

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, 2015**
Appendix 1
CD Supplement

RIFE – 21

October 2016

Contents

| | Page |
|---|-----------|
| 1. Introduction | 5 |
| 2. Methods of sampling, measurement and presentation | 6 |
| 2.1 Sampling programmes | 6 |
| 2.1.1 Nuclear sites..... | 6 |
| 2.1.2 Industrial and landfill sites | 7 |
| 2.1.3 Fallout in the UK from overseas accidents and regional monitoring..... | 7 |
| 2.2 Methods of measurement | 8 |
| 2.2.1 Sample analysis | 9 |
| 2.2.2 Measurement of dose rates and contamination..... | 9 |
| 2.3 Presentation of results | 10 |
| 2.4 Detection limits | 10 |
| 2.5 Additional information | 11 |
| 3. Assessment methods and data..... | 12 |
| 3.1 Radiation protection standards..... | 12 |
| 3.2 Assessment methods..... | 13 |
| 3.3 Concentrations of radionuclides in foodstuffs, drinking water sources, sediments and air | 14 |
| 3.4 Consumption, drinking and inhalation rates | 14 |
| 3.4.1 Source specific assessments..... | 14 |
| 3.4.2 <i>Total dose</i> assessments..... | 15 |
| 3.5 Dose coefficients..... | 15 |
| 3.6 External exposure | 15 |
| 3.7 Subtraction of 'background levels'..... | 16 |
| 3.8 Uncertainties in dose assessment..... | 16 |
| 4. References..... | 17 |
| Annex 1. Modelling of concentrations of radionuclides in foodstuffs, air and sewage systems..... | 18 |
| Annex 2. Consumption, inhalation, handling and occupancy rates | 21 |
| Annex 3. Dosimetric data..... | 25 |
| Annex 4. Estimates of concentrations of natural radionuclides | 28 |

List of Tables

| Abbreviated Title | Number | Page |
|-----------------------------------|--------------|------|
| Annex 1 | | |
| Models - food chain data | X1.1 | 19 |
| Models - predicted concentrations | X1.2 | 19 |
| Air - assessment data 1 | X1.3 | 20 |
| Air - assessment data 2 | X1.4 | 20 |
| Sewer assessment data | X1.5 | 20 |
| Annex 2 | | |
| Terrestrial habit data | X2.1 | 21 |
| Aquatic habit data | X2.2 | 22 |
| Annex 3 | | |
| Dosimetric data | X3.1 | 26 |
| Annex 4 | | |
| Naturals in seafood | X4.1 | 28 |
| Carbon-14 in terrestrial foods | X4.2 | 29 |

List of Figures

| | | |
|-------------------|------------|----|
| Total dose method | X1.1 | 13 |
|-------------------|------------|----|

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). FSA completed a public consultation exercise to review the way it monitors radioactivity in food in June 2013 (FSA, 2012a and 2013). The review found that the risks from radioactivity in food were low and reductions in sampling and analysis were introduced in 2014. The main changes were:

- Reductions in the scope of food sampling and analysis at the main nuclear sites in England and Wales
- Removal of sampling and analysis of crops remote from nuclear sites

In 2012/2013 SEPA undertook a review of its environmental radioactivity monitoring programme coordinated through SEPA's Environmental Radioactivity Monitoring Task Team (ERMTT). The ERMTT includes representatives from SEPA, Scottish Government, PHE, FSA, FSS and Scottish Natural Heritage. The review took into account new habits data, recent environmental monitoring data and the joint guidance published by SEPA, FSA and the Environment Agency concerning planning and implementing routine environmental radiological monitoring programmes (Environment Agency, FSA and SEPA, 2010). Minor modifications were made to the programme which came into effect on 1st January 2014.

In 2014, the Environment Agency began a review of their environmental monitoring around nuclear sites. The review is to ensure the programmes are appropriate and are consistent with advice in the joint Agency technical guidance (Environment Agency, FSA and SEPA, 2010). The majority of the review was completed during 2015, with some further minor follow up work continuing into 2016. The overall outcome was an adjustment and consolidation of the monitoring around some sites. The Environment Agency's monitoring programme for 2016 will be changed to reflect the review outcomes.

