ENVIRONMENT AGENCY
FOOD STANDARDS AGENCY
FOOD STANDARDS SCOTLAND
NATURAL RESOURCES WALES
NORTHERN IRELAND ENVIRONMENT AGENCY
SCOTTISH ENVIRONMENT PROTECTION AGENCY

Radioactivity in Food and the Environment, 2020 Appendix 1 CD Supplement

RIFE 26

November 2021

Contents Page

List of Tables

List of Figures

1. Introduction

This appendix contains a summary of the sampling, measurement, presentation and assessment methods of data used in producing the RIFE report. This information is included as a separate document accompanying the main report. Accompanying this file is a further set of files giving full details of each assessment of 'total dose' summed over all sources at each site.

Annexes are provided to this appendix giving further information on:

- modelling to extend or improve the results of monitoring
- consumption, occupancy and other habits data
- dosimetric data
- estimates of concentrations of natural radionuclides

References in this appendix are given in the main report.

Guidance on planning and implementing routine environmental radiological monitoring programmes has been published (Environment Agency, FSA and SEPA, 2010). In recent years, the Environment Agency Food Standards Agency (FSA), Food Standards Scotland (FSS) and Scottish Environment Protection Agency (SEPA) have all completed reviews of their environmental radioactivity monitoring programmes. Further information is available in earlier RIFE reports and in section 1.1 of the main report.

tens of kilometres in an environment of changing concentrations in seawater, sediments and lower trophic levels. The resulting quantity of contamination therefore represents an average over a large area. Similarly, cows providing milk at a farm may feed on grass and other fodder collected over a distance of a few kilometres of the farm. In the case of dose rate measurements, the position where the measurement is conducted is within a few metres of other measurements made within a year. Each observation consists of the mean of many instrument readings at a given location.

The numbers of farms that were sampled to provide information on activities in milk at nuclear sites are indicated in the tables of results. Milk samples collected weekly or monthly are generally bulked to provide four quarterly samples for analysis each year. Otherwise, the number of sampling observations in the tables of concentrations refers to the number of samples that were prepared for analysis during the year. In the case of small animals such as molluscs, one sample may include several hundred individual animals.

The number of sampling observations does not necessarily indicate the number of individual analyses conducted for a specific radionuclide. In particular, determinations by radiochemical methods are sometimes conducted less frequently than those by gamma-ray spectrometry. However, results are often based on bulking of samples such that the resulting determination remains representative.

2.4 Detection limits

There are two main types of results presented in the tables (i) positively detected values and (ii) values preceded by a 'less than' symbol (<). Where the results are an average of more than one value, and each value is positive, the result is positive. Alternatively, where there is a mixture of data, or all data is at the limit of detection (LoD) or minimum reporting level (MRL), the result is preceded by a 'less than' symbol. Gamma-ray spectrometry can provide many 'less than' results.

Limits of detection are governed by various factors relating to the measurement method used and these are described in earlier reports (MAFF, 1995). There are also a few results quoted as "not detected" (ND) by the methods used. This refers to the analysts' judgement that there is insufficient evidence to determine whether the radionuclide is present or absent.

2.5 Additional information

The main aim of this report is to present all the results of routine monitoring from the programmes described previously. However, it is necessary to carry out some averaging for clarity and to exclude some basic data that may be of use only to those with specific research interests. Full details of the additional data are available from the environment agencies and FSA. Provisional results of concentrations of radionuclides in food samples collected in the vicinity of nuclear sites in England, Northern Ireland (milk and canteen meals) and Wales are published on FSA's website (https://www.food.gov.uk).

The main categories of additional data are:

- data for individual samples prior to averaging
- uncertainties in measurements
- data for very short-lived radionuclides supported by longer-lived parents
- data which are not relevant to a site's discharges for naturally occurring radionuclides and for artificial radionuclides below detection limits
- measurements conducted as part of the research programme described in Appendix 4 of the main report

Very short-lived radionuclides such as yttrium-90, rhodium-103m, rhodium-106m, barium-137m and protactinium-234m (formed by decay of, strontium-90, ruthenium-103, ruthenium-106, caesium-137 and thorium-234, respectively) are taken into account for calculating exposures to members of the public. They are not listed in the tables of results. As a first approximation, their concentrations can be taken to be the same as those of their respective parents.

3. Assessment methods and data

3.1 Radiation protection standards

The monitoring results in this report are interpreted in terms of radiation exposures of the public, commonly termed ’doses‘. This section describes the dose standards that apply in ensuring protection of the public.

UK practice relevant to the general public was based on the recommendations of the International Commission on Radiological Protection (ICRP) as set out in ICRP Publication 60 (ICRP, 1991). The dose standards were embodied in national policy on radioactive waste (United Kingdom - Parliament, 1995b) and in guidance from the International Atomic Energy Agency (IAEA) in their Basic Safety Standards (BSS) for Radiation Protection (IAEA, 1996). Legislative dose standards were contained in the BSS Directive 96/29/Euratom (CEC, 1996) and were subsequently incorporated into UK law in the Ionising Radiations Regulations 1999 (United Kingdom - Parliament, 1999). To implement the BSS Directive, ministers provided the Environment Agency and SEPA with Directions concerning radiation doses to members of the public and their methods of estimation and regulation for all pathways (Department of the Environment, Transport and the Regions, 2000; Scottish Executive, 2000). In Northern Ireland, regulations were made to implement the requirements of the BSS Directive in the Radioactive Substances (Basic Safety Standards) Regulations (Northern Ireland) 2003 (Northern Ireland Assembly, 2003). The methods and data used in this report are consistent with these (and subsequent) Directions.

The ICRP issued revised recommendations for a system of radiological protection in 2007 as set out in ICRP Publication 103 (ICRP, 2007). PHE (formerly Health Protection Agency (HPA)) have provided advice on the application of the ICRP 2007 recommendations to the UK (HPA, 2009). Overall, they consider that the new recommendations do not imply any major changes to the system of protection applied in the UK. In particular, for authorised/permitted releases, limits for effective and skin doses remain unchanged. Dose coefficients are also unchanged until such a time as new values are available and receive legislative endorsement.

ICRP (2007) use the term ’representative person‘ for assessing doses to members of the public. It is defined as ’an individual receiving a dose that is representative of the more highly exposed individuals in the population‘. The new term is equivalent to ’critical group‘ which has been used in some previous RIFE reports. Where appropriate, the term ’representative person‘ has been adopted in this report. The EU has updated the BSS Directive to account for the changes in ICRP recommendations (EC, 2014). The revised directive, 2013/59/Euratom, was published in 2013 and arrangements for transposition of the Directive into UK law are complete. In 2017, the Health and Safety Executive (HSE) consulted on the changes to the Ionising Radiations Regulations 1999, aiming to transpose the requirements of the revised Euratom Basic Safety Standards Directive 2013 (BSSD 13) (Directive 2013/59/Euratom). The new Ionising Radiations Regulations 2017 (IRR 17) came into force on 1 January 2018 (United Kingdom - Parliament, 2017), replacing the Ionising Radiations Regulations 1999.

Revised standards in England and Wales concerning radiation doses to members of the public, and their methods of estimation and regulation for all pathways, came into force in 2018 in the Environmental Permitting (England and Wales) (Amendment) (No. 2) Regulations 2018 (EPR 18) (United Kingdom - Parliament, 2018). Also, in 2018, the Radioactive Substances (Modification of Enactments) Regulations (Northern Ireland) 2018 and the Environmental Authorisations (Scotland) Regulations 2018 (EASR) came into force for radioactive substances activities in Northern Ireland (Statutory Rules of Northern Ireland, 2018) and in Scotland (Scottish Government, 2018). Further changes in UK radiological protection law and standards will be taken into account for future issues of this RIFE report.

The relevant dose limits, for authorised/permitted releases, to members of the public are 1mSv (millisievert) per year for whole-body (more formally ’committed effective‘) dose and 50mSv per year specifically for skin. The latter limit exists to ensure that specific effects on skin due to external exposure are prevented and is applicable, for example, in the case of handling of fishing gear. The dose limits are for use in assessing the impact of direct radiations and controlled releases (authorised/permitted discharges) from radioactive sources. In situations that present a novel exposure pathway for members of the public, “potential” exposure routes and standards are determined, and these are discussed further in relation to particles of radioactivity (Dale and others, 2008). For contamination, known to be due to radioactive particles in the UK, a site-specific assessment is considered in the relevant section of the main RIFE report.

