDL is dominated by the ingrown progeny of ^{210}Pb and ^{210}Po. The external pathway would be more important for ^{226}Ra if no progeny ingrowth was considered.

Sea washed pasture

This GDL is intended for coastal land which is occasionally inundated by spring high tides. Contamination of the land can result from authorised discharges of radionuclides to the marine environment.

FIGURE C1
Contribution of each exposure pathway to the GDL for well-mixed soil (%)



The dominant pathways in the GDLs for sea washed pasture are illustrated in Figure C2. The GDLs for all radionuclides are dominated by ingestion of foods, except for ^{235}U. For ^{234}U and ^{238}U the GDL is entirely due to infants in the first year of life consuming milk. For ^{210}Po and ^{210}Pb other foods also contribute and the GDL is limited by infants on a mixed diet. External exposure accounts for 68% of the GDL for ^{235}U for which adults are limiting. Again for ^{226}Ra the GDL is dominated by the ingrown progeny of ^{210}Pb and ^{210}Po.

Shoreline sediment

These GDLs apply to deposits of radionuclides in sediments well mixed to a depth of 0.3 m by natural scour, wave action and biological activities. The dominant pathways in the GDLs for sediment are illustrated in Figures C3 and C4.

Marine sediment Inadvertent ingestion accounts for nearly 100% of the GDL for ^{210}Po and 96% of the GDL for ^{210}Pb. The external pathway accounts for between 90% and 99% of the GDLs for ^{226}Ra, ^{235}U and ^{238}U. The GDLs for ^{234}U are dominated by inhalation of resuspended sediment (53%) with inadvertent ingestion contributing about 45% of the