2. Methods of sampling, measurement and presentation

This section explains the scope of the monitoring programmes presented in this report and summarises the methods and data used to measure and assess radioactivity in food and the environment. The bulk of the programmes and assessment methods and data have continued in 2015 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

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 habit survey results at Bradwell, Harwell, Sizewell, Sellafield and Springfields in England and Chapelcross and Rosyth in Scotland

2.1 Sampling programmes

The primary purpose of the programmes is to check on levels of radioactivity in food and the environment. The results are used to demonstrate that the safety of people is not compromised and that doses, as a result of discharges of radioactivity, are below the dose limit. The scope in 2015 extends throughout the UK and the Insular States (the Channel Islands and the Isle of Man) 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 programme 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 authorisations for disposal of radioactive wastes
- 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 under the Radioactive Substances Act, 1993 (RSA 93) (United Kingdom - Parliament, 1993) and/or the Environmental Permitting (England and Wales) Regulations, 2010 (United Kingdom – Parliament, 2010a). 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 levels to compare with results from around nuclear sites and to show the variation in levels across the UK. Levels 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 accident in 1986 at Chernobyl in Ukraine.

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 largely on the basis of the origin of radioactivity in the environment:

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

2.1.1 Nuclear sites

Nuclear sites are the prime focus of the programme 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 with the exception of any which have a very low impact. In the case of Sellafield, some radionuclides

that were discharged in liquid effluent can be detected in the marine environment in many parts of north-European waters and so the monitoring 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. As a result, 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 when applicable, for example, in response to incidents or reports of unusual or high discharges of radioactivity with the potential to get into the food chain or the environment. The 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 in order 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 be at an even lower level of risk. 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 levels can be put in an historical context.

The European Commission (EC) undertakes a verification programme of discharge and environmental monitoring programmes in support of the objectives of Articles 35 and 36 of the Euratom Treaty. The objectives are for Member States to have monitoring programmes to ensure compliance with the Basic Safety Standards (BSS) (CEC, 1996). The Commission undertakes periodic inspections of operator and Government facilities in the UK and has undertaken a project to investigate the need for harmonisation of procedures across the Community (Hunt *et al.*, 2007).

2.1.2 Industrial and landfill sites

Whilst the main focus of the programme is the nuclear industry, a watching brief is kept on other activities, which 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 (which is considered separately in Section 3 of the main report).

The impact of the non-nuclear industry was studied at four locations in 2015, Aberdeen, East Northants Resource Management Facility (near Kings Cliffe), River Clyde (near Glasgow) and Whitehaven. In addition, 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 enhanced levels of naturally-occurring radionuclides from non-nuclear industrial activity (i.e. Technologically enhanced Naturally-Occurring Radioactive Materials (TNORM)). 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 2015 is shown in Figure 7.1 of the main text. They were studied to assess the extent, if any, of the contamination 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 engineered facility at LLWR near Drigg, in Cumbria.

2.1.3 Fallout in the UK from overseas accidents and regional monitoring

Monitoring of the long range effects of the Fukushima Daiichi accident was initiated across the UK in March 2011. Samples from all sectors of the environment were taken and analysed by gamma spectrometry. Key determinants were iodine-131 and caesium-137 which were prevalent in the release from the accident. Further details of the programme and the results are given in the report for 2011. Very little radioactivity was detected and the extended programme ceased in 2011.

Monitoring of the effects of the 1986 Chernobyl accident is undertaken in relation to the upland contamination of lakes but 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.

The programme of regional monitoring considers the levels of radionuclides 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, the Isle of Man and Northern Ireland
- Dietary surveys
- Sampling of milk
- Drinking water sources, groundwater, rain and airborne particulates
- Seawater surveys

Channel Islands, Isle of Man and Northern Ireland

The programmes for the Insular States 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 ceased in 2014 following the risk-based review by FSA. 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 whole population, rather than to those in the vicinity of 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 also 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 (CEC, 2000a; Joint Research Centre, 2009).

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 2015. Samples were regularly taken and 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. Joint Research Centre, 2009).

Meat and crop sampling in the UK ceased in 2014 following the risk-based review by FSA. However, in 2015, surveillance of imported food at ports of entry using radiation screening equipment continued as a means of detecting the effects of overseas incidents. Where screening and subsequent sample analysis shows levels which fail to comply with EU food standards, 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 rain water 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 Defra to provide information on radionuclide levels 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.

