Derivation of Liquid Exclusion or Exemption Levels to Support the RSA93 Exemption Order Review

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ABSTRACT

As part of the better regulation initiative, the Department of Energy and Climate Change (DECC) and the Devolved Administrations have consulted on a new exemption orders regime under the Radioactive Substances Act 1993 and the Environmental Permitting regulations 2010. The overall aim is to have a simpler set of exemption orders, informed by risk, that are more easily linked to the European Basic Safety Standards.

As part of the work to support the review of the exemption orders, DECC asked HPA to calculate activity concentration values for aqueous liquids that could be used as either exclusion (unconditional clearance) levels or as exemption levels.

HPA has derived activity concentration levels for aqueous liquids for around 280 radionuclides, using a dose criterion of 10 μSv y^{-1}. The calculations were based on the methodology used for Generalised Derived Limits (GDL) published by HPA. The rounded derived levels range from 10^{-4} Bq l^{-1} to 10^{3} Bq l^{-1}, and 80% of the values are between 0.01 Bq l^{-1} and 1 Bq l^{-1}. HPA recommends that the volume of aqueous liquid at these derived levels that can be disposed of to a sewer is restricted to 3000 m^3 y^{-1} and hence that the derived levels are suitable for exemption rather than for exclusion.

HPA undertook a preliminary investigation to determine whether the derived activity levels could be measured under laboratory based conditions. Based on the preliminary findings, HPA estimates that out of around 280 radionuclides, around 35% have such short half lives that the derived activity levels would not be measurable. Of the remaining 65%, over half of the derived levels could potentially be measured in the laboratory.

This study was part funded by DECC.

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Chilton, Didcot
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Approval: August 2010
Publication: August 2010
£21.00
ISBN 0-978-85951-673-0

This work was undertaken under the Environmental Assessment Department's Quality Management System, which has been approved by Lloyd's Register Quality Assurance to the Quality Management Standards ISO 9001:2000 and TickIT Guide Issue 5, certificate number 956546.

Report version 1.0

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1 INTRODUCTION

The Radioactive Substances Act (RSA 93) (Great Britain, 1993) provides the framework for controlling the accumulation and disposal of solid, liquid and gaseous radioactive waste in the UK so as to protect the public and the environment. In particular, RSA 93 requires prior authorisation for the accumulation, disposal or discharge of radioactive wastes to the environment unless they are outside the scope of the Act (in Schedule 1) or they meet the provisions of one of the Exemption Orders under the Act. The UK Environment Agencies are required to ensure that doses to members of the public do not exceed specified dose constraints, as part of the process of authorising such disposals or discharges.

The Department of Energy and Climate Change (DECC) and the Devolved Administrations (DA) are currently developing a new exemption orders regime under the RSA 93 and the Environmental Permitting regulations (EPR) 2007 (Great Britain, 2007). In England and Wales it is proposed that the revised regime will be incorporated into the EPR in 2010. In Scotland and Northern Ireland RSA 93 will be amended and the new exemption orders will be made at the same time. The overall aim is to have a simpler set of exemption orders, informed by risk, that are more easily linked to the European Basic Safety Standards (EC BSS) (European Commission, 1996). A consultation on the proposed new regime was held by DECC and DA in summer 2009 (UK Government et al, 2009). The proposed new regime included a set of exclusion levels defining levels that are outside the scope of the regulation (equivalent to the EC concept of unconditional clearance) and a single Exemption Order containing a set of exemption levels with specified conditions.

As part of the work to support the review of the exemption orders, DECC asked HPA to calculate activity concentration values that could be used as either exclusion or exemption levels for aqueous liquids, based on a dose criterion of 10 μSv y^{-1}. The intention was to complement the unconditional clearance levels for solids given in European guidance in Radiation Protection 122 Part 1 (RP122 part 1) (EC, 2001). Hence values were required for about 280 radionuclides.

HPA was also asked to undertake a preliminary investigation to examine whether the derived activity levels could potentially be measured under laboratory based conditions. This would enable the practicability of using the derived levels as exemption or exclusion levels to be investigated: if they are too low to measure then they would not be useful. With about 280 radionuclides to consider, it was not possible to conduct a full investigation and subsequently the findings should be considered to be indicative only.

2 APPROACH

2.1 Radionuclides

The radionuclides considered for the study were those radionuclides listed in Table 1 of RP122 Part 1 (EC, 2001). Some of these have short lived progeny included in secular

equilibrium and this is denoted by the '+' symbol in the table in RP122 Part 1. However, it was not possible to include all these short lived progeny in this study because of insufficient data. Using the same nomenclature as in RP122 Part 1, the radionuclides with short lived progeny considered to be in secular equilibrium with their parent or which would decay significantly during the timescales considered are marked with a '+' symbol in this report and the list of progeny included is given in Table 1. This list of progeny is taken from the Generalised Derived Limits (GDL) reports (NRPB 1998, 2000, 2005). Short lived progeny were not considered for any other radionuclides in this study.

TABLE 1 List of progeny radionuclides included in the derived levels

	Progeny
Parent radionuclide	In secular equilibrium
Sr-90+	Y-90
Zr-95+	Nb-95
Ru-106+	Rh-106
Cs-137+	Ba-137m
Ra-224+	Pb-212
Ra-226+	Rn-222, Po-218, Pb-214, B-214, Po-214
U-235+	Th-231
U-238+	Th-234, Pa-234m, Pa-234

2.2 Dose criteria

Dose criteria for exemption and clearance are specified in the EC BSS (EC,1996) and it was agreed with DECC that these criteria are also appropriate for exclusion or exemption levels for the revised RSA 93 and EPR 2010 because the concept of 'exclusion' in the revised RSA93 and EPR 2010 is essentially the same as the concept of unconditional clearance in the EC BSS. The EC BSS specifies different dose criteria for practices (situations where the radionuclides are processed for their radioactive properties) and for work activities (situations involving naturally occurring radioactive material) and these have been used to derive the clearance levels presented in RP122 Part 1 (practices) and Part 2 (NORM). This report considers practices and complements RP122 Part 1. Therefore the criteria used for the calculations were: the dose to an individual representative of those most highly exposed should be less than 10 μSv y^{-1} and the collective dose per year of practice should be less than 1man Sv or exemption should be demonstrated to be the optimum option. Since the dose criteria for exemption and clearance are the same, the derived values could be used for either exclusion or exemption.

2.3 Methodology

The DECC and DA consultation document on the proposed revised exemption orders (UK Government et al, 2009) suggested that the UK drinking water levels could be used as exclusion levels for aqueous liquids. However, these only consider exposure from the

drinking water pathway and other exposure pathways may be important for some radionuclides, see for example the Generalised Derived Levels (GDLs) for fresh water (NRPB, 1998, 2000 and 2005). HPA was therefore asked by DECC to develop a methodology that included the important pathways of exposure to derive appropriate exclusion or exemption levels for aqueous liquids. The GDL methodology for freshwater was used because it considers a number of exposure pathways and estimates the dose to a person representative of those most exposed, using conservative assumptions. The pathways considered in the GDL methodology for freshwater are listed in Table 2.

TABLE 2 Exposure pathways considered in freshwater GDLs

Aquatic	Soil irrigation
Ingestion of river water	Inadvertent ingestion of irrigated soil
Ingestion of freshwater fish	Ingestion of plant products from irrigated soil
External exposure from shoreline sediment	External exposure from irrigated soil
Inhalation of resuspended shoreline sediment	Inhalation of resuspended irrigated soil

HPA has published GDLs for about 35 radionuclides and these results can be scaled to produce activity concentrations in water that would give rise to a dose of 10 μSv y^{-1}. However, an approach was also needed to produce values for the remaining radionuclides. Unfortunately, it was not possible to use the entire GDL freshwater methodology for the remaining 240 or so radionuclides because the irrigation pathways could not be modelled due to limitations in the available data for the foodchain model. Therefore a simplified methodology was developed based on the most important exposure pathways in the GDL methodology: the first three aquatic exposure pathways listed in Table 2. The simplified methodology and data are described in Appendix A. Hence, for radionuclides where GDLs are published, the GDL values were scaled to give activity concentrations in freshwater that would lead to 10 μSv y^{-1}. The simplified methodology was used for all the other radionuclides. The collective dose criterion was addressed separately, see section 3.

2.4 Comparison with other results

To investigate the validity of the approach, the derived levels using the simplified methodology were compared with existing GDLs for freshwater and with concentrations published in the report describing the EA initial radiological assessment methodology (Allot et al, 2006 and Lambers and Thorne, 2006). These comparisons are discussed in Appendix B.

The comparison highlighted a few limitations in the approach for some radionuclides and exposure pathways and these are described in Appendix B. However, the simplified approach was considered to be adequate for the calculation of exclusion or exemption levels in aqueous liquids for all the radionuclides for which GDL values were not available.

2.5 Measurement

The practicability of measuring the derived (unrounded) exclusion or exemption levels for the radionuclides under laboratory based conditions has been investigated. With approximately 280 radionuclides to consider it was not possible to undertake a detailed investigation of all the possible techniques that could be used. Hence the findings should be considered to be indicative only.

The investigation was based on laboratory methods in common use in the UK and an indication has been given of which radionuclides are likely to be impractical to measure. Limitations of the investigation for gamma emitting radionuclides include the fact that no account has been taken of potential interference in the measurement from naturally occurring radionuclides that may also be in the sample. Also, only the gamma ray energies and probabilities of emission were considered when determining whether the level was measurable using gamma ray spectrometry, and other chemical or physical characteristics may prevent measurements being achievable.

Around 103 of the radionuclides are potentially measurable at the derived levels, 67 are considered unlikely to be measurable due to their short half-lives with respect to the sample preparation time, with a further 30 also unlikely to be measurable in part due to their short half-lives. No data on possible measurement techniques were found for around 20 radionuclides in this preliminary study, though measurement techniques may exist for these radionuclides. Full details are given in Appendix C of this report.

3 RECOMMENDED EXCLUSION OR EXEMPTION LEVELS

3.1 Derived levels based on the Individual dose criterion

Table 3 gives the derived levels (Bq l^{-1}) for aqueous liquids which could be used for either exclusion or exemption. These values are based on the 10 μSv y^{-1} individual dose criterion and the collective dose criterion is addressed below. The radionuclides with short lived progeny considered to be in secular equilibrium are marked with a '+' symbol and the list of progeny included is given in Table 1. Short lived progeny were not considered for any other radionuclides. The derived values were then rounded to the nearest order of magnitude using the rounding procedure described in RP122 Part 1 and these rounded values are also listed in Table 3.

Figure 1 presents the distribution of the rounded derived levels and shows that the rounded derived levels range from 10^{-4} Bq l^{-1} to 10^{3} Bq l^{-1}, and that 80% are between 0.01 Bq l^{-1} and 1 Bq l^{-1}.

There may be a need for restrictions on the volume of aqueous liquids at these derived levels that could be disposed of per year and this was investigated. If control of the volumes of liquids at these derived levels of activity concentration is considered to be desirable then exemption would be the preferred concept. Otherwise, exclusion (which is equivalent to the EC concept of unconditional clearance) would be the preferred approach.

TABLE 3 Recommended liquid exemption levels (Bq l^{-1}) based on 10 μSv y^{-1}

Radionuclide	Activity concentration (Bq l^{-1})[a]			
	Scaled GDL value[b]	Derived levels (this study)[c]	Derived levels/scaled GDLs rounded to 1 significant figure	Recommended rounded values
H-3 (HTO)	$5.0\ 10^{2}$		$5\ 10^{2}$	$1\ 10^{3}$ [d]
Be-7		$3.7\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
C-14	$1.0\ 10^{-1}$		$1\ 10^{-1}$	$1\ 10^{-1}$
F-18		$1.1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Na-22		$1.3\ 10^{0}$	$1\ 10^{0}$	$1\ 10^{0}$
Na-24		$1.3\ 10^{0}$	$1\ 10^{0}$	$1\ 10^{0}$
Si-31		$1.6\ 10^{1}$	$2\ 10^{1}$	$1\ 10^{1}$
P-32	$4.0\ 10^{-4}$		$4\ 10^{-4}$	$1\ 10^{-3}$
P-33	$2.0\ 10^{-3}$		$2\ 10^{-3}$	$1\ 10^{-3}$
S-35(inorganic)	$1.0\ 10^{1}$		$1\ 10^{1}$	$1\ 10^{1}$
S-35(organic)	$1.0\ 10^{0}$		$1\ 10^{0}$	$1\ 10^{0}$
Cl-36		$5.2\ 10^{0}$	$5\ 10^{0}$	$1\ 10^{1}$
Cl-38		$7.6\ 10^{-2}$	$8\ 10^{-2}$	$1\ 10^{-1}$
K-42		$1.8\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
K-43		$5.2\ 10^{-3}$	$5\ 10^{-3}$	$1\ 10^{-2}$
Ca-45		$8.6\ 10^{-1}$	$9\ 10^{-1}$	$1\ 10^{0}$
Ca-47		$3.2\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-1}$
Sc-46		$8.5\ 10^{-4}$	$9\ 10^{-4}$	$1\ 10^{-3}$
Sc-47		$1.6\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Sc-48		$5.1\ 10^{-4}$	$5\ 10^{-4}$	$1\ 10^{-3}$
V-48		$3.2\ 10^{-1}$	$3\ 10^{-1}$	$1\ 10^{0}$
Cr-51	$4.0\ 10^{0}$		$4\ 10^{0}$	$1\ 10^{1}$
Mn-51		$2.3\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$
Mn-52		$6.8\ 10^{-4}$	$7\ 10^{-4}$	$1\ 10^{-3}$
Mn-52m		$9.7\ 10^{-4}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Mn-53		$1.7\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Mn-54	$1.0\ 10^{-2}$		$1\ 10^{-2}$	$1\ 10^{-2}$
Mn-56		$1.4\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Fe-52		$6.7\ 10^{-3}$	$7\ 10^{-3}$	$1\ 10^{-2}$
Fe-55		$2.3\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Fe-59		$4.2\ 10^{-3}$	$4\ 10^{-3}$	$1\ 10^{-2}$
Co-55		$1.7\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$
Co-56		$9.4\ 10^{-4}$	$9\ 10^{-4}$	$1\ 10^{-3}$
Co-57	$2.0\ 10^{-1}$		$2\ 10^{-1}$	$1\ 10^{-1}$
Co-58	$4.0\ 10^{-2}$		$4\ 10^{-2}$	$1\ 10^{-1}$
Co-58m		$1.6\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Co-60	$5.0\ 10^{-3}$		$5\ 10^{-3}$	$1\ 10^{-2}$
Co-60m		$4.8\ 10^{-1}$	$5\ 10^{-1}$	$1\ 10^{0}$
Co-61		$3.7\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
Co-62m		$1.2\ 10^{-3}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Ni-59		$2.0\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Ni-63		$3.8\ 10^{1}$	$4\ 10^{1}$	$1\ 10^{2}$

TABLE 3 Recommended liquid exemption levels (Bq l^{-1}) based on 10 µSv y^{-1}

Radionuclide	Activity concentration (Bq l^{-1})[a]			
	Scaled GDL value[b]	Derived levels (this study)[c]	Derived levels/scaled GDLs rounded to 1 significant figure	Recommended rounded values
Ni-65		$9.1\ 10^{-3}$	$9\ 10^{-3}$	$1\ 10^{-2}$
Cu-64		$9.6\ 10^{-2}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Zn-65	$9.0\ 10^{-2}$		$9\ 10^{-2}$	$1\ 10^{-1}$
Zn-69		$1.6\ 10^{1}$	$2\ 10^{1}$	$1\ 10^{1}$
Zn-69m		$8.0\ 10^{-2}$	$8\ 10^{-2}$	$1\ 10^{-1}$
Ga-67		$3.2\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-1}$
Ga-72		$1.9\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$
Ge-71		$1.1\ 10^{0}$	$1\ 10^{0}$	$1\ 10^{0}$
As-73		$3.3\ 10^{0}$	$3\ 10^{0}$	$1\ 10^{1}$
As-74		$4.0\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
As-76		$4.3\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
As-77		$2.3\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Se-75	$2.0\ 10^{-1}$		$2\ 10^{-1}$	$1\ 10^{-1}$
Br-82		$4.2\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
Rb-86		$3.8\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
Sr-85		$3.6\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
Sr-85m		$8.4\ 10^{-2}$	$8\ 10^{-2}$	$1\ 10^{-1}$
Sr-87m		$5.7\ 10^{-2}$	$6\ 10^{-2}$	$1\ 10^{-1}$
Sr-89	$2.0\ 10^{0}$		$2\ 10^{0}$	$1\ 10^{0}$
Sr-90+[e]	$2.0\ 10^{-1}$		$2\ 10^{-1}$	$1\ 10^{-1}$
Sr-91		$2.6\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-2}$
Sr-92		$1.4\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Y-90		$2.1\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Y-91		$1.7\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Y-91m		$1.9\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Y-92		$4.0\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
Y-93		$1.1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Zr-93		$5.5\ 10^{0}$	$6\ 10^{0}$	$1\ 10^{1}$
Zr-95+[e]		$2.9\ 10^{-3}$	$3\ 10^{-3}$	$1\ 10^{-3}$
Zr-97		$1.2\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Nb-93m		$1.2\ 10^{1}$	$1\ 10^{1}$	$1\ 10^{1}$
Nb-94		$1.7\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Nb-95		$3.7\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
Nb-97		$5.0\ 10^{-1}$	$5\ 10^{-1}$	$1\ 10^{0}$
Nb-98		$1.4\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Mo-90		$4.2\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
Mo-93		$1.8\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Mo-99		$2.3\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Mo-101		$2.7\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-2}$
Tc-96		$1.2\ 10^{0}$	$1\ 10^{0}$	$1\ 10^{0}$
Tc-96m		$6.1\ 10^{1}$	$6\ 10^{1}$	$1\ 10^{2}$
Tc-97		$7.2\ 10^{1}$	$7\ 10^{1}$	$1\ 10^{2}$