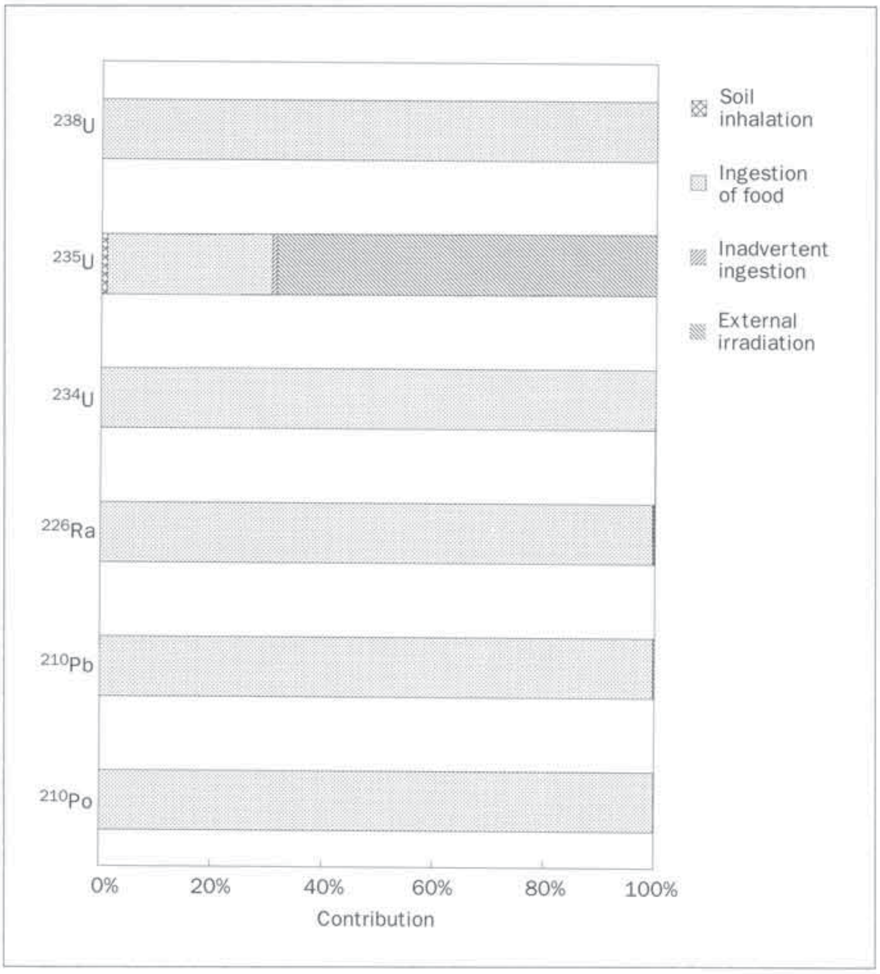
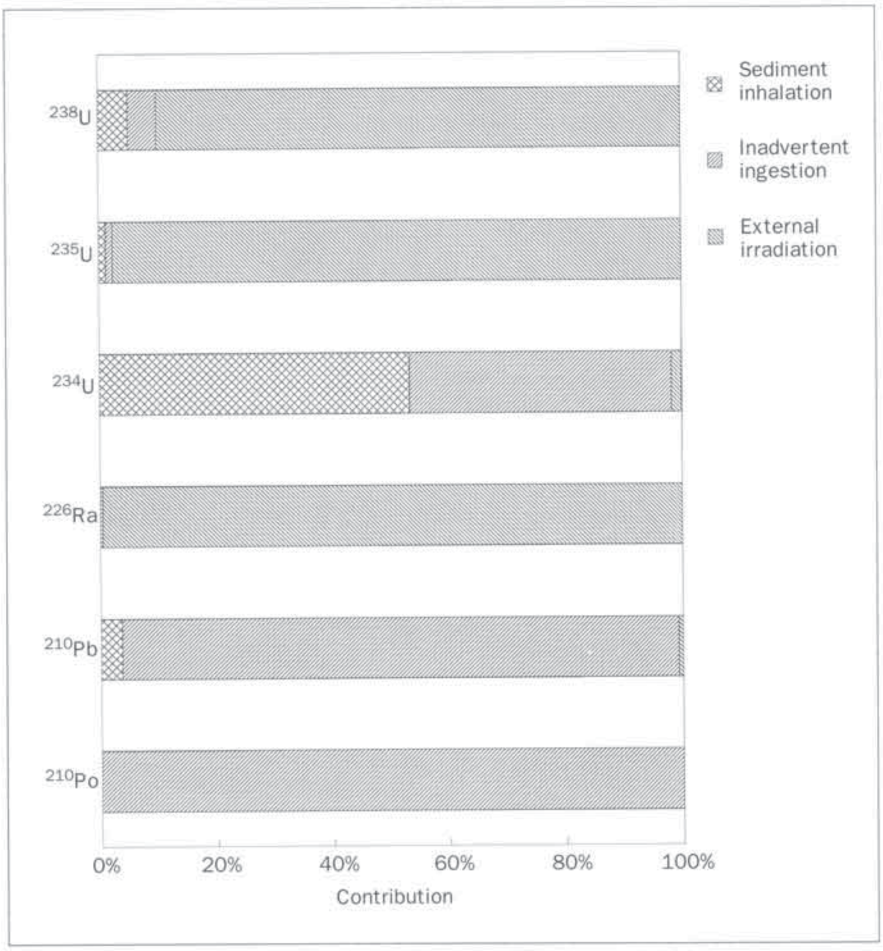


FIGURE C2
Contribution of each exposure pathway to the GDL for sea washed pasture (%)

FIGURE C3
Contribution of each exposure pathway to the GDL for marine sediment (%)



GDL. In all cases, adults are the limiting age group, a function of the 2000 h y^{-1} occupancy assumed for marine sediments.

Freshwater sediment The exposure pathways dominating the freshwater sediment GDLs are the same as those for marine sediment apart from ^{234}U, which is now dominated by the inadvertent ingestion pathway. Also, in this case 10 year old children are limiting for all radionuclides, because of the higher inadvertent ingestion rate assumed for children than for adults. An occupancy of 500 h y^{-1} over freshwater sediments is assumed for both adults and children.

Freshwater

This GDL is intended for the monitoring of freshwater from inland rivers and lakes. The GDL for freshwater accounts for the activity dissolved in solution and associated with suspended sediment, and is expressed as Bq l^{-1} of whole water (dissolved and suspended). The GDL takes into account exposure from ingestion of fish and drinking water and external irradiation and inhalation of resuspended sediments. In addition, pathways associated with the irrigation of agricultural land with freshwater were also considered. The dominant pathways in the GDLs for freshwater are illustrated in Figure C5.