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.

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

2.2.1 Sample analysis

The analyses conducted on samples vary according 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 radionuclides commonly found in radioactive wastes and is used for most samples. The latter comprise a range of analyses involving chemical separation techniques to quantify the alpha and beta emitting radionuclides under study. They are sensitive but more labour intensive. They are, therefore, only used when there is clear expectation that information is needed on specific radionuclides that 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
- ESG Environmental Sciences Group, gamma-ray spectrometry and radiochemistry of environment related samples 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. In most cases, contractors are third-party assessed for their operating procedures, i.e. they are accredited by an agency such as the UK Accreditation Service that certifies they meet the requirements of the international standard ISO 17025 (International Organisation for Standardisation, 2005). 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. Where bulking of samples is undertaken, 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 as a result of 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, for example, the shells of shellfish and the pods of some of the legumes are discarded before analysis. Foodstuff samples are prepared in such a way so 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 of the activity in the raw foodstuff could be consumed.

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 Mini Instruments* environmental radiation meters type 6-80 with 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 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 we have presented the total gamma dose rate. PHE reports terrestrial gamma dose rates to SEPA. Terrestrial gamma dose rate is converted to total gamma dose rate by the addition

* 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.

of $0.037 \mu\text{Gy h}^{-1}$ which is an approximation of 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. In England and Wales, a Mini Instruments series 900 mini monitor with a beach monitoring probe is used. The aim is to cover a large area including strand-lines where radioactive debris may become deposited. Any item found with activity levels 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 Dounreay and Dalgety Bay, 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 Dounreay, Dalgety Bay 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 radioactivity levels 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 for the farm where the highest mean concentration is observed. 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 when foods are harvested at times when levels of contamination are high. For such foods, we have presented the maximum concentration observed of each radionuclide at any time in the relevant year as well as the mean value. The maximum is labelled 'max' in the tables and forms the basis for the assessment of dose.

Results are presented for each location or source of supply where a sample is taken or a measurement is made. 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 samples collected. A fish may move some tens of kilometres in an environment of changing concentrations in seawater, sediments and lower tropic levels. The resulting level 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, the 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) positive 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 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. In order to minimise the presentation of redundant information for gamma-ray spectrometry, 'less than' values are only reported for one, or more, of the following reasons: (i) the radionuclide is one which is in the relevant authorisation, (ii) it has been analysed by radiochemistry, (iii) it has been reported as being a positive value in that table in the previous 5 years, (iv) a positive result is detected in any other sample presented in the table in the relevant year. Naturally occurring radionuclides measured by gamma-ray spectrometry are not usually reported unless they are intended to establish whether there is any enhancement above the expected background levels.

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 particular 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 (which are formed by decay of, strontium-90, ruthenium-103, ruthenium-106, caesium-137 and thorium-234, respectively) are taken into account when calculations of exposure are made. 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.

Current UK practice relevant to the general public is based on the recommendations of the ICRP as set out in ICRP Publication 60 (ICRP, 1991). The dose standards are 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 are contained in the BSS Directive 96/29/Euratom (CEC, 1996) and subsequently incorporated into UK law in the Ionising Radiations Regulations 1999 (United Kingdom - Parliament, 1999). In order to implement the BSS Directive, Ministers have provided the Environment Agency and SEPA with Directions concerning radiation doses to 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 the Directions.

The ICRP issued revised recommendations for a system of radiological protection in 2007 as set out in ICRP Publication 103 (ICRP, 2007). PHE (formally 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 we have adopted the term 'representative person' in this report. The implications of the new ICRP recommendations in relation to UK radiation protection law and standards are being considered. The EU has updated the BSS Directive to account for the changes in ICRP recommendations (EC, 2014). The new directive, 2013/59/Euratom, was published in December 2013 and

arrangements for transposition of the Directive into UK law are underway. Changes in UK radiological protection law and standards will be taken into account for future issues of this 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. It 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 discharges) from radioactive sources. These limits are appropriate for 'certain' exposure situations where the encounter with radioactivity is expected to occur. In situations where this is not certain, 'potential' exposure routes and standards are determined. These are discussed further by Dale *et al.*, (2008) in relation to particles of radioactivity. Where contamination due to particles is known in the UK, a site-specific assessment is considered in the relevant section of the main report.

