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Protecting and improving the nation's health

Assessing the risk to people's health from radioactive objects on beaches around the Sellafield site

Technical report

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Public Health England
133–155 Waterloo Road
Wellington House
London SE1 8UG
T: 020 7654 8000

www.gov.uk/phe
Twitter: @PHE_uk
Facebook: www.facebook.com/PublicHealthEngland

Any enquiries regarding this publication should be sent to:

Chilton Information Office

Centre for Radiation, Chemical and Environmental Hazards
Public Health England
Chilton, Didcot, Oxfordshire OX11 0RQ
E: CRCEDirectorsOffice@phe.gov.uk

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Assessing the risk to people's health from radioactive objects on beaches around the Sellafield site

Technical report

WB Oatway, T Cabianca and AL Jones

Executive Summary

Historic activities on the Sellafield site have resulted in the presence of radioactive objects in the environment. Since 2006 an intensive programme of monitoring for radioactive objects on beaches near the Sellafield site has been carried out. The focus of that monitoring programme is on beaches between Drigg and St Bees although other beaches have been monitored occasionally. Up until the end of 2017, this monitoring programme has resulted in the detection and retrieval of nearly 3000 radioactive objects. The recovered objects, which range in size from approximately 100 µm to up to several centimetres, generally contain a few tens of kBq of either ^{241}Am or ^{137}Cs although objects with more than 100 kBq of these radionuclides are occasionally detected.

This report describes in detail the approach used to estimate the risk to health posed by radioactive objects which are present in the environment near to the Sellafield site and provides a detailed discussion of the conclusions drawn from that assessment. A complementary report, which summarises the approach used in the assessment and the main conclusions for the non-technical audience, has also been produced.

In this assessment, the risks to health were assessed by estimating both the lifetime risk of developing fatal cancer from using a beach or consuming seafood for a year, and the absorbed dose to the skin or colon assuming a person came into contact with an object. The assessment used information relating to objects detected by the Groundhog Synergy detection system between 2009 and the end of 2017 and data collected during habits surveys carried out between 2003 and 2017. This information was assumed to reflect not only the current situation but also that into the foreseeable future.

To best represent a large and highly variable population of both individuals who are potentially exposed and of objects present in the environment, a statistical approach was used to estimate the risk to health. Using that approach, the 97.5th percentile of the lifetime risk of developing fatal cancer from an annual use of a beach or consumption of seafood was estimated to be of the order of 10^{-11}. This magnitude of risk is the same as that estimated in previous assessments. Due to the data used and assumptions made in this assessment, the

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assessed risk to health is that to a high rate beach user or seafood consumer; the risks to health to members of the general population are much lower than that estimated in this assessment. An annual risk of 10^{-11} is about one hundred thousand times lower than the level of risk given in HSE guidance which would not usually require action to be taken to reduce those risks further, or the risk used in the UK for the management of radioactive waste by the environment agencies.

This assessment estimated that no severe tissue damage to the colon would occur if an object were to be ingested. However, it was estimated that there is a very small probability that tissue damage may occur if an object with significantly above average levels of activity were to be in direct contact with the skin for several hours. However, even if damage to the skin did occur it would be no more than a small blister with no significant impact on the health of the individual.

Based on the outcome of this assessment, PHE concludes that the radiological risks posed by radioactive objects on the beaches near to the Sellafield site are very low and measures to control them are not warranted on public health grounds. Public Health England suggests that there is little justification to continue with the current monitoring programme on the beaches near the Sellafield site on public health grounds and that it could be replaced with a programme which is reduced in scope, whose aim is to collect information to provide reassurance that the assumptions made in this risk assessment remain valid and that the risks to health remain extremely low. Public Health England have also suggested new criteria, derived from the output of this risk assessment, against which the results of monitoring could be compared. These criteria related to both quantities associated with the activity present on a detected object as well as to changes in the average object find rate.

