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Radioactivity in Food and the Environment, 2018
Appendix 1
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1. Introduction

This appendix contains a summary of the sampling, measurement, presentation and assessment methods and 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 FSA, FSS and SEPA have all completed reviews of their environmental radioactivity monitoring programmes. Further information is available in earlier RIFE reports and the latest information is given in Section 1.1 of the main report.

2. Methods of sampling, measurement and presentation

This section explains the scope of the monitoring programmes presented in this report (hereafter referred to as "programmes") and summarises the methods and data used to measure and assess radioactivity in food and the environment. The bulk of the programmes, assessment methods and data have continued in 2018 unchanged. The main changes are:

Sampling and measurement

- Special sampling at nuclear sites - this was continued (if required) where there were unusual short-term increases in discharges and inadvertent releases
- Sampling directed at determining the polonium-210 concentrations further afield from the Sellafield area and to compare these concentrations with those enhanced above background in the Sellafield area

Assessment and presentation

- Site maps - maps of sites and sampling locations have been revised and updated
- New habits data - consumption and occupancy rates have been updated with the benefit of recent habits survey results at Sellafield in England, Dounreay in Scotland and Trawsfynydd in Wales

2.1 Sampling programmes

The primary purpose of the programmes is to check on the quantities of radioactivity in food and the environment. Results are used to demonstrate that the safety of the public is not compromised and that doses, resulting from discharges of radioactivity, are below the statutory dose limits. The scope in 2018 extends throughout the UK (and the Channel Islands) and is undertaken independently of the industries which discharge wastes to the environment. Samples of food, water and other materials are collected from the environment and analysed in specialist laboratories. *In situ* measurements of radiation dose rates and contamination are also made and the results of the programmes are assessed in terms of limits and trends in this report. Subsidiary objectives for the programmes are:

- To provide information to assess the impact on non-human species
- To enable indirect confirmation of compliance with authorised/permitted waste disposals
- To determine whether undisclosed releases of radioactivity have occurred from sites
- To establish a baseline from which to judge the importance of accidental releases of radioactivity should they occur
- To demonstrate compliance with international obligations, such as OSPAR and Article 35

Routine sampling is focused on nuclear sites licensed under the Nuclear Installations Act, 1965 (United Kingdom - Parliament, 1965) since these generally discharge more radioactivity (than from non-nuclear sites) and have a greater impact on the environment. The programmes also serve to provide information to assist the environment agencies to fulfil statutory duties, which are further described in Section 1.1 of the main report. Additional sampling is conducted in areas remote from nuclear sites to establish the general safety of the food chain, drinking water and the environment. Results from this sampling generate data that are used as 'background' activity concentrations to compare with results from around nuclear sites and to show the variation in the quantities of radioactivity across the UK. Quantities of radioactivity in the environment can also be affected by disposals of radioactive waste from nuclear sites abroad and show the legacy of atmospheric fallout from both past nuclear weapons testing and the nuclear reactor accidents (such as at Chernobyl in Ukraine in 1986).

Various methods for undertaking sampling and analysis are available. The programmes are primarily directed at relatively widespread contamination where the likelihood of encounter or consumption is certain. Where a source of potential exposure to particles of radioactivity is concerned, the likelihood of encounter is an important factor. This is considered separately in the main report in site specific programmes targeted at contamination from radioactive particles.

The programmes can be divided into three main sectors, generally based on the source of radioactivity in the environment:

1. Nuclear licensed sites discharging gaseous and liquid radioactive wastes
2. Industrial and landfill sites
3. UK regional monitoring and Overseas accidents

2.1.1 Nuclear licensed sites

Nuclear licensed sites are the prime focus of the programmes as they have been responsible for the largest individual discharges of radioactive waste. Sampling and direct monitoring is conducted close to most of the sites shown in Figure 1.4 of the main text (except those which have a very low impact). At Sellafield, liquid discharges of some radionuclides can be detected in the marine environment in many parts of north-European waters. Therefore, programmes (undertaken by the relevant agencies) for this site extend beyond national boundaries.