TABLE 3 Recommended liquid exemption levels (Bq l^{-1}) based on 10 μSv y^{-1}

Radionuclide	Activity concentration (Bq l^{-1})[a]			
	Scaled GDL value[b]	Derived levels (this study)[c]	Derived levels/scaled GDLs rounded to 1 significant figure	Recommended rounded values
Tc-97m		$8.7\ 10^{0}$	$9\ 10^{0}$	$1\ 10^{1}$
Tc-99		$7.4\ 10^{0}$	$7\ 10^{0}$	$1\ 10^{1}$
Tc-99m		$2.5\ 10^{1}$	$3\ 10^{1}$	$1\ 10^{1}$
Ru-97		$2.7\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-2}$
Ru-103		$1.4\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Ru-105		$8.3\ 10^{-3}$	$8\ 10^{-3}$	$1\ 10^{-2}$
Ru-106+[e]	$1.0\ 10^{-1}$		$1\ 10^{-1}$	$1\ 10^{-1}$
Rh-103m		$2.0\ 10^{1}$	$2\ 10^{1}$	$1\ 10^{1}$
Rh-105		$4.5\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
Pd-103		$2.3\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Pd-109		$2.8\ 10^{-1}$	$3\ 10^{-1}$	$1\ 10^{-1}$
Ag-105		$3.2\ 10^{-1}$	$3\ 10^{-1}$	$1\ 10^{0}$
Ag-108m		$1.0\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Ag-110m		$6.1\ 10^{-2}$	$6\ 10^{-2}$	$1\ 10^{-1}$
Ag-111		$4.0\ 10^{0}$	$4\ 10^{0}$	$1\ 10^{1}$
Cd-109		$6.1\ 10^{-1}$	$6\ 10^{-1}$	$1\ 10^{0}$
Cd-115		$1.4\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Cd-115m		$4.8\ 10^{-1}$	$5\ 10^{-1}$	$1\ 10^{0}$
In-111		$1.2\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
In-113m		$1.9\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
In-114m		$1.4\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
In-115m		$3.0\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-2}$
Sn-113		$1.3\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Sn-125		$1.3\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Sb-122		$1.5\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Sb-124		$3.7\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
Sb-125	$6.0\ 10^{-1}$		$6\ 10^{-1}$	$1\ 10^{0}$
Te-123m		$7.5\ 10^{-1}$	$7\ 10^{-1}$	$1\ 10^{0}$
Te-125m		$1.3\ 10^{0}$	$1\ 10^{0}$	$1\ 10^{0}$
Te-127		$6.7\ 10^{0}$	$7\ 10^{0}$	$1\ 10^{1}$
Te-127m		$5.0\ 10^{-1}$	$5\ 10^{-1}$	$1\ 10^{0}$
Te-129		$9.3\ 10^{0}$	$9\ 10^{0}$	$1\ 10^{1}$
Te-129m		$3.8\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
Te-131		$2.2\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Te-131m		$3.5\ 10^{-1}$	$3\ 10^{-1}$	$1\ 10^{0}$
Te-132		$2.9\ 10^{-1}$	$3\ 10^{-1}$	$1\ 10^{-1}$
Te-133		$1.1\ 10^{0}$	$1\ 10^{0}$	$1\ 10^{0}$
Te-133m		$4.4\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
Te-134		$1.1\ 10^{0}$	$1\ 10^{0}$	$1\ 10^{0}$
I-123		$7.5\ 10^{-1}$	$8\ 10^{-1}$	$1\ 10^{0}$
I-125	$4.0\ 10^{-1}$		$4\ 10^{-1}$	$1\ 10^{0}$
I-126		$1.2\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$

TABLE 3 Recommended liquid exemption levels (Bq l^{-1}) based on 10 μSv y^{-1}

Radionuclide	Activity concentration (Bq l^{-1})[a]			
	Scaled GDL value[b]	Derived levels (this study)[c]	Derived levels/scaled GDLs rounded to 1 significant figure	Recommended rounded values
I-129	$5.0\ 10^{-2}$		$5\ 10^{-2}$	$1\ 10^{-1}$
I-130		$5.2\ 10^{-2}$	$5\ 10^{-2}$	$1\ 10^{-1}$
I-131		$1.5\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
I-132		$5.0\ 10^{-2}$	$5\ 10^{-2}$	$1\ 10^{-1}$
I-133		$1.7\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
I-134		$4.4\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
I-135		$7.2\ 10^{-2}$	$7\ 10^{-2}$	$1\ 10^{-1}$
Cs-129		$1.8\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Cs-131		$2.1\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Cs-132		$7.1\ 10^{-3}$	$7\ 10^{-3}$	$1\ 10^{-2}$
Cs-134	$1.0\ 10^{-2}$		$1\ 10^{-2}$	$1\ 10^{-2}$
Cs-134m		$1.9\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Cs-135		$1.8\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Cs-136		$2.3\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$
Cs-137+[e]	$2.0\ 10^{-2}$		$2\ 10^{-2}$	$1\ 10^{-2}$
Cs-138		$2.2\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$
Ba-131		$4.0\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
Ba-140		$9.9\ 10^{-2}$	$1\ 10^{-1}$	$1\ 10^{-1}$
La-140		$9.6\ 10^{-4}$	$1\ 10^{-3}$	$1\ 10^{-3}$
Ce-139		$3.1\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-1}$
Ce-141		$6.5\ 10^{-2}$	$7\ 10^{-2}$	$1\ 10^{-1}$
Ce-143		$1.8\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Ce-144		$2.2\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Pr-142		$3.4\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-1}$
Pr-143		$2.4\ 10^{1}$	$2\ 10^{1}$	$1\ 10^{1}$
Nd-147		$1.6\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Nd-149		$5.9\ 10^{-3}$	$6\ 10^{-3}$	$1\ 10^{-2}$
Pm-147		$2.3\ 10^{1}$	$2\ 10^{1}$	$1\ 10^{1}$
Pm-149		$7.3\ 10^{-1}$	$7\ 10^{-1}$	$1\ 10^{0}$
Sm-151		$6.8\ 10^{1}$	$7\ 10^{1}$	$1\ 10^{2}$
Sm-153		$1.3\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Eu-152		$4.3\ 10^{-3}$	$4\ 10^{-3}$	$1\ 10^{-2}$
Eu-152m		$1.7\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Eu-154		$4.0\ 10^{-3}$	$4\ 10^{-3}$	$1\ 10^{-2}$
Eu-155		$8.6\ 10^{-2}$	$9\ 10^{-2}$	$1\ 10^{-1}$
Gd-153		$4.8\ 10^{-2}$	$5\ 10^{-2}$	$1\ 10^{-1}$
Gd-159		$1.0\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Tb-160		$4.5\ 10^{-3}$	$4\ 10^{-3}$	$1\ 10^{-2}$
Dy-165		$1.9\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Dy-166		$1.2\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Ho-166		$1.7\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Er-169		$1.9\ 10^{1}$	$2\ 10^{1}$	$1\ 10^{1}$

TABLE 3 Recommended liquid exemption levels (Bq l^{-1}) based on 10 μSv y^{-1}

Radionuclide	Activity concentration (Bq l^{-1})[a]			
	Scaled GDL value[b]	Derived levels (this study)[c]	Derived levels/scaled GDLs rounded to 1 significant figure	Recommended rounded values
Er-171		$1.3\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Tm-170		$8.4\ 10^{-1}$	$8\ 10^{-1}$	$1\ 10^{0}$
Tm-171		$7.2\ 10^{0}$	$7\ 10^{0}$	$1\ 10^{1}$
Yb-175		$1.3\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Lu-177		$1.6\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Hf-181		$4.0\ 10^{-3}$	$4\ 10^{-3}$	$1\ 10^{-2}$
Ta-182		$1.5\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$
W-181		$5.8\ 10^{-2}$	$6\ 10^{-2}$	$1\ 10^{-1}$
W-185		$3.0\ 10^{0}$	$3\ 10^{0}$	$1\ 10^{0}$
W-187		$4.9\ 10^{-3}$	$5\ 10^{-3}$	$1\ 10^{-2}$
Re-186		$1.8\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Re-188		$1.3\ 10^{0}$	$1\ 10^{0}$	$1\ 10^{0}$
Os-185		$9.0\ 10^{-3}$	$9\ 10^{-3}$	$1\ 10^{-2}$
Os-191		$8.1\ 10^{-2}$	$8\ 10^{-2}$	$1\ 10^{-1}$
Os-191m		$7.0\ 10^{-1}$	$7\ 10^{-1}$	$1\ 10^{0}$
Os-193		$8.8\ 10^{-2}$	$9\ 10^{-2}$	$1\ 10^{-1}$
Ir-190		$2.3\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$
Ir-192		$4.1\ 10^{-3}$	$4\ 10^{-3}$	$1\ 10^{-2}$
Ir-194		$3.7\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
Pt-191		$1.7\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Pt-193m		$3.8\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
Pt-197		$2.0\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Pt-197m		$6.0\ 10^{-2}$	$6\ 10^{-2}$	$1\ 10^{-1}$
Au-198		$4.0\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
Au-199		$1.7\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Hg-197[f]		$4.3\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
Hg-197m[f]		$3.0\ 10^{-1}$	$3\ 10^{-1}$	$1\ 10^{-1}$
Hg-203[f]		$1.1\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Tl-200		$3.8\ 10^{-3}$	$4\ 10^{-3}$	$1\ 10^{-2}$
Tl-201		$5.3\ 10^{-2}$	$5\ 10^{-2}$	$1\ 10^{-1}$
Tl-202		$1.0\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Tl-204		$6.1\ 10^{-2}$	$6\ 10^{-2}$	$1\ 10^{-1}$
Pb-203		$1.6\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Pb-210		$3.0\ 10^{-3}$	$3\ 10^{-3}$	$1\ 10^{-3}$
Pb-212		$3.1\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-1}$
Bi-206		$2.1\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Bi-207		$4.4\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
Bi-210		$3.9\ 10^{0}$	$4\ 10^{0}$	$1\ 10^{1}$
Bi-212		$3.7\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
Po-203		$1.5\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$
Po-205		$1.6\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$
Po-207		$1.9\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$

TABLE 3 Recommended liquid exemption levels (Bq l^{-1}) based on 10 µSv y^{-1}

Radionuclide	Activity concentration (Bq l^{-1})[a]			
	Scaled GDL value[b]	Derived levels (this study)[c]	Derived levels/scaled GDLs rounded to 1 significant figure	Recommended rounded values
Po-210	$3.0\ 10^{-3}$		$3\ 10^{-3}$	$1\ 10^{-3}$
At-211		$4.7\ 10^{-1}$	$5\ 10^{-1}$	$1\ 10^{0}$
Ra-223		$3.0\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-2}$
Ra-224+[e]		$2.7\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-2}$
Ra-225		$2.8\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-2}$
Ra-226+[e]	$2.0\ 10^{-2}$		$2\ 10^{-2}$	$1\ 10^{-2}$
Ra-227		$4.1\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
Ra-228		$4.4\ 10^{-3}$	$4\ 10^{-3}$	$1\ 10^{-2}$
Ac-227		$6.0\ 10^{-2}$	$6\ 10^{-2}$	$1\ 10^{-1}$
Ac-228		$2.2\ 10^{-3}$	$2\ 10^{-3}$	$1\ 10^{-3}$
Th-226		$1.9\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Th-227		$1.6\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Th-228		$4.9\ 10^{-1}$	$5\ 10^{-1}$	$1\ 10^{0}$
Th-229		$1.7\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Th-230		$8.7\ 10^{-1}$	$9\ 10^{-1}$	$1\ 10^{0}$
Th-231		$6.6\ 10^{-2}$	$7\ 10^{-2}$	$1\ 10^{-1}$
Th-232		$9.7\ 10^{-1}$	$1\ 10^{0}$	$1\ 10^{0}$
Th-234		$1.8\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Pa-230		$1.3\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Pa-231		$2.0\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Pa-233		$4.1\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
U-230		$1.2\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
U-231		$6.9\ 10^{0}$	$7\ 10^{0}$	$1\ 10^{1}$
U-232		$3.8\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
U-233		$2.5\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
U-234	$2.0\ 10^{-1}$		$2\ 10^{-1}$	$1\ 10^{-1}$
U-235+[e]	$2.0\ 10^{-1}$		$2\ 10^{-1}$	$1\ 10^{-1}$
U-236		$2.7\ 10^{-1}$	$3\ 10^{-1}$	$1\ 10^{-1}$
U-237		$3.7\ 10^{0}$	$4\ 10^{0}$	$1\ 10^{1}$
U-238+[e]	$2.0\ 10^{-1}$		$2\ 10^{-1}$	$1\ 10^{-1}$
U-239		$1.3\ 10^{1}$	$1\ 10^{1}$	$1\ 10^{1}$
U-240		$4.6\ 10^{0}$	$5\ 10^{0}$	$1\ 10^{1}$
Np-237		$7.5\ 10^{-2}$	$7\ 10^{-2}$	$1\ 10^{-1}$
Np-239		$3.8\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
Np-240		$5.2\ 10^{-2}$	$5\ 10^{-2}$	$1\ 10^{-1}$
Pu-234		$2.9\ 10^{-2}$	$3\ 10^{-2}$	$1\ 10^{-2}$
Pu-235		$2.1\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Pu-236		$3.6\ 10^{-1}$	$4\ 10^{-1}$	$1\ 10^{0}$
Pu-237		$3.8\ 10^{-2}$	$4\ 10^{-2}$	$1\ 10^{-1}$
Pu-238	$1.0\ 10^{-1}$		$1\ 10^{-1}$	$1\ 10^{-1}$
Pu-239	$1.0\ 10^{-1}$		$1\ 10^{-1}$	$1\ 10^{-1}$
Pu-240	$1.0\ 10^{-1}$		$1\ 10^{-1}$	$1\ 10^{-1}$

TABLE 3 Recommended liquid exemption levels (Bq l^{-1}) based on 10 μSv y^{-1}

Radionuclide	Activity concentration (Bq l^{-1})[a]			
	Scaled GDL value[b]	Derived levels (this study)[c]	Derived levels/scaled GDLs rounded to 1 significant figure	Recommended rounded values
Pu-241	$4.0\ 10^{0}$		$4\ 10^{0}$	$1\ 10^{1}$
Pu-242	$1.0\ 10^{-1}$		$1\ 10^{-1}$	$1\ 10^{-1}$
Pu-243		$7.8\ 10^{-2}$	$8\ 10^{-2}$	$1\ 10^{-1}$
Pu-244		$1.8\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Am-241	$1.0\ 10^{-1}$		$1\ 10^{-1}$	$1\ 10^{-1}$
Am-242		$9.6\ 10^{-2}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Am-242m		$2.5\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Am-243	$4.0\ 10^{-2}$		$4\ 10^{-2}$	$1\ 10^{-1}$
Cm-242	$2.0\ 10^{0}$		$2\ 10^{0}$	$1\ 10^{0}$
Cm-243	$5.0\ 10^{-2}$		$5\ 10^{-2}$	$1\ 10^{-1}$
Cm-244	$6.0\ 10^{-2}$		$6\ 10^{-2}$	$1\ 10^{-1}$
Cm-245		$1.9\ 10^{-2}$	$2\ 10^{-2}$	$1\ 10^{-2}$
Cm-246		$2.0\ 10^{-1}$	$2\ 10^{-1}$	$1\ 10^{-1}$
Cm-247		$6.2\ 10^{-3}$	$6\ 10^{-3}$	$1\ 10^{-2}$
Cm-248		$6.3\ 10^{-2}$	$6\ 10^{-2}$	$1\ 10^{-1}$
Bk-249		$5.6\ 10^{1}$	$6\ 10^{1}$	$1\ 10^{2}$
Cf-246		$1.4\ 10^{0}$	$1\ 10^{0}$	$1\ 10^{0}$
Cf-248		$8.3\ 10^{-1}$	$8\ 10^{-1}$	$1\ 10^{0}$
Cf-249		$5.8\ 10^{-3}$	$6\ 10^{-3}$	$1\ 10^{-2}$
Cf-250		$2.6\ 10^{-1}$	$3\ 10^{-1}$	$1\ 10^{-1}$
Cf-251		$1.4\ 10^{-2}$	$1\ 10^{-2}$	$1\ 10^{-2}$
Cf-252		$1.0\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Cf-253		$1.9\ 10^{1}$	$2\ 10^{1}$	$1\ 10^{1}$
Cf-254		$1.1\ 10^{-4}$	$1\ 10^{-4}$	$1\ 10^{-4}$
Es-253		$1.6\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Es-254		$1.0\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$
Es-254m		$4.3\ 10^{-3}$	$4\ 10^{-3}$	$1\ 10^{-2}$
Fm-254		$1.6\ 10^{0}$	$2\ 10^{0}$	$1\ 10^{0}$
Fm-255		$1.5\ 10^{-1}$	$1\ 10^{-1}$	$1\ 10^{-1}$

Notes

(a) Including activity in the dissolved and suspended fractions, see Appendix A and Documents of the NRPB (1998), (2000) and (2005).

(b) GDLs taken from Documents of the NRPB (1998), (2000) and (2005) and scaled to an individual dose criterion of 10 μSv y^{-1}.

(c) Derived liquid exclusion or exemption levels based on an individual dose criterion of 10 μSv y^{-1} using methodology in Appendix A.

(d) For H-3 (organic), a value of $1\ 10^{0}$ is recommended, based on the ratio of H-3 and H-3 (organic) DPURs given in Allot et al Lambers (2006) and Lambers and Thorne (2006), see also Table B1 in Appendix B.

(e) Radionuclides with short lived progeny considered to be in secular equilibrium. The list of progeny included is given in Table 1.

(f) Values given correspond to those for organic Hg.

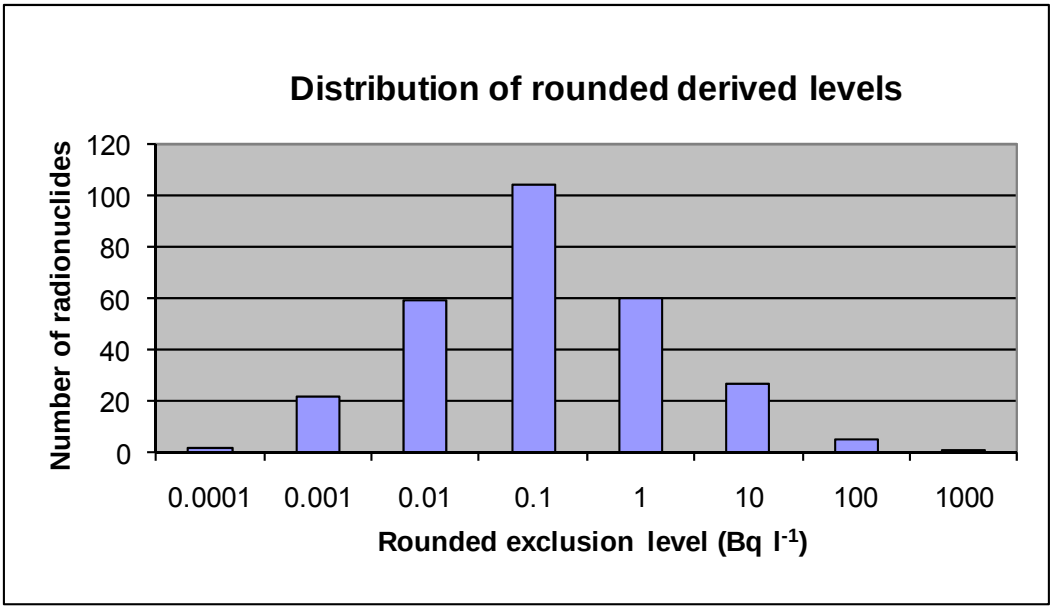

Figure 1. Distribution of rounded derived levels given in Table 3.