This work was undertaken under the Radiation Assessments Department's Quality Management System, which has been approved by Lloyd's Register Quality Assurance to the Quality Management Standard ISO 9001:2015, Approval No: ISO 9001 – 00002655.

Report version 1

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1 Introduction

Discharges of radioactivity from the Sellafield site from routine operations are made under appropriate authorisations and permits and are therefore regularly assessed and monitored. Some historical activities on the Sellafield site, including dismantling of redundant sea pipelines, have resulted in the release into the Irish Sea of objects which contain relatively high levels of radioactivity and which can be washed up onto beaches by the action of the tide and storm events. Over the years, a significant number of radioactive objects which were released into the Irish Sea have been detected on the beaches around the Sellafield site.

Since 2006 an intensive programme of monitoring for radioactive objects on beaches near the Sellafield site has been carried out. The focus of this monitoring programme is in the area between Drigg and St Bees as this is where the highest numbers of objects have been detected (Sellafield Limited, 2018). Up until the end of 2017 the monitoring programme resulted in the detection and retrieval of nearly 3000 radioactive objects. The recovered objects generally contain either ^{241}Am or ^{137}Cs with activities of a few tens of kBq. The physical size of the recovered objects ranges from approximately 100 µm to several centimetres. In addition to the beach monitoring programme, an offshore monitoring programme was also trialled between 2011 and 2014; the monitoring proved to be technically challenging and resulted in the detection of only a single object. Little information is therefore available on the number or location of radioactive objects currently present in the Irish Sea.

In 2011 the Health Protection Agency (HPA), a precursor organisation to Public Health England (PHE), carried out an assessment of the risk to health posed by radioactive objects on beaches in the vicinity of the Sellafield site, which was published as report HPA-CRCE-018 (Brown and Etherington, 2011). That risk assessment did not consider the radiological impact from exposure to radionuclides which are present in the environment because of routine authorised discharges as such risks are regularly assessed by the regulator. The assessment described in report HPA-CRCE-018 considered the risk to health posed by objects which had been detected by the Groundhog Evolution2^{TM} detection system which was in use from 2006 to 2009. In 2012 the risk assessment was revised to account for changes in the efficiency of detecting objects following the introduction of the Groundhog Synergy detection system in late 2009 which had improved detection of ^{241}Am; the revised assessment is described in report HPA-CRCE-038 (Etherington et al, 2012). More recently, in 2015, an updated assessment of the risks to seafood consumers from the possible presence of particles in marine animals was described in report PHE-CRCE-021 (Oatway and Brown, 2015). Based on the results of those risk assessments, a monitoring programme is devised annually by Sellafield Ltd. and agreed with the Environment Agency (EA) following consultation with members of the Sellafield Particles Working Group (SPWG)*. In addition, the EA also produced an intervention plan to describe the steps that should be taken by different organisations following the detection and recovery of objects on Cumbrian beaches.

* The Sellafield Particles Working Group is composed of regulators (Environment Agency, Food Standards Agency), Public Health England, Sellafield Ltd. and the Nuclear Decommissioning Authority. Its aim is to review findings from the beach monitoring programme and to facilitate the sharing of information between relevant stakeholders.

As more information has become available since the 2011 assessment on both the number and location of radioactive objects present on the beaches around the Sellafield site and on the habits of the people who may come into contact with those objects, the EA contracted PHE to undertake a new assessment of the risks to health of beach users and seafood consumers. Additionally, the EA requested PHE to provide advice on whether sufficient investigatory work has been completed or, if not, to provide advice on what additional work should be undertaken and to provide advice on the long-term routine beach monitoring programme.

The risk to health estimated in this assessment was the lifetime risk of cancer incidence or of cancer fatality from the potential contact with radioactive objects assuming that a member of the public used a beach or consumed seafood for a year. In addition, the likelihood that deterministic effects may arise from contact with a radioactive object was also assessed. In this assessment, the risk to health was estimated using a probabilistic approach in which several parameters were defined using a probability density function rather than a single value. This approach was adopted because of the difficulty in selecting appropriate parameter values to best represent a large and highly variable population of both individuals who are potentially exposed and of objects present in the environment. To undertake the required calculations, use was made of the Crystal Ball™ probabilistic tool which uses Monte Carlo simulation to calculate a range of possible outcomes and the likelihood of achieving them.