The mean annual dose received by the ’representative person‘ is compared with the dose limit. The term ’representative person‘ refers to those people most exposed to radiation. In this report, they are usually people of the public consuming large quantities of locally harvested food (high-rate consumers) or spending long periods of time in locations being assessed for external exposure. The limits apply to all age groups. Children may receive higher doses than adults because of their physiology, anatomy and dietary habits. The embryo/foetus can also receive higher doses than its mother. Consequently, doses have been assessed for different age groups; for example, adults, children (10-year-old), infants (1-year-old) and prenatal children, and from this information it is possible to determine which of these age groups receives the highest doses.

For drinking water, the EU Directive on the quality of water intended for human consumption in respect of radioactive substances was published in 2013 (EC, 2013). The Directive specifies values for radon, tritium and “Indicative Dose” (ID) above which Member States shall assess whether the presence of radioactive substances in drinking water poses a risk to human health that requires action and, where necessary, shall take remedial action to improve the quality of water to a level which complies with the requirement for the protection of human health from a radiation protection point of view. The values are concentrations of 100Bq l^{-1} for radon or tritium and a dose of 0.1mSv from an intake over one year. ID is the sum of the doses from individual radionuclides in drinking water excluding tritium, potassium-40 and radon and its short-lived decay products. Drinking water is taken to include bottled waters (spring and drinking).

The Directive also specifies screening values for gross alpha and beta activity of 0.1 and 1.0Bq l-1, respectively. If concentrations are below these values, further investigations are not needed unless it is known that specific radionuclides are present in the water that are liable to cause an ID in excess of 0.1mSv from an intake over one year. Transposition of the Drinking Water Directive into law has now taken place for the whole of the UK. The Water Supply (Water Quality) Regulations 2016 came into force in 2016 in England and Wales (Statutory Instruments, 2016).

Accidental releases may be judged against EU and ICRP standards in emergency situations (CEC, 1989 and ICRP, 2007). In addition, it is government policy that EU food intervention levels will be taken into account for setting discharge limits. Guidelines for radionuclides in foods following accidental radiological contamination for use in international trade has been published by the Codex Alimentarius Commission (Codex Alimentarius Commission, 2011).

The focus of this report, and radiological regulation and monitoring more generally, is towards protection of humans. However, ICRP in its 2007 recommendations has concluded that there was a need for a systematic approach for the radiological assessment of non-human species to support the management of radiation effects in the environment (ICRP, 2007). More recently ICRP considered the use of a set of reference animals and plants (RAPs) for dose assessments (ICRP, 2008) and have now published their aims in terms of environmental protection, that is (i) prevention or reduction of the frequency of deleterious radiation effects on biota to a level where they would have a negligible impact on the maintenance of biological diversity, (ii) the conservation of species and the health and status of natural habitats, communities and ecosystems (ICRP, 2014). No doses limits are proposed to apply but a set of derived consideration reference levels of dose for representative species are recommended for use in assessing the impact of different sources of exposure. The Habitats Directive (CEC, 1992) requires a three-stage approach to the assessment of the impact of radioactive discharges on sensitive habitats. Details are provided in section 1 of the main text of this report.

3.2 Assessment methods

Calculations of exposures to members of the public in this report are primarily based on the environmental monitoring data for the year shown under study. The methods used have been assessed for conformity with the principles endorsed by the UK National Dose Assessment Working Group (Allott, 2005), and were found to be compatible (Camplin and Jenkinson, 2007). There are two types of dose assessment made. The first type gives an estimate of the 'total dose' to people around the nuclear sites. It considers the effects of all sources, that is the discharges of gaseous and liquid wastes and direct radiation from sources on the site premises (Camplin and others, 2005). A flow diagram of the method is given as Figure X1.1.

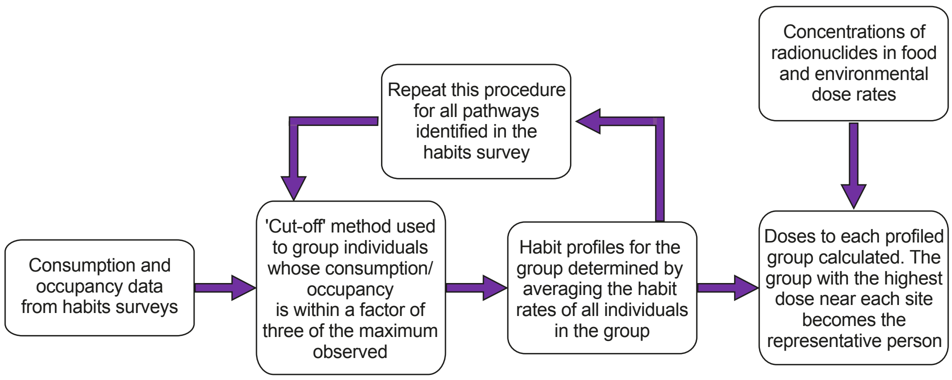

Figure X1.1 Steps in the 'total dose' methodology

The second type of assessment is focused on specific sources and their associated pathways. It serves as a check on the adequacy of the 'total dose' assessment and is also compatible with the approach used prior to the introduction of 'total dose' in 2004.

'Total dose' assessments include direct radiation. The estimates of direct radiation dose are provided by ONR based on information supplied by industry (Croston, 2021). Both types of assessment provide information on two other main pathways:

- ingestion of foodstuffs
- external exposure from contaminated materials in the aquatic environment

Monitoring data is also used to assess doses from pathways, which are generally of lesser importance:

- drinking water

- inadvertent ingestion of water and sediments
- inhalation of re-suspended soil and sediment

In addition, models are used to supplement the monitoring data in four situations:

- atmospheric dispersion models are used for non-food pathways where monitoring is not an effective method of establishing concentrations or dose rates in the environment
- food chain models provide additional data to fill gaps and to adjust for high limits of detection
- modelling of exposures of sewage workers is undertaken for discharges from Aldermaston and Amersham

Full details are given in annex 1.

For pathways involving intakes of radionuclides, the data required for assessment are:

- concentrations in foodstuffs, drinking water sources, sediments or air
- the amounts eaten, drunk or inhaled
- the dose coefficients that relate an intake or activity to a dose

For external radiation pathways, the data required are:

- the dose rate from the source, for example a beach or fishermen’s nets
- the time spent near the source

In both cases, the assessment estimates exposures from these pathways for people who are likely to be most exposed.

3.3 Concentrations of radionuclides in foodstuffs, drinking water sources, sediments and air

In nearly all cases, the concentrations of radionuclides are determined by monitoring and are given in the main text of this report. The concentrations chosen for the assessment are intended to be representative of the intakes of the most exposed consumers in the population. All of the positively determined concentrations tabulated are included irrespective of the origin of the radionuclide. In some cases, this means that the calculated exposures could include contributions due to disposals from other sites as well as from fallout from nuclear weapon testing and activity deposited following a nuclear reactor accident (such as at Chernobyl in 1986). Where possible, corrections for ‘background’ concentrations of naturally occurring radionuclides are made in the calculations of dose (see section 3.7).

For aquatic foodstuffs, drinking water sources, sediments and air, the assessment is based on the mean concentration near the site in question. For milk, the mean concentration at a nearby farm with the highest individual result is used in the dose assessment. This procedure accounts for the possibility that any farm close to a site can act as the sole source of supply of milk to high-rate consumers.

For other foodstuffs, the maximum activity concentrations are selected for the assessment. This allows for the possibility of storage of food harvested at a particular time when the peak quantities in a year may have been present in the environment.

The tables of activity concentrations include ‘less than’ values as well as positive determinations. This is particularly evident for gamma-ray spectrometry of terrestrial foodstuffs. Where a result is presented as a ’less than‘ value, the dose assessment methodology treats it as if it were a positive determination as follows: (i) when that radionuclide is specified in the relevant permit/authorisation (gaseous or liquid), (ii) when that radionuclide was determined using radiochemical methods or (iii) when a positive result is reported for that radionuclide in another sample from the same sector of the environment at the site (aquatic or terrestrial). Although this approach may produce an overestimation of dose, particularly at sites where activity concentrations are low, it ensures that estimated exposures are unlikely to be understated.