3.2 Disposal of aqueous liquids at the derived levels

The volume of aqueous liquid with activity concentrations given in Table 3 that could be disposed of per year to a sewer and still give rise to doses below the 10 μSv y^{-1} individual dose criterion was estimated as follows. HPA has published Generalised Derived Constraints (GDCs) for disposal to sewer for several radionuclides (NRPB, 2000). The GDC for disposal to sewer is the discharge rate to a sewer, in Bq y^{-1}, that corresponds to a dose criterion of 300 μSv y^{-1}. The GDCs are based on a very small sewage treatment works (STW), serving 500 people and with a throughput of 2.2 10^4 m^3 y^{-1}. The activity disposed of per year that corresponds to the 10 μSv y^{-1} dose criterion was then calculated by scaling the GDC for disposal to sewer (NRPB, 2000; Harvey et al, 2010) and then dividing this by the activity concentration given in Table 3. This gives the following relationship:

Volume (m^3 y^{-1}) = 10^{-3} (m^3 l^{-1})*GDC (Bq y^{-1})/(30*Derived level (Bq/l)).

The resulting volume estimates ranged from 3 10^1 m^3 y^{-1} to 1 10^7 m^3 y^{-1} for the 50 radionuclides for which GDCs have been calculated; the majority were above the throughput of the STW. Only one value was below 3 10^3 m^3 y^{-1} and the smallest estimated volume, 3 10^1 m^3 y^{-1}, represents 0.14% of the total throughput of the STW. If a STW has a larger throughput then the dose per unit discharge to the STW would be lower due to the additional dilution and hence the corresponding volume limit would be higher. The scaling is not strictly linear and for STW serving more than 50,000 people the GDC is increased by a factor of 40 or more, depending on the radionuclide (NRPB, 2000). This would result in a smallest estimated volume of about 1 10^3 m^3 y^{-1} for a large STW.

A separate calculation was performed for 27 radionuclides, including 13 radionuclides not considered in the GDC calculation, using the sewer model that was developed by

HPA for the Environment Agency (Titley et al, 2000) set up to represent a small STW with a throughput of 3.7 10^5 m^3 y^{-1}. The volume that could be disposed of at the derived level given in Table 3 and which would meet the individual dose criterion was above the throughput of the STW for all radionuclides except one: the smallest estimated volume was 1 10^5 m^3 y^{-1}.

Additional estimates of the volume at the activity concentration in Table 3 that could be disposed of to a sewer were obtained from IAEA clearance levels for discharge to a river or to a STW serving 20,000 people (IAEA, 1998). The volume at the derived level that could be disposed of to a sewer was determined by dividing the IAEA clearance level, in Bq y^{-1}, by the derived level; for 19 radionuclides the resulting volume was greater than the throughput of the STW (assumed to be 9 10^5 m^3 y^{-1}) and for two radionuclides it was below 3000 m^3 y^{-1}, with a smallest estimated volume of 100 m^3 y^{-1} for one radionuclide. A similar calculation was performed using the EA initial assessment methodology (Allot et al, 2006; Lambers and Thorne, 2006) to estimate the volumes that could be disposed of to a STW with a throughput of 3.6 10^4 m^3 y^{-1} and meet the individual dose criterion. The majority of the volumes were above the throughput of the STW; three radionuclides had estimated volumes below 3000 m^3 y^{-1}, and the smallest estimated volume was 300 m^3 y^{-1}, for one radionuclide.

These results are summarised in Table 4.

TABLE 4 Comparison of volumes that can be disposed of to sewer at the rounded derived level in Table 3

Description	GDC[(a)]	HPA[(b)]	IAEA[©]	EA[(d)]
Throughput of STW, m^3 y^{-1}	2.2 10^4	3.7 10^5	9 10^5	3.6 10^4
Number of radionuclides considered	50	27	34	85
Number of radionuclides with volume below STW throughput	7	1	15	4
Smallest estimated volume, m^3 y^{-1}	3 10^1	1 10^5	1 10^2	3 10^2
Number of radionuclides with estimated volume below 3 10^3 m^3 y^{-1}	1 (^{99}Tc)	0	2 (^{22}Na, ^{232}Th)	3 (^{36}Cl, ^{99}Tc, ^{232}Th)

Notes

a) Derived from GDC for discharges to sewers (NRPB, 2000 and Harvey et al, 2010)

b) Calculated using the HPA sewer model (Titley et al, 2000) set up with the parameter values chosen for the NDAWG intercomparison case (Watson, 2010)

c) Derived from IAEA clearance levels for discharge to river or sewer (IAEA, 1998)

d) Derived from EA initial assessment methodology (Allot et al, 2006 and Lambers and Thorne, 2006)

The estimated volumes for a particular radionuclide vary between the four approaches (by factors of more than 10^3 for some radionuclides) and the radionuclide corresponding to the smallest estimated volume also varies. It should be noted that the calculations listed in Table 4 are all for small STW and the throughput for a STW serving a city population will be larger, leading to lower doses; Becton STW serves 3 10^6 people in London and has a throughput of nearly 10^9 m^3 y^{-1} (Titley et al, 2000).

The results given in Table 4 indicate that a limit on the volume of aqueous liquids containing radionuclides at the derived activity concentration levels in Table 3 that can

be disposed of to a sewer is required and DECC asked HPA to make a recommendation for the value of this volume limit. Considering the variation in the results, the fact that they are all for a small STW and the fact that it is unlikely that large volumes of aqueous liquids containing only one radionuclide at 100% of the derived level would be disposed of to any one sewer, a value of 3000 m^3 y^{-1} was selected as a reasonable value for the volume limit.

Hence, HPA recommends that a volume limit of 3000 m^3 y^{-1} is specified for the disposal to a sewer of aqueous liquids containing radionuclides at the derived levels given in Table 3. This volume limit indicates that exclusion of aqueous liquids at the derived levels would not be appropriate and exemption, with the specified volume limit, would be the preferred option.

There is no need for a restriction on the volume that can be disposed of to a river as the derived levels are based on the assumption that the concentration in river water is at these levels. Discharge to coastal waters would give rise to lower doses because of the additional dilution and hence, based on the individual dose criterion, there is no need for restrictions on the volume of water containing the activity concentrations in Table 3 that can be disposed of to coastal waters.

3.3 Collective dose

PC-CREAM08 (HPA, 2009) was used to estimate the collective dose per Bq per year discharged, for 38 radionuclides (23 single radionuclides and 15 decay chains), using standard data. This was used to calculate the volume of aqueous liquid (m^3 y^{-1}) containing a radionuclide at the derived levels in Table 3 that would give rise to a collective dose of 1 man Sv. The results indicate that discharges of 7 10^8 m^3 y^{-1} or greater would give rise to collective doses below 1 man Sv, the exact value depending on the radionuclide. Hence a discharge of 7 10^8 m^3 y^{-1} of aqueous liquids containing activity concentrations at the derived levels in Table 3 would meet the collective dose criterion of 1 man Sv per year of practice.

Using a simplified conservative assumption that all the activity in the liquid is eventually ingested in drinking water after it has been discharged, and an annual water intake of 600l, then disposal of 600 l of aqueous liquid at the derived level for a radionuclide could result in a dose of about 10 μSv (10^{-5} Sv) to one person; hence a collective dose of 1 man Sv per year of practice would result from discharge of 10^5 times this amount per year, i.e. 6 10^4 m^3 y^{-1}. This is an extremely conservative assumption, as confirmed by the PC-CREAM08 results.

The proposed restriction on the volume disposed to a sewer would ensure that the collective dose resulting from disposal to a sewer was well below 1 man Sv per year of practice. In the case of disposal to a river or to coastal waters, the PC-CREAM08 results indicate that the collective dose would be below 1 man Sv even with extremely large discharge rates. Hence, unconditional exemption of aqueous liquids at the derived levels for disposal to rivers or coastal waters may be the optimum option taking into account costs and benefits.

3.4 Recommended levels

HPA considers that the values in columns 4 or 5 of Table 3 would be suitable for use as exemption levels for aqueous liquids, with a volume limit of 3 10^3 m^3 y^{-1} for disposal of aqueous liquids containing activity concentrations at these levels to a sewer. There is no need for a disposal limit for disposal to a river as the derived levels are based on the assumption that the concentration in river water is at these levels. Discharge to coastal waters would give rise to lower doses because of the additional dilution and hence there is no need for restrictions on the volume of water containing the activity concentrations in Table 3 that can be disposed of to coastal waters, based on radiological protection criteria.

3.5 Derived levels for work activities

As discussed in section 2.2, the EC BSS specifies different dose criteria for practices and for work activities. Derived exemption levels have also been calculated for naturally occurring radionuclides for work activities using the appropriate dose criteria and the results are given in Appendix D.

4 SUMMARY AND CONCLUSION

HPA has derived recommended values for use as exemption levels for aqueous liquids, for around 280 radionuclides. The calculations were based on the methodology used for Generalised Derived Limits published by HPA. Scaled GDL values were used where available and the remaining values were derived using a simplified methodology that incorporated the important GDL exposure pathways. The derived levels were rounded to the nearest order of magnitude using the rounding procedure in RP122. The rounded exemption levels range from 10^{-4} Bq l^{-1} to 10^3 Bq l^{-1}, and 80% of the values are between 0.01 Bq l^{-1} and 1 Bq l^{-1}. The volume of aqueous liquids containing activity concentrations at these levels that can be disposed of to a sewer should be restricted to 3 10^3 m^3 y^{-1}. No volume restrictions are required for disposal to river or to coastal waters.

The results from the simplified methodology were compared with results from existing GDL and EA methodologies, for the radionuclides for which values existed, and found to give reasonable agreement.

HPA has undertaken a preliminary investigation to examine whether the derived activity levels for each radionuclide could be measured under laboratory based conditions. The following findings should be considered to be only indicative. HPA estimates that around 103 (37%) of the radionuclides are potentially measurable at the derived activity levels and 97 (35%) are unlikely to be measurable due to their short half-lives with respect to the sample preparation time.

Derived levels for naturally occurring radionuclides in work activities are given in Appendix D.

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APPENDIX A - Methodology for deriving the exemption and exclusion levels

A1 INTRODUCTION

Generalised derived limits for freshwater have been published for a number of radionuclides (NRPB, 1998, 2000 and 2005). These were scaled to calculate activity concentrations in fresh water that would give rise to a dose of 10 μSv y^{-1}. However, GDLs are only reported for about 35 radionuclides, therefore a new approach was taken to calculate the derived levels for the remaining 240 or so radionuclides considered in this study.

As mentioned in the main text, it was not feasible to use the GDL methodology in full for the remaining radionuclides due to lack of available data. Therefore, a simplified methodology was developed based on the important exposure pathways in the GDL methodology, and this was implemented in a spreadsheet. Appendix B describes a comparison of the values derived using the simplified methodology with the corresponding GDLs for freshwater and an EA study (Allot et al 2006 and Lambers and Thorne, 2006).

A2 SCALED HPA GDL VALUES

Table A1 shows the existing GDLs for freshwater, which are based on an effective dose limit of 1 mSv y^{-1}, and the scaled GDL values that correspond to an effective dose of 10 μSv y^{-1}.

TABLE A1 Derived levels based on GDLs for fresh water (Bq l^{-1})

Radionuclide[(a)]	GDL[(b)] at 1 mSv y^{-1}	Age limiting Group[(c)]	GDL scaled to 10 μSv y^{-1}
H-3 (HTO)	$5.0\ 10^{4}$	Fetus	$5.0\ 10^{2}$
C-14	$1.0\ 10^{1}$	Fetus	$1.0\ 10^{-1}$
P-32	$4.0\ 10^{-2}$	Fetus	$4.0\ 10^{-4}$
P-33	$2.0\ 10^{-1}$	Fetus	$2.0\ 10^{-3}$
S-35 (organic)	$1.0\ 10^{2}$	Fetus	$1.0\ 10^{0}$
S-35 (inorganic)	$1.0\ 10^{3}$	Fetus	$1.0\ 10^{1}$
Cr-51	$4.0\ 10^{2}$	Adult	$4.0\ 10^{0}$
Mn-54	$1.0\ 10^{0}$	Adult	$1.0\ 10^{-2}$
Co-57	$2.0\ 10^{1}$	Adult	$2.0\ 10^{-1}$
Co-58	$4.0\ 10^{0}$	Adult	$4.0\ 10^{-2}$
Co-60	$5.0\ 10^{-1}$	Adult	$5.0\ 10^{-3}$
Zn-65	$9.0\ 10^{0}$	Adult	$9.0\ 10^{-2}$
Se-75	$2.0\ 10^{1}$	Fetus	$2.0\ 10^{-1}$
Sr-89	$2.0\ 10^{2}$	Infant	$2.0\ 10^{0}$
Sr-90+	$2.0\ 10^{1}$	Adult	$2.0\ 10^{-1}$
Ru-106+	$1.0\ 10^{1}$	Children	$1.0\ 10^{-1}$
Rh-106	$1.0\ 10^{1}$	Children	$1.0\ 10^{-1}$
Sb-125	$6.0\ 10^{1}$	Adult	$6.0\ 10^{-1}$
I-125	$4.0\ 10^{1}$	Children	$4.0\ 10^{-1}$
I-129	$5.0\ 10^{0}$	Adult	$5.0\ 10^{-2}$
Cs-134	$1.0\ 10^{0}$	Adult	$1.0\ 10^{-2}$
Cs-137+	$2.0\ 10^{0}$	Adult	$2.0\ 10^{-2}$
Po-210	$3.0\ 10^{-1}$	Infants	$3.0\ 10^{-3}$
Pb-210	$3.0\ 10^{-1}$	Adult	$3.0\ 10^{-3}$
Ra-226+	$2.0\ 10^{0}$	Children	$2.0\ 10^{-2}$
U-234	$2.0\ 10^{1}$	Adult	$2.0\ 10^{-1}$
U-235	$2.0\ 10^{1}$	Adult	$2.0\ 10^{-1}$
U-238	$2.0\ 10^{1}$	Adult	$2.0\ 10^{-1}$
Pu-238	$1.0\ 10^{1}$	Adult	$1.0\ 10^{-1}$
Pu-239	$1.0\ 10^{1}$	Adult	$1.0\ 10^{-1}$
Pu-240	$1.0\ 10^{1}$	Adult	$1.0\ 10^{-1}$
Pu-241+	$4.0\ 10^{2}$	Adult	$4.0\ 10^{0}$
Pu-242	$1.0\ 10^{1}$	Adult	$1.0\ 10^{-1}$
Am-241	$1.0\ 10^{1}$	Adult	$1.0\ 10^{-1}$
Am-243	$4.0\ 10^{0}$	Adult	$4.0\ 10^{-2}$
Cm-242	$2.0\ 10^{2}$	Children	$2.0\ 10^{0}$
Cm-243	$5.0\ 10^{0}$	Adult	$5.0\ 10^{-2}$
Cm-244	$6.0\ 10^{0}$	Children	$6.0\ 10^{-2}$

Notes

(a) Radionuclides with progeny included are marked with a '+' symbol. See Table 1 in main text for explanation.

(b) GDLs for freshwater include activity in the dissolved and suspended fractions. Documents of the NRPB (1998), (2000) and (2005).

(c) GDLs apply to uniform conditions over a year and are based on the limiting age group, which is either fetus, infant, child or adult.

A3 SIMPLIFIED METHODOLOGY

Three exposure pathways were identified as the most important from a review of the GDL reports. These were: intake of drinking water, ingestion of fish and external dose from radionuclides in sediment. Hence these three pathways were considered in the simplified methodology. These pathways are also the same as those considered in the EA assessments of the dose to an angler family for a release to a river (Allot et al, 2006 and Lambers and Thorne, 2006). The full GDL methodology considers eight exposure pathways, as listed in Table 2 of the main text.

The dose (Sv y^{-1}) from 1 Bq l^{-1} of each radionuclide in fresh (unfiltered) water was calculated using the formulae given below.

Intakes of drinking water

$DRINK_i = A_{fw,i} \times I \times DING_i$

Where

$DRINK_i$ = dose from ingestion of drinking water for radionuclide i (Sv y^{-1})

$A_{fw,i}$ = Activity concentration in filtered water (Bq l^{-1})

I =intake rate (l y^{-1})

$DING_i$ = dose coefficient for intake by ingestion for radionuclide i (Sv Bq^{-1})

The activity concentration in filtered water, $A_{fw,i}$ is obtained from the activity concentration in unfiltered water, $A_{ufw,i}$ using the formula:

$$\frac{A_{fw,i}}{A_{ufw,i}} = \frac{1}{1 + (K_{d,i} \times ssl)}$$

Where

ssl = suspended sediment load, assumed to be 5×10^{-5} (t m^{-3})

$K_{d,i}$ = radionuclide sediment distribution coefficient (m^3 t^{-1})

Hence

$DRINK_i$ = Drinking water dose per unit concentration in freshwater * $A_{ufw,i}$

$= S_{1,i} \times A_{ufw,i}$

Where

$$S_{1,i} = \frac{I \times DING_i}{1 + (K_{d,i} \times ssl)}$$

Ingestion of fish

$DFISH_i = A_{fw,i} \times CF_i \times INGFISH \times DING_i$

Where

$DFISH_i$ = dose from ingestion of fish for radionuclide i (Sv y^{-1})

INGFISH = intake rate of fish (kg y^{-1})

CF_i = Concentration factor between fish and water for radionuclide i (l kg^{-1}, which is the same value as for m^3 t^{-1})

Hence

$DFISH_i$ = Fish dose per unit concentration in freshwater * $A_{ufw,i}$

$= S_{2,i} \times A_{ufw,i}$

Where

$$S_{2,i} = \frac{CF_i \times INGFISH \times DING_i}{1 + (K_{d,i} \times ssl)}$$

External dose from sediment

$DEXT_i = A_{sed,i} * TIME * GEOM * GAM_i$

Where

$DEXT_i$ = dose from exposure to contaminated sediment on a riverbank for radionuclide i (Sv y^{-1})

$A_{sed,i}$ = activity concentration in sediment for radionuclide i (Bq kg^{-1})

TIME = time spent on riverbank (hr y^{-1})

GEOM = gamma dose rate from semi-infinite source (Sv hr^{-1} per (MeV. Bq kg^{-1}))

GAM_i = mean gamma energy per disintegration for radionuclide i (MeV)

$A_{sed,i} = A_{fw,i} * K_{d,i}$ where $K_{d,i}$ is the radionuclide sediment distribution coefficient for river bank sediments (l kg^{-1}, which is the same value as for m^3 t^{-1})

Hence

$DEXT_i$ = External sediment dose per unit concentration in freshwater * $A_{ufw,i}$

$= S_{3,i} * A_{ufw,i}$

Where

$$S_{3,i} = \frac{K_{d,i} \times TIME \times GEOM \times GAM_i}{1 + (K_{d,i} \times ssl)}$$

Dose from all three pathways

The total dose (D_i) (Sv y^{-1}) is given by:

$D_i = DRINK_i + DFISH_i + EXT_i = A_{ufw} (S_{1,i} + S_{2,i} + S_{3.i})$

Calculation of exclusion or exemption level

Finally, for each age group (fetus, infant, child and adult) the activity concentration in the unfiltered water, E_i (Bq l^{-1}), that would give rise to a dose of 10 μSv y^{-1} was calculated:

$$E_i = \frac{10^{-5}}{S_{1,i} + S_{2,i} + S_{3,i}}$$

The spreadsheet was used to derive exclusion or exemption levels (Bq l^{-1}) giving rise to a dose of 10 μSv y^{-1} for fetus, infants, children and adults together with identification of the most restrictive age groups. Fetus was only considered for 14 radionuclides, as recommended in (HPA, 2008).