The work undertaken in this study is presented in two reports. A summary report is intended for a non-technical audience and provides an overview of the methodology and main conclusions of this assessment (Oatway et al, 2020). This supporting technical report provides a full description of the methodology used to assess the risk to health, and a detailed description of results of the assessment. Although risks are quoted to two significant figures to allow comparison between them, they are only discussed by reference to order of magnitude quantities to reflect the level of uncertainty associated with them.

2 Areas near the Sellafield site considered in the assessment

In report HPA-CRCE-018 (Brown and Etherington, 2011), risks to health were assessed for populations who make use of five separate beaches: St. Bees, Braystones, Sellafield, Seascale and Drigg. These five beaches cover an area of about 400 hectares in total and front a coastline of about 20 km in length. A description of the five beaches is given in sections 3.1.1 to 3.1.5 of HPA-CRCE-018 (supplement) (Oatway et al, 2011).

A review of the habits of those using beaches between St Bees and Drigg, which is discussed in Section 5.1.2 of this report, showed that most beaches are used in much the same way. Information reported in the habits surveys also shows that this is the case for beaches further afield such as at Allonby and Parton. The exception is Sellafield beach which does not appear to be used by children and where adults only spend time walking or fishing. This is because Sellafield beach is relatively inaccessible and mainly covered in stones.

Data from the monitoring programme carried out by Sellafield Ltd. indicate that the find rate on Sellafield beach is consistently higher than that on any other beach. In addition, the find rates on beaches between St Bees and Braystones were similar and higher than the find rates at Seascale and Drigg; this is discussed further in Section 3.

To avoid unrealistic levels of accuracy being assigned to the estimated risk to health associated with using individual beaches along the Cumbrian coast due to variability and uncertainty associated with the habit and the monitoring data, this assessment estimated the radiation risks to people using only 3 separate areas of beach. Based on the information on activities undertaken on the beaches and find rates of radioactive objects, the three areas of beach considered in this assessment are northern beaches (St Bees to Braystones); Sellafield beach, and southern beaches (Seascale to Drigg). The location of these beach areas is illustrated in Figure 1. It is noted that the radiation risks from using beaches outside of the area between St Bees and Drigg is likely to be lower than that estimated to those using beaches between St Bees and Drigg because of the lower number of radioactive objects detected on those beaches.

Figure 1 Map illustrating the approximate extent of beaches included in the assessment (Contains Ordnance Survey data © Crown copyright and database right 2019)

3 Monitoring programme

Discharges of radioactive material from operations at the Sellafield nuclear licenced site to the marine environment have occurred since the early 1950s. However, it was only after an event in 1983 (Woodhead et al, 1985) lead to contamination of local beaches by radioactive material that routine strandline monitoring on beaches near the Sellafield site has been carried out.

In 2003, following the detection by the routine strandline monitoring programme of a particle containing relatively high levels of ^{90}Sr, the Environment Agency (EA) placed several actions on Sellafield Ltd. including a requirement to review the monitoring techniques applied to large areas of beach. One of the outcomes of that review has been, since 2006, the use of specialised, vehicle mounted detection equipment in the beach monitoring programme. The equipment used to monitor beaches has since been upgraded to improve the capability for detecting radioactive objects. The first upgrade occurred in 2009 when the detection system changed from the Groundhog Evolution2^{TM} system to the Groundhog Synergy detection system. This upgrade added 8 Field Instrument for the Detection of Low Energy Radiation (FIDLER) probes, which significantly improved the detection of ^{241}Am. A second upgrade occurred in 2014 when the Groundhog Synergy2 detection system was deployed. This upgrade was intended to improve the detection of ^{90}Sr and ^{241}Am due to the use of thinner carbon-fibre detector windows and a specific low energy alarm. The impact of the change to the Groundhog Synergy detection system was found to be relatively minor and resulted in an increase in the detection rate of alpha-rich particles (those containing ^{241}Am) by around 13% (Sellafield Limited, 2018).