3.4 Consumption, drinking and inhalation rates

3.4.1 Source specific assessments

In the assessment of the effects of disposals of liquid effluents, the amounts of fish and shellfish consumed are determined by site-specific dietary habits surveys. Data are collected primarily by direct interviews with potential high-rate consumers who are often found in fishing communities. Children are rarely found to eat large quantities of seafood and their resulting doses are invariably less than those of adults. The calculations presented in this report are therefore representative of adult seafood consumers or their unborn children if the prenatal children age group is more restrictive.

In assessments of terrestrial foodstuffs, the amounts of food consumed are derived from national surveys of diet and are defined for three ages: adults, children (10-year-old) and infants (1-year-old) (based on Byrom and others, 1995). Adult consumption rates are used in the assessment of doses to prenatal children. For each food type, consumption rates at the 97.5th percentile of consumers have been taken to represent the people consuming a particular foodstuff at a high rate (the ’representative person‘ consumption rate).

Drinking and inhalation rates are general values for the population, adjusted according to the times spent in the locations being studied.

The consumption, drinking and inhalation rates are given in annex 2. Estimates of dose are based on the most up to date information available at the time of writing the report. Where appropriate, the data from site-specific surveys are averaged over a period of five years following the recommendation of the report of the consultative exercise on dose assessments (CEDA) (FSA, 2001a).

The assessment of terrestrial foodstuffs is based on two assumptions: (i) that the foodstuffs eaten by the most exposed individuals are those that are sampled for the purposes of monitoring; and (ii) that the consumption of such foodstuffs is sustained wholly by local sources. The two food groups resulting in the highest dose are taken to be consumed at 'high' consumption rates, while the remainder are consumed at mean rates. The choice of two food groups at the higher consumption rates is based on statistical analysis of national diet surveys. This shows that only a very small percentage of the population were critical rate consumers in more than two food groups (MAFF, 1996). Locally grown cereals are not considered in the assessment of exposures as it is considered highly unlikely that a significant proportion of cereals will be made into locally consumed (as opposed to nationally consumed) foodstuffs, notably bread.

3.4.2 'Total dose' assessments

The 'total dose' assessments are based on consumption and occupancy data collected from site specific surveys which are targeted at those most likely to be exposed around the site. The habits profiles that give rise to the highest doses in the assessment of RIFE data are given in files on the CD accompanying this report. Care should be taken in using these data in other circumstances because the profile leading to the highest doses may change if the measured or forecast concentrations and dose rates change.

3.5 Dose coefficients

Dose calculations for intakes of radionuclides by ingestion and inhalation are based on the compendium of dose coefficients taken from ICRP Publication 119 (ICRP, 2012), and from ICRP 88 (ICRP, 2001) and National Radiological Protection Board (NRPB) (2005).

These coefficients (often referred to as "dose per unit intake") relate the committed dose received to the amount of radioactivity ingested or inhaled. The dose coefficients used in this report are provided in annex 3 for ease of reference.

Calculations are performed for four ages: adults, children (10-year-old), infants (1-year-old) and prenatal children as appropriate to the pathways being considered. The prenatal age group was introduced following the publication of recommendations by NRPB in 2005 (NRPB, 2005). In RIFE, the dose assessment of the embryo and foetus is from a pregnant 'representative person'. This assumption is considered reasonable in the context of making comparisons with dose limits because it is difficult to demonstrate otherwise. When applied in practice, the doses estimated for the prenatal group are rarely larger than the values for other age groups.

The dose assessments include the use of appropriate gut uptake factors (proportion of radioactivity being absorbed from the digestive tract). Where there is a choice of gut uptake factors for a radionuclide, we have generally chosen the one that gives the highest predicted exposure. In particular, where results for total tritium are available, we have assumed that the tritium content is wholly in an organic form. However, we have also taken into account specific research work of relevance to the foods considered in this report. This affects the assessments for tritium, polonium, plutonium, and americium radionuclides as discussed in annex 3.

3.6 External exposure

In the assessment of external exposure, there are two factors to consider: (i) the dose rate from the source and (ii) the time spent near the source. In the case of external exposure to penetrating gamma radiation, uniform whole-body exposure has been assumed. The radiation as measured is in terms of the primary quantity known as 'air kerma rate', a measure of the energy released when the radiation passes through air. This has been converted into exposure using the factor 1 milligray = 0.85 millisievert (ICRP, 2010). This factor applies to a rotational geometry with photon energies ranging from 50keV to 2MeV. This is appropriate for the instrument used whose sensitivity is much reduced below 50keV, and to the geometry of deposits of artificial radionuclides. Applying an isotropic geometry gives a value of 0.70Sv Gy^{-1} which would be more appropriate for natural background radiation. The choice of 0.85 will therefore tend to overestimate dose rates for the situations considered in this report which include both artificial and natural radiation.

For external exposure of skin, the measured quantity is contamination in Bq cm^{-2}. In this case, dose rate factors in Sv y^{-1} per Bq cm^{-2} are used, which are calculated for a depth in tissue of 7mg cm^{-2} (Kocher and Eckerman, 1987). The time spent near sources of external exposure are determined by site-specific habits surveys in a similar manner to consumption rates of seafood. The occupancy and time spent handling fishing gear are given in annex 2.

3.7 Subtraction of ’background‘ activity concentrations

For assessing internal exposures in seafood due to the ingestion of carbon-14 and radionuclides in the uranium and thorium decay series, “background” activity concentrations are subtracted. Background carbon-14 concentrations in terrestrial foods are also subtracted. The estimates of background activity concentrations are given in annex 4. For assessing the man-made effect on external exposures to gamma radiation, dose rates due to background are subtracted. Since measurements made previously as part of the monitoring programmes reported here, the gamma dose rate backgrounds in the aquatic environment are taken to be 0.05µGy h^{-1} for sandy substrates, 0.07µGy h^{-1} for mud and salt marsh and 0.06µGy h^{-1} for other substrates. These data are compatible with those presented by McKay and others, (1995). However, where it is difficult to distinguish the result of a dose rate measurement from natural background, the method of calculating exposures based on the concentrations of man-made radionuclides in sediments is used (Hunt, 1984). Estimates of external exposures to beta radiation include a component due to naturally occurring (and un-enhanced) sources because of the difficulty in distinguishing between naturally occurring and man-made contributions. Such estimates are therefore conservative, compared with the relevant dose limit that excludes natural sources of radiation.

3.8 Uncertainties in dose assessment

Various methods are used to reduce the uncertainties in the process of the dose estimation of the representative person. These address the following main areas of concern:

- programme design
- sampling and in situ measurement
- laboratory analysis
- description of pathways to humans
- radiation dosimetry
- calculational and presentational error

Quantitative estimation of uncertainties in doses is beyond the scope of this report.

4. References

References for Appendix 1 are given in section 8 of the main report.

Annex 1. Modelling of concentrations of radionuclides in foodstuffs, air, and sewage systems

A1.1 Foodstuffs

At Sellafield and the LLWR near Drigg, a simple food chain model has been used to provide concentrations of activity in milk and livestock for selected radionuclides to supplement data obtained by direct measurements. This is done where relatively high limits of detection exist or where no measurements were made.

Activities in milk, meat and offal were calculated for technetium-99, ruthenium-106, cerium-144, and plutonium-241 using the equations:

$$C_m = F_m \, Ca \, Q_f \quad \text{and}$$
$$C_f = F_f \, Ca \, Q_f \quad \text{where}$$

C_m is the concentration in milk (Bq l^{-1}),
C_f is the concentration in meat or offal (Bq kg^{-1} (fresh)),
F_m is the fraction of the animal's daily intake by ingestion transferred to milk (d l^{-1})
F_f is the fraction of the animal's daily intake by ingestion transferred to meat or offal (d kg^{-1} (fresh)),
Ca is the concentration in fodder (Bq kg^{-1} (dry)),
Q_f is the amount of fodder eaten per day (kg (dry) d^{-1})

No direct account is taken of radionuclide decay or the intake by the animal of soil associated activity. The concentration in fodder is assumed to be the same as the maximum observed concentration in grass or, in the absence of such data, in leafy green vegetables. The food chain data for the calculations are given in Table X1.1 (Simmonds and others, 1995; Brenk and others, unpublished) and the estimated concentrations in milk, meat and offal are presented in Table X1.2.

A1.2 Air

For some sites, discharges to air may lead to significant doses. Doses may arise from radionuclides transferred from the plume to food crops and animal products, inhalation of radionuclides in the plume itself and external doses from radionuclides in the plume.