A4 INPUT DATA FOR SIMPLIFIED METHODOLOGY

The input parameters and data required were: intake rates, occupancy factors, dose coefficients (for infants, children and adults), sediment distribution factors for suspended and riverbank sediments (assumed to be the same) and concentration factors for freshwater fish, for the 280 or so radionuclides of interest. The dose coefficients published in ICRP-72 (ICRP, 1996) were used in the calculations, together with the data listed in Tables A2 and A3. Dose coefficients for the fetus were taken from (HPA, 2008).

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TABLE A2 Sediment distribution coefficients (k_d), for freshwater environments and concentration factors for freshwater fish

	Sediment distribution coefficient k_d ($m^3\ t^{-1}$)		Freshwater fish concentration factor ($m^3\ t^{-1}$)[(a)]	
Element	Value	Reference and notes	Value	Reference and notes
H	$3\ 10^{-2}$	Kane, 1984	$1\ 10^{0}$	NCRP, 1996. Lambers and Thorne (2006) use this value for H-3 and a value of $2.2\ 10^{4}$ for H-3 (organic)
Be	$2\ 10^{3}$	Sub group IIa element (Alkaline earths) similar to strontium	$1\ 10^{2}$	IAEA, 1994
C	$2\ 10^{3}$	IAEA, 1982	$5\ 10^{3}$ – $5\ 10^{4}$[(b)]	A value of $5\ 10^{3}$ was used for this study
N			$1.5\ 10^{5}$	Thomson, 1972
O			$1\ 10^{0}$	NCRP, 1996
F	$3\ 10^{2}$	Sub Group VIIa element similar to iodine	$1\ 10^{1}$	Thomson, 1972
Na	$6\ 10^{0}$	Booth, 1976	$2\ 10^{1}$	IAEA, 2001
Mg	$1\ 10^{3}$	Group IIa Alkaline earth element, next to calcium	$5\ 10^{1}$	Thomson, 1972
Si	$2\ 10^{3}$	Sub Group IVa element next to carbon (non-metal)	$2\ 10^{1}$	NCRP, 1996
P	$5\ 10^{1}$	IAEA, 2001	$5\ 10^{3}$ – $5\ 10^{4}$[(c)]	A value of $5\ 10^{3}$ was used for this study
S	$2\ 10^{2}$	Booth, 1976	$8\ 10^{2}$	IAEA, 2001
Cl	$3\ 10^{2}$	Sub group VIIa element similar to iodine	$5\ 10^{1}$	Thomson, 1972
K	$1\ 10^{4}$	Coughtrey et al., 1985. Similar to rubidium	$1\ 10^{3}$	Thomson, 1972
Ca	$1\ 10^{3}$	Kane, 1984	$4\ 10^{1}$	Thomson, 1972)
Sc	$7\ 10^{5}$	Booth, 1976	$1\ 10^{2}$	Thomson, 1972
V	$1\ 10^{2}$	Group Vb next to niobium	$1\ 10^{1}$	IAEA, 2001
Cr	$2\ 10^{4}$	Booth, 1976	$2\ 10^{2}$	IAEA, 2001
Mn	$5\ 10^{4}$	Zeevaert, 1987	$4\ 10^{2}$	IAEA, 2001
Al	$1\ 10^{4}$	NCRP, 1996. Assume similar to others in IIIa group (eg gallium)	$5\ 10^{2}$	NCRP, 1996
Fe	$1\ 10^{4}$	Booth, 1976	$2\ 10^{2}$	IAEA, 2001
Co	$2\ 10^{4}$	Zeevaert et al., 1987	$3\ 10^{2}$	IAEA, 2001
Ni	$1\ 10^{4}$	Coughtrey et al., 1985	$1\ 10^{2}$	IAEA, 2001
Cu	$2\ 10^{3}$	Booth, 1976	$2\ 10^{2}$	IAEA, 2001
Zn	$1\ 10^{3}$	Booth, 1976	$1\ 10^{3}$	IAEA, 2001
Ga	$1\ 10^{4}$	NCRP, 1996 Similar to others in IIIa Group eg aluminium	$4\ 10^{2}$	Thomson, 1972
Ge	$1\ 10^{4}$	Sub Group IVa element next to tin	$4\ 10^{3}$	NCRP, 1996
As	$5\ 10^{1}$	Sub group Va element similar to phosphorus (non-metal)	$5\ 10^{2}$	IAEA, 2001
Se	$4\ 10^{3}$	Coughtrey et al., 1984	$2\ 10^{2}$	IAEA, 2001
Br	$3\ 10^{2}$	Sub group VIIa element similar to iodine	$4\ 10^{2}$	IAEA, 2001
Rb	$1\ 10^{4}$	Coughtrey et al., 1984	$2\ 10^{3}$	IAEA, 2001
Sr	$2\ 10^{3}$	IAEA, 1982	$1.5\ 10^{1}$ – $7.5\ 10^{1}$[(d)]	IAEA, 1994; IAEA, 2001. A value of $5\ 10^{1}$ was used for this study
Y	$4\ 10^{3}$	IAEA, 1982	$3\ 10^{1}$	IAEA, 2001
Zr	$6\ 10^{4}$	Booth, 1976	$3\ 10^{2}$	IAEA, 2001
Nb	$1\ 10^{2}$	IAEA, 1982	$3\ 10^{2}$	IAEA, 2001
Mo	$1\ 10^{3}$	Booth, 1976	$1\ 10^{1}$	IAEA, 2001

TABLE A2 Sediment distribution coefficients (k_d), for freshwater environments and concentration factors for freshwater fish

	Sediment distribution coefficient k_d (m^3 t^{-1})		Freshwater fish concentration factor (m^3 t^{-1})[(a)]	
Element	Value	Reference and notes	Value	Reference and notes
Tc	$1\ 10^1$	Kane, 1984	$2\ 10^1$	IAEA, 2001
Ru	$7\ 10^3$	Zeevaert, 1987	$1\ 10^1$	IAEA, 2001
Rh	$1\ 10^3$	Booth, 1976	$1\ 10^1$	IAEA, 2001
Pd	$2\ 10^4$	Kane, 1984	$1\ 10^1$	Thomson, 1972
Ag	$2\ 10^2$	Booth, 1976	$5\ 10^0$	IAEA, 2001
Cd	$1\ 10^3$	Group IIb transition element similar to zinc	$2\ 10^2$	IAEA, 2001
In	$1\ 10^4$	NCRP, 1996. Assume similar to others in IIIa group eg gallium	$1\ 10^4$	IAEA, 2001
Sn	$1\ 10^4$	Kane, 1984	$3\ 10^3$	Thomson, 1972
Sb	$5\ 10^2$	Zeevaert, 1987	$1\ 10^2$	IAEA, 2001
Te	$3\ 10^1$	Booth, 1976	$4\ 10^2$	IAEA, 2001
I	$3\ 10^2$	Coughtrey et al., 1985	$4\ 10^1$	IAEA, 2001
Cs	$1\ 10^4$	Brach-Papa et al., 2005	$2\ 10^3$ – $1\ 10^{4(f)}$	IAEA, 2001
Ba	$2\ 10^3$	Sub group IIa element (Alkaline earth) similar to strontium	$4\ 10^0$	IAEA, 2001
Lu	$1\ 10^4$	Similar to cerium (Lanthanides)	$2.5\ 10^1$	Thomson, 1972
Hf	$6\ 10^4$	Sub Group IVa element, next to zirconium	$3\ 10^0$	Thomson, 1972
Ta	$1\ 10^5$	Booth, 1976	$3\ 10^2$	Staven, 2003. Similar to niobium in sub group Vb (transition elements)
W	$5\ 10^4$	Booth, 1976	$1.2\ 10^3$	Thomson, 1972
La	$6\ 10^4$	Booth, 1976	$3\ 10^1$	NCRP, 1996. Use Ce, closest value to La in the lanthanide series
Ce	$1\ 10^4$	IAEA, 2001	$3\ 10^1$	IAEA, 2001. A value of $2\ 10^3$ was used for this study
Pr	$1\ 10^5$	Booth, 1976	$2.5\ 10^1$	Thomson, 1972. Similar to Lanthanum (Lanthanides)
Nd	$6\ 10^4$	Booth, 1976	$1\ 10^2$	IAEA, 1994
Pm	$5\ 10^3$	IAEA, 2001	$3\ 10^1$	IAEA, 2001
Sm	$5\ 10^3$	Kane, 1984	$2.5\ 10^1$	Thomson, 1972
Eu	$1\ 10^4$	Similar to cerium (Lanthanides)	$5\ 10^1$	IAEA, 2001
Gd	$1\ 10^4$	Similar to cerium (Lanthanides)	$3\ 10^1$	NCRP, 1996
Tb	$1\ 10^4$	Similar to cerium (Lanthanides)	$2.5\ 10^1$	Thomson, 1972
Dy	$1\ 10^4$	Similar to cerium (Lanthanides)	$2.5\ 10^1$	Thomson, 1972
Ho	$1\ 10^4$	Similar to cerium (Lanthanides)	$2.5\ 10^1$	Thomson, 1972. Similar to lanthanum
Er	$1\ 10^4$	Similar to cerium (Lanthanides)	$2.5\ 10^1$	Thomson, 1972. Similar to lanthanum
Tm	$1\ 10^4$	Similar to cerium (Lanthanides)	$2.5\ 10^1$	Thomson, 1972
Yb	$1\ 10^4$	Similar to cerium (Lanthanides)	$2.5\ 10^1$	Thomson, 1972. Similar to lanthanum
Re	$2\ 10^2$	Group VIIb element next to technetium	$1.2\ 10^2$	Thomson, 1972. Similar order of magnitude to manganese, Group VIII (transition elements)
Os	$7\ 10^3$	Group VIII element similar to ruthenium	$1\ 10^1$	Thomson, 1972
Ir	$2\ 10^4$	Group VIII element similar to cobalt	$1\ 10^1$	Thomson, 1972. As Ru. Ir & Ru both in Group 8A of the periodic table and in the 'platinum' group
Pt	$1\ 10^4$	Group VIII element similar to nickel and	$1\ 10^2$	Thomson, 1972

TABLE A2 Sediment distribution coefficients (k_d), for freshwater environments and concentration factors for freshwater fish

	Sediment distribution coefficient k_d (m^3 t^{-1})		Freshwater fish concentration factor (m^3 t^{-1})[(a)]	
Element	Value	Reference and notes	Value	Reference and notes
		palladium		
Au	$2\ 10^2$	Sub group Ib element similar to silver	$3\ 10^1$	Thomson, 1972
Hg	$1\ 10^3$	Group II transition metal next to cadmium, assume same as cadmium and zinc	$1\ 10^3$	IAEA, 2001
Tl	$1\ 10^4$	ASTDR, 2007; NCRP, 1996. Assume similar to others in IIIa Group eg indium and gallium	$1\ 10^4$	Thomson, 1972
Pb	$1\ 10^4$	Kane, 1984	$3\ 10^2$	IAEA, 2001
Bi	$5\ 10^2$	Sub group Va element similar to antimony (other metal)	$1\ 10^1$	IAEA, 2001
Po	$4\ 10^4$	Shahul Hameed et al., 1997	$5\ 10^1$	IAEA, 2001
At	$3\ 10^2$	Sub group VIIa element similar to iodine	$1.5\ 10^1$	IAEA, 2001
Fr	$1\ 10^4$	Sub Group Ia element (Alkali metals) next to caesium	$4\ 10^2$	Thomson, 1972
Ra	$5\ 10^2$	IAEA, 2001. Consistent with Alkaline earth metals	$5\ 10^1$	IAEA, 2001
Ac	$1\ 10^5$	Actinide group similar to curium	$1.5\ 10^1$	IAEA, 2001
Th	$5\ 10^6$	Kane, 1984	$1\ 10^2$	IAEA, 2001
Pa	$5\ 10^3$	Kane, 1984	$1\ 10^1$	IAEA, 2001
U	$5\ 10^1$	IAEA, 2001	$1\ 10^1$	IAEA, 2001
Np	$5\ 10^2$	Kane, 1984	$3\ 10^1$	IAEA, 2001
Pu	$1\ 10^5$	IAEA, 2001	$3\ 10^1$	IAEA, 2001. Similar to americium (actinides)
Am	$4\ 10^5$	Coughtrey et al., 1985	$3\ 10^1$	IAEA, 2001
Cm	$1\ 10^5$	Coughtrey et al., 1984; Matsunaga et al., 1998	$3\ 10^1$	IAEA, 2001
Bk	$1\ 10^5$	Actinide similar to plutonium	$2.5\ 10^1$	Thomson, 1972
Cf	$1\ 10^5$	Use Cm as closest to Cf in the Actinide series	$3\ 10^1$	Thomson, 1972. Use Cm as closest to Cf in the actinide series
Es	$1\ 10^5$	Use Cm as closest to Es in the Actinide series	$1\ 10^1$	Thomson, 1972
Fm	$1\ 10^5$	Similar to curium in the Actinide series	$1\ 10^1$	Thomson, 1972
Md	$1\ 10^5$	Similar to curium in the Actinide series	$1\ 10^1$	NCRP, 1996

Notes

(a) Concentration factors for freshwater fish are for edible parts.

TABLE A3 Intake rates and occupancy factors[(a)]

Aquatic Intakes rates for fresh water fish (kg y^{-1})		
Infant	Child	Adult
1	5	20
Water intake rates (l yr^{-1})		
Infant	Child	Adult
260	350	600
River and lake occupancy factors (hr y^{-1})		
Infant	Child	Adult
30	500	1000

Notes

(a) Smith and Jones (2003).

APPENDIX B - Comparison of results

B1 Introduction

To investigate the acceptability of the simplified methodology described in Appendix A, the derived levels were compared with the scaled GDLs for freshwater and with values taken from the EA initial assessment methodology (Allot et al, 2006 and Lambers and Thorne, 2006).

The EA methodology considers different scenarios for the release of authorised radioactive material into the environment for 84 radionuclides. The methodology uses an approach based on cautious assumptions to ensure that radiation doses are not underestimated but without creating unduly unrealistic results. This is similar to the approach adopted in this study. The EA methodology provides dose per unit release factors (DPUR) for four types of radioactive discharges: radioactive gaseous releases to air and radioactive liquid discharges into estuary/coastal waters, rivers and public sewers. The doses to an angler family from liquid releases to a river were chosen for the intercomparison. The annual doses to the angler family were obtained from the DPUR factors and the concentration in freshwater as follows:

Dose (Sv y^{-1}) = Activity concentration (Bq l^{-1}) * river flow rate (l y^{-1}) * DPUR (Sv y^{-1} per Bq y^{-1})

Hence the activity concentration (EL, Bq l^{-1}) giving rise to a dose of 10 μSv y^{-1} is given by:

EL (Bq l^{-1}) = 10^{-5} (Sv y^{-1}) / (river flow rate (l y^{-1}) * DPUR (Sv y^{-1} per Bq y^{-1}))

The river flow rate specified in the EA methodology, 1 m^3 s^{-1} (3.15 10^{10} l y^{-1}), was used to determine the activity concentrations corresponding to a dose of 10 μSv y^{-1}.

The results of the comparison are shown in Table B1. This table gives the most restrictive age groups and exposure pathways for the three approaches, the activity concentrations in freshwater that would lead to a dose of 10 μSv y^{-1} for the EA model, the scaled GDLs, and the corresponding results using the simplified methodology using the same age group, for the 85 radionuclides of interest. The last two columns of the table give the ratio of the derived levels to the scaled GDLs for freshwater and to the EA model, respectively, using the same age group.

Derived ratios greater than 1 indicate that the simplified methodology gives a derived level that is less restrictive than the EA model or the full HPA GDL methodology. A ratio value of 0.3 to 3 was considered to represent a reasonable level of agreement between the different approaches. Ratios of less than 0.3 or greater than 3.0 were investigated further and these values are highlighted in bold type in Table B1.

The results of the comparison are discussed in the following sections.