Objects detected and recovered during the monitoring programme are classified by physical size and radioactivity content by Sellafield Ltd to provide a practical scheme for the purposes of evaluating radiation risks. With respect to physical size, Sellafield Ltd. classifies any object with an average size of 2 mm or greater as a larger object while objects smaller than 2 mm are classed as particles. This classification system is based on the well-established Wentworth geological grain size classification scheme (Wentworth, 1922).

The most common radionuclides detected on objects are ^{137}Cs, ^{90}Sr*, ^{241}Am and isotopes of plutonium (Pu) – ^{238}Pu, ^{239}Pu, ^{240}Pu and ^{241}Pu. Other radionuclides, including ^{235}U, are also detected on some objects although with very low levels of activity; these radionuclides do not contribute significantly to the risk to health and hence they were not considered further in this assessment. With respect to radionuclide content, detected objects are classified by Sellafield Ltd. as either 'alpha-rich' or 'beta-rich'. An alpha-rich object is an object on which the ^{241}Am activity is greater than the ^{137}Cs activity. On an alpha-rich object, ^{241}Am and the alpha emitting isotopes of plutonium are the most important radionuclides with respect to radiation hazard. A beta-rich object is one on which the ^{137}Cs activity is greater than the ^{241}Am activity. The most radiologically important radionuclides detected on beta-rich objects are ^{137}Cs and ^{90}Sr.

Another class used by Sellafield Ltd. is for objects on which the ^{60}Co activity is greater than the ^{137}Cs activity. However, as only a total of 18 such objects have been detected to the end of 2017, the risks posed by them were not evaluated separately but were instead included within that estimated for exposure to beta-rich objects.

Objects detected on beaches are recorded by Sellafield Ltd. in a database which contains information on the type of object detected (particle or larger object), the date the object was detected on, an estimate of the depth the object was detected at, the radionuclides present on the object and their estimated activity, and the class of the object (alpha-rich or beta-rich).

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* Strontium-90 is present in equilibrium with its radioactive progeny ^{90}Y.

Information contained in this database on objects detected between September 2009 and the end of December 2017 was used in the risk assessment. Objects detected using the Groundhog Evolution2™ detection system, in use until to September 2009, were excluded from the assessment.

Excluding objects which were detected using the Groundhog Evolution2™ detection system from the risk assessment was appropriate as that detection system had both a low efficiency of detecting ^{241}Am and it was used in a considerable amount of exploratory work to determine how such a monitoring program should be run (trialling different monitoring speeds, detector heights etc.). This latter point is significant as, although the Groundhog Evolution2™ detection system was able to detect beta-rich objects relatively effectively, these objects were not detected in a systematic and repeatable way. Consequently, if the find rates associated with the use of the Groundhog Evolution2™ detection system were to be used in this assessment to estimate the true object populations (see Section 5.1.1), those estimates would be associated with large uncertainties. In contrast the Groundhog Synergy detection system, used since September 2009, included specific detectors for ^{241}Am and has been employed in a much more systematic way; these both reduce uncertainties in the associated find rates.

A summary of the area monitored by the Groundhog Synergy detection system and number of alpha- and beta-rich particles detected and retrieved from beaches between September 2009 and December 2017 is shown in Table 1 and Table 2 respectively. Out of 1827 particles detected on beaches between St Bees and Drigg, 1656 were alpha-rich particles and 171 were beta-rich particles. About 60% of the alpha-rich particles and over 80% of the beta-rich particles were detected on the beach at Sellafield with most of the remainder being detected on beaches between St Bees and Braystones. An additional 33 particles have been detected using the Groundhog Synergy detection system on beaches to the north of St Bees, for example at Allonby and Whitehaven, of which 31 were alpha-rich and two were beta-rich.