The frequency and type of measurement and the materials sampled vary from site to site and are chosen to be representative of existing exposure pathways. Knowledge of such pathways is gained from surveys of local peoples' diets and way of life (from habits surveys). Consequently, the programme may vary from site to site and from year to year. Detailed information on the scope of the programme at individual sites is given in the tables of results. The routine programme is supplemented by additional monitoring if applicable; e.g., in response to incidents or reports of unusual or high discharges of radioactivity with the potential to enter the food chain or the environment. Results of both routine and additional monitoring are included in this report.

The main aim of the programme is to monitor the environment and diet of people who live or work near nuclear sites, to estimate exposures for those small groups of people who are most at risk from disposals of radioactive waste. It is assumed that if the most exposed people have a dose below the national and international legal limit then all others should receive an even lower exposure. For liquid wastes, the pathways that are the most relevant to discharges are the ingestion of seafood and freshwater fish, drinking water and external exposure from contaminated materials. For gaseous wastes, the effects are due to the ingestion of terrestrial foods, inhalation of airborne activity and external exposure from material in the air and deposited on land. Inhalation of airborne activity and external exposure from airborne material and surface deposition are difficult to assess by direct measurement but can be assessed using environmental models. The main thrust of the monitoring is therefore directed at a variety of foodstuffs and measurements of external dose rates on the shores of seas, rivers and lakes. The programme also includes some key environmental indicators, in order that quantities of radioactivity can be put in an historical context.

The European Commission (EC) undertakes a verification programme of discharge and environmental programmes in support of the objectives of Articles 35 and 36 of the Euratom Treaty. The objectives are for Member States to have programmes to ensure compliance with the Basic Safety Standards (BSS) (EC, 2014). The Commission undertakes periodic inspections of operator and Government facilities in the UK.

2.1.2 Industrial and landfill sites

Although the emphasis of the programme is the nuclear industry, a watching brief is kept on other activities that may have a radiological impact on people and the food chain. This part of the programme considers the impact of disposals of naturally-occurring and man-made radionuclides from non-nuclear industries and of disposal into landfill sites, other than at Dounreay (considered separately in Section 3 of the main report).

The impact of the non-nuclear industry was studied at a number of locations in 2018 including East Northants Resource Management Facility (near Kings Cliffe), the River Clyde (Glasgow) and Whitehaven. As in recent years, a small-scale programme was undertaken near Hartlepool over and above that directed at the effects of the power station itself. Sampling and analysis reflected the nature of the sources under study and, where appropriate, included consideration of the enhanced concentrations of naturally-occurring radionuclides from non-nuclear industrial activity. In addition, a small-scale programme was undertaken in 2018 to determine polonium-210 concentrations in seafood further afield from the Sellafield area (i.e. spatially). There are also occasional specific programmes that consider, for example, the effects of land contaminated with historical sources of radioactivity and discharges from non-nuclear sites such as hospitals.

The distribution of landfill sites considered in 2018 is shown in Figure 7.1 (in main text). Sites were studied to assess the extent of contamination, if any, leaching from the site and re-entering the terrestrial environment in leachates collected in surface waters close to the sites. The most significant site is the LLWR engineered facility (near Drigg) in Cumbria.

2.1.3 UK regional monitoring and fallout in the UK from overseas accidents

The programme of regional monitoring considers the quantities of radioactivity in the environment in areas away from specific sources as an indication of general contamination of the food supply and the environment. The component parts of this programme are:

- Monitoring of the Channel Islands and Northern Ireland
- Dietary surveys
- Sampling of milk
- Drinking water sources, groundwater, rain and airborne particulates
- Seawater surveys
- Fallout in the UK from overseas accidents

Channel Islands and Northern Ireland

The programmes for the Channel Islands and Northern Ireland are designed to complement that for the rest of the UK and to take account of the possibility of long-range transport of radionuclides.

Channel Islands monitoring is conducted on behalf of the Channel Island States. It consists of sampling and analysis of seafood and indicator materials as a measure of the potential effects of UK and French disposals into the English Channel and historical disposal of solid waste in the Hurd Deep.