The mean dose received by the 'representative person' is compared with the dose limit. The term 'representative person' refers to those who are most exposed to radiation. In this report they are generally people who eat large quantities of locally harvested food (high-rate consumers) or who spend long periods of time in areas where radiation sources may exist. 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, 10-year-old children, 1-year-old infants 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 (EC, 2013) was published in 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 daughter 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 levels 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 in the UK is taking place (see for example Defra, 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 when 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 main 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

(DCRLs) for representative species are recommended for use in assessing the impact of different sources of exposure. The Habitats Directive (CEC, 1992) requires a 3-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, 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. Both types of assessment provide information on two other main pathways:

- Ingestion of foodstuffs
- External exposure from contaminated materials in the aquatic environment

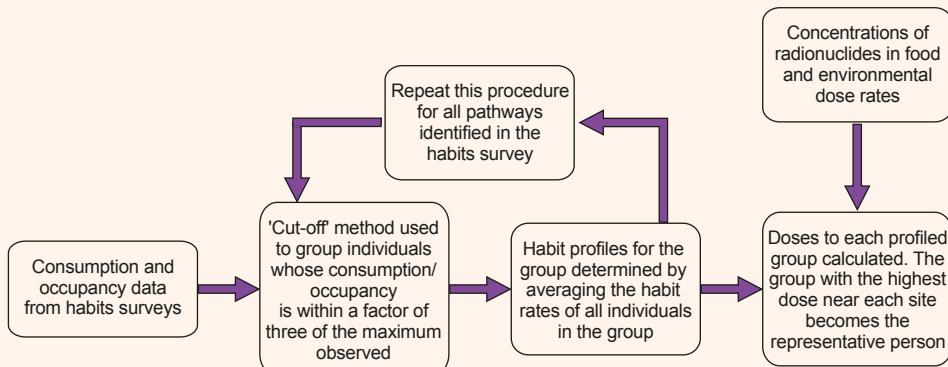


Figure X1.1. Steps in the total dose methodology

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 resuspended 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, Amersham and Cardiff

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 weapon test fallout and activity deposited following the Chernobyl accident. 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 concentrations are selected for the assessment. This allows for the possibility of storage of food harvested at a particular time when the peak levels in a year may have been present in the environment.

The tables of 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 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 levels 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 habit 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 foetal 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, 10-year-old children and 1-year-old infants (based on Byrom *et al.*, 1995). Adult consumption rates are used in the assessment of foetal doses. For each food type, consumption rates at the 97.5th percentile of consumers have been taken to represent the

people who consume a particular foodstuff at a high level (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 level' 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 habit 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 dose coefficients taken from ICRP Publication 72 (ICRP, 1996a), ICRP Publication 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, 10-year-old children, 1-year-old infants 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). We have 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, 1996b). 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 levels'

When assessing internal exposures due to ingestion of carbon-14, and radionuclides in the uranium and thorium decay series, in seafood, concentrations due to natural background levels are subtracted. Background carbon-14 concentrations in terrestrial foods are also subtracted. The estimates of background concentrations are given in Annex 4. When assessing the man-made effect on external exposures to gamma radiation, dose rates due to background levels are subtracted. On the basis of 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 $\mu\text{Gy h}^{-1}$ for sandy substrates, 0.07 $\mu\text{Gy h}^{-1}$ for mud and salt marsh and 0.06 $\mu\text{Gy h}^{-1}$ 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 when 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 from monitoring programmes. 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 10 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:

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

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)),

C_a 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 (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 (i.e. shielding factor of 0.2) has been made. Internal radiation doses from inhalation of discharged radionuclides were assessed using breathing rates. Doses were initially assessed for three age groups: infants (1y), children (10y) and adults. 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 foetal age group was taken to be the same as that for an adult.