Since the introduction of the Groundhog Synergy detection system in 2009, three alpha-rich and 261 beta-rich larger objects have been detected. All larger objects were detected on Sellafield beach except for two beta-rich larger objects which were detected at Workington in 2014 and Allonby in 2017. Given the distance between Sellafield and both Workington and Allonby, the conceptual site model developed to understand how objects move in the environment does not adequately explain how those larger objects may have reached those beaches (Atkins Limited, 2018). As a result, several hypotheses have been put forward to explain how these larger objects may have moved so far including that they were inadvertently moved through the dredging of sediment during commercial fishing or that they had become, despite checks in place to prevent such occurrences, attached to monitoring equipment which had been moved from other beaches. Given the relatively low activities present on these larger objects, of around 10 to 20 kBq of ^{137}Cs, they do not pose a high hazard when compared to some of the larger objects detected on Sellafield beach which have more than 1 MBq of ^{137}Cs present on them.

Table 1 Area monitored and number of alpha-rich particles detected by the Groundhog Synergy detection system between 2009 and 2017

	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Northern beaches										
Area (ha)	30	102	75	72	73	66	41	47	44	551
No. detected	20	158	78	49	80	78	46	46	39	594
Find rate (ha^{-1})	0.68	1.56	1.03	0.68	1.09	1.18	1.12	0.97	0.89	1.08
Sellafield beach										
Area (ha)	14	51	43	37	44	40	77	81	80	468
No. detected	31	135	113	72	93	139	186	114	103	986
Find rate (ha^{-1})	2.17	2.65	2.60	1.95	2.14	3.46	2.40	1.41	1.28	2.11
Southern beaches										
Area (ha)	14	82	40	30	18	49	20	29	23	303
No. detected	1	22	3	8	6	19	7	3	7	76
Find rate (ha^{-1})	0.07	0.27	0.07	0.27	0.34	0.39	0.36	0.10	0.31	0.25

Table 2 Area monitored and number of beta-rich particles detected by the Groundhog Synergy detection system between 2009 and 2017 inclusive

	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Northern beaches										
Area (ha)	30	102	75	72	73	66	41	47	44	551
No. detected	2	11	2	4	3	2	2	0	0	26
Find rate (ha^{-1})	0.07	0.11	0.03	0.06	0.04	0.03	0.05	0	0	0.05
Sellafield beach										
Area (ha)	14	51	43	37	44	40	77	81	80	468
No. detected	2	12	14	13	11	28	21	19	22	142
Find rate (ha^{-1})	0.14	0.24	0.32	0.35	0.25	0.70	0.27	0.23	0.27	0.30
Southern beaches										
Area (ha)	14	82	40	30	18	49	20	29	23	303
No. detected	0	0	0	0	1	2	0	0	0	3
Find rate (ha^{-1})	0	0	0	0	0.06	0.04	0	0	0	0.01

4 Methodology adopted in the assessment

The methodology used in this assessment is consistent with the approach adopted in radiological assessments for regulatory purposes. The objective of this assessment was not to estimate risks to particular individuals who make use of the beaches or who eat seafood caught in the area but to determine whether the risk to any individual is greater than a risk of 10^{-6} y^{-1} which is set out in regulatory guidance. Therefore, the methodology developed for this assessment aimed at identifying people who are likely to receive the highest doses from exposure to radioactivity on objects and included cautious assumptions to estimate the highest level of risk to people and ensure that the risk to anybody residing in the area would be below this risk.

The methodology used to estimate the risk to health in this assessment was based on that described in reports HPA-CRCE-018 (supplement) (Oatway et al, 2011) and PHE-CRCE-021 (Oatway and Brown, 2015). This report describes the main aspects of the methodology used in this assessment and makes reference to specific sections of reports HPA-CRCE-018 (supplement) and PHE-CRCE-021 where appropriate. A summary of the key assumptions made in this assessment is provided in Appendix A.