Monitoring on the Isle of Man for foodstuffs and indicator materials ceased in 2014 and 2015, respectively. Monitoring of the marine environment is primarily directed at the effects of current and historical disposals from Sellafield.

The Northern Ireland programme is directed at the far-field effects of disposals of liquid radioactive wastes into the Irish Sea. Dose rates are monitored on beaches and seafood and indicator materials are collected from a range of coastal locations including marine loughs.

General diet

The purpose of the general diet surveys is to provide information on radionuclides in the food supply to the wider population (regional diets), rather than to those living near particular sources of contamination such as the nuclear industry. This programme, based on sampling and analysis of canteen meals, provides background information that is useful in interpreting site-related measurements and helps ensure that all significant sources of contamination form part of the site-related programme. Data are also supplied as part of the UK submission to the EC under Article 36 of the Euratom Treaty* to allow comparison with those from other EU Member States (e.g. CEC, 2000a).

Specific foods, freshwater, rain and airborne particulates

Further background information on the relative concentrations of radionuclides is gained from the sampling and analysis of milk. Freshwater, rain and airborne particulates are also analysed to add to the understanding of radionuclide intakes by the population via ingestion and inhalation and as general indicators of the state of the environment.

Milk sampling took place at dairies throughout the UK in 2018. Samples were taken regularly. Milk data are also supplied as part of the UK submission to the EC under Article 36 of the Euratom Treaty to allow comparison with those from other EU Member States.

Meat and crop monitoring of naturally occurring and man-made radionuclides, as a check on general food contamination (remote from nuclear sites), ceased in 2014. However, in 2018, surveillance of imported food at ports of entry using radiation screening equipment continued as a means of detecting the effects of overseas incidents. If screening (and subsequent sample analysis) show quantities of radioactivity fail to comply with EU food standards, then consignments are removed from the UK market.

Freshwater used for the supply of drinking water was sampled throughout England, Northern Ireland, Scotland and Wales. Regular measurements of radioactivity in air and rainwater were also made. The UK provides information from these programmes of work to the EC under Article 36 of the Euratom Treaty.

Seawater surveys

Seawater surveys are conducted in the seas around the UK on behalf of BEIS to provide information on radionuclide concentrations and fluxes in the coastal seas of northern Europe. Such information is used to support international studies of the health of the seas under the aegis of the OSPAR Conventions (OSPAR, 2000b), to which the UK is a signatory and in support of research on the fate of radionuclides discharged to sea. These surveys are mounted using government research vessels and are supplemented by a programme of spot sampling of seawater at coastal locations.

Fallout in the UK from overseas accidents

Monitoring of the long-range effects of the Fukushima Dai-ichi accident was initiated across the UK in March 2011. Samples from all sectors of the environment were taken and analysed by gamma spectrometry. Key determinands were iodine-131 and caesium-137 which were prevalent in the release from the accident. Very little radioactivity was detected and the extended programme and ceased later in 2011. Further details of the programme and the results are given in the RIFE report for 2011 (RIFE 17, Environment Agency, FSA, NIEA and SEPA, 2012).

Monitoring of the effects of the 1986 Chernobyl accident was undertaken in relation to the upland contamination of lakes. Earlier RIFE reports have provided detailed results of monitoring by the environment agencies and FSA (Environment Agency, FSA, NIEA and SEPA, 2013). Sheep monitoring ceased in 2012 due to the removal of restrictions on the movement, sale and slaughter of sheep in parts of Cumbria and North Wales. Sampling for freshwater fish in locations affected by Chernobyl ceased in 2014.

* *The treaty establishing the European Atomic Energy Community (Euratom) was signed in Rome on 25th March 1957.*

2.2 Methods of measurement

There are two basic types of measurement made: (i) dose rates are measured directly in the environment; and (ii) samples collected from the environment are analysed for their radionuclide content in a laboratory.