Table B1 Comparison of derived levels using the simplified methodology, scaled GDLs for freshwater and the EA methodology (Bq l^{-1} giving 10 μSv y^{-1})

Radionuclide	Age limiting group			Activity concentration (Bq l^{-1})[(d)]				Ratio	
	EA model[(b)]	Scaled GDL[(c)]	Simplified methodology	EA model, total dose, river release to angler family	Scaled GDL	Simplified methodology value using same age limiting group as EA model	Simplified methodology value using same age limiting group as scaled GDL	Simplified methodology / GDL	Simplified methodology / EA
H-3 inorganic	Fetus	Fetus	Fetus	$5.3\ 10^{2}$	$5.0\ 10^{2}$	$5.2\ 10^{2}$	$5.2\ 10^{2}$	1.0	1.0
C-14	Fetus	Fetus	Fetus	$3.2\ 10^{-2}$	$1.0\ 10^{-1}$	$1.4\ 10^{-1}$	$1.4\ 10^{-1}$	1.4	4.4
Na-22	Infant	NC	Fetus	$2.4\ 10^{0}$	NC	$2.3\ 10^{0}$	No HPA GDL	NC, No GDL	0.9
Na-24	Infant	NC	Adult	$1.4\ 10^{1}$	NC	$1.2\ 10^{1}$	No HPA GDL	NC, No GDL	0.8
P-32	Fetus	Fetus	Fetus	$2.3\ 10^{-3}$	$4.0\ 10^{-4}$	$4.0\ 10^{-3}$	$4.0\ 10^{-3}$	**10.0**[(f)]	1.8
P-33	Fetus	Fetus	Fetus	$1.1\ 10^{-2}$	$2.0\ 10^{-3}$	$2.1\ 10^{-2}$	$2.1\ 10^{-2}$	**10.5**[(f)]	1.9
S-35 inorganic	NC	Fetus	Fetus	NC	$1.0\ 10^{1}$	NC for Fetus	$3.0\ 10^{0}$	0.3	NC No EA value
S-35 organic	Fetus	Fetus	Fetus	$1.2\ 10^{1}$	$1.0\ 10^{0}$	$3.8\ 10^{-1}$	$3.8\ 10^{-1}$	0.4	**0.03**[(f)]
Cl-36	Infant	NC	Infant	$5.1\ 10^{0}$	NC	$5.2\ 10^{0}$	No HPA GDL	NC, No GDL	1.0
Ca-45	Fetus	NC	Fetus	$9.1\ 10^{-1}$	NC	$8.6\ 10^{-1}$	No HPA GDL	NC, No GDL	1.0
Ca-47	Fetus	NC	Fetus	$4.1\ 10^{-1}$	NC	$3.2\ 10^{-2}$	No HPA GDL	NC, No GDL	**0.1**[(f)]
V-48	Adult	NC	Adult	$8.3\ 10^{-3}$	NC	$3.2\ 10^{-1}$	No HPA GDL	NC, No GDL	**38.5**[(f)]
Cr-51	Adult	Adult	Adult	$9.9\ 10^{-1}$	$4.0\ 10^{0}$	$1.0\ 10^{-1}$	$1.0\ 10^{-1}$	**0.03**[(f)]	**0.1**[(f)]
Mn-52	Adult	NC	Adult	$2.9\ 10^{-2}$	NC	$6.8\ 10^{-4}$	No HPA GDL	NC, No GDL	**0.02**[(f)]
Mn-54	Adult	Adult	Adult	$2.3\ 10^{-2}$	$1.0\ 10^{-2}$	$2.8\ 10^{-3}$	$2.8\ 10^{-3}$	**0.3**[(f)]	**0.1**[(f)]
Fe-55	Child	NC	Adult	$1.6\ 10^{1}$	NC	$3.7\ 10^{0}$	No HPA GDL	NC, No GDL	**0.2**[(f)]
Fe-59	Adult	NC	Adult	$3.3\ 10^{-2}$	NC	$4.2\ 10^{-3}$	No HPA GDL	NC, No GDL	**0.1**[(f)]
Co-56	Adult	NC	Adult	$7.2\ 10^{-3}$	NC	$9.4\ 10^{-4}$	No HPA GDL	NC, No GDL	**0.1**[(f)]
Co-57	Adult	Adult	Adult	3.510^{-1}	$2.0\ 10^{-1}$	$2.7\ 10^{-2}$	$2.7\ 10^{-2}$	**0.1**[(f)]	**0.08**[(f)]
Co-58	Adult	Adult	Adult	$2.9\ 10^{-2}$	$4.0\ 10^{-2}$	$3.4\ 10^{-3}$	$3.4\ 10^{-3}$	**0.1**[(f)]	**0.1**[(f)]
Co-60	Adult	Adult	Adult	$1.0\ 10^{-2}$	$5.0\ 10^{-3}$	$1.3\ 10^{-3}$	$1.3\ 10^{-3}$	**0.3**[(f)]	**0.1**[(f)]
Ni-63	Adult	NC	Adult	$5.1\ 10^{1}$	NC	$3.8\ 10^{1}$	No HPA GDL	NC, No GDL	0.8
Zn-65	Adult	Adult	Adult	$2.5\ 10^{-2}$	$9.0\ 10^{-2}$	$4.1\ 10^{-2}$	$4.1\ 10^{-2}$	0.5	1.6

Radionuclide	Age limiting group			Activity concentration (Bq l^{-1})[d]				Ratio	
	EA model[b]	Scaled GDL[c]	Simplified methodology	EA model, total dose, river release to angler family	Scaled GDL	Simplified methodology value using same age limiting group as EA model	Simplified methodology value using same age limiting group as scaled GDL	Simplified methodology / GDL	Simplified methodology / EA
Ga-67	Adult	NC	Adult	$5.5\ 10^{0}$	NC	$3.2\ 10^{-2}$	No HPA GDL	NC, No GDL	**0.01**[f]
Se-75	Adult	Fetus	Fetus	$4.5\ 10^{-1}$	$2.0\ 10^{-1}$	$2.5\ 10^{-2}$	$2.5\ 10^{-2}$	0.1	**0.06**[f]
Br-82	Adult	NC	Adult	$2.1\ 10^{0}$	NC	$4.2\ 10^{-2}$	No HPA GDL	NC, No GDL	**0.02**[f]
Rb-83	Adult	NC	Adult	$6.1\ 10^{-2}$	NC	$9.4\ 10^{-3}$	No HPA GDL	NC, No GDL	**0.2**[f]
Sr-89	Fetus	Infant	Fetus	$5.1\ 10^{-1}$	$2.0\ 10^{0}$	$1.0\ 10^{0}$	$2.2\ 10^{0}$	1.1	2.0
Sr-90+	Fetus	Adult	Fetus	$1.4\ 10^{-1}$	$2.0\ 10^{-1}$	$2.8\ 10^{-1}$	$4.0\ 10^{-1}$	2.0	2.0[f]
Y-90	Infant	NC	Infant	$2.0\ 10^{0}$	NC	$2.1\ 10^{0}$	No HPA GDL	NC, No GDL	1.0
Zr-95+	Adult	NC	Adult	$1.3\ 10^{-2}$ [h]	NC	$2.9\ 10^{-3}$	No HPA GDL	NC, No GDL	**0.22**
Nb-95	Adult	NC	Adult	$1.5\ 10^{0}$	NC	$3.7\ 10^{-1}$	No HPA GDL	NC, No GDL	**0.2**[f]
Mo-99	Adult	NC	Adult	$4.6\ 10^{0}$	NC	$2.3\ 10^{-1}$	No HPA GDL	NC, No GDL	**0.05**[f]
Tc-99	Infant	NC	Infant	$7.7\ 10^{0}$	NC	$7.4\ 10^{0}$	$1.6\ 10^{1}$	NC, No GDL	0.1
Tc-99m	Adult	NC	Adult	$5.4\ 10^{1}$	NC	$2.5\ 10^{1}$	$2.5\ 10^{1}$	NC, No GDL	0.5
Ru-103	Adult	NC	Adult	$1.2\ 10^{-1}$	NC	$1.4\ 10^{-2}$	$1.4\ 10^{-2}$	NC, No GDL	**0.1**[f]
Ru-106+	Adult	Child	Adult	$2.2\ 10^{-1}$	$1.0\ 10^{-1}$	$3.2\ 10^{-2}$	$6.2\ 10^{-2}$	0.62	**0.15**
Ag-110m	Adult	NC	Adult	$4.6\ 10^{-1}$	NC	$6.2\ 10^{-2}$	No HPA GDL	NC, No GDL	**0.1**[f]
In-III	Adult	NC	Adult	$1.9\ 10^{-1}$	NC	$1.2\ 10^{-2}$	No HPA GDL	NC, No GDL	**0.06**[f]
Sb-125	Adult	Adult	Adult	$1.3\ 10^{0}$	$6.0\ 10^{-1}$	$1.5\ 10^{-1}$	$1.5\ 10^{-1}$	0.3	**0.1**[f]
1-123	Adult	NC	Adult	$1.7\ 10^{1}$	NC	$7.5\ 10^{-1}$	No HPA GDL	NC, No GDL	**0.04**[f]
1-125	Adult	Children	Adult	$4.9\ 10^{-1}$	$4.0\ 10^{-1}$	$4.1\ 10^{-1}$	$5.4\ 10^{-1}$	1.3	0.8
1-129	Adult	Adult	Adult	$6.6\ 10^{-2}$	$5.0\ 10^{-2}$	$6.5\ 10^{-2}$	$6.5\ 10^{-2}$	1.3	1.0
1-131	Infant	NC	Fetus	$1.8\ 10^{-1}$	NC	$1.8\ 10^{-1}$	$1.6\ 10^{-1}$	NC, No GDL	1.0
I-132	NC	NC	Adult	NC	NC	NC	$5.0\ 10^{-2}$	NC, No GDL	NC No EA value
1-133	Infant	NC	Adult	$7.6\ 10^{-1}$	NC	$6.8\ 10^{-1}$	No HPA GDL	NC, No GDL	0.9
I-134	NC	NC	Adult	NC	NC	NC	$4.4\ 10^{-2}$	NC, No GDL	NC No EA value

Radionuclide	Age limiting group			Activity concentration (Bq l^{-1})[d]				Ratio	
	EA model[b]	Scaled GDL[c]	Simplified methodology	EA model, total dose, river release to angler family	Scaled GDL	Simplified methodology value using same age limiting group as EA model	Simplified methodology value using same age limiting group as scaled GDL	Simplified methodology / GDL	Simplified methodology / EA
1-135	Adult	NC	Adult	$2.3\ 10^{0}$	NC	$7.2\ 10^{-2}$	$7.2\ 10^{-2}$	NC, No GDL	**0.03**[f]
Cs-134	Adult	Adult	Adult	$1.2\ 10^{-2}$	$1.0\ 10^{-2}$	$2.8\ 10^{-3}$	$2.8\ 10^{-3}$	**0.3/**[f]	**0.2**[f]
Cs-136	Adult	NC	Adult	$7.2\ 10^{-2}$	NC	$2.3\ 10^{-3}$	$2.3\ 10^{-3}$	NC, No GDL	**0.03**[f]
Cs-137+	Adult	Adult	Adult	$1.9\ 10^{-2}$	$2.0\ 10^{-2}$	$6.8\ 10^{-3}$	$6.8\ 10^{-3}$	0.3	0.4
Ba-140	Adult	NC	Adult	$1.5\ 10^{-1}$	NC	$9.9\ 10^{-2}$	No HPA GDL	NC, No GDL	0.7
La-140	Adult	NC	Adult	$5.3\ 10^{-2}$	NC	$9.6\ 10^{-4}$	No HPA GDL	NC, No GDL	**0.02**[f]
Ce-141	Adult	NC	Adult	$4.6\ 10^{-1}$	NC	$6.5\ 10^{-2}$	No HPA GDL	NC, No GDL	**0.1**[f]
Ce-144	Adult	NC	Adult	$3.7\ 10^{-1}$	NC	$2.2\ 10^{-1}$	No HPA GDL	NC, No GDL	0.6
Pm-147	Infant	NC	Infant	$2.2\ 10^{1}$	NC	$2.3\ 10^{1}$	No HPA GDL	NC, No GDL	1.1
Sm-153	Adult	NC	Adult	$2.4\ 10^{0}$	NC	$1.3\ 10^{-1}$	No HPA GDL	NC, No GDL	**0.05**[f]
Eu-152	Adult	NC	Adult	$2.0\ 10^{-2}$	NC	$4.3\ 10^{-3}$	No HPA GDL	NC, No GDL	**0.2**[f]
Eu-154	Adult	NC	Adult	$1.9\ 10^{-2}$	NC	$4.0\ 10^{-3}$	No HPA GDL	NC, No GDL	**0.2**[f]
Eu-155	Adult	NC	Adult	$8.2\ 10^{-1}$	NC	$8.6\ 10^{-2}$	No HPA GDL	NC, No GDL	**0.1**[f]
Er-169	Infant	NC	Infant	$3.1\ 10^{1}$	NC	$1.9\ 10^{1}$	No HPA GDL	NC, No GDL	0.6
Lu-177	Adult	NC	Adult	$3.3\ 10^{0}$	NC	$1.6\ 10^{-1}$	No HPA GDL	NC, No GDL	**0.05**[f]
Au-198	Adult	NC	Adult	$2.8\ 10^{-1}$	NC	$4.0\ 10^{-1}$	No HPA GDL	NC, No GDL	1.4
Tl-201	Adult	NC	Adult	$6.7\ 10^{-1}$	NC	$5.3\ 10^{-2}$	No HPA GDL	NC, No GDL	**0.08**[f]
Pb-210	Adult	Adult	Adult	$2.9\ 10^{-3}$	$3.0\ 10^{-3}$	$3.3\ 10^{-3}$	$3.3\ 10^{-3}$	1.1	1.1
Po-210	Infant	Infants	Infant	$5.0\ 10^{-3}$	$3.0\ 10^{-3}$	$1.1\ 10^{-2}$	$1.1\ 10^{-2}$	**3.7**[f]	2.2
Ra-223	Infant	NC	Infant	$3.0\ 10^{-2}$	NC	$3.0\ 10^{-2}$	No HPA GDL	NC, No GDL	1.0
$Ra\text{-}226^{+}$	Fetus	Child	Fetus	$2.0\ 10^{-2}$	$2.0\ 10^{-2}$	$1.3\ 10^{-2}$	$1.7\ 10^{-2}$	0.9	0.7
Th-230	Adult	NC	Adult	$2.7\ 10^{-2}$	NC	$8.7\ 10^{-1}$	$8.7\ 10^{-1}$	NC, No GDL	**32.2**[f]
Th-232	Adult	NC	Adult	$9.7\ 10^{-3}$	NC	$9.7\ 10^{-1}$	No HPA GDL	NC, No GDL	**100.0**[f]
Th-234	Adult	NC	Adult	$8.7\ 10^{-1}$	NC	$1.8\ 10^{-1}$	$1.8\ 10^{-1}$	NC, No GDL	**0.2**[f]

Radionuclide	Age limiting group			Activity concentration (Bq l^{-1})[(d)]				Ratio	
	EA model[(b)]	Scaled GDL[(c)]	Simplified methodology	EA model, total dose, river release to angler family	Scaled GDL	Simplified methodology value using same age limiting group as EA model	Simplified methodology value using same age limiting group as scaled GDL	Simplified methodology / GDL	Simplified methodology / EA
U-234	Adult	Adult	Adult	$1.3\ 10^{-1}$	$2.0\ 10^{-1}$	$2.6\ 10^{-1}$	$2.6\ 10^{-1}$	1.3	2.0
U-235+	Adult	Adult	Adult	$1.3\ 10^{-1}$	$2.0\ 10^{-1}$	$2.5\ 10^{-2}$	$2.5\ 10^{-2}$	**0.1**	**0.2**
U-238+	Adult	Adult	Adult	$1.4\ 10^{-1}$	$2.0\ 10^{-1}$	$1.5\ 10^{-1}$	$1.5\ 10^{-1}$	1.1	0.8
Np-237	Adult	NC	Adult	$7.5\ 10^{-2}$	NC	$7.5\ 10^{-2}$	$7.5\ 10^{-2}$	NC, No GDL	1.0
Pu-238	Adult	Adult	Adult	$1.6\ 10^{-1}$	$1.0\ 10^{-1}$	$2.2\ 10^{-1}$	$2.2\ 10^{-1}$	2.2	1.3
Pu-239	Adult	Adult	Adult	$1.5\ 10^{-1}$	$1.0\ 10^{-1}$	$2.0\ 10^{-1}$	$2.0\ 10^{-1}$	2.0	1.3
Pu-240	Adult	Adult	Adult	$1.5\ 10^{-1}$	$1.0\ 10^{-1}$	$1.7\ 10^{-1}$	$1.7\ 10^{-1}$	1.7	1.1
Pu-241	Adult	Adult	Adult	$7.9\ 10^{0}$	$4.0\ 10^{0}$	$1.0\ 10^{1}$	$1.0\ 10^{1}$	2.6	1.3
Pu-242	Adult	Adult	Adult	$1.5\ 10^{-1}$	$1.0\ 10^{-1}$	$1.8\ 10^{-1}$	$1.8\ 10^{-1}$	1.8	1.2
Am-241	Adult	Adult	Adult	$5.0\ 10^{-2}$	$1.0\ 10^{-1}$	$7.5\ 10^{-2}$	$7.5\ 10^{-2}$	0.8	1.5
Am-242	Adult	NC	Adult	$5.2\ 10^{0}$	NC	$9.6\ 10^{-2}$	$9.6\ 10^{-2}$	NC, No GDL	**0.02**[(f)]
Am-243	Adult	Adult	Adult	$3.5\ 10^{-2}$	$4.0\ 10^{-2}$	$3.0\ 10^{-2}$	$3.0\ 10^{-2}$	0.8	0.9
Cm-242	Infant	Children	Adult	$9.6\ 10^{0}$	$2.0\ 10^{0}$	$2.5\ 10^{0}$	$1.5\ 10^{0}$	0.8	**0.3**[(f)]
Cm-243	Adult	Adult	Adult	$1.4\ 10^{-1}$	$5.0\ 10^{-2}$	$1.4\ 10^{-2}$	$1.4\ 10^{-2}$	**0.3**[(f)]	**0.1**[(f)]
Cm-244	Adult	Children	Adult	$1.6\ 10^{0}$	$6.0\ 10^{-2}$	$4.0\ 10^{-1}$	$8.2\ 10^{-1}$	**13.7**[(f)]	**0.3**[(f)]

Notes

(a) The most critical (age limiting) group; Fetus, infants, children or adults.

(b) Allot et al (2006) and Lambers and Thorne (2006) for a river release scenario: doses to an angler family from liquid releases to a river.

(c) HPA GDLs for fresh water (NRPB, 1998, 2000 and 2005).

(d) Activity concentrations in freshwater that would lead to a dose of 10 μSv y^{-1} for a river release scenario for an angler family (DPUR), scaled HPA GDLs for freshwater and derived levels for same age limiting groups as the EA model and HPA GDLs.

(e) HPA GDL includes progeny in secular equilibrium, see Table 1

(f) A ratio of less than 0.3 or greater than 3 is highlighted in Bold, see text.

NC, Not calculated.

B2 Comparisons of derived levels with scaled GDLS for freshwater

Table B1 shows that for thirteen radionuclides the ratio between the derived level and the scaled GDL for freshwater is less than 0.3 or greater than 3, and these were investigated further. The results for these thirteen radionuclides are extracted from Table B1 and listed in Table B2. For four of these radionuclides, the dominant exposure pathway or limiting age group differs between the two approaches; for two radionuclides, ^{134}Cs and ^{235}U, the dominant exposure pathways differ, even though the dominant age groups are the same. For the remaining nine radionuclides the most important exposure pathways and age groups were the same in both approaches.