In addition to lifetime risks from exposure to radiation, the absorbed dose to a tissue or organ was estimated for comparison against the dose threshold to evaluate whether tissue reactions could occur. The methodology used to estimate the absorbed dose to the colon and the skin, the organ and tissue assumed to be most likely to be exposed to radiation emitted from a radioactive object, is described in Sections 7.1.2.1 and 7.2.2 respectively.

The lifetime risk of a stochastic health effect was evaluated by combining the effective dose that people may receive if they were to come into contact with a radioactive object with the likelihood that a person would come into contact with such an object and a detriment-adjusted risk coefficient for stochastic effects. The principal components of detriment considered by the International Commission on Radiological Protection (ICRP) when recommending a value of risk coefficient for use in radiation protection are the probability of fatal cancer, the weighted probability of attributable non-fatal cancer and of severe heritable effects, and the length of life lost if the harm occurs. The lifetime risk of developing a stochastic health effect from using a beach or consuming seafood for a year is expressed using the equation below:

$$R_i = \sum_j P_i(j) D_i(j,k) F_i$$

Where R_i is the lifetime risk to an individual in age group i of developing cancer when using a beach or consuming seafood for a year from the presence of radioactive objects (y^{-1}); $P_i(j)$ is the annual probability that an individual in age group i comes into contact with an object via exposure pathway j[*] (y^{-1}); $D_i(j,k)$ is the effective dose to an individual in age group i exposed via pathway j to the activity of radionuclide k on the object (Sv); and F_i is the risk of developing cancer per unit dose to an individual in age group i (Sv^{-1}). In this assessment, the only radionuclides considered for an alpha-rich object were ^{241}Am and isotopes of plutonium while for beta-rich objects the radionuclides considered were ^{137}Cs and ^{90}Sr.

[*] As it was the case in report HPA-CRCE-018 (supplement) the term ‘probability of encounter’ is used in this report to refer to the likelihood of a person coming into contact and being exposed to a radioactive object present on the beach or in seafood

Many radiological impact assessments define each parameter, for example those describing the habits of the representative person or the level of activity present, with a single value where that value is taken from the upper end of the possible range. This approach is used where an estimate is needed of the upper magnitude of the risk rather than a best estimate of its value.

To provide a best estimate of the risk, this assessment adopted a different approach in that as many parameters as possible were defined using a probability density function rather than a single value. This approach was taken because of the difficulty in selecting appropriate parameter values to best represent the large and variable populations of both individuals who are potentially exposed and of objects present in the environment.

The outputs of this assessment take the form of a probability density function. The 97.5th percentile of these functions represent a reasonable worst case value whilst the 50th percentile represents the functions median value. To provide an indication of the potential range in the estimated quantities, the 2.5th percentile values of those functions are also presented.

4.1 Groups included and exposure pathways

The lifetime risk from the presence of radioactive objects in the environment was estimated to a member of a population who either used a Cumbrian beach for a year or who consumed seafood caught off the Cumbrian coast for a year. The risks to these two groups were calculated separately; the total risk to members of both groups was not estimated in this assessment.

For this assessment, risks were calculated, whenever possible, to individuals in three age groups: 1-year-old children (defined as young children), 10-year-old children (defined simply as children), and those of 16 years and older (defined as adults). This approach follows recommendations issued by the ICRP on this topic (ICRP, 2006a). It is important to recognise that, as this risk assessment did not make use of information related to any specific individual, the estimated quantities relate to a general beach user or seafood consumer in each age group rather than to any specific person.

In a previous assessment, described in report PHE-CRCE-021 (Oatway and Brown, 2015), the lifetime risk to commercial fishermen from a possible encounter with a radioactive object was not estimated separately. This was because the habits of commercial fishermen and their families were assumed to be included within the distribution defining the ingestion rate of the representative seafood consumer. In addition, it is very unlikely that commercial fishermen would come in contact with an object while pulling a catch onto their boats as the vast majority of sediment that may become attached to netting or pots is likely to be removed by the action of water. The lifetime risk to an individual who commercially fished was therefore assumed to be bounded by the estimated risk to a high rate seafood consumer. This approach was retained in this current assessment.