2.2.1 Sample analysis

Analysis of samples varies depending to the nature of the radionuclide under investigation. The types of analysis can be broadly categorised into two groups: (i) gamma-ray spectrometry: and (ii) radiochemical methods. The former is a cost-effective method of detecting a wide range of (gamma-emitting) radionuclides, commonly found in radioactive wastes, and is used for most samples. Radiochemical methods comprise of a range of analyses involving the application of chemical separation and purification techniques to quantify the concentrations of alpha- and beta-emitting radionuclides. These are sensitive determinations, but generally more labour intensive; therefore, only used if alpha and beta concentration data are required for specific radionuclides and are not detectable using gamma-ray spectrometry (see Section 2.4 for discussion on limits of detection).

Several laboratories analysed samples in the programmes described in this report. Their main responsibilities were as follows:

- Cefas — Centre for Environment, Fisheries and Aquaculture Science, analysis of food samples in England, Wales, Northern Ireland and the Channel Islands
- SOCOTEC — SOCOTEC UK Limited, gamma-ray spectrometry and radiochemistry of environment related samples (including analysis of drinking water) in England and Wales
- PHE — Public Health England, gamma-ray spectrometry and radiochemistry of food and environmental samples from Scotland, air and rain samples in England, Wales and Northern Ireland, and freshwater for Northern Ireland
- LGC — Laboratory of the Government Chemist, analysis of drinking water in England and Wales

Each laboratory operates quality control procedures to the standards required by the environment agencies and FSA. Each laboratory is third-party assessed for their operating procedures, i.e. accredited by an agency, such as the UK Accreditation Service (UKAS), that certifies the requirements of the international standard ISO 17025 (International Organisation for Standardisation, 2005) are maintained. Regular calibration of detectors is undertaken and intercomparison exercises are held with participating laboratories. The quality assurance procedures and data are made available to the UK environment agencies and FSA for auditing. The methods of measurement include alpha and gamma-ray spectrometry, beta and Cerenkov scintillation counting and alpha and beta counting using proportional detectors.

Corrections are made for the radioactive decay of short-lived radionuclides between the time of sample collection and measurement in the laboratory. This is particularly important for sulphur-35 and iodine-131. If a sample is bulked from a sequence of samples over time, the date of collection of the bulked sample is assumed to be in the middle of the bulking period. Otherwise the actual collection date for the sample is used. In a few cases where short-lived radionuclides are part of a radioactive decay chain, the additional activity ('in-growth' and equilibrium status) produced from radioactive decay of parent and daughter radionuclides after sample collection is also considered. Where necessary, corrections to the activity present at the time of measurement are made to take this into account for the radionuclides protactinium-233 and thorium-234.

The analysis of foodstuffs is conducted on that part of the sampled material that is normally eaten (e.g., shells of shellfish and the pods of some legumes are discarded before analysis). Foodstuff samples are prepared in such a way, as to minimise losses of activity during the analytical stage. Most shellfish samples are boiled soon after collection to minimise losses from the digestive gland. Although some activity may be lost, these generally reflect the effects of the normal cooking process for shellfish. Most other foodstuffs are analysed raw, as it is conceivable that all the activity could be consumed in the raw foodstuff.

2.2.2 Measurement of dose rates and contamination

Measurements of gamma dose in air over intertidal and other areas are normally made at 1 m above the ground using RadEye SX Survey Meters or Mini Instruments* environmental radiation meters type 6-80, with both type of meters connected to compensated Geiger-Muller tubes, type MC-71. For certain key activities, for example for people living on houseboats or for wildfowlers lying on the ground, measurements at other distances from the ground may be made. External beta doses are measured on contact with the source, for example fishing nets, using Mini Instruments, Smart ION and Electra PB19RD monitors*. These portable instruments are calibrated against recognised reference standards and the inherent

* *The reference to proprietary products in this report should not be construed as an official endorsement of those products, nor is any criticism implied of similar products which have not been mentioned.*

instrument background is subtracted. There are two quantities that can be presented as measures of external gamma dose rate, total gamma dose rate or terrestrial gamma dose rate. Total gamma dose rate includes all sources external to the measuring instrument. Terrestrial gamma dose rate excludes cosmic sources of radiation but includes all others. In this report, the total gamma dose rate is presented. PHE reports terrestrial gamma dose rates to SEPA. Terrestrial gamma dose rate is converted to total gamma dose rate by the addition of 0.037 μGy h^{-1} which approximates the contribution made by cosmic radiation (HMIP, 1995).