TABLE B2 Derived levels requiring investigation when compared with scaled HPA GDLs for freshwater (Bq l^{-1} giving 10 µSv y^{-1})

Radionuclide[d]	Age limiting group / dominant exposure pathway[a]		Activity concentration (Bq l^{-1})[b]		Ratio
	HPA GDL for freshwater (%contribution)	Simplified methodology	Scaled HPA GDL	Derived level using simplified methodology for same age limiting group as HPA GDL	Simplified methodology / HPA GDL
P-32	Fetus/fish (100)	Fetus/fish	4.0 10^{-4}	4.0 10^{-3}	10.0
P-33	Fetus/fish (100)	Fetus/fish	2.0 10^{-3}	2.1 10^{-2}	10.5
Cr-51	Adult/external (100)	Adult/external	4.0 10^{0}	1.0 10^{-1}	0.03
Mn-54	Adult/external (100)	Adult/external	1.0 10^{-2}	2.8 10^{-3}	0.3
Co-57	Adult/external (98)	Adult/external	2.0 10^{-1}	2.7 10^{-2}	0.1
Co-58	Adult/external (99)	Adult/external	4.0 10^{-2}	3.4 10^{-3}	0.1
Co-60	Adult/external (99)	Adult/external	5.0 10^{-3}	1.3 10^{-3}	0.3
Cs-134	Adult/fish (75)	Adult/external	1.0 10^{-2}	2.8 10^{-3}	0.3
Po-210	Infant/drinking water and terrestrial food (45 each)	Infant /drinking water	3.0 10^{-3}	1.1 10^{-2}	3.7
U-235+	Adult/drinking water (66)	Adult/external	2.0 10^{-1}	2.5 10^{-2}	0.1
Am-242	Adult/external (100)	Adult/external	5.2 10^{0}	9.6 10^{-2}	0.02
Cm-243	Adult/external (75)	Adult/external	5.0 10^{-2}	1.4 10^{-2}	0.3
Cm-244	Child/inhalation(95)	Adult/fish	6.0 10^{-2}	8.2 10^{-1}	13.7

Notes

(a) The most critical (age limiting) groups; fetus, infant, child or adult. Also included is the dominant exposure pathway with the % contribution to the freshwater GDL (NRPB, 1998, 2000 and 2005).

(b) Activity concentrations in freshwater that would lead to a dose of 10 µSv y^{-1}.

(c) Simplified methodology does not include contribution from Pa-234m

(d) Radionuclides with progeny included are marked with a '+' symbol. See Table 1 in main text for explanation

A ratio of greater than 1 suggests that the simplified methodology is less restrictive than the GDL model and therefore the investigation focussed on the four radionuclides with ratios above 3, namely ^{32}P, ^{33}P, ^{210}Po, and ^{244}Cm.

Several factors could lead to differences between the derived levels from the simplified methodology and the GDLs. These can be grouped into exposure pathway related, model related, data related, and decay chain related factors, for example:

a) ingestion of food and inhalation of dust and aerosols pathways were included in GDLs for freshwater but not in the simplified methodology;

b) the external gamma dose models differ between the two approaches. The GDLs for freshwater used the GRANIS model (Gamma Radiation Above Nuclides In Soil) (Kowe et al, 2007). This is a model developed to calculate external photon dose from layers of contaminated material which have finite thickness yet are effectively infinite in horizontal extent. There are differences between this and the semi-infinite sphere approach taken in this study, especially at low photon energies;

c) different sediment distribution coefficients (k_d) values or concentration factors for freshwater fish may have been used in the two models for some radionuclides;

d) some of the daughters considered to be in secular equilibrium with their parent or which would ingrow significantly were considered in the GDLs but were not included in the simplified methodology.

For ^{32}P and ^{33}P, the ingestion of freshwater fish is the dominant pathway. The concentration factor for fish is in the range 5 10^3 to 5 10^4 m^3 t^{-1} (IAEA, 1994): the simplified methodology used the lower value since this is more appropriate for UK rivers (Hilton et al, 2002) whereas the GDL used the upper value and this explains the difference.

For ^{210}Po, the ingestion of terrestrial food and ingestion of drinking water are the dominant pathways contributing equally to the GDL for freshwater. Since the ingestion of terrestrial foods was not considered in the simplified methodology due to lack of appropriate foodchain data for all the radionuclides considered, this explains the discrepancy. The ratio of 3.7 is not considered to represent a significant underestimate in the context of deriving exemption or exclusion levels.

Inhalation of radionuclides in sediment is the dominant exposure pathway for ^{244}Cm, contributing around 95% of the dose using the full freshwater GDL model. Inhalation of sediment was not included in the simplified methodology, so accounting for the ratio of 13.7.

Since the scaled GDLs would be used where available, the simplified methodology was considered fit for purpose.

B3 Comparisons of derived levels with EA results

Table B1 also gives a comparison of derived levels calculated using the simplified methodology with the results, based on the EA published dose per unit release (DPUR) values (Allot et al, 2006 and Lambers and Thorne, 2006), for the 85 radionuclides in common. This shows that just over 50% of the radionuclides had ratios less than 0.3 or greater than 3; the results for these radionuclides were extracted from Table B1 and are

shown in Table B3. The limiting age group differs for 2 of these radionuclides (^{55}Fe and ^{242}Cm) and for 15 of the radionuclides the dominant exposure pathways are different even though the limiting age group is the same.

Table B3 Derived levels requiring investigation when compared to EA model (Bq l^{-1} giving 10 μSv y^{-1})

Radionuclide	Age limiting group / dominant exposure pathway[a]		Activity concentration (Bq l^{-1})[c]		Ratio [d]
	EA model [b]	Simplified methodology	EA model[b]	Derived level using simplified methodology, for same limiting age group as EA	Simplified methodology / EA model
S-35 (organic)	Fetus/external	Fetus/fish	1.2 10^{1}	3.8 10^{-1}	0.03
Ca-47	Fetus/drinking water	Fetus/fish	4.1 10^{-1}	3.2 10^{-2}	0.1
V-48	Adult/fish	Adult/external	8.3 10^{-3}	3.2 10^{-1}	38.5
Cr-51	Adult/external	Adult/external	9.9 10^{-1}	1.0 10^{-1}	0.1
Mn-52	Adult/external	Adult/external	2.9 10^{-2}	6.8 10^{-4}	0.02
Mn-54	Adult/external	Adult/external	2.3 10^{-2}	2.8 10^{-3}	0.1
Fe-55	Child/fish	Adult/external	1.6 10^{1}	3.7 10^{0}	0.2
Fe-59	Adult/external	Adult/external	3.3 10^{-2}	4.2 10^{-3}	0.1
Co-56	Adult/external	Adult/external	7.2 10^{-3}	9.4 10^{-4}	0.1
Co-57	Adult/external	Adult/external	3.5 10^{-1}	2.7 10^{-2}	0.08
Co-58	Adult/external	Adult/external	2.9 10^{-2}	3.4 10^{-3}	0.1
Co-60	Adult/external	Adult/external	1.0 10^{-2}	1.3 10^{-3}	0.1
Ga-67	Adult/fish	Adult/external	5.5 10^{0}	3.2 10^{-2}	0.01
Se-75	Adult/fish	Fetus/external	4.5 10^{-1}	2.5 10^{-2}	0.06
Br-82	Adult/fish	Adult/external	2.1 10^{0}	4.2 10^{-2}	0.02
Rb-83	Adult/external	Adult/external	6.1 10^{-2}	9.4 10^{-3}	0.2
Sr-90+	Fetus/fish	Fetus/drinking water	1.4 10^{-1}	2.8 10^{-1}	2.0
Zr-95+	Adult/external	Adult/external	1.3 10^{-2}	2.9 10^{-3}	0.2
Nb-95	Adult/fish	Adult/external	1.5 10^{0} [e]	3.7 10^{-1}	0.2
Mo-99	Adult/external	Adult/external	4.6 10^{0}	2.3 10^{-1}	0.05
Ru-103	Adult/external	Adult/external	1.2 10^{-1}	1.4 10^{-2}	0.1
Ru-106+	Adult/external	Adult/external	2.2 10^{-1} [e]	3.2 10^{-2}	0.15
Ag-110m	Adult/external	Adult/external	4.6 10^{-1}	6.1 10^{-2}	0.1
In-Ill	Adult/external	Adult/external	1.9 10^{-1}	1.2 10^{-2}	0.06
Sb-125	Adult/external	Adult/external	1.3 10^{0}	1.5 10^{-1}	0.1
1-123	Adult/external	Adult/external	1.7 10^{1}	7.5 10^{-1}	0.04
1-135	Adult/external	Adult/external	2.3 10^{0}	7.2 10^{-2}	0.03
Cs-134	Adult/fish	Adult/external	1.2 10^{-2}	2.8 10^{-3}	0.2
Cs-136	Adult/fish	Adult/external	7.2 10^{-2}	2.3 10^{-3}	0.03
La-140	Adult/external	Adult/external	5.3 10^{-2}	9.6 10^{-4}	0.02
Ce-141	Adult/external	Adult/external	4.6 10^{-1}	6.5 10^{-2}	0.1
Sm-153	Adult/external	Adult/external	2.4 10^{0}	1.3 10^{-1}	0.05

Table B3 Derived levels requiring investigation when compared to EA model (Bq l^{-1} giving 10 µSv y^{-1})

Radionuclide	Age limiting group / dominant exposure pathway[a]		Activity concentration (Bq l^{-1})[c]		Ratio [d]
	EA model [b]	Simplified methodology	EA model[b]	Derived level using simplified methodology, for same limiting age group as EA	Simplified methodology / EA model
Eu-152	Adult/external	Adult/external	$2.0\ 10^{-2}$	$4.3\ 10^{-3}$	0.2
Eu-154	Adult/external	Adult/external	$1.9\ 10^{-2}$	$4.0\ 10^{-3}$	0.2
Eu-155	Adult/external	Adult/external	$8.2\ 10^{-1}$	$8.6\ 10^{-2}$	0.1
Lu-177	Adult/external	Adult/external	$3.3\ 10^{0}$	$1.6\ 10^{-1}$	0.05
Tl-201	Adult/fish	Adult/external	$6.7\ 10^{-1}$	$5.3\ 10^{-2}$	0.08
Th-230	Adult/fish	Adult/external	$2.7\ 10^{-2}$	$8.7\ 10^{-1}$	32.2
Th-232	Adult/external	Adult/external	$9.7\ 10^{-3}$ [e]	$9.7\ 10^{-1}$ ($1.5\ 10^{-3}$ [e])	100.0 (0.15)
Th-234	Adult/external	Adult/external	$8.7\ 10^{-1}$	$1.8\ 10^{-1}$	0.2
U-235+ (e)	Adult/external	Adult/external	$1.3\ 10^{-1}$	$2.5\ 10^{-2}$	0.2
Am-242	Adult/external	Adult/external	$5.2\ 10^{0}$	$9.6\ 10^{-2}$	0.02
Cm-242	Infant/drinking water	Adult/external	$9.6\ 10^{0}$	$2.5\ 10^{0}$	0.3
Cm-243	Adult/external	Adult/external	$1.4\ 10^{-1}$	$1.4\ 10^{-2}$	0.1
Cm-244	Adult/ drinking water	Adult/fish	$1.6\ 10^{0}$	$4.0\ 10^{-1}$	0.3

Notes

(a) The most critical (age limiting) groups; infants, children or adults. Also included the dominant exposure pathway.

(b) Allot et al (2006) and Lambers and Thorne (2006) for a river release scenario: doses to an angler family from liquid releases to a river.

(c) Activity concentrations in freshwater (river release scenario: doses to an angler family from liquid releases to a river) that would lead to a dose of 10 µSv y^{-1}. Also included derived exclusion levels reported at same age limiting group as the EA dataset.

(d) Ratio of calculated exclusion level for this study compared to that reported for EA DPUR. A ratio of less than 0.3 or greater than 3 indicates that the values obtained from this study were not comparable with the HPA dataset, see text.

(e) Assuming the entire decay chain from ^{232}Th to ^{208}Tl is in secular equilibrium

As discussed in section B2, several factors can lead to differences between the results: exposure pathway related, model related, data related, and decay chain related. The external dose model in the EA methodology has an additional modifying factor of 0.2 and hence the simplified methodology will give lower derived activity concentrations for radionuclides where the dominant exposure pathway is exposure to sediment. Further investigation was focussed on the three radionuclides with ratios above 3, namely ^{48}V, ^{230}Th and ^{232}Th.

Significant differences were noted in the input data used for these radionuclides. For ^{48}V, the concentration factor used by the EA study for freshwater fish was 3 10^4 m^3 t^{-1} whereas the simplified methodology used a value of 1 10^1 m^3 t^{-1} based on consideration of its position in the periodic table (Appendix A - Table A2) since no published data were found. This would result in a more restrictive activity concentration for the EA study, as shown in Table B3.

For the isotopes of thorium the simplified methodology used a value of 5 10^6 m^3 t^{-1} (Appendix A – Table A2) for the sediment distribution coefficient (k_d) whereas the EA study used a lower k_d of 1 10^4 m^3 t^{-1}. For radionuclides with a k_d value below about 10^3 m^3 t^{-1} the fraction in the filtered water (and hence in fish) is practically independent of the k_d but the external dose from sediment is proportional to the k_d ; for radionuclides with higher k_d values the fraction in the filtered water (and hence in fish) is inversely proportional to k_d and the external dose from sediment is effectively independent of k_d . ^{230}Th and ^{232}Th have high k_d values in both models and therefore the fraction in the filtered water is dependent on the k_d value (the fraction in filtered water in the EA model is about 100 times that in the simplified model) and the fraction in the sediment is essentially independent of the k_d value. For ^{230}Th, this results in the dominant pathway in the EA model being ingestion of fish whereas in the simplified methodology it is external exposure from sediment. The difference in the fraction in the filtered water accounts for the more restrictive derived level in the EA model, as seen in Table B3.

For ^{232}Th the dominant pathway is external exposure from sediment in both models and hence is independent of the choice of the k_d value. However, the EA model also includes the contribution from its progeny ^{228}Ra to ^{208}Tl, in secular equilibrium. If these progeny are included then the resulting derived level is 1.5 10^{-3} Bq l^{-1} (see Table B3). The ratio between this value and the corresponding EA value for ^{232}Th is 0.15. Hence the models are in good agreement since the EA methodology includes an additional modifying factor of 0.2 in the external dose model.

In conclusion, the agreement between the simplified methodology and the EA methodology was generally acceptable and where differences occurred they were due to the use of different parameter values. The simplified methodology was therefore considered to be fit for purpose.

B4 REFERENCES

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APPENDIX C - Measurement of radionuclides at derived levels

C1 Introduction

The practicability of measuring the derived (unrounded) exclusion or exemption levels for the radionuclides under laboratory based conditions has been investigated. With approximately 280 radionuclides to consider it was not possible to undertake a detailed investigation of all the possible techniques that could be used. Hence the findings should be considered to be indicative only.

The practicability was assessed based on laboratory methods in common use in the UK and an indication given of which radionuclides are likely to be practical to measure. Limitations of the investigation for gamma emitting radionuclides include the fact that no account has been taken of potential interferences in the results from naturally occurring radionuclides that may also be in the sample. Also, only the gamma ray energies and probabilities of emission were considered when determining whether the level was measurable using gamma ray spectrometry; other chemical or physical characteristics may also prevent measurements being achievable.

Generally the derived levels for aqueous liquids are low so that large volumes have to be collected to obtain enough activity to measure. A substantial reduction in volume is then often necessary before analysis. This is achieved in the laboratory by either evaporation of water to concentrate the radionuclides, precipitation of the radionuclide from solution, or by using a specific separation technique. Specific techniques do exist for some elements such as the use of ion exchange resins for actinide analysis or ion chromatography separations.

C2 Measurement of radionuclides at derived levels

The derived levels for the 280 radionuclides, based on the 10 μSv yr^{-1} dose criterion, and an indication of whether measurement of this level is possible are given in Table C1. The table also includes some suggested measurement techniques and an estimate of the sample size required in the laboratory. The measurement techniques suggested in this study are by no means exhaustive and others may give a better Limit of Detection (LoD) or be easier to perform. As mentioned above, further investigation may demonstrate that it is not possible to measure these levels of activity concentration for more radionuclides than indicated in Table C1.

The sample size estimated for the analysis is cautious and considers the measurement LoD if known (or a likely estimation of the LoD) and the requirement to achieve reasonable counting statistics.

From Table C1 around 103 of the radionuclides are potentially measurable at the derived (unrounded) levels, 67 are considered unlikely to be measurable due to their short half-lives with respect to the sample preparation time, with a further 30 unlikely to be measurable in part due to their short half-lives with respect to the sample preparation time. No data on possible measurement techniques were found for around 20 radionuclides in this preliminary study. However, measurement techniques may exist for these radionuclides. Factors that adversely affected the potential to measure the radionuclides at the derived levels were generally the practicalities of handling large sample sizes or the potential difficulty in detection of the radionuclide.

For radionuclides considered to be measurable by alpha spectrometry, activity levels that are lower than the derived levels could potentially be detected. In addition, for those that require radiochemical isolation (such as some of the isotopes of plutonium, americium, uranium and thorium) measurements can be carried out sequentially from the same sample aliquot.

LoDs are generally higher for radionuclides measured by gamma-ray spectrometry which are based on a 60,000 second count. However, by increasing count times, LoDs using this technique could potentially be further reduced. Similarly, in many cases a general gamma measurement could be carried out to detect a range of radionuclides from the same sample aliquot.