Exposure to radioactivity on an object may occur through both internal irradiation, if the object is taken into the body via inhalation following resuspension or ingestion, or external irradiation. For this assessment, it was assumed that external irradiation was limited to the time when an object was in direct contact with the skin as external gamma exposure from objects not in direct contact with the body would be very small, even for ^{60}Co-rich and beta-rich objects which have high energy gamma-ray emissions.

The chance that an individual may encounter an object through a particular exposure pathway depends on, amongst other things, the size of the object. Table 3, which reproduces Table 27 from report HPA-CRCE-018 (supplement), provides upper limits on the size of objects which could deliver a dose through different exposure pathways and the size of larger items which may be deliberately placed in the mouth. Table 3 shows that all exposure pathways are relevant for particles although it is acknowledged that only the very smallest of particles may be inhaled and reach the alveolar region of the lungs.

Table 3 Upper size limits for objects to be ingested, inhaled or adhere to the skin

Route of exposure	Upper size limit (mm)
Inadvertent ingestion without detection in the mouth	0.1
Inadvertent ingestion following detection in the mouth*	1
Deliberate ingestion, adult	70
Deliberate ingestion, child	40
Deliberate ingestion, young child	20
Respirable size for inhalation (alveolar-interstitial region of the lungs)	0.01
Lodged under fingernail	1
Adhesion to skin	1

* Assumes few objects are detected prior to swallowing and subject to individual tolerances

In the methodology adopted for the assessment it was assumed that individuals would be either unaware of the radioactive particle or not concerned by its presence, effectively treating it just like any other grain of sand. As particles were assumed to be treated by individuals on the beach like grains of sand, in this assessment the probability of coming into contact with a particle was assumed to be related to the mass of sand that an individual came into contact with. For example, the annual probability of a particle getting onto the skin was assumed to be related to the annual mass of sand that became attached to the skin.

It was assumed that a larger object could not be inhaled and that it would not be in contact with the skin or be swallowed without the individual being aware of it. This is because the likelihood that of an object can remain in contact with the skin or be swallowed decreases rapidly with an increase in the object's size. The potential risk posed by larger objects is discussed in this report, but was not evaluated explicitly as insufficient information could be found to quantify several of the required parameters.

5 Probability of coming into contact with a particle when using a beach near to the Sellafield site

The risks estimated by this assessment were based on annual habit data (for example, time spent on the beach or annual consumption of seafood). Implicit in this approach was the assumption that the risks do not vary throughout the year. This assumption is dependent on the population of objects per unit mass of sand being constant. To investigate the validity of this assumption, the beach monitoring programme has included repeat monitoring of areas of beach since 2011. An analysis of the data from the Sellafield Repeat Area indicates that find rates of alpha-rich particles are mainly influenced by external factors that accrete or erode sediments along the coastal frontage on a timescale of the order of months; basing this assessment on the assumption that the particle population present on any beach over the course of a year is relatively constant is therefore reasonable.

It should be noted that none of the repeat areas have provided information on intra-annual variation of the populations of beta-rich particles or larger objects as these finds are constrained to a limited area of the Cumbrian coast that do not intersect with any of the repeat areas. However, there is no reason to assume that these objects behave differently to alpha-rich particles other than that larger objects may require longer timescales for repopulation or mixing because they are less mobile.

This section provides a detailed description of the methodology used to determine the annual probability that an individual who uses a beach may encounter a particle via each exposure pathway.

5.1.1 Actual number of particles present on a beach

One of the key elements that determine the probability of encountering a particle is the number of particles present on the beaches. As the risk to a beach user is dependent on the actual number of particles present, not just those which have been detected, it is important that account is made of those particles which are present on the beach but have been missed by the detection system because they are located at depth or possess low levels of activity.