Average annual concentrations of radionuclides in the air at nearest habitations were calculated using a Gaussian plume model, PC CREAM 08 (Smith and others, 2009), and the reported discharges of radionuclides to air. Each site assessment uses generic meteorological data based on the Pasquill stability category shown in Table X1.3. The core modelling assumptions (such as the effective discharge/stack height and distance to habitation) are also shown in Table X1.3. The discharge stack is assumed to be at the centre of the site. For multi-station sites (for example, Sizewell A and B), the gaseous discharges are summed together and assumed to be discharged via a common discharge point (at the centre of both sites).

External radiation doses from radionuclides in the plume and from deposited activity were calculated taking into account occupancy indoors and outdoors and location factors to allow for building shielding. During the time people are assumed to be indoors, the standard assumption that the dose from gamma-emitting radionuclides in the plume will be reduced by 80% has been made. Internal radiation doses from inhalation of discharged radionuclides were assessed using breathing rates. Doses were initially assessed for three age groups: adults, children (10-year-old), and infants (1-year-old). All ages are assumed to have year-round occupancy at the nearest habitation. The assumptions of the inhalation and occupancy rates assessment are shown in Table X1.4. The dose to the prenatal children age group was taken to be the same as that for an adult.

A1.3 Sewage systems

The facilities at Aldermaston and Amersham discharge liquid radioactive waste to local sewers. Wastes are processed at local sewage treatment works (STW). The prolonged proximity to raw sewage and sludge experienced by sewage treatment workers could lead to an increase in the dose received, via a combination of external irradiation from the raw sewage and sludge and the inadvertent ingestion and inhalation of resuspended radionuclides.

An assessment of the dose received by workers at the Maple Lodge STW, near Amersham and the Silchester STW near Aldermaston has been conducted using the methodology and data given by the Environment Agency (Environment Agency 2006a; b). The flow rate through the sewage works is used to calculate a mean concentration in raw sewage and sludge of each nuclide discharged. These mean concentrations are combined with habits data concerning the workers’ occupancy near raw sewage and sludge, external and internal dosimetric data, and physical data such as inhalation rates to provide dose estimates. Workers are assumed to spend 75% of a working year in proximity to the raw sewage, and the other 25% in proximity to the sewage sludge. Where liquid discharges are not nuclide-specific, a composition has been assumed based on advice from the operators and concentrations calculated accordingly.

The model parameters and habits data used to assess the dose to sewage treatment workers are given in Table X1.5, and the amounts of radioactivity discharged from each site can be found in Appendix 2 of the main report.

Table X1.1 Data for food chain model

Parameter	Nuclide	Food				
		Milk	Beef	Beef offal	Sheep	Sheep offal
Q_f		13	13	13	1.5	1.5
F_m or F_f	^{99}Tc	10^{-2}	10^{-2}	$4\ 10^{-2}$	10^{-1}	$4\ 10^{-1}$
	^{106}Ru	10^{-6}	10^{-3}	10^{-3}	10^{-2}	10^{-2}
	^{144}Ce	$2\ 10^{-5}$	10^{-3}	$2\ 10^{-1}$	10^{-2}	2
	^{241}Pu	10^{-6}	10^{-4}	$2\ 10^{-2}$	$4\ 10^{-4}$	$3\ 10^{-2}$

Table X1.2 Predicted concentrations of radionuclides from food chain model used in assessments of exposures

Foodstuff	Location	Radioactivity concentration (fresh weight), Bq kg^{-1}			
		^{99}Tc	^{106}Ru	^{144}Ce	^{241}Pu
Milk	Sellafield	[b]	$4.3\ 10^{-5}$	[b]	$2.7\ 10^{-5}$
	LLWR near Drigg[c]	[a]	$1.8\ 10^{-4}$	$2.2\ 10^{-3}$	$8.5\ 10^{-5}$
Beef	Sellafield	[b]	$4.3\ 10^{-2}$	[b]	$2.7\ 10^{-3}$
	LLWR near Drigg[c]	$2.1\ 10^{-1}$	$1.8\ 10^{-1}$	$1.1\ 10^{-1}$	$8.5\ 10^{-3}$
Sheep	Sellafield	[b]	$5.0\ 10^{-2}$	[b]	$1.2\ 10^{-3}$
	LLWR near Drigg[c]	[a]	$2.1\ 10^{-1}$	$1.3\ 10^{-1}$	$3.9\ 10^{-3}$
Beef offal	Sellafield	[b]	$4.3\ 10^{-2}$	[b]	$5.4\ 10^{-1}$
	LLWR near Drigg[c]	$8.2\ 10^{-1}$	$1.8\ 10^{-1}$	$2.2\ 10^{1}$	$1.7\ 10^{-0}$
Sheep offal	Sellafield	[b]	$5.0\ 10^{-2}$	[b]	$9.3\ 10^{-2}$
	LLWR near Drigg[c]	[a]	$2.1\ 10^{-1}$	[a]	$2.9\ 10^{-1}$

[a] Positive result used, or LoD result used because modelling result greater than LoD
[b] No grass or leafy green vegetable data available
[c] 2020 data for LLWR near Drigg based on oats sample (no grass or leafy green samples available)

Table X1.3 Air concentrations modelling assumptions

Nuclear site	Stack height, m	Estimated site diameter, km	Estimated distance from stack to nearest habitation, km	Frequency of Pasquill stability category D
Aldermaston	15	2.0	0.3	60
Amersham	20	0.4	0.3	55
Berkeley	20	1.6	0.4	55
Bradwell	14	0.4	0.3	65
Burghfield	15	0.6	0.3	60
Capenhurst	15	1.1	0.3	65
Cardiff	20	0.4	0.4	60
Chapelcross	30	1.2	0.7	60
Derby	50	0.5	0.5	55
Devonport	15	1.0	0.3	65
Dounreay	15	1.0	1.0	75
Dungeness	17	1.0	0.3	70
Hartlepool	23	0.6	2.0	70
Harwell	20	1.0	0.2	55
Heysham	21	1.0	0.5	70
Hinkley	21	0.8	1.0	55
Hunterston	15	0.4	0.4	60
Oldbury	20	0.8	0.7	55
Sellafield	93	2.0	0.5	65
Sizewell	18	0.4	1.0	70
Springfields	27	1.0	0.3	70
Torness	72	0.5	0.6	70
Trawsfynydd	18	0.6	0.6	70
Winfrith	15	1.6	0.4	60
Wylfa	17	1.0	0.4	70

Table X1.4 Inhalation and occupancy data for dose assessment of discharges to air

Age group	Inhalation rates, $m^3 h^{-1}$	Fraction of time indoors
1-year-old	0.22	0.9
10-year-old	0.64	0.8
Adults	0.92	0.7

Table X1.5 Sewage workers dose assessment modelling assumptions and occupancy data

Flow rate, $m^3 d^{-1}$	Aldermaston (Silchester STW)	[a]6.7 10^3
	Amersham (Maple Lodge STW)	[b]1.5 10^5
Occupancy - sewage, h y^{-1}		1380
Occupancy - sludge, h y^{-1}		[c]460
Inadvertent ingestion rate, kg h^{-1}		[d]5 10^{-6}
Inhalation rate, $m^3 h^{-1}$		[d]1.2
Airborne concentration of sewage or sludge, kg m^{-3}		[d]1 10^{-7}
Density of raw sewage and treated sludge, kg l^{-1}		[d]1.0

[a] Based on average flow rate of 0.078 $m^3 s^{-1}$ (Dick, 2012)
[b] Based on average flow rate of 1.8 $m^3 s^{-1}$ (Jobling and others, 2006)
[c] A working year is assumed to be 40 hours per week and 48 weeks per year
[d] Parameter values used in Environment Agency methodology (see text for reference)

Annex 2. Consumption, inhalation, handling and occupancy rates

This annex gives the consumption, handling and occupancy rate data used in the source specific assessment of exposures from terrestrial consumption and aquatic pathways. Consumption rates for terrestrial foods are based on Byrom and others (1995) and are given in Table X2.1. These are derived from national statistics and are taken to apply at each site. Site-specific data for aquatic pathways based on local surveys are given in Table X2.2. These site-specific data have been supplemented with referenceable generic information (Environment Agency, 2002; Smith and Jones, 2003), where appropriate. Occupancy over intertidal areas and rates of handling from local surveys has been reassessed to take account of a change in the factor used to determine the range of rates typical of those most exposed. Previously, for using the "cut-off" method to define those most exposed (Hunt and others, 1982; Preston and others, 1974), a factor of 1.5 was used to describe the ratio of the maximum to the minimum rate within the group. From 2002, sites in England and Wales with new local surveys were adjusted to adopt a factor of 3.0 to make the selection process consistent with that used for consumption pathways. From 2003, all sites in Scotland were adjusted to adopt a factor of 3.0 also. Data used for routine assessments of external and inhalation pathways from gaseous discharges are given in annex 1.