A1.3 Sewage systems

The facilities at Aldermaston, Amersham and Cardiff 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, the Silchester STW near Aldermaston and at the Cardiff East WWTW 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 F_m or F_f | ^{99}Tc | 13 | 13 | 13 | 1.5 | 1.5 |
| | ^{106}Ru | 10^{-2} | 10^{-2} | $4 \cdot 10^{-2}$ | 10^{-1} | $4 \cdot 10^{-1}$ |
| | ^{144}Ce | 10^{-6} | 10^{-3} | 10^{-3} | 10^{-2} | 10^{-2} |
| | ^{241}Pu | $2 \cdot 10^{-5}$ | 10^{-3} | $2 \cdot 10^{-1}$ | 10^{-2} | 2 |
| | | 10^{-6} | 10^{-4} | $2 \cdot 10^{-2}$ | $4 \cdot 10^{-4}$ | $3 \cdot 10^{-2}$ |

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 | $3.9 \cdot 10^{-5}$ | b | $2.0 \cdot 10^{-5}$ |
| | LLWR near Drigg | a | $9.1 \cdot 10^{-5}$ | $1.3 \cdot 10^{-3}$ | $3.7 \cdot 10^{-5}$ |
| Beef | Sellafield | b | $3.9 \cdot 10^{-2}$ | b | $2.0 \cdot 10^{-3}$ |
| | LLWR near Drigg | $4.8 \cdot 10^{-1}$ | $9.1 \cdot 10^{-2}$ | $6.7 \cdot 10^{-2}$ | $3.7 \cdot 10^{-3}$ |
| Sheep | Sellafield | b | $4.4 \cdot 10^{-2}$ | b | $9.1 \cdot 10^{-4}$ |
| | LLWR near Drigg | a | $1.1 \cdot 10^{-1}$ | $7.8 \cdot 10^{-2}$ | $1.7 \cdot 10^{-3}$ |
| Beef offal | Sellafield | b | $3.9 \cdot 10^{-2}$ | b | a |
| | LLWR near Drigg | $1.9 \cdot 10^0$ | $9.1 \cdot 10^{-2}$ | $1.3 \cdot 10^1$ | $7.4 \cdot 10^{-1}$ |
| Sheep offal | Sellafield | b | $4.4 \cdot 10^{-2}$ | b | $6.8 \cdot 10^{-2}$ |
| | LLWR near Drigg | a | $1.1 \cdot 10^{-1}$ | a | $1.3 \cdot 10^{-1}$ |

^a Positive result used, or LoD result used because modelling result greater than LoD^b No grass or leafy green vegetable data available

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 | 1 | 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 |
| Winfirth | 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, y | Inhalation rates, $\text{m}^3 \text{ h}^{-1}$ | Fraction of time indoors |
|--------------|---|--------------------------|
| 1 | 0.22 | 0.9 |
| 10 | 0.64 | 0.8 |
| Adult | 0.92 | 0.7 |

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

| | | |
|--|---|---|
| Flow rate, $\text{m}^3 \text{ d}^{-1}$ | Aldermaston (Silchester STW) Amersham (Maple Lodge STW) Cardiff (Cardiff East WWTW) | $6.7 \cdot 10^{3a}$ $1.5 \cdot 10^{5b}$ $2.6 \cdot 10^{4c}$ |
| Occupancy – sewage, $\text{h} \text{ y}^{-1}$ | | 1380 |
| Occupancy – sludge, $\text{h} \text{ y}^{-1}$ | | 460 ^d |
| Inadvertent ingestion rate, $\text{kg} \text{ h}^{-1}$ | | $5 \cdot 10^{-6e}$ |
| Inhalation rate, $\text{m}^3 \text{ h}^{-1}$ | | 1.2 ^e |
| Airborne concentration of sewage or sludge, $\text{kg} \text{ m}^{-3}$ | | $1 \cdot 10^{-7e}$ |
| Density of raw sewage and treated sludge, $\text{kg} \text{ l}^{-1}$ | | 1 ^e |

^a Based on average flow rate of $0.078 \text{ m}^3 \text{ s}^{-1}$ (Dick, 2012)^b Based on average flow rate of $1.8 \text{ m}^3 \text{ s}^{-1}$ (Jobling et al., 2006)^c Based on an average flow rate of $0.3 \text{ m}^3 \text{ s}^{-1}$, this has been derived as 5% of the maximum flow rate at the works (McTaggart, 2003)^d A working year is assumed to be 40 hours per week and 48 weeks per year^e 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. The site-specific data has been supplemented with generic information from 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, when 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 | 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 |