Beta/gamma monitoring of contamination on beaches or riverbanks is undertaken using similar instrumentation to that for measurements of dose rates. The aim is to cover a large area including strand-lines where radioactive debris may become deposited. Any item found with activity rates in excess of the action levels is removed for analysis. An action level of 100 counts per second (equivalent to 0.01 mSv h^{-1}) is used in England and Wales. At Dalgety Bay and Dounreay, in Scotland, and at Sellafield, in Cumbria, special monitoring procedures are in place due to the potential presence of radioactive particles on beaches. Further information regarding Dalgety Bay and Dounreay, and Sellafield is provided in the main report.

2.3 Presentation of results

The tables of monitoring results contain summarised values of observations obtained during the year under review. The data are generally rounded to two significant figures. Values near to the limits of detection will not have the precision implied by using two significant figures. Observations at a given location, for activity concentrations and dose rates, may vary throughout the year. This variability may be due to changes in rates of discharge, different environmental conditions and uncertainties arising from the methods of sampling and analysis.

The method of presentation of the summarised results allows the data to be interpreted in terms of public radiation exposures for comparison with agreed safety standards.

For milk samples, the most appropriate quantity for use in assessments is the arithmetic mean in the year sampled from the farm with the highest mean activity concentration. This is labelled 'max' in the tables of results to distinguish it from the values that are averaged over a range of farms. For other terrestrial foods, an alternative approach is adopted since it is recognised that the possible storage of foods (harvested during a particular time of the year) has to be taken into account. Greater public exposures would be observed coincidental with foods being harvested at times of elevated contamination. For such foods, as well as the mean value, the maximum activity concentration observed for each radionuclide is presented at any time in the relevant year. The maximum is labelled 'max' in the tables and forms the basis for the assessment of dose.

Results are presented, where a sample is taken or a measurement is made, for each location or source of supply. Sample collectors are instructed to obtain samples from the same location during the year. Spatial averaging is therefore not generally undertaken though it is inherent in the nature of some collected samples. A fish may move some tens of kilometres in an environment of changing concentrations in seawater, sediments and lower tropic 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 a number of 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 datum, and each datum is positive, the result is positive. Alternatively, where there is a mixture of data, or all data are 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 a large number of '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 and Wales are published on FSA's website (**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 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 IAEA in their 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). In order 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 (DETR, 2000 and 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 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, in order 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 on 2 May 2018 in the Environmental Permitting (England and Wales) (Amendment) (No. 2) Regulations 2018 (EPR 18) (United Kingdom - Parliament, 2018). On 1 June 2018, the Radioactive Substances (Modification of Enactments) Regulations (Northern Ireland) 2018 came into force for radioactive substances activities in Northern Ireland (Statutory Rules of Northern Ireland, 2018). On 1 September 2018, the Environmental Authorisations (Scotland) Regulations 2018 (EASR) came into force for radioactive substances activities 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 1 mSv (millisievert) per year for whole-body (more formally 'committed effective') dose and 50 mSv 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 *et al.*, 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 general 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, i.e. 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 100 Bq l^{-1} for radon or tritium and a dose of 0.1 mSv 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 1.0 Bq 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 0.1 mSv from an intake over one year. Transposition of the Drinking Water Directive into law has now taken place for the whole of in the UK. The Water Supply (Water Quality) Regulations 2016 came into force on 27 June 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, 2006).