Consumption rates refer to the mass of a foodstuff as prepared for consumption (with, for example, stalks or shells removed) and are consistent with the mass quantity used for presentation of concentration data in this report. The term "fresh weight" is used in the data tables of concentrations. For shellfish, the consumption rates and concentrations are for cooked weights. For other foodstuffs, uncooked weights are used.

Table X2.1 Consumption rates for terrestrial foods

Food Group	Consumption rates (kg y^{-1})#					
	Average			Above average consumption rate*		
	Adult	10-year-old	Infant	Adult	10-year-old	Infant
Beef	15	15	3	45	30	10
Cereals	50	45	15	100	75	30
Eggs	8.5	6.5	5	25	20	15
Fruit	20	15	9	75	50	35
Game	6	4	0.8	15	7.5	2.1
Green vegetables	15	6	3.5	45	20	10
Honey	2.5	2	2	9.5	7.5	7.5
Legumes	20	8	3	50	25	10
Milk	95	110	130	240	240	320
Mushrooms	3	1.5	0.6	10	4.5	1.5
Nuts	3	1.5	1	10	7	2
Offal	5.5	3	1	20	10	5.5
Pig	15	8.5	1.5	40	25	5.5
Potatoes	50	45	10	120	85	35
Poultry	10	5.5	2	30	15	5.5
Root crops	10	6	5	40	20	15
Sheep	8	4	0.8	25	10	3
Wild fruit	7	3	1	25	10	2

Except for milk where units are l y^{-1}
* These rates are the 97.5th percentile of the distribution across all consumers

Table X2.2 Consumption, inhalation, handling and occupancy rates for aquatic pathways

Site (Year of Last Survey)	Representative person[a]	Rates
Aldermaston (2011)		1 kg y^{-1} pike
		660 h y^{-1} over riverbank
Amersham (2016)		1 kg y^{-1} pike
		1 kg y^{-1} crayfish
		530 h y^{-1} over riverbank
Barrow (2012)	A	27 kg y^{-1} fish
		12 kg y^{-1} crabs and lobsters
		5.9 kg y^{-1} molluscs
		760 h y^{-1} over mud and sand
	B (houseboat)	2600 h y^{-1} over mud and sand
Berkeley and Oldbury (2014)	A	10 kg y^{-1} fish
		0.3 kg y^{-1} crabs and lobsters
		310 h y^{-1} over mud, stones and saltmarsh
	B (houseboat)	3700 h y^{-1} over mud
Bradwell (2015)		21 kg y^{-1} fish
		1.0 kg y^{-1} lobsters
		5.0 kg y^{-1} Pacific and European oysters
		2800 h y^{-1} over mud
Capenhurst (2008)	10 year old children	500 h y^{-1} over sediment
		5 10^{-3} kg y^{-1} sediment by inadvertent ingestion
		20 l y^{-1} water by inadvertent ingestion
Cardiff	A (2003)	24 kg y^{-1} fish
		3.8 kg y^{-1} prawns and lobster
		500 h y^{-1} over mud
	B (NA)	500 h y^{-1} over bank of River Taff
		2.5 10^{-3} kg y^{-1} sediment by inadvertent ingestion
		34 l y^{-1} water by inadvertent ingestion
	C (2003)	5.6 kg y^{-1} wildfowl
Channel Islands (1997)		62 kg y^{-1} fish
		30 kg y^{-1} crabs, spider crabs and lobsters
		30 kg y^{-1} scallops and whelks
		1400 h y^{-1} over mud and sand
Chapelcross (2015)	A	26 kg y^{-1} salmonids
		2.3 kg y^{-1} molluscs
		16 kg y^{-1} wildfowl
		560 h y^{-1} over mud and salt marsh
	B	21 kg y^{-1} shrimps
	C	500 h y^{-1} handling nets
Clyde (small users) (NA)		20 kg y^{-1} molluscs
Culham (NA)		600 l y^{-1} water
Derby (2009)		600 l y^{-1} water
		1 kg y^{-1} pike
		610 h y^{-1} over riverbank

Table X2.2 continued

Site (Year of Last Survey)	Representative person[a]	Rates
Devonport (2017)	A	38 kg y^{-1} fish
		3.4 kg y^{-1} Crustaceans
		1.2 kg y^{-1} Molluscs
		580 h y^{-1} over mud, sand and stones
	B	2100 h y^{-1} over mud
Dounreay (2018)	A	1800 h y^{-1} handling fishing gear
	B	48 kg y^{-1} fish
		21 kg y^{-1} crab and lobster
		21 kg y^{-1} Molluscs
		750 h y^{-1} over sand
	C (2013)	6 h y^{-1} in a Geo
Drinking water (NA)	Adults	600 l y^{-1}
	10-year-old children	350 l y^{-1}
	1-year-old infants	260 l y^{-1}
Dungeness (2019)		49 kg y^{-1} fish
		34 kg y^{-1} crustaceans
		18 kg y^{-1} molluscs
		770 h y^{-1} over sand
Faslane (2016)		201 kg y^{-1} fish
		13 kg y^{-1} crustaceans
		1.2 kg y^{-1} winkles
		800 h y^{-1} sand
Hartlepool (2014)		42 kg y^{-1} fish
		26 kg y^{-1} crab and lobster
		11 kg y^{-1} winkles and whelks
		1100 h y^{-1} over sand
Harwell (2015)		1.0 kg y^{-1} fish
		1.0 kg y^{-1} crayfish
		520 h y^{-1} over riverbank
Heysham (2016)	A	24 kg y^{-1} fish
		10 kg y^{-1} shrimps
		4.5 kg y^{-1} mussels
		750 h y^{-1} over sand
	B	560 h y^{-1} over salt marsh
Hinkley Point (2017)	A	45 kg y^{-1} fish
		12 kg y^{-1} shrimps
		0.7 kg y^{-1} whelks
		910 h y^{-1} over mud
	B	1500 h y^{-1} over mud
Holy Loch (1989)		730 h y^{-1} over mud
Hunterston (2017)	A	66 kg y^{-1} fish
		18 kg y^{-1} crustaceans
		24 kg y^{-1} Mussels and scallops
		590 h y^{-1} over sand
	B	48 kg y^{-1} wildfowl
		560 h y^{-1} over sand and stones
	C	1800 h y^{-1} handling fishing gear
		460 h y^{-1} handling sediment