TABLE C1 Measurement of radionuclides at the derived levels

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
H-3 (HTO)	$5.0\ 10^{2}$		Y	Distillation, radiochemistry, low level liquid scintillation counting	0.05
Be-7		$3.7\ 10^{-1}$	Y	Evaporation, gamma ray spectrometry	5
C-14	$1.0\ 10^{-1}$		Y	Evaporation, combustion, radiochemistry, low level liquid scintillation counting	5
F-18		$1.1\ 10^{-1}$	ND, $T_{1/2}$ 109.7 mins		
Na-22		$1.3\ 10^{0}$	Y	Gamma ray spectrometry	1
Na-24		$1.3\ 10^{0}$	Y, but $T_{1/2}$ 15 hrs	Gamma ray spectrometry	1
Si-31		$1.6\ 10^{1}$	N, $T_{1/2}$ 2.6 hrs		
P-32	$4.0\ 10^{-4}$		Y	Radiochemistry, low level liquid scintillation counting	30
P-33	$2.0\ 10^{-3}$		Y	Radiochemistry, low level liquid scintillation counting	20
S-35(inorganic)	$1.0\ 10^{1}$		Y	Radiochemistry, low level liquid scintillation counting	0.05
S-35(organic)	$1.0\ 10^{0}$		Y	Radiochemistry, low level liquid scintillation counting	0.05
Cl-36		$5.2\ 10^{0}$	ND		

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
Cl-38		$7.6\ 10^{-2}$	N, $T_{1/2}$ 37.2 mins		
K-42		$1.8\ 10^{-2}$	N, $T_{1/2}$ 12.4 hrs, sample size required too large	Evaporation, gamma ray spectrometry	280
K-43		$5.2\ 10^{-3}$	N, $T_{1/2}$ 22.6 hrs, sample size required too large	Evaporation, gamma ray spectrometry	150
Ca-47		$3.2\ 10^{-2}$	Possibly, but $T_{1/2}$ 4.5 days and would need to evaporate down	Evaporation, gamma ray spectrometry	40
Sc-46		$8.5\ 10^{-4}$	N, sample size required too large	Evaporation, gamma ray spectrometry	600
Sc-47		$1.6\ 10^{-2}$	ND		
Sc-48		$5.1\ 10^{-4}$	ND, $T_{1/2}$ 43.7 hrs		
V-48		$3.2\ 10^{-1}$	Y	Evaporation, gamma ray spectrometry	5
Cr-51	$4.0\ 10^{0}$		Y	Evaporation, gamma ray spectrometry	2.5
Mn-51		$2.3\ 10^{-3}$	ND, $T_{1/2}$ 46.2 mins		
Mn-52		$6.8\ 10^{-4}$	N, $T_{1/2}$ 5.5 days, sample size required too large	Evaporation, gamma ray spectrometry	600
Mn-52m		$9.7\ 10^{-4}$	N, $T_{1/2}$ 21.1 mins		
Mn-53		$1.7\ 10^{0}$	N, gamma energy too low		
Mn-54	$1.0\ 10^{-2}$		Y	Evaporation, gamma ray spectrometry	50
Mn-56		$1.4\ 10^{-3}$	N, $T_{1/2}$ 2.5 hrs		
Fe-52		$6.7\ 10^{-3}$	N, $T_{1/2}$ 8.3 hrs		
Fe-55		$2.3\ 10^{0}$	Y	Possible radiochemistry, low level liquid scintillation counting	1
Fe-59		$4.2\ 10^{-3}$	Y	Evaporation, gamma ray spectrometry	40
Co-55		$1.7\ 10^{-3}$	ND, $T_{1/2}$ 17.5 hrs		
Co-56		$9.4\ 10^{-4}$	N, sample size required too large	Evaporation, gamma ray spectrometry	150
Co-57	$2.0\ 10^{-1}$		Y	Evaporation, gamma ray spectrometry	5
Co-58	$4.0\ 10^{-2}$		Y	Evaporation, gamma ray spectrometry	15
Co-58m		$1.6\ 10^{0}$	N, $T_{1/2}$ 9.2 hrs		
Co-60	$5.0\ 10^{-3}$		N, sample size required too large	Evaporation, gamma ray spectrometry	170
Co-60m		$4.8\ 10^{-1}$	N, $T_{1/2}$ 10.4 mins		
Co-61		$3.7\ 10^{-2}$	N, $T_{1/2}$ 1.7 hrs		
Co-62m		$1.2\ 10^{-3}$	N, $T_{1/2}$ 13.9 mins		
Ni-59		$2.0\ 10^{0}$	N, gamma energy too		

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
			low		
Ni-63		$3.8\ 10^{1}$	Y	Possible radiochemistry, low level liquid scintillation counting	0.5
Ni-65		$9.1\ 10^{-3}$	N, $T_{1/2}$ 2.5 hrs		
Cu-64		$9.6\ 10^{-2}$	N, $T_{1/2}$ 12.7 hrs		
Zn-65	$9.0\ 10^{-2}$		Y	Evaporation, gamma ray spectrometry	20
Zn-69		$1.6\ 10^{1}$	N, $T_{1/2}$ 57.0 min		
Zn-69m		$8.0\ 10^{-2}$	N, $T_{1/2}$ 13.8 hrs		
Ga-67		$3.2\ 10^{-2}$	N, $T_{1/2}$ 3.3 days, would need to evaporate down	Evaporation, gamma ray spectrometry	20
Ga-72		$1.9\ 10^{-3}$	N, $T_{1/2}$ 14.1 hrs, sample size required too large	Evaporation, gamma ray spectrometry	100
Ge-71		$1.1\ 10^{0}$	N, gamma energy too low		
As-73		$3.3\ 10^{0}$	Possibly, but gamma energies low	Gamma ray spectrometry	1
As-74		$4.0\ 10^{-1}$	Y	Evaporation, gamma ray spectrometry	5
As-76		$4.3\ 10^{-1}$	Unlikely, $T_{1/2}$ 1.1 days, would need to evaporate down	Evaporation, gamma ray spectrometry	5
As-77		$2.3\ 10^{0}$	N, $T_{1/2}$ 38.9 hrs, would need to evaporate down	Evaporation, gamma ray spectrometry	40
Se-75	$2.0\ 10^{-1}$		Y	Evaporation, gamma ray spectrometry	7
Br-82		$4.2\ 10^{-2}$	Unlikely, $T_{1/2}$ 35.3 hrs, difficult to measure		10
Rb-86		$3.8\ 10^{-2}$	N, sample size required too large	Evaporation, gamma ray spectrometry	250
Sr-85		$3.6\ 10^{-2}$	Y	Evaporation, gamma ray spectrometry	30
Sr-85m		$8.4\ 10^{-2}$	N, $T_{1/2}$ 69.6 min		
Sr-87m		$5.7\ 10^{-2}$	N, $T_{1/2}$ 2.8 hrs		
Sr-89	$2.0\ 10^{0}$		Y	Radiochemistry, low level liquid scintillation	0.5
Sr-90+[f]	$2.0\ 10^{-1}$		Y	Radiochemistry, beta spectrometry	5
Sr-91		$2.6\ 10^{-2}$	N, $T_{1/2}$ 9.5 hrs		
Sr-92		$1.4\ 10^{-2}$	N, $T_{1/2}$ 2.7 hrs		
Y-90		$2.1\ 10^{0}$	Y, $T_{1/2}$ 64.1 hrs	Radiochemistry, beta spectrometry	0.5
Y-91		$1.7\ 10^{0}$	ND		
Y-91m		$1.9\ 10^{-2}$	N, $T_{1/2}$ 49.7 min		

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
Y-92		$4.0\ 10^{-2}$	N, $T_{1/2}$ 3.5 hrs		
Y-93		$1.1\ 10^{-1}$	N, $T_{1/2}$ 10.1 hrs		
Zr-93		$5.5\ 10^{0}$	ND		
Zr-95+[ff]		$2.9\ 10^{-3}$	N, sample size required too large	Evaporation, gamma ray spectrometry	300
Zr-97		$1.2\ 10^{-2}$	N, $T_{1/2}$ 16.9 hrs and sample size required too large	Evaporation, gamma ray spectrometry	100
Nb-93m		$1.2\ 10^{1}$	N, gamma energies too low		
Nb-94		$1.7\ 10^{-1}$	Y	Evaporation, gamma ray spectrometry	2.5
Nb-95		$3.7\ 10^{-1}$	Y	Evaporation, gamma ray spectrometry	2
Nb-97		$5.0\ 10^{-1}$	N, $T_{1/2}$ 72.0 mins		
Nb-98		$1.4\ 10^{-1}$	N, $T_{1/2}$ 51.5 mins		
Mo-90		$4.2\ 10^{-2}$	N, $T_{1/2}$ 5.7 hrs		
Mo-93		$1.8\ 10^{0}$	N, gamma energies too low		
Mo-99		$2.3\ 10^{-1}$	Y, $T_{1/2}$ 66.0 hrs	Evaporation, gamma ray spectrometry	40
Mo-101		$2.7\ 10^{-2}$	N, $T_{1/2}$ 14.7 mins		
Tc-96		$1.2\ 10^{0}$	Y	Evaporation, gamma ray spectrometry	2.0
Tc-96m		$6.1\ 10^{1}$	N, $T_{1/2}$ 51.5 mins		
Tc-97		$7.2\ 10^{1}$	N, gamma energies too low		
Tc-97m		$8.7\ 10^{0}$	N, gamma energies too low		
Tc-99		$7.4\ 10^{0}$	Y	Radiochemistry, beta spectrometry	1
Tc-99m		$2.5\ 10^{1}$	Possibly, but $T_{1/2}$ 6.0 hrs	Gamma ray spectrometry	1
Ru-97		$2.7\ 10^{-2}$	Unlikely, $T_{1/2}$ 2.9 days and need to evaporate down	Evaporation, gamma ray spectrometry	40
Ru-103		$1.4\ 10^{-2}$	Y	Evaporation, gamma ray spectrometry	40
Ru-105		$8.3\ 10^{-3}$	N, $T_{1/2}$ 4.4 hrs		
Ru-106+[f]	$1.0\ 10^{-1}$		Y	Evaporation, gamma ray spectrometry	40
Rh-103m		$2.0\ 10^{1}$	N, $T_{1/2}$ 56.1 mins		
Rh-105		$4.5\ 10^{-1}$	Unlikely, $T_{1/2}$ 35.3 hrs and need to evaporate down	Evaporation, gamma ray spectrometry	10
Pd-103		$2.3\ 10^{-1}$	N, gamma energies too low		
Pd-109		$2.8\ 10^{-1}$	N, $T_{1/2}$ 13.4 hrs,		

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
			gamma emissions low and need to evaporate down		
Ag-105		$3.2\ 10^{-1}$	ND		
Ag-108m		$1.0\ 10^{-1}$	Y	Evaporation, gamma ray spectrometry	5
Ag-110m		$6.1\ 10^{-2}$	Y	Evaporation, gamma ray spectrometry	15
Ag-111		$4.0\ 10^{0}$	Y, $T_{1/2}$ 7.5 days	Gamma ray spectrometry	1
Cd-109		$6.1\ 10^{-1}$	N, gamma energies too low		
Cd-115		$1.4\ 10^{-1}$	Unlikely, $T_{1/2}$ 53.5 hrs and need to evaporate down	Evaporation, gamma ray spectrometry	20
Cd-115m		$4.8\ 10^{-1}$	N, sample size required too large	Evaporation, gamma ray spectrometry	200
In-111		$1.2\ 10^{-2}$	N, $T_{1/2}$ 2.8 days and need to evaporate down	Evaporation, gamma ray spectrometry	50
In-113m		$1.9\ 10^{-2}$	N, $T_{1/2}$ 1.7 hrs		
In-114m		$1.4\ 10^{-2}$	N, sample size required too large	Evaporation, gamma ray spectrometry	400
In-115m		$3.0\ 10^{-2}$	N, $T_{1/2}$ 4.5 hrs		
Sn-113		$1.3\ 10^{-1}$	ND		
Sn-125		$1.3\ 10^{-2}$	N, sample size required too large	Evaporation, gamma ray spectrometry	800
Sb-122		$1.5\ 10^{-1}$	Possibly, but $T_{1/2}$ 2.7 days and need to evaporate down	Evaporation, gamma ray spectrometry	10
Sb-124		$3.7\ 10^{-2}$	Y	Evaporation, gamma ray spectrometry	20
Sb-125	$6.0\ 10^{-1}$		Y	Evaporation, gamma ray spectrometry	6
Te-123m		$7.5\ 10^{-1}$	Y	Evaporation, gamma ray spectrometry	2
Te-125m		$1.3\ 10^{0}$	N, gamma energies too low		
Te-127		$6.7\ 10^{0}$	N, $T_{1/2}$ 9.4 hrs		
Te-127m		$5.0\ 10^{-1}$	Possibly	Possible radiochemistry, low level liquid scintillation	2
Te-129		$9.3\ 10^{0}$	N, $T_{1/2}$ 69.6 mins		
Te-129m		$3.8\ 10^{-1}$	Possibly, but sample size required large	Evaporation, gamma ray spectrometry	90
Te-131		$2.2\ 10^{0}$	N, $T_{1/2}$ 25.0 mins		
Te-131m		$3.5\ 10^{-1}$	Unlikely, $T_{1/2}$ 30.0 hrs and need to evaporate down	Evaporation, gamma ray spectrometry	7
Te-132		$2.9\ 10^{-1}$	Possibly, $T_{1/2}$ 3.3 days and need to	Evaporation, gamma ray spectrometry	7

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
			evaporate down		
Te-133		$1.1\ 10^{0}$	N, $T_{1/2}$ 12.4 mins		
Te-133m		$4.4\ 10^{-1}$	N, $T_{1/2}$ 55.4 mins		
Te-134		$1.1\ 10^{0}$	N, $T_{1/2}$ 41.8 mins		
I-123		$7.5\ 10^{-1}$	Possibly but $T_{1/2}$ 13.2 hrs	Gamma ray spectrometry	1
I-125	$4.0\ 10^{-1}$		Y	Radiochemistry, gamma ray spectrometry	3
I-126		$1.2\ 10^{-1}$	Y	Evaporation, gamma ray spectrometry	20
I-129	$5.0\ 10^{-2}$		Y	Radiochemistry, gamma ray spectrometry	50
I-130		$5.2\ 10^{-2}$	Unlikely, $T_{1/2}$ 12.4 hrs		
I-131		$1.5\ 10^{-1}$	Y	Evaporation, gamma ray spectrometry	5
I-132		$5.0\ 10^{-2}$	N, $T_{1/2}$ 2.3 hrs	Evaporation, gamma ray spectrometry	10
I-133		$1.7\ 10^{-1}$	N, $T_{1/2}$ 20.8 hrs and need to evaporate down	Evaporation, gamma ray spectrometry	12
I-134		$4.4\ 10^{-2}$	N, $T_{1/2}$ 52.5 mins	Evaporation, gamma ray spectrometry	10
I-135		$7.2\ 10^{-2}$	N, $T_{1/2}$ 6.5 hrs	Evaporation, gamma ray spectrometry	50
Cs-129		$1.8\ 10^{-2}$	N, $T_{1/2}$ 32.2hrs, large sample size and need to evaporate down	Evaporation, gamma ray spectrometry	100
Cs-131		$2.1\ 10^{-1}$	N, gamma energies too low		
Cs-132		$7.1\ 10^{-3}$	Unlikely, $T_{1/2}$ 6.5 days, large sample size and need to evaporate down	Evaporation, gamma ray spectrometry	75
Cs-134	$1.0\ 10^{-2}$		Y	Evaporation, gamma ray spectrometry	50
Cs-134m		$1.9\ 10^{-1}$	N, $T_{1/2}$ 2.9 hrs		
Cs-135		$1.8\ 10^{-1}$	ND		
Cs-136		$2.3\ 10^{-3}$	N, $T_{1/2}$ 13.1 days, sample size required too large	Evaporation, gamma ray spectrometry	400
Cs-137+[f]	$2.0\ 10^{-2}$		Y	Evaporation, gamma ray spectrometry	25
Cs-138		$2.2\ 10^{-3}$	N, $T_{1/2}$ 32.2 mins		
Ba-131		$4.0\ 10^{-2}$	N, $T_{1/2}$ 11.8 days and sample size required too large	Evaporation, gamma ray spectrometry	130
Ba-140		$9.9\ 10^{-2}$	Y, $T_{1/2}$ 12.7 days and need to evaporate down	Evaporation, gamma ray spectrometry	40

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
La-140		$9.6\ 10^{-4}$	N, sample size required too large	Evaporation, gamma ray spectrometry	1000
Ce-139		$3.1\ 10^{-2}$	Y	Evaporation, gamma ray spectrometry	30
Ce-141		$6.5\ 10^{-2}$	Y	Evaporation, gamma ray spectrometry	30
Ce-143		$1.8\ 10^{-2}$	N, sample size required too large	Evaporation, gamma ray spectrometry	150
Ce-144		$2.2\ 10^{-1}$	Y	Evaporation, gamma ray spectrometry	50
Pr-142		$3.4\ 10^{-2}$	ND		
Pr-143		$2.4\ 10^{1}$	Possibly, if suitable method can be found by radiochemistry and low level liquid scintillation		Unknown
Nd-147		$1.6\ 10^{-2}$	N, sample size required too large	Evaporation, gamma ray spectrometry	600
Nd-149		$5.9\ 10^{-3}$	N, $T_{1/2}$ 1.7 hrs		
Pm-147		$2.3\ 10^{1}$	Y	Possible radiochemistry, low level liquid scintillation counting	0.5
Pm-149		$7.3\ 10^{-1}$	N, $T_{1/2}$ 53.1 hrs and need to evaporate down	Evaporation, Gamma ray spectrometry	50
Sm-151		$6.8\ 10^{1}$	Y	Possible radiochemistry, low level liquid scintillation counting	0.5
Sm-153		$1.3\ 10^{-1}$	Y, $T_{1/2}$ 46.8 hrs and need to evaporate down	Evaporation, gamma ray spectrometry	30
Eu-152		$4.3\ 10^{-3}$	N, sample size required too large	Evaporation, gamma ray spectrometry	800
Eu-152m		$1.7\ 10^{-2}$	N, $T_{1/2}$ 9.3 hrs		
Eu-154		$4.0\ 10^{-3}$	N, size required too large	Evaporation, gamma ray spectrometry	1000
Eu-155		$8.6\ 10^{-2}$	Y, sample size needed large	Evaporation, gamma ray spectrometry	60
Gd-153		$4.8\ 10^{-2}$	Y, sample size needed large	Evaporation, gamma ray spectrometry	60
Gd-159		$1.0\ 10^{-1}$	N, sample size needed large	Evaporation, gamma ray spectrometry	100
Tb-160		$4.5\ 10^{-3}$	N, sample size needed too large	Evaporation, gamma ray spectrometry	800
Dy-165		$1.9\ 10^{-1}$	N, $T_{1/2}$ 2.3 hrs		
Dy-166		$1.2\ 10^{-1}$	Y, but $T_{1/2}$ 81.7 hrs and need to evaporate down	Evaporation, gamma ray spectrometry or low level liquid scintillation counting	50
Ho-166		$1.7\ 10^{-1}$	Possibly, but $T_{1/2}$ 26.9 hrs and need to	Evaporation, low level liquid scintillation counting	5