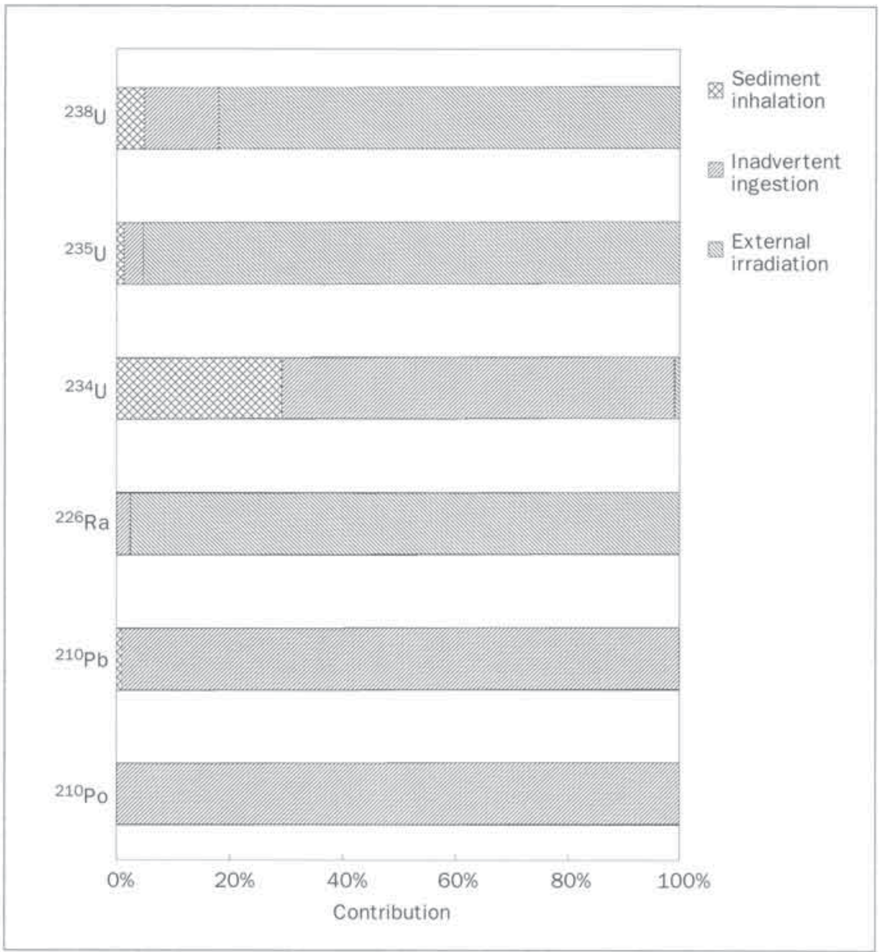


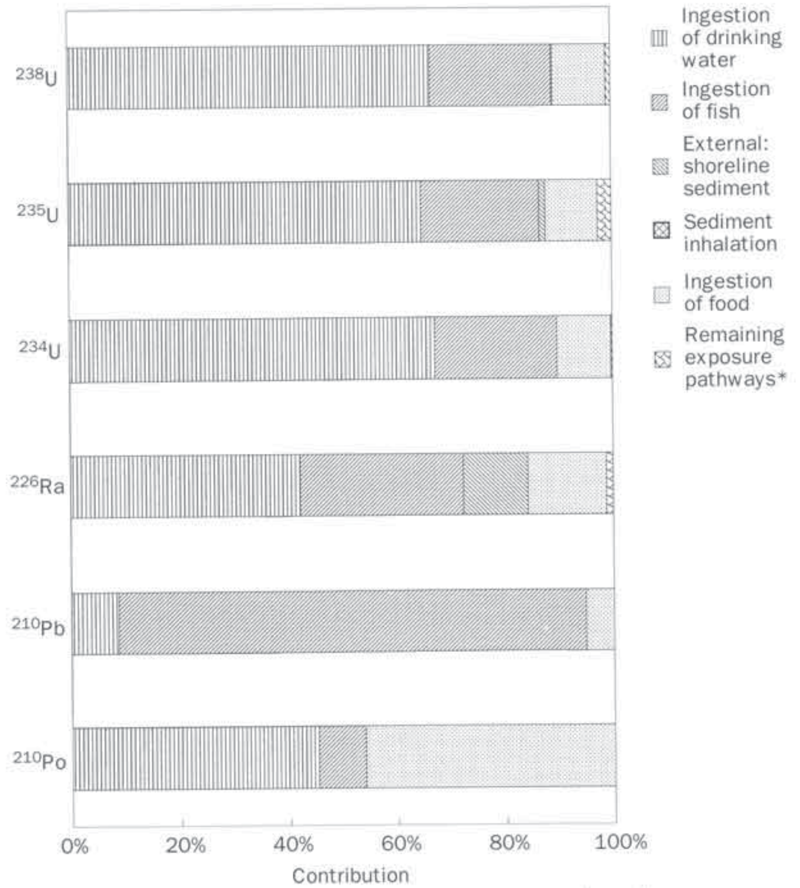
FIGURE C4
Contribution of each exposure pathway to the GDL for freshwater sediment (%)