Table X2.2 continued

Site (Year of Last Survey)	Representative person[a]	Rates
Landfill (NA)		2.5 l y^{-1} water
LLWR near Drigg	NA	35 l y^{-1} water
	2012	Marine pathways as Sellafield
Rosyth (2015)		86 kg y^{-1} fish
		18 kg y^{-1} crabs and lobsters
		10 kg y^{-1} winkles
		1700 h y^{-1} over mud and sand
Sellafield	A (Sellafield fishing community) (2020)	34 kg y^{-1} cod (15%) and other fish (85%)
		30 kg y^{-1} crab (30%), lobster (50%) and
		other crustaceans (20%)
		14 kg y^{-1} winkles (50%) and other molluscs (50%)
		690 h y^{-1} over mud and sand
	B (Fishermen's nets and pots) (2018)	1400 h y^{-1} handling nets and pots
	C (Bait digging and mollusc collecting) (2018)	510 h y^{-1} handling sediment
	D (Whitehaven commercial) (1998)	40 kg y^{-1} plaice and cod
		9.7 kg y^{-1} *Nephrops*
		15 kg y^{-1} whelks
	E (Morecambe Bay)	see Heysham
	F (Fleetwood) (1995)	93 kg y^{-1} plaice and cod
		29 kg y^{-1} shrimps
		23 kg y^{-1} whelks
	G (Dumfries and Galloway) (2017)	33 kg y^{-1} fish
		60 kg y^{-1} crabs and other crustaceans
		14 kg y^{-1} winkles and other molluscs
		30 kg y^{-1} wildfowl
		720 h y^{-1} over mud and salt marsh
	H (Laverbread) (1972)	47 kg y^{-1} laverbread
	I (Typical fish consumer) (NA)	15 kg y^{-1} cod and plaice
	J (Isle of Man) (NA)	100 kg y^{-1} fish
		20 kg y^{-1} crustaceans
		20 kg y^{-1} molluscs
	K (Northern Ireland) (2000)	99 kg y^{-1} haddock and other fish
		34 kg y^{-1} *Nephrops* and crabs
		7.7 kg y^{-1} mussels and other molluscs
		1100 h y^{-1} over mud and sand
	L (North Wales) (NA)	100 kg y^{-1} fish
		20 kg y^{-1} crustaceans
		20 kg y^{-1} molluscs
		300 h y^{-1} over mud and sand
	M (Sellafield fishing community 2016-2020) (NA)	16 kg y^{-1} cod
		30 kg y^{-1} other fish
		10 kg y^{-1} crabs
		14 kg y^{-1} lobsters
		9.3 kg y^{-1} other crustaceans
		7.4 kg y^{-1} winkles
		5.0 kg y^{-1} other molluscs
		760 h y^{-1} over mud and sand
	N (Typical recreational use over beaches, muddy areas or salt marsh) (NA)	300 h y^{-1} over intertidal substrates
	O (Typical beach user e.g. tourist) (NA)	1 kg y^{-1} fish
		0.2 kg y^{-1} crustaceans
		0.2 kg y^{-1} molluscs
		30 h y^{-1} over sand
	P (Ravenglass marsh users) (2020)	510 h y^{-1} over salt marsh
		5.0 10^{-6} kg h^{-1} mud by inadvertent ingestion
		9.2 10^{-8} kg h^{-1} mud by resuspension and inhalation

Table X2.2 continued

Site (Year of Last Survey)	Representative person[a]	Rates
Sizewell (2015)	A	23 kg y^{-1} fish
		10 kg y^{-1} crab and lobster
		3.2 kg y^{-1} whelks
		710 h y^{-1} over mud
	B (houseboats)	420 hy^{-1} over mud
Springfields	A (2012)	10 kg y^{-1} fish
		7.2 kg y^{-1} shrimps
		0.8 kg y^{-1} cockles
		530 h y^{-1} over mud and sand
	B (2012)	340 h y^{-1} handling nets
	C (Ribble Estuary houseboats) (2016-2020)	3000 h y^{-1} over mud
	D (10 year old children) (NA)	30 h y^{-1} over mud
		1.0 10^{-5} kg h^{-1} mud by inadvertent ingestion
		6.3 10^{-8} kg h^{-1} mud by resuspension and inhalation
	E (Farmers) (2012)	900 h y^{-1} over salt marsh
	F (Wildfowlers) (2012)	14 kg y^{-1} wildfowl
		140 h y^{-1} over mud
Torness (2016)	A	102 kg y^{-1} fish
		29 kg y^{-1} crab and lobster
		35 kg y^{-1} mollucs
		940 h y^{-1} over sand
	B	116 kg y^{-1} wildfowl
		280 h y^{-1} over mud
	C	1500 h y^{-1} handling fishing gear
Trawsfynydd (2018)		12 kg y^{-1} brown trout
		50 kg y^{-1} rainbow trout
		470 h y^{-1} over lake shore
Upland lake (NA)		37 kg y^{-1} fish
Whitehaven (phosphate processing) (2012)		Marine pathways as Sellafield
Winfrith (2019)		21 kg y^{-1} fish
		20 kg y^{-1} crustaceans
		14 kg y^{-1} molluscs
		560 h y^{-1} over sand and stones
Wylfa (2013)		33 kg y^{-1} fish
		7.9 kg y^{-1} crabs, lobsters and prawns
		1.8 kg y^{-1} mussels
		420 h y^{-1} over mud and sand

[a] Where more than one group exists at a site the groups are denoted A, B etc. Year of habits survey is given where appropriate
NA Not appropriate

Annex 3. Dosimetric data

The dose coefficients used in assessments in this report are provided in Table X3.1 for ease of reference. For adults and postnatal children, they are based on generic data contained in ICRP Publication 119 (ICRP, 2012). Dose coefficients for prenatal children have been obtained primarily from ICRP 88 (ICRP, 2001) and NRPB (2005). For a few radionuclides where prenatal dose coefficients are unavailable the relevant adult dose coefficient has been used.

In the case of tritium, polonium, plutonium and americium radionuclides, dose coefficients have been adjusted according to specific research work of relevance to assessments in this report.

A3.1 Polonium

The current ICRP advice is that a gut uptake factor of 0.5 is appropriate for dietary intakes of polonium by adults (ICRP, 1994). A study involving the consumption of crab meat containing natural concentrations of polonium-210 has suggested that the factor could be as high as 0.8 (Hunt and Allington, 1993). More recently, similar experiments with mussels, cockles and crabs suggested a factor in the range 0.15 to 0.65, close to the ICRP value of 0.5 (Hunt and Rumney, 2004, 2005 and 2007). Previous assessments have considered the effects of a factor of 0.8 for considering monitoring results in RIFE. In view of the most recent review (Hunt and Rumney, 2007), a value of 0.5 has been adopted for all food, consistent with ICRP advice.

A3.2 Plutonium and americium

Studies using adult human volunteers have suggested a gut uptake factor of 0.0002 is appropriate for the consumption of plutonium and americium in winkles from near Sellafield (Hunt and others, 1986; 1990). For these and other actinides in food in general, a factor of 0.0005 is considered as a reasonable best estimate (NRPB, 1990). These values are to be used if data are not available for the specific circumstances under consideration. In this report, a gut uptake factor of 0.0002 is used for plutonium and americium, for estimating doses to consumers of winkles from Cumbria and this is consistent with PHE advice. For other foods and for winkles outside Cumbria, the factor of 0.0005 is used for these radionuclides. This choice is supported by studies of cockle consumption (Hunt, 1998).

A3.3 Technetium-99

Volunteer studies have been extended to consider the transfer of technetium-99 in lobsters across the human gut (Hunt and others, 2001). Although values of the gut uptake factor found in this study were lower than the ICRP value of 0.5, dose coefficients are relatively insensitive to changes in the gut uptake factor. This is because the effective dose is dominated by ‘first pass’ dose to the gut (Harrison and Phipps, 2001). In this report, we have therefore retained use of the standard ICRP factor and dose coefficient for technetium-99.

A3.4 Tritium

In 2002, PHE reviewed the use of dose coefficients for tritium associated with organic material (Harrison and others, 2002). Subsequently, PHE published a study of the uptake and retention of organically bound tritium (OBT) in rats fed with fish from Cardiff Bay (Hodgson and others, 2005). These experiments suggested that the dose coefficient for OBT in fish from the Severn Estuary near Cardiff should be 6.0×10^{-11} Sv Bq^{-1}, higher than the standard ICRP value for OBT ingestion. The higher value is used for adults in the assessment of seafood collected near the Cardiff site in this report, and the standard ICRP value for other assessments. This approach is consistent with advice (Cooper, 2008) which takes account of the conclusions reached by the Independent Advisory Group on Ionising Radiation (AGIR) concerning relative biological effectiveness and radiation weighting (HPA, 2007). Thereafter, results of uptake experiments involving adult volunteers, who ate samples of sole from Cardiff Bay, provided further evidence that this approach is indeed cautious (Hunt and others, 2009).