The focus of this report, and radiological regulation and monitoring more generally, is towards protection of man. 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

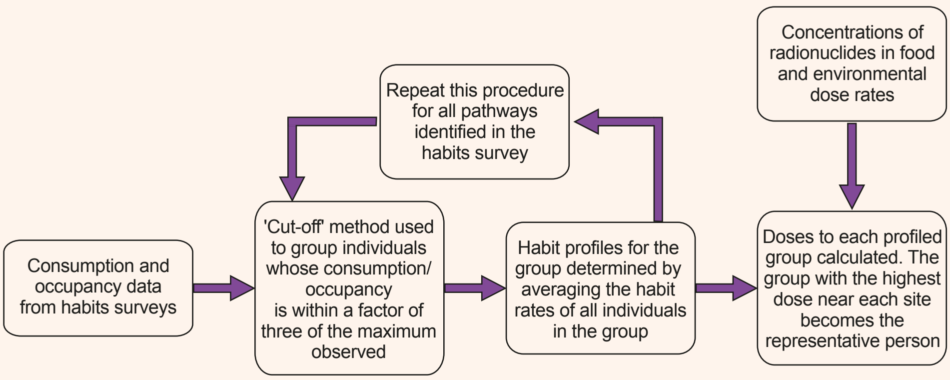

Figure X1.1. Steps in the *total dose* methodology

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, i.e. discharges of gaseous and liquid wastes and direct radiation from sources on the site premises (Camplin *et al.*, 2005). A flow diagram of the method is given as Figure X1.1.

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 (Boyd and Goodwin, 2019). 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 are 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 of 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 *et al.*, 1995). Adult consumption rates are used in the assessment of prenatal children doses. 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 5 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 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, it is assumed that the 'representative person' is pregnant in order for the dose assessment of the embryo and foetus to be valid. 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 50 keV to 2 MeV. This is appropriate for the instrument used whose sensitivity is much reduced below 50 keV, and to the geometry of deposits of artificial radionuclides. Applying an isotropic geometry gives a value of 0.70 Sv 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 7 mg cm^{-2} (Kocher and Eckerman, 1987). The times 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 times 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 programmes reported here, the gamma dose rate backgrounds in the aquatic environment are taken to be 0.05 µGy h^{-1} for sandy substrates, 0.07 µGy h^{-1} for mud and salt marsh and 0.06 µGy h^{-1} for other substrates. These data are compatible with those presented by McKay *et al*., (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 man
- 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 9 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 *et al*., 1995; Brenk *et al*., 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 can 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 *et al*., 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 key modelling assumptions (i.e. discharge height, distance to habitation) are also shown in Table X1.3.

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 per cent 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 inhalation and occupancy rates assumed in this 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 in Environment Agency (2006a; b). The flow rate through the sewage works are 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 estimates of dose. Workers are assumed to spend 75 per cent of a working year in proximity to the raw sewage, and the other 25 per cent 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]	$2.2\ 10^{-5}$	[b]	$1.9\ 10^{-5}$
	LLWR near Drigg[c]	[a]	$9.8\ 10^{-5}$	$2.0\ 10^{-3}$	$5.4\ 10^{-5}$
Beef	Sellafield	[b]	$2.2\ 10^{-2}$	[b]	$1.9\ 10^{-3}$
	LLWR near Drigg[c]	$1.8\ 10^{-1}$	$9.8\ 10^{-2}$	$1.0\ 10^{-1}$	$5.4\ 10^{-3}$
Sheep	Sellafield	[b]	$2.6\ 10^{-2}$	[b]	$8.7\ 10^{-4}$
	LLWR near Drigg[c]	[a]	$1.1\ 10^{-1}$	$1.2\ 10^{-1}$	$2.5\ 10^{-3}$
Beef offal	Sellafield	[b]	$2.2\ 10^{-2}$	[b]	[a]
	LLWR near Drigg[c]	$7.4\ 10^{-1}$	$9.8\ 10^{-2}$	$2.0\ 10^{1}$	$1.1\ 10^{-0}$
Sheep offal	Sellafield	[b]	$2.6\ 10^{-2}$	[b]	$6.5\ 10^{-2}$
	LLWR near Drigg[c]	[a]	$1.1\ 10^{-1}$	[a]	$1.9\ 10^{-1}$