For all radionuclides, ingestion of drinking water, freshwater fish and terrestrial foods are the most important contributors to the GDL. For isotopes of uranium ingestion of drinking water contributes between 65% and 67% of the GDLs, whereas for ^{210}Po ingestion of terrestrial foods and drinking water are equally important. These pathways are also important for ^{226}Ra, with ingestion from drinking water and freshwater fish being the dominant pathways. Ingestion of terrestrial foods contributes 15% of the GDL, mostly from ingrowth of ^{210}Pb and ^{210}Po in the plants. External irradiation from shoreline sediments is the least important pathway, with a contribution of 12%. Ingestion of freshwater fish contributes 86% of the GDL for ^{210}Pb, a reflection of the high fish concentration factor for lead (300 Bq kg^{-1} per Bq l^{-1}, Table B7). Ingestion of terrestrial foods is the least important pathway, with a contribution of 5%, some of which is from the ingrowth of ^{210}Po in the plants.

Sewage sludge

This GDL is intended for the monitoring of sewage sludge which has become contaminated by previous authorised discharges to sewers, and is presented for wet sewage sludge (Bq kg^{-1}). Two main exposure situations were considered in the calculation of the

FIGURE C5
Contribution of each exposure pathway to the GDL for freshwater (%)



*Remaining exposure pathways include inhalation, inadvertent ingestion and external irradiation from irrigated soil, each contributing <3% to the GDL.

GDL. The first exposure situation considered sewage sludge at a treatment works (adults only), and the second considered exposures due to the conditioning of agricultural land with sludge (all age groups). The sewage sludge GDL has been calculated on the basis that the groups of people exposed in the two situations are not the same, therefore simply to sum exposure over all the pathways was considered inappropriate. Table C1 shows the GDLs from both exposure situations. The most restrictive value arising from the two exposure situations has been presented as the GDL for sewage sludge, given in Table 4 of the main text.

The dominant pathways in the GDLs for sewage sludge applied to land are illustrated in Figure C6. The most restrictive GDL was due to conditioning of agricultural land for all the radionuclides considered. A combination of exposure routes associated with agricultural land was important. Consumption of terrestrial food (for 1 year old infants) accounts for between 74% and 91% of the GDLs for all radionuclides except ^{235}U. For this radionuclide external irradiation from land treated with sewage sludge contributes about 77% of the GDL, where adults are the dominant age group.