Table X3.1 Dosimetric data

Radionuclide	Half life (years)	Mean β energy (MeV per disintegration)	Mean γ energy (MeV per disintegration)	Dose per unit intake by ingestion using ICRP-60 methodology (Sv Bq^{-1})			
				Adults	10 yr	1 yr	Foetus
H-3	1.24E+01	5.68E–03	0.00E+00	1.8E–11	2.3E–11	4.8E–11	3.1E–11
H-3[f]				4.2E–11	5.7E–11	1.2E–10	6.3E–11
H-3[h]				6.0E–11	8.0E–11	2.0E–10	9.0E–11
C–14	5.73E+03	4.95E–02	0.00E+00	5.8E–10	8.0E–10	1.6E–09	8.0E–10
P-32	3.91E–02	6.95E–01	0.00E+00	2.4E–09	5.3E–09	1.9E–08	2.5E–08
S-35[g]	2.39E–01	4.88E–02	0.00E+00	7.7E–10	1.6E–09	5.4E–09	1.6E–09
Ca-45	4.46E–01	7.72E–02	0.00E+00	7.1E–10	1.8E–09	4.9E–09	8.7E–09
Cr-51	7.59E–02	0.00E+00	3.20E–01	3.8E–11	7.8E–11	2.3E–10	3.8E–11
Mn-54	8.56E–01	4.22E–03	8.36E–01	7.1E–10	1.3E–09	3.1E–09	7.1E–10
Fe-55	2.70E+00	4.20E–03	1.69E–03	3.3E–10	1.1E–09	2.4E–09	8.1E–11
Co-57	7.42E–01	1.86E–02	1.25E–01	2.1E–10	5.8E–10	1.6E–09	1.1E–10
Co-58	1.94E–01	3.41E–02	9.98E–01	7.4E–10	1.7E–09	4.4E–09	5.8E–10
Co-60	5.27E+00	9.66E–02	2.50E+00	3.4E–09	1.1E–08	2.7E–08	1.9E–09
Zn-65	6.67E–01	6.87E–03	5.85E–01	3.9E–09	6.4E–09	1.6E–08	4.1E–09
Se-75	3.28E–01	1.45E–02	3.95E–01	2.6E–09	6.0E–09	1.3E–08	2.7E–09
Sr-90 †	2.91E+01	1.13E+00	3.16E–03	3.1E–08	6.6E–08	9.3E–08	4.6E–08
Zr-95 †	1.75E–01	1.61E–01	1.51E+00	1.5E–09	3.0E–09	8.8E–09	7.6E–10
Nb-95	9.62E–02	4.44E–02	7.66E–01	5.8E–10	1.1E–09	3.2E–09	3.7E–10
Tc-99	2.13E+05	1.01E–01	0.00E+00	6.4E–10	1.3E–09	4.8E–09	4.6E–10
Ru–103 †	1.07E–01	7.48E–02	4.69E–01	7.3E–10	1.5E–09	4.6E–09	2.7E–10
Ru–106 †	1.01E+00	1.42E+00	2.05E–01	7.0E–09	1.5E–08	4.9E–08	3.8E–10
Ag–110m †	6.84E–01	8.70E–02	2.74E+00	2.8E–09	5.2E–09	1.4E–08	2.1E–09
Sb–124	1.65E–01	1.94E–01	1.69E+00	2.5E–09	5.2E–09	1.6E–08	1.0E–09
Sb–125	2.77E+00	1.01E–01	4.31E–01	1.1E–09	2.1E–09	6.1E–09	4.7E–10
Te–125m	1.60E–01	1.09E–01	3.55E–02	8.7E–10	1.9E–09	6.3E–09	8.7E–10
I–125	1.65E–01	1.94E–02	4.21E–02	1.5E–08	3.1E–08	5.7E–08	9.1E–09
I–129	1.57E+07	6.38E–02	2.46E–02	1.1E–07	1.9E–07	2.2E–07	4.4E–08
I–131 †	2.20E–02	1.94E–01	3.81E–01	2.2E–08	5.2E–08	1.8E–07	2.3E–08
Cs–134	2.06E+00	1.63E–01	1.55E+00	1.9E–08	1.4E–08	1.6E–08	8.7E–09
Cs–137 †	3.00E+01	2.49E–01	5.65E–01	1.3E–08	1.0E–08	1.2E–08	5.7E–09
Ba–140 †	3.49E–02	8.49E–01	2.50E+00	4.6E–09	1.0E–08	3.1E–08	3.5E–09
Ce–144 †	7.78E–01	1.28E+00	5.28E–02	5.2E–09	1.1E–08	3.9E–08	3.1E–11
Pm–147	2.62E+00	6.20E–02	4.37E–06	2.6E–10	5.7E–10	1.9E–09	2.6E–10
Eu–154	8.80E+00	2.92E–01	1.24E+00	2.0E–09	4.1E–09	1.2E–08	2.0E–09
Eu–155	4.96E+00	6.34E–02	6.06E–02	3.2E–10	6.8E–10	2.2E–09	3.2E–10
Pb-210 †	2.23E+01	4.28E–01	4.81E–03	6.9E–07	1.9E–06	3.6E–06	1.4E–07
Bi-210	1.37E–02	3.89E–01	0.00E+00	1.3E–09	2.9E–09	9.7E–09	6.6E–12
Po-210[c]	3.79E–01	0.00E+00	0.00E+00	1.2E–06	2.6E–06	8.8E–06	1.3E–07
Po-210[d]				1.9E–06	4.2E–06	1.4E–05	2.1E–07
Ra-226 †	1.60E+03	9.56E–01	1.77E+00	2.8E–07	8.0E–07	9.6E–07	3.2E–07
Th-228 †	1.91E+00	9.13E–01	1.57E+00	1.4E–07	4.3E–07	1.1E–06	2.4E–07
Th-230	7.70E+04	1.46E–02	1.55E–03	2.1E–07	2.4E–07	4.1E–07	8.6E–09
Th-232	1.41E+10	1.25E–02	1.33E–03	2.3E–07	2.9E–07	4.5E–07	9.4E–09
Th-234 †	6.60E–02	8.82E–01	2.10E–02	3.4E–09	7.4E–09	2.5E–08	1.5E–11
U-234	2.44E+05	1.32E–02	1.73E–03	4.9E–08	7.4E–08	1.3E–07	1.5E–08
U-235 †	7.04E+08	2.15E–01	1.82E–01	4.7E–08	7.1E–08	1.3E–07	1.4E–08
U-238, †	4.47E+09	8.92E–01	2.24E–02	4.8E–08	7.5E–08	1.5E–07	1.3E–08
Np-237 †	2.14E+06	2.67E–01	2.38E–01	1.1E–07	1.1E–07	2.1E–07	3.6E–09
Pu-238[a]	8.77E+01	1.06E–02	1.81E–03	2.3E–07	2.4E–07	4.0E–07	9.0E–09
Pu-238[b]				9.2E–08	9.6E–08	1.6E–07	3.6E–09
Pu-239[a]	2.41E+04	6.74E–03	8.07E–04	2.5E–07	2.7E–07	4.2E–07	9.5E–09
Pu-239[b]				1.0E–07	1.1E–07	1.7E–07	3.8E–09
Pu-α[e]	2.41E+04	6.74E–03	8.07E–04	2.5E–07	2.7E–07	4.2E–07	9.5E–09
Pu-240[a]	6.54E+03	1.06E–02	1.73E–03	2.5E–07	2.7E–07	4.2E–07	9.5E–09
Pu-240[b]				1.0E–07	1.1E–07	1.7E–07	3.8E–09
Pu-241[a]	1.44E+01	5.25E–03	2.55E–06	4.8E–09	5.1E–09	5.7E–09	1.1E–10
Pu-241[b]				1.9E–09	2.0E–09	2.3E–09	4.4E–11
Am-241[a]	4.32E+02	5.21E–02	3.25E–02	2.0E–07	2.2E–07	3.7E–07	2.7E–09
Am-241[b]				8.0E–08	8.8E–08	1.5E–07	1.1E–09
Cm-242	4.46E–01	9.59E–03	1.83E–03	1.2E–08	2.4E–08	7.6E–08	4.7E–10
Cm-243	2.85E+01	1.38E–01	1.35E–01	1.5E–07	1.6E–07	3.3E–07	1.5E–07
Cm-244	1.81E+01	8.59E–03	1.70E–03	1.2E–07	1.4E–07	2.9E–07	2.2E–09