* 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 (2009) | | 1 kg y ⁻¹ pike 1100 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) | 2800 h y ⁻¹ over mud and sand |
| Berkeley and Oldbury (2014) | A | 10 kg y ⁻¹ fish 0.3 kg y ⁻¹ shrimps 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 2600 h y ⁻¹ over mud |
| Capenhurst (2008) | 10 year old child | 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 |
| Devonport (2011) | A | 30 kg y ⁻¹ fish 2.4 kg y ⁻¹ crabs 0.1 kg y ⁻¹ queen scallops 400 h y ⁻¹ over mud, sand and stones |
| | B | 2100 h y ⁻¹ over mud |
| Dounreay (2013) | A | 1400 h y ⁻¹ handling fishing gear |
| | B | 18 kg y ⁻¹ fish 14 kg y ⁻¹ crab and lobster 0.3 kg y ⁻¹ winkles |
| | C | 1000 h y ⁻¹ over sand 6 h y ⁻¹ in a Geo |
| LLWR near Drigg | NA 2012 | 35 l y ⁻¹ water Marine pathways as Sellafield |
| Drinking water (NA) | Adult 10 y 1 y | 600 l y ⁻¹ 350 l y ⁻¹ 260 l y ⁻¹ |

Table X2.2. continued

| Site (Year of Last Survey) | Representative person ^a | Rates |
|----------------------------|--|---|
| 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 houseboat) | | 2000 h y ⁻¹ over mud |
| Faslane (2011) | | 19 kg y ⁻¹ fish 1.2 kg y ⁻¹ winkles 160 h y ⁻¹ sand and stones |
| Hartlepool (2014) | | 42 kg y ⁻¹ fish 26 kg y ⁻¹ crabs and lobsters 11 kg y ⁻¹ winkles and whelks 1100 h y ⁻¹ over mud and sand |
| Harwell (2015) | | 1.0 kg y ⁻¹ fish 1.0 kg y ⁻¹ crayfish 520 h y ⁻¹ over riverbank |
| Heysham (2011) | A | 27 kg y ⁻¹ fish 11 kg y ⁻¹ shrimps 6.7 kg y ⁻¹ cockles and mussels 750 h y ⁻¹ over sand 510 h y ⁻¹ over salt marsh |
| Hinkley Point (2010) | B | 14 kg y ⁻¹ fish 13 kg y ⁻¹ shrimps 0.8 kg y ⁻¹ whelks 1000 h y ⁻¹ over mud |
| | | 730 h y ⁻¹ over mud |
| Holy Loch (1989) | | 11 kg y ⁻¹ fish 12 kg y ⁻¹ <i>Nephrops</i> and other crustaceans 11 kg y ⁻¹ king scallops and oysters 440 h y ⁻¹ over sand |
| Landfill (NA) | | 2.5 l y ⁻¹ water |
| 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) (2015) | 64 kg y ⁻¹ cod (25%) and other fish (75%) 38 kg y ⁻¹ crab (30%), lobster (40%) and other crustaceans (30%) 12 kg y ⁻¹ winkles (55%) and other molluscs (45%) 1000 h y ⁻¹ over mud and sand |
| | B (Fishermen's nets and pots) (2013) | 1100 h y ⁻¹ handling nets and pots |
| | C (Bait digging and mollusc collecting) (2013) | 460 h y ⁻¹ handling sediment |
| | D (Whitehaven commercial) (1998) | 40 kg y ⁻¹ plaice and cod 9.7 kg y ⁻¹ <i>Nephrops</i> 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 18 kg y ⁻¹ fish |
| | G (Dumfries and Galloway) (2012) | 15 kg y ⁻¹ crabs and other crustaceans 19 kg y ⁻¹ winkles and other molluscs 31 kg y ⁻¹ wildfowl 600 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 <i>Nephrops</i> and crabs 7.7 kg y ⁻¹ mussels and other molluscs 1100 h y ⁻¹ over mud and sand |