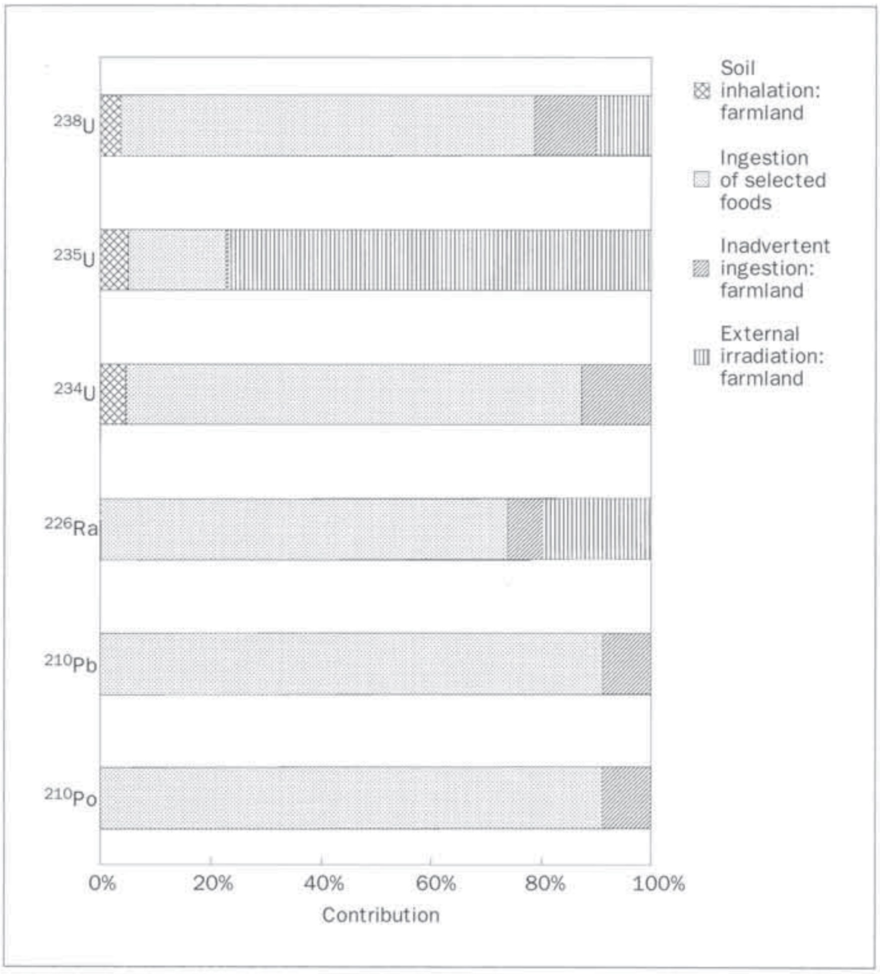


FIGURE C6
Contribution of each exposure pathway to the GDL for sewage sludge (%)

TABLE C1
Generalised derived limits for sewage sludge for application to farmland and at sewage works

Nuclide	Generalised derived limit ($Bq\ kg^{-1}$)			
	Application to farmland		At sewage works	
^{210}Po	$8\ 10^{2}$	1 y old	$2\ 10^{5}$	Adult
^{210}Pb*	$8\ 10^{1}$	1 y old	$3\ 10^{5}$	Adult
^{226}Ra†	$3\ 10^{2}$	1y old	$3\ 10^{3}$	Adult
^{234}U	$8\ 10^{3}$	1 y old	$1\ 10^{6}$	Adult
^{235}U	$4\ 10^{3}$	Adult	$3\ 10^{4}$	Adult
^{238}U	$8\ 10^{3}$	1 y old	$1\ 10^{5}$	Adult

* The GDL for sewage sludge, when applied to land for ^{210}Pb, includes the ingrowth of ^{210}Po over a 50 year period.

† The GDL for sewage sludge, when applied to land for ^{226}Ra, includes the ingrowth of ^{210}Pb and ^{210}Po over a 50 year period.

Documents of the NRPB

Further information on these and other NRPB publications is available on the NRPB website (www.nrpb.org.uk).

VOLUME 1 (1990)

No. 1 Radiological Protection Act 1970

Directions by the Health Ministers under the Radiological Protection Act 1970

Statement by NRPB: limitation of human exposure to radon in homes

Human exposure to radon in homes: recommendations for the practical application of the Board's Statement

No. 2 Gut transfer factors: values proposed by a Nuclear Energy Agency Expert Group for radionuclides ingested by members of the public

Gut transfer factors: values for plutonium and americium in shellfish and best estimates for actinides in food

No. 3 Patient dose reduction in diagnostic radiology (Joint report with the Royal College of Radiologists)

No. 4 Statement by NRPB: principles for the protection of the public and workers in the event of accidental releases of radioactive materials into the environment and other radiological emergencies

Emergency reference levels of dose for early countermeasures to protect the public: recommendations for the practical application of the Board's Statement

Radon affected areas: Cornwall and Devon

VOLUME 2 (1991)

No. 1 Statement by NRPB: principles for the protection of patients and volunteers during clinical magnetic resonance diagnostic procedures

Limits on patient and volunteer exposure during clinical magnetic resonance diagnostic procedures: recommendations for the practical application of the Board's Statement

VOLUME 3 (1992)

No. 1 Electromagnetic fields and the risk of cancer (Report of an Advisory Group on Non-ionising Radiation)