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
			evaporate down		
Er-169		$1.9\ 10^{1}$	ND		
Er-171		$1.3\ 10^{-2}$	N, $T_{1/2}$ 7.5 hrs		
Tm-170		$8.4\ 10^{-1}$	Y	Evaporation, gamma ray spectrometry	50
Tm-171		$7.2\ 10^{0}$	Possibly, if method exists by radiochemistry and low level liquid scintillation	Possible radiochemistry, low level liquid scintillation	5
Yb-175		$1.3\ 10^{-1}$	N,$T_{1/2}$ 4.1 days and need to evaporate down	Evaporation, gamma ray spectrometry	100
Lu-177		$1.6\ 10^{-1}$	Unlikely, $T_{1/2}$ 6.7 days and need to evaporate down	Evaporation, gamma ray spectrometry	60
Hf-181		$4.0\ 10^{-3}$	N, sample size needed too large	Possible radiochemistry, low level liquid scintillation counting	250
Ta-182		$1.5\ 10^{-3}$	N, sample size required too large		300
W-181		$5.8\ 10^{-2}$	Y	Evaporation, gamma ray spectrometry	60
W-185		$3.0\ 10^{0}$	Y	Possible radiochemistry, low level liquid scintillation counting	0.5
W-187		$4.9\ 10^{-3}$	N, sample size needed too large	Evaporation, gamma ray spectrometry	700
Re-186		$1.8\ 10^{0}$	Y, but $T_{1/2}$ 3.8 days	Evaporation, gamma ray spectrometry	5
Re-188		$1.3\ 10^{0}$	Possibly, but $T_{1/2}$ 17.0 hrs and need to evaporate down	Evaporation, Gamma ray spectrometry	7
Os-185		$9.0\ 10^{-3}$	Possibly, but large sample size needed	Evaporation, gamma ray spectrometry	90
Os-191		$8.1\ 10^{-2}$	Y, $T_{1/2}$ 15.4 days and large sample size needed	Evaporation, gamma ray spectrometry	60
Os-191m		$7.0\ 10^{-1}$	Possibly, but $T_{1/2}$ 13.0 hrs	Evaporation, possible radiochemistry, low level liquid scintillation counting	Unknown
Os-193		$8.8\ 10^{-2}$	Possibly but $T_{1/2}$ 30.0 hrs	Evaporation, low level liquid scintillation counting	10
Ir-190		$2.3\ 10^{-3}$	N, sample size required too large		200
Ir-192		$4.1\ 10^{-3}$	N, sample size needed too large	Evaporation, gamma ray spectrometry	300
Ir-194		$3.7\ 10^{-2}$	N, $T_{1/2}$ 19.1 hrs and need to evaporate down	Evaporation, gamma ray spectrometry	300
Pt-191		$1.7\ 10^{-2}$	N, $T_{1/2}$ 2.8 days and	Evaporation, gamma ray	150

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
			need to evaporate down	spectrometry	
Pt-193m		$3.8\ 10^{-1}$	N, probability of gamma emission too low		
Pt-197		$2.0\ 10^{-1}$	N, $T_{1/2}$ 18.3 hrs and need to evaporate down	Evaporation, gamma ray spectrometry	25
Pt-197m		$6.0\ 10^{-2}$	N, $T_{1/2}$ 94.3 mins		
Au-198		$4.0\ 10^{-1}$	Y, $T_{1/2}$ 2.7 days and need to evaporate down	Evaporation, gamma ray spectrometry	2
Au-199		$1.7\ 10^{0}$	Y, $T_{1/2}$ 3.1 days and need to evaporate down	Evaporation, gamma ray spectrometry	2
Hg-197		$4.3\ 10^{-1}$	Possibly, $T_{1/2}$ 64.1 hrs and need to evaporate down slowly due to volatility	Evaporation, gamma ray spectrometry	6
Hg-197m		$3.0\ 10^{-1}$	N, $T_{1/2}$ 23.8 hrs, volatility issues	Evaporation, gamma ray spectrometry	10
Hg-203		$1.1\ 10^{-1}$	Y, but need to evaporate down slowly due to volatility	Evaporation, gamma ray spectrometry	20
Tl-200		$3.8\ 10^{-3}$	N, $T_{1/2}$ 26.1 hrs, sample size required too large		115
Tl-201		$5.3\ 10^{-2}$	Possibly, $T_{1/2}$ 73.1 hrs and need to evaporate down	Evaporation, gamma ray spectrometry	40
Tl-202		$1.0\ 10^{-2}$	Y, $T_{1/2}$ 12.2 days and need to evaporate down	Evaporation, gamma ray spectrometry	60
Tl-204		$6.1\ 10^{-2}$	Y	Radiochemistry, low level liquid scintillation	15
Pb-203		$1.6\ 10^{-2}$	N, $T_{1/2}$ 52.0 hrs and need to evaporate down	Evaporation, gamma ray spectrometry	60
Pb-210		$3.3\ 10^{-3}$	Y	Radiochemistry, alpha spectrometry	40
Pb-212		$3.1\ 10^{-2}$	N, $T_{1/2}$ 10.6 hrs and need to evaporate down	Evaporation, gamma ray spectrometry	80
Bi-206		$2.1\ 10^{-2}$	Possibly, but $T_{1/2}$ 6.2 days and need to evaporate down	Evaporation, gamma ray spectrometry	25
Bi-207		$4.4\ 10^{-2}$	Y	Evaporation, gamma ray spectrometry	20
Bi-210		$3.9\ 10^{0}$	Possibly but $T_{1/2}$ 5.0 days	Radiochemistry, low level liquid scintillation counting	0.5
Bi-212		$3.7\ 10^{-1}$	N, $T_{1/2}$ 60.6 mins		

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
Po-203		$1.5\ 10^{-3}$	N, $T_{1/2}$ 36.7 mins		
Po-205		$1.6\ 10^{-3}$	N, $T_{1/2}$ 1.8 hrs		
Po-207		$1.9\ 10^{-3}$	N, $T_{1/2}$ 5.8 hrs		
Po-210	$3.0\ 10^{-3}$		Y	Radiochemistry, alpha spectrometry	40
At-211		$4.7\ 10^{-1}$	N, $T_{1/2}$ 7.2 hrs		
Ra-223		$3.0\ 10^{-2}$	Y, $T_{1/2}$ 11.4 days and need to evaporate down	Evaporation, gamma ray spectrometry	20
Ra-224+[f]		$2.7\ 10^{-2}$	Y, but $T_{1/2}$ 3.7 days and need to evaporate down	Radiochemistry, low level liquid scintillation counting	30
Ra-225		$2.8\ 10^{-2}$	Y, $T_{1/2}$ 14.8 days and need to evaporate down	Radiochemistry, low level liquid scintillation counting	40
Ra-226+[f]	$2.0\ 10^{-2}$		Y	Radiochemistry, low level liquid scintillation counting	30
Ra-227		$4.1\ 10^{-1}$	N, $T_{1/2}$ 42.2 mins		
Ra-228		$4.4\ 10^{-3}$	ND		
Ac-227		$6.0\ 10^{-2}$	Y	Evaporation, possible radiochemistry, low level liquid scintillation counting	15
Ac-228		$2.2\ 10^{-3}$	N, $T_{1/2}$ 6.1 hrs		
Th-226		$1.9\ 10^{-1}$	N, $T_{1/2}$ 30.9 mins		
Th-227		$1.6\ 10^{-2}$	ND		
Th-228		$4.9\ 10^{-1}$	Y	Radiochemistry, alpha spectrometry	1
Th-229		$1.7\ 10^{-2}$	Y, if suitable tracer can be found	Radiochemistry, alpha spectrometry	30
Th-230		$8.7\ 10^{-1}$	Y	Radiochemistry, alpha spectrometry	1
Th-231		$6.6\ 10^{-2}$	Unlikely, N, $T_{1/2}$ 25.5 hrs and would need to evaporate down	Evaporation, possible gamma spectrometry	25
Th-232		$9.7\ 10^{-1}$	Y	Radiochemistry, alpha spectrometry	0.5
Th-234		$1.8\ 10^{-1}$	Possibly	Possibly by radiochemistry, low level beta counting	10
Pa-230		$1.3\ 10^{-2}$	Possibly but $T_{1/2}$ 17.4 days and need to evaporate down	Evaporation, possible radiochemistry, low level liquid scintillation counting	50
Pa-231		$2.0\ 10^{-2}$	Y	Evaporation, radiochemistry, mass spectrometry	Not known
Pa-233		$4.1\ 10^{-2}$	Y but $T_{1/2}$ 27.0 days and need to evaporate down	Evaporation, gamma ray spectrometry	60
U-230		$1.2\ 10^{-1}$	Unlikely, probably of gamma emission low		
U-231		$6.9\ 10^{0}$	N, $T_{1/2}$ 4.2 days		

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
U-232		$3.8\ 10^{-2}$	Y	Radiochemistry, alpha spectrometry	15
U-233		$2.5\ 10^{-1}$	Possibly	Radiochemistry, alpha spectrometry	5
U-234	$2.0\ 10^{-1}$		Y	Radiochemistry, alpha spectrometry	2.5
U-235+[f]	$2.0\ 10^{-1}$		Y	Radiochemistry, alpha spectrometry	2.5
U-236		$2.7\ 10^{-1}$	Y	Radiochemistry, alpha spectrometry	2.5
U-237		$3.7\ 10^{0}$	N, $T_{1/2}$ only 6.7 days		
U-238+[f]	$2.0\ 10^{-1}$		Y	Radiochemistry, alpha spectrometry	2.5
U-239		$1.3\ 10^{1}$	N, $T_{1/2}$ only 23.5 mins		
U-240		$4.6\ 10^{0}$	N, $T_{1/2}$ only 14.1 hrs		
Np-237		$7.5\ 10^{-2}$	Y	Radiochemistry, alpha spectrometry	7
Np-239		$3.8\ 10^{-1}$	Y	Radiochemistry, alpha spectrometry	2
Np-240		$5.2\ 10^{-2}$	N, $T_{1/2}$ only 64.8 mins		
Pu-234		$2.9\ 10^{-2}$	N, $T_{1/2}$ 8.8 hrs		
Pu-235		$2.1\ 10^{-2}$	N, $T_{1/2}$ 25.3 mins		
Pu-236		$3.6\ 10^{-1}$	Y	Radiochemistry, alpha spectrometry	5
Pu-237		$3.8\ 10^{-2}$	Y, $T_{1/2}$ only 45.3 days	Radiochemistry, ICPMS	unknown
Pu-238	$1.0\ 10^{-1}$		Y	Radiochemistry, alpha spectrometry	5
Pu-239	$1.0\ 10^{-1}$		Y	Radiochemistry, alpha spectrometry	5
Pu-240	$1.0\ 10^{-1}$		Y	Radiochemistry, alpha spectrometry	5
Pu-241 [g]	$4.0\ 10^{0}$		ND		
Pu-242	$1.0\ 10^{-1}$		Y	Radiochemistry, alpha spectrometry	5
Pu-243		$7.8\ 10^{-2}$	N, $T_{1/2}$ only 5.0 hrs		
Pu-244		$1.8\ 10^{-1}$	Y	Radiochemistry, mass spectrometry	unknown
Am-241	$1.0\ 10^{-1}$		Y	Radiochemistry, alpha spectrometry	5
Am-242		$9.6\ 10^{-2}$	N, $T_{1/2}$ only 16.2 hrs		
Am-242m		$2.5\ 10^{-1}$	Y	Radiochemistry, alpha spectrometry	2
Am-243	$4.0\ 10^{-2}$		Y	Radiochemistry, low level liquid scintillation counting or ICPMS	25
Cm-242	$2.0\ 10^{0}$		Y	Radiochemistry, alpha spectrometry	0.5

Radionuclide	Level corresponding to 10 μSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]
Cm-243	$5.0\ 10^{-2}$		Y	Radiochemistry, alpha spectrometry	10
Cm-244	$6.0\ 10^{-2}$		Y	Radiochemistry, low level liquid scintillation counting or ICPMS	10
Cm-245		$1.9\ 10^{-2}$	N, sample size required too large	Evaporation, gamma ray spectrometry	250
Cm-246		$2.0\ 10^{-1}$	Y	Radiochemistry, alpha spectrometry	2.5
Cm-247		$6.2\ 10^{-3}$	Y, but sample size required large	Radiochemistry, alpha spectrometry	80
Cm-248		$6.3\ 10^{-2}$	Y	Radiochemistry, alpha spectrometry	8
Bk-249		$5.6\ 10^{1}$	Y	Radiochemistry, low level liquid scintillation counting or ICPMS	0.1
Cf-246		$1.4\ 10^{0}$	ND		
Cf-248		$8.3\ 10^{-1}$	Possibly, probability of gamma emission very low	Radiochemistry, low level liquid scintillation counting or ICPMS?	Not known
Cf-249		$5.8\ 10^{-3}$	N, sample size required too large	Evaporation, gamma ray spectrometry	450
Cf-250		$2.6\ 10^{-1}$	ND		
Cf-251		$1.4\ 10^{-2}$	N, sample size required too large	Evaporation, gamma ray spectrometry	350
Cf-252		$1.0\ 10^{-1}$	Possibly	Radiochemistry, alpha spectrometry	5
Cf-253		$1.9\ 10^{1}$	Possibly, but $T_{1/2}$ only 17.8 days	Radiochemistry, alpha spectrometry	5
Cf-254		$1.1\ 10^{-4}$	ND		
Es-253		$1.6\ 10^{0}$	ND		
Es-254		$1.0\ 10^{-1}$	Possibly	Radiochemistry, alpha spectrometry	5
Es-254m		$4.3\ 10^{-3}$	N, $T_{1/2}$ only 39.3 hrs		
Fm-254		$1.6\ 10^{0}$	N, $T_{1/2}$ only 3.2 hrs		
Fm-255		$1.5\ 10^{-1}$	N, $T_{1/2}$ only 20.1 hrs		

Notes

(a) Scaled to 10 μSv y^{-1} derived exclusion levels given for all radionuclides where HPA GDLs do not exist.

(b) GDLs for freshwater included activity in the dissolved and suspended fractions. Documents of the NRPB (1998), (2000) and (2005).

(c) Indication given whether the radionuclide could potentially be measurable. **Caution**: The data presented are from a brief review since a full investigation of potential measurability was outside the scope of the study, data must only be used a rough guide, see text.

(d) Suggested measurement technique. This only gives an indication and by no means gives the only available technique (see text). See caution in (c) and text.

(e) Estimation of sample size, considers the measurement LoD if known (or a likely estimation of the LoD) and the need to achieve reasonable measurement uncertainties.

Radionuclide	Level corresponding to 10 µSv y^{-1} (Bq l^{-1})[a]				
	Scaled freshwater GDL[b]	Derived level (this study)	Potentially measurable? / comments[c]	Suggested measurement technique[d]	Estimation of sample size (l)[e]

(f) Radionuclides with short lived progeny considered to be in secular equilibrium. List of progeny included is given in (see section 2.1 Table 1.

(g) GDLs for Pu-241 are calculated on the assumption of ingrowth of Am-241 in the environment.

ND, no data could be found to suggest whether this radionuclide could potentially be measured in the laboratory.

APPENDIX D Derived levels for work activities

D1 WORK ACTIVITIES

European Basic Safety Standards (EC BSS) (European Commission, 1996) consider two types of situation: practices and work activities. Work activities are situations that involve naturally occurring radionuclides but where the radionuclides are not being processed for their fertile or fissile properties. EC guidance on clearance levels for solids for naturally occurring radionuclides in work activities is given in Radiation Protection 122 Part 2 (RP122 Part 2) (European Commission, 2002). This complements the clearance levels for solids for practices given in RP122 Part 1. RP122 Part 2 specifies an individual dose criterion of 300 μSv y^{-1} for clearance of naturally occurring radionuclides in work activities. HPA were asked to calculate derived levels for naturally occurring radionuclides in aqueous liquids from work activities to complement the results for solids given in RP122 Part 2. This was done by scaling the unrounded results in Table 3 of the main text to 300 μSv y^{-1} and then rounding to the nearest order of magnitude. The results for the radionuclide chains were obtained by using the summation rule:

Derived level for chain (Bq l^{-1}) = $(1/E_1+1/E_2+1/E_3\ldots)^{-1}$

where E_1, E_2 etc are the unrounded derived levels (Bq l^{-1}) for the radionuclide chain members.

The value for natural uranium (Unat) also takes into account the natural abundance of uranium isotopes (1Bq of Unat contains 0.477 Bq of U238 + 0.477 Bq of U234 + 0.046 Bq of U235). The results are given in Table D1, together with the corresponding RP122 Part 2 values for solids.

The volume of aqueous liquids containing activity concentrations at these levels that can be disposed of to a STW and meet the individual dose criterion was investigated using the four approaches described in section 3.2 of the main text. In all cases the volume was found to be greater than the throughput of the STW and therefore no limit on the volume of aqueous liquids containing these activity concentration levels is required.

D2 REFERENCES

European Commission (1996). Council Directive 96/29/Euratom of 13 May 1996 laying down the basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation *Off J Eur Commun.* **L159** p.1

European Commision (2002). Practical use of the concepts of clearance and exemption – Part II. European Commission (Radiation Protection 122 Part II).

TABLE D1 Derived levels for work activities

Radionuclide	Derived level in aqueous liquids (Bq l^{-1})		Clearance level in solids (Bq g^{-1}) from RP122 Part 2
	Unrounded	Rounded	
U-238sec	$4.30\ 10^{-2}$	0.1	0.5
(including U-238, Th-234, Pa-234m, Pa-234, U-234, Th-230, Ra-226, Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210, Po-210)			
U-238sec including U-235sec	$4.46\ 10^{-2}$	0.1	0.5
U-nat	6.0	10	5
(including U-238, Th-234, Pa-234m, Pa-234, U-234, U-235, Th-231)			
U-238+	6.0	10	5(a)
(including U-238, Th-234, Pa-234m, Pa-234)			
U-234	6.0	10	5(a)
Th-230	$2.61\ 10^{1}$	10	10
Ra-226+	$6.00\ 10^{-1}$	1	0.5
(including Ra-226, Rn-222, Po-218, Pb-214, Bi-214, Po-214)			
Pb-210+	$9.89\ 10^{-2}$	0.1	5
(including Pb-210, Bi-210, Po-210)			
Po-210	$9.00\ 10^{-2}$	0.1	5
U-235sec	$1.79\ 10^{-1}$	0.1	1
(including U-235, Th-231, Pa-231, Ac-227, Th-227, Fr-223, Ra-223, Rn-219, Po-215, Pb-211, Bi-211, Tl-207, Po-211)			
U-235+	6.00	10	5
(including U235, Th-231)			
Pa-231	$6.00\ 10^{-1}$	1	5
Ac-227+	$2.67\ 10^{-1}$	0.1	1
(including Ac-227, Th-227, Fr-223, Ra-223, Rn-219, Po-215, 0.1Pb-211, Bi-211, Tl-207, Po-211)			
Th-232sec	$4.1\ 10^{-2}$	0.1	0.5
(including Th-232, Ra-228, Ac-228, Th-228, Ra-224, Rn-220, Po-216, Pb-212, Bi-212, Po-212, Tl-208)			
Th-232	$2.91\ 10^{1}$	10	5
Ra-228+	$4.40\ 10^{-2}$	0.1	1
(including Ra-228, Ac-228)			
Th-228+	$5.26\ 10^{-1}$	1	0.5
(including Th-228, Ra-224, Rn-220, Po216, Pb-212,Bi-212, Tl-208)			

Notes

(a) Value not given in RP122 Part 2 but derived from the dose calculations given in RP122 Part 2