[a] *Positive result used, or LoD result used because modelling result greater than LoD*
[b] *No grass or leafy green vegetable data available*
[c] *2017 data for LLWR near Drigg (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	0.3	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	0.3	65
Dounreay	15	1	1	75
Dungeness	17	1	0.3	70
Hartlepool	23	0.6	2	70
Harwell	20	1	0.2	55
Heysham	21	1	0.5	70
Hinkley	21	0.8	1	55
Hunterston	15	0.4	0.4	60
Oldbury	20	0.8	0.7	55
Sellafield	93	2	0.5	65
Sizewell	18	0.4	1	70
Springfields	27	1	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	0.4	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
Infants (1 year-old)	0.22	0.9
Children (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

[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* et al.*, 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 *et al*., (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 generic information from the Environment Agency (2002a) and 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 *et al*., 1982; Preston, *et al*., 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. 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	Children (10 year-old)	Infant (1 year-old)	Adult	Children (10 year-old)	Infant (1 year-old)
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
		31 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 y	350 l y^{-1}
	1 y	260 l y^{-1}
Dungeness (2010)	A	87 kg y^{-1} fish
		11 kg y^{-1} crabs and shrimps
		11 kg y^{-1} king scallops
		900 h y^{-1} over mud and sand
	B (Rye Harbour houseboats)	2000 h y^{-1} over mud
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

Table X2.2 continued

Site (Year of Last Survey)	Representative person[a]	Rates
Hunterston (2017)	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
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) (2018)	41 kg y^{-1} cod (40%) and other fish (60%)
		35 kg y^{-1} crab (40%), lobster (45%) and other crustaceans (15%)
		12 kg y^{-1} winkles (75%) and other molluscs (25%)
		700 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 2014-2018) (NA)	20 kg y^{-1} cod
		32 kg y^{-1} other fish
		10 kg y^{-1} crabs
		10 kg y^{-1} lobsters
		12 kg y^{-1} other crustaceans
		8.1 kg y^{-1} winkles
		4.3 kg y^{-1} other molluscs
		880 h y^{-1} over mud and sand

Table X2.2 continued

Site (Year of Last Survey)	Representative person[a]	Rates
	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) (2018)	210 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
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) (2014-2018)	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 (2003)		40 kg y^{-1} fish
		15 kg y^{-1} crabs and lobsters
		14 kg y^{-1} scallops and whelks
		300 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 *et al.,* 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); 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 *et al.,* 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 *et al.*, 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 *et al.*, 2005). These experiments suggested that the dose coefficient for OBT in fish from the Severn Estuary near Cardiff should be 6.0E-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 *et al*., 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	Child (10 year-old)	Infant (1 year-old)	Pre-natal children
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-04 for consumption of all foodstuffs except Cumbrian winkles*
[b] *Gut transfer factor 2.00E-04 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 *et al.*, 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 ppm 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 **www.esrl.noaa.gov/gmd/ccgg/trends/co2_data_mlo.html**.

The initial specific activity of carbon-14 was 256 Bq kg^{-1} (MAFF, 1995). In 2018, the adjusted value used as the basis for Table X4.1 was 220 Bq 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 2018 (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	21			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	0.005			0.010	0.04	0.010
Thorium-230	0.001			0.003	0.008	0.003
Thorium-232	0.001			0.001	0.01	0.001
Uranium-234	0.005			0.040	0.055	0.040
Uranium-238	0.004			0.035	0.046	0.035

Radionuclide	Concentration of radioactivity (Bq kg^{-1} (fresh))[a]					
	Molluscs	Winkles	Mussels	Cockles	Whelks	Limpets
Carbon-14	21					
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	38
Sheep meat	21	46
Pig meat	21	46
Poultry	28	62
Game	15	33
Offal	12	27
Eggs	15	33
Green vegetables	3	7
Root vegetables	3	7
Legumes / other domestic vegetables	8	17
Dry beans	20	44
Potato	9	20
Cereals	41	90
Cultivated fruit	4	9
Wild fruit	4	9
Mushrooms	2	4
Honey	31	68
Nuts	58	127