No. 2 Statement by NRPB: approval of consumer goods containing radioactive substances

Criteria of acceptability relating to the approval of consumer goods containing radioactive substances

Radiological protection standards: ionisation chamber smoke detectors; radiological time measurements instruments; tritium light sources; compasses containing gaseous tritium light sources; thoriated gas mantles

No. 3 Statement by NRPB: radiological protection objectives for the land-based disposal of solid radioactive wastes

Radiological protection objectives for the land-based disposal of solid radioactive wastes: recommendations for the practical application of the Board's Statement

No. 4 Protection of the patient in x-ray computed tomography

Radon affected areas: Derbyshire, Northamptonshire and Somerset

VOLUME 4 (1993)

No. 1 Statement by NRPB: 1990 recommendations of ICRP

1990 recommendations of ICRP: recommendations for the practical application of the Board's Statement

No. 2 Occupational exposure: guidance on the 1990 recommendations of ICRP

Public exposure: guidance on the 1990 recommendations of ICRP

Medical exposure: guidance on the 1990 recommendations of ICRP

Values of unit collective dose for use in the 1990s

No. 3 Dose quantities for protection against external radiations: guidance on the 1990 recommendations of ICRP

No. 4 Statement by NRPB: diagnostic medical exposures to ionising radiations during pregnancy

Diagnostic medical exposures: exposure to ionising radiation of pregnant women – biological basis of the Board's Statement

Estimates of late radiation risks to the UK population

No. 5 Statement by NRPB: restrictions on human exposure to static and time varying electromagnetic fields and radiation

Restrictions on human exposure to static and time varying electromagnetic fields and radiation: scientific basis and recommendations for the implementation of the Board's Statement

Electromagnetic fields and the risk of cancer (Summary of the views of the Advisory Group on Non-ionising Radiation on epidemiological studies published since its 1992 report)

No. 6 Radon affected areas: Scotland and Northern Ireland

VOLUME 5 (1994)

No. 1 Guidance on restrictions on food and water following a radiological accident

No. 2 Health effects related to the use of visual display units (Report of an Advisory Group on Non-ionising Radiation)

Electromagnetic fields and the risk of cancer (Supplementary Report by the Advisory Group on Non-ionising Radiation of 12 April 1994)

No. 3 Guidelines on radiology standards for primary dental care (Joint report with the Royal College of Radiologists)

VOLUME 6 (1995)

No. 1 Risk of radiation-induced cancer at low doses and low dose rates for radiation protection purposes (Also published in French)

No. 2 Statement by NRPB: effects of ultraviolet radiation on human health

Health effects from ultraviolet radiation (Report of an Advisory Group on Non-ionising Radiation)

VOLUME 7 (1996)

No. 2 Radon affected areas: England and Wales

No. 3 Risk from deterministic effects of ionising radiation

VOLUME 8 (1997)

No. 1 Intervention for recovery after accidents

Guidance on the application of emergency reference levels of dose in emergency planning and response

Identification and investigation of abnormally high gamma dose rates

No. 2 Relative biological effectiveness of neutrons for stochastic effects

No. 3 Assessment of skin doses

VOLUME 9 (1998)

No. 1 Revised generalised derived limits for radioisotopes of strontium, ruthenium, iodine, caesium, plutonium, americium and curium

Application of generalised derived limits

No. 2 Radiological protection objectives for land contaminated with radionuclides

No. 3 Radon affected areas: Wales - 1998 review

No. 4 Standards for intakes of radionuclides

VOLUME 10 (1999)

No. 1 Guidelines on patient dose to promote the optimisation of protection for diagnostic medical exposures (Report of an Advisory Group on Ionising Radiation)

No. 2 Statement by NRPB: advice on the 1998 ICNIRP Guidelines for Limiting Exposure to Time-varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz)

1998 ICNIRP Guidelines for Limiting Exposure to Time-varying Electric, Magnetic and Electromagnetic Fields (up to 300 GHz): NRPB advice on aspects of implementation in the UK

No. 3 Genetic heterogeneity in the population and its implications for radiation risk (Report of an Advisory Group on Ionising Radiation)

No. 4 Radon affected areas: Northern Ireland - 1999 review

Price £15.00

ISSN 0958-5648

ISBN 0-85951-445-5