Table X3.1 continued

Radionuclide	Dose per unit intake by inhalation using ICRP-60 methodology (Sv Bq^{-1})			
	Adults	10 yr.	1 yr.	Foetus
H-3	4.5E-11	8.2E-11	2.7E-10	2.6E-12
H-3(f)	4.1E-11	5.5E-11	1.1E-10	6.3E-11
C-14	2.0E-09	2.8E-09	6.6E-09	6.6E-11
P-32	3.4E-09	5.3E-09	1.5E-08	6.5E-09
S-35(g)	1.4E-09	2.0E-09	4.5E-09	1.5E-11
Ca-45	2.7E-09	3.9E-09	8.8E-09	1.7E-09
Cr-51	3.7E-11	6.6E-11	2.1E-10	3.7E-11
Mn-54	1.5E-09	2.4E-09	6.2E-09	1.5E-09
Fe-55	3.8E-10	6.2E-10	1.4E-09	6.6E-11
Co-57	5.5E-10	8.5E-10	2.2E-09	6.1E-11
Co-58	1.6E-09	2.4E-09	6.5E-09	2.5E-10
Co-60	1.0E-08	1.5E-08	3.4E-08	1.2E-09
Zn-65	1.6E-09	2.4E-09	6.5E-09	7.4E-10
Se-75	1.0E-09	2.5E-09	6.0E-09	1.1E-09
Sr-90†	3.8E-08	5.4E-08	1.2E-07	1.0E-08
Zr-95†	6.3E-09	9.0E-09	2.1E-08	4.6E-10
Nb-95	1.5E-09	2.2E-09	5.2E-09	1.6E-10
Tc-99	4.0E-09	5.7E-09	1.3E-08	8.3E-11
Ru-103†	2.4E-09	3.5E-09	8.4E-09	1.1E-10
Ru-106†	2.8E-08	4.1E-08	1.1E-07	4.1E-10
Ag-110m†	7.6E-09	1.2E-08	2.8E-08	1.5E-09
Sb-124	6.4E-09	9.6E-09	2.4E-08	4.4E-10
Sb-125	4.8E-09	6.8E-09	1.6E-08	2.6E-10
Te-125m	3.4E-09	4.8E-09	1.1E-08	3.4E-09
I-125	5.1E-09	1.1E-08	2.3E-08	3.1E-09
I-129	3.6E-08	6.7E-08	8.6E-08	1.5E-08
I-131†	7.4E-09	1.9E-08	7.2E-08	8.1E-09
Cs-134	6.6E-09	5.3E-09	7.3E-09	3.0E-09
Cs-137†	4.6E-09	3.7E-09	5.4E-09	2.0E-09
Ba-140†	6.2E-09	9.6E-09	2.6E-08	1.4E-09
Ce-144†	3.6E-08	5.5E-08	1.6E-07	4.2E-10
Pm-147	5.0E-09	7.0E-09	1.8E-08	5.0E-09
Eu-154	5.3E-08	6.5E-08	1.5E-07	5.3E-08
Eu-155	6.9E-09	9.2E-09	2.3E-08	6.9E-09
Pb-210†	1.2E-06	1.6E-06	4.0E-06	6.1E-08
Bi-210	9.3E-08	1.3E-07	3.0E-07	9.1E-12
Po-210	3.3E-06	4.6E-06	1.1E-05	1.9E-08
Ra-226†	3.5E-06	4.9E-06	1.1E-05	9.9E-08
Th-228†	4.3E-05	5.9E-05	1.4E-04	2.5E-07
Th-230	1.4E-05	1.6E-05	3.5E-05	2.6E-08
Th-232	2.5E-05	2.6E-05	5.0E-05	2.8E-08
Th-234†	7.7E-09	1.1E-08	3.1E-08	6.7E-12
U-234	3.5E-06	4.8E-06	1.1E-05	4.9E-08
U-235†	3.1E-06	4.3E-06	1.0E-05	4.5E-08
U-238†	2.9E-06	4.0E-06	9.4E-06	4.4E-08
Np-237†	2.3E-05	2.2E-05	4.0E-05	4.3E-07
Pu-238	4.6E-05	4.4E-05	7.4E-05	1.1E-06
Pu-239	5.0E-05	4.8E-05	7.7E-05	1.2E-06
Pu-α(e)	5.0E-05	4.8E-05	7.7E-05	1.2E-06
Pu-240	5.0E-05	4.8E-05	7.7E-05	1.2E-06
Pu-241	9.0E-07	8.3E-07	9.7E-07	1.4E-08
Am-241	4.2E-05	4.0E-05	6.9E-05	3.2E-07
Cm-242	5.2E-06	7.3E-06	1.8E-05	5.1E-08
Cm-243	3.1E-05	3.1E-05	6.1E-05	3.1E-05
Cm-244	2.7E-05	2.7E-05	5.7E-05	2.6E-07

† Energy and dose per unit intake data include the effects of radiations of short-lived daughter products
[a] Gut transfer factor 5.00E-4 for consumption of all foodstuffs except Cumbrian winkles
[b] Gut transfer factor 2.00E-4 for consumption of Cumbrian winkles
[c] Gut transfer factor 0.5
[d] Gut transfer factor 0.8
[e] Pu-239 data used
[f] Organically bound tritium
[g] Organically bound sulphur
[h] Organically bound tritium for seafood near the Cardiff site

Annex 4. Estimates of concentrations of natural radionuclides

A4.1 Aquatic foodstuffs

Table X4.1 gives estimated values of concentrations of radionuclides due to natural sources in aquatic foodstuffs. The values are based on sampling and analysis conducted by Cefas (Young and others, 2002; 2003). Data for lead-210 and polonium-210 are quoted as medians with minimum and maximum values given in brackets. Dose assessments for aquatic foodstuffs are based on concentrations of these radionuclides net of natural background.

The carbon-14 concentrations are adjusted to take account of the dilution of natural atmospheric carbon-14 by the emission of carbon dioxide from fossil fuel burning. A dilution of 0.28% for each part per million of carbon dioxide added due to fossil fuel burning is used (Graven and Gruber, 2011). Values for the carbon dioxide additions are taken each year from https://www.esrl.noaa.gov/gmd/webdata/ccgg/trends/co2/co2_annmean_mlo.txt.

The initial specific activity of carbon-14 was 256Bq kg^{-1} (MAFF, 1995). In 2020, the adjusted value used as the basis for Table X4.1 was 216Bq kg^{-1}.

A4.2 Terrestrial foodstuffs

The values of carbon-14 in terrestrial foodstuffs due to natural sources that are used in dose assessments are given in Table X4.2 and based on earlier data (MAFF, 1995). The value for the specific activity of carbon-14 in 2020 (given in section A4.1) was used to derive these estimates.

Table X4.1 Concentrations of radionuclides in seafood due to natural sources

Radionuclide	Concentration of radioactivity (Bq kg^{-1} (fresh))[a]					
	Fish	Cod	Plaice	Crustaceans	Crabs	Lobsters
Carbon-14	20			24		
Lead-210	0.042			0.20	0.24	0.080
	(0.0030-0.55)			(0.013–2.4)	(0.043–0.76)	(0.020–0.79)
Polonium-210	0.82	0.38	2.5	9.1	19	5.3
	(0.18-4.4)	(0.18–1.1)	(0.88–4.4)	(1.1–35)	(4.1–35)	(1.9–10)
Radium-226	0.04			0.03	0.03	0.06
Thorium-228	0.0054			0.0096	0.04	0.0096
Thorium-230	0.00081			0.0026	0.008	0.0026
Thorium-232	0.00097			0.0014	0.01	0.0014
Uranium-234	0.0045			0.040	0.055	0.040
Uranium-238	0.0039			0.035	0.046	0.035

Radionuclide	Concentration of radioactivity (Bq kg^{-1} (fresh))[a]					
	Molluscs	Winkles	Mussels	Cockles	Whelks	Limpets
Carbon-14	20					
Lead-210	1.2	1.5	1.6	0.94	0.39	1.5
	(0.18–6.8)	(0.69–2.6)	(0.68–6.8)	(0.59–1.3)	(0.18–0.61)	(0.68–4.9)
Polonium-210	17	13	42	18	6.5	8.4
	(1.2–69)	(6.1–25)	(19–69)	(11–36)	(1.2–11)	(5.9–15)
Radium-226	0.08	0.08				
Thorium-228	0.37	0.46		0.37		
Thorium-230	0.19	0.26		0.19		
Thorium-232	0.28	0.33		0.28		
Uranium-234	0.99	0.99				
Uranium-238	0.89	0.89				

[a] Values are quoted as medians with minimum and maximum values given in brackets

Table X4.2 Carbon-14 in terrestrial foodstuffs due to natural sources

Food category	% Carbon content (fresh)	Concentration of carbon-14 (Bq kg^{-1} (fresh))
Milk	7	15
Beef meat	17	37
Sheep meat	21	46
Pig meat	21	46
Poultry	28	61
Game	15	32
Offal	12	26
Eggs	15	32
Green vegetables	3	7
Root vegetables	3	7
Legumes / other domestic vegetables	8	17
Dry beans	20	43
Potato	9	19
Cereals	41	89
Cultivated fruit	4	8
Wild fruit	4	8
Mushrooms	2	4
Honey	31	67
Nuts	58	125