Table X2.2. continued

| Site (Year of Last Survey) | Representative person ^a | Rates |
|--|---|---|
| | 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 2011-2015) (NA) | 16 kg y ⁻¹ cod 35 kg y ⁻¹ other fish 9.0 kg y ⁻¹ crabs 8.6 kg y ⁻¹ lobsters 13 kg y ⁻¹ other crustaceans 7.8 kg y ⁻¹ winkles 4.0 kg y ⁻¹ other molluscs 910 h y ⁻¹ over mud and sand 300 h y ⁻¹ over intertidal substrates |
| | N (Typical recreational use over beaches, muddy areas or salt marsh) (NA) | 1 kg y ⁻¹ fish 0.2 kg y ⁻¹ crustaceans 0.2 kg y ⁻¹ molluscs 30 h y ⁻¹ over sand |
| | O (Typical beach user e.g. tourist) (NA) | 250 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, sand and stones 420 h y ⁻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 340 h y ⁻¹ handling nets 3200 h y ⁻¹ over mud 30 h y ⁻¹ over mud 1.0 10 ⁻⁵ kg h ⁻¹ mud by inadvertent ingestion 6.4 10 ⁻⁸ kg h ⁻¹ mud by resuspension and inhalation 900 h y ⁻¹ over salt marsh 14 kg y ⁻¹ wildfowl 140 h y ⁻¹ over mud |
| Torness (2011) | A | 33 kg y ⁻¹ fish 10 kg y ⁻¹ crab and lobster 12 kg y ⁻¹ winkles 690 h y ⁻¹ over sand and stones 1500 h y ⁻¹ handling fishing gear |
| Trawsfynydd (2005) | | 1.3 kg y ⁻¹ brown trout 60 kg y ⁻¹ rainbow trout 450 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 and lobsters 1.8 kg y ⁻¹ king scallops 420 h y ⁻¹ over mud and sand |

^a Where more than one representative person exists at a site the person is 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 72 (ICRP, 1996a). Doses 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 levels 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 when 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, PHE (formally NRPB) considers a factor of 0.0005 to be a reasonable best estimate (NRPB, 1990) to be used when data for the specific circumstances under consideration are not available. In this report, when estimating doses to consumers of winkles from Cumbria,

a gut uptake factor of 0.0002 is used for plutonium and americium and this is consistent with PHE advice. For other foods and for winkles outside Cumbria, the factor of 0.0005 is used for these radioelements. 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 $6.0 \times 10^{-11} \text{ Sv Bq}^{-1}$, 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). More recent experimental evidence provided by Hunt *et al.*, (2009) involving adult volunteers who ate samples of sole from Cardiff Bay confirms that this approach is indeed cautious.

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 *et al.*, 2002; 2003). Data for lead-210 and polonium-210 are from a detailed study and are quoted as medians with minimum and maximum values given in brackets. Dose assessments for aquatic foodstuffs are based on activity 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, H.D. and Gruber, N., 2011). Values for the carbon dioxide additions are taken each year from http://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 2015 the adjusted value used as the basis for Table X4.1 was 226 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 (MAFF, 1995). The value for the specific activity of carbon-14 in 2015 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 | | | 25 | | |
| Lead-210 | 0.042 (0.0030-0.55) | | | 0.20 (0.013-2.4) | 0.24 (0.043-0.76) | 0.080 (0.020-0.79) |
| Polonium-210 | 0.82 (0.18-4.4) | 0.38 (0.18-1.1) | 2.5 (0.88-4.4) | 9.1 (1.1-35) | 19 (4.1-35) | 5.3 (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 | 21 | | | | | |
| Lead-210 | 1.2 (0.18-6.8) | 1.5 (0.69-2.6) | 1.6 (0.68-6.8) | 0.94 (0.59-1.3) | 0.39 (0.18-0.61) | 1.5 (0.68-4.9) |
| Polonium-210 | 17 (1.2-69) | 13 (6.1-25) | 42 (19-69) | 18 (11-36) | 6.5 (1.2-11) | 8.4 (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 | 16 |
| Beef meat | 17 | 39 |
| Sheep meat | 21 | 48 |
| Pig meat | 21 | 48 |
| Poultry | 28 | 64 |
| Game | 15 | 34 |
| Offal | 12 | 27 |
| Eggs | 15 | 34 |
| Green vegetables | 3 | 7 |
| Root vegetables | 3 | 7 |
| Legumes / other domestic vegetables | 8 | 18 |
| Dry beans | 20 | 45 |
| Potato | 9 | 20 |
| Cereals | 41 | 93 |
| Cultivated fruit | 4 | 9 |
| Wild fruit | 4 | 9 |
| Mushrooms | 2 | 4 |
| Honey | 31 | 70 |
| Nuts | 58 | 131 |