In the previous assessment, described in report HPA-CRCE-018 (supplement) (Oatway et al, 2011), two approaches were developed to estimate the actual number of particles present per unit area of beach. The first approach assumed that particles were deposited on the surface and then migrated into the bulk material of the beach with time. A core assumption of this approach was that the number of particles per unit area of beach decreased with depth and that they were only present to a depth of 0.15 m or 0.4 m for alpha- or beta-rich particles respectively, which are the maximum depths each type of particle could be detected at. In contrast the second approach assumed that particles were evenly distributed within the bulk material of the beach as would occur, for example, through tidal mixing of sand. The population density per unit mass of sand assumed in the second approach was therefore a constant down to a defined depth, which for simplicity was again taken to be equal to the maximum depth particles had been detected.

A comparison of the particle populations estimated using the two approaches was described in report HPA-CRCE-018 (supplement). That comparison showed that, based on the information available at the time, neither approach was significantly more robust than the other. The assessment described in report HPA-CRCE-018 (Brown and Etherington, 2011) estimated the actual particle population using the first approach in order to use all available information, specifically the depth at which particles were detected at. To retain consistency between assessments, all subsequent risk assessments (Oatway and Brown, 2015) estimated the actual number of particles present in the environment using the same approach.

A recent review of the morphology of beaches along the Cumbrian coast determined that the beaches are regularly mixed by tidal action and other natural processes (CH2M Hill, 2016).

That review therefore supports the use of the second approach described in HPA-CRCE-018 (supplement) to estimate the actual particle population; that approach was therefore used in this assessment.

Although the depth to which mixing of beach sediment occurs varies even within short distances, a typical depth over all beaches considered in this assessment was estimated to be about 0.5 m (CH2M Hill, 2016). It was also assumed that people on the beach may encounter a particle down to a depth of 0.5 m, for example through digging or playing in the sand. An analysis of the impact of selecting alternative values for the mixing depth is discussed in Appendix B. The actual population of particles present on a beach, N_m, was estimated using the following equation:

$$N_m = \sum_{i}^{N_d} \frac{1}{P_{det}(a_i)}$$

Where $P_{det}(a_i)$ is the probability of detecting a particle with an activity a_i within a volume of sand defined by a depth of 0.5 m and N_d is the number of particles detected on that beach.

Sellafield Ltd. determined that, for the Groundhog Synergy detection system, the probability of detecting a particle with a specific activity and located at a specific depth could be represented by a point on a log-normal distribution (Hill, 2017). $P_{det}(a_i)$ is therefore the overall probability of detecting a particle with a specific activity but which could be present at any depth down to 0.5 m. To estimate values for this probability for each particle, the function describing the log-normal distribution of the detection probability was integrated over the depth using the extended Simpson's rule formula for pairs of intervals (Abramowitz and Stegun, 1972), where each interval represented a change in depth equal to 0.01 m.

Very large uncertainties are introduced into the estimated actual particle population when particles with very low activity are included due to the very low detection probability associated with these particles. The minimum activity which had to be present on a particle for it to be included in the assessment was selected on the basis that a person exposed to that particle would receive an annual effective dose of at least 1 mSv when the relative activity of different radionuclides present on that particle are accounted for. This dose is equal to the dose criterion for exemption for low probability events (i.e. with an annual probability of occurrence of less than 10^{-2} y^{-1}) given in the IAEA Basic Safety Standards (IAEA, 2004) which PHE considers to represent the appropriate dose criterion to use in this situation.

For both alpha- and beta-rich particles, the exposure pathway contributing most to the effective dose is intake via ingestion. To receive an effective dose of 1 mSv, an alpha-rich particle would need in total about 20 kBq of activity, recognising that the dose coefficients for ingestion of ^{241}Am and the alpha-emitting isotopes of plutonium are very similar. However, as it is the radiation emitted by ^{241}Am which is detected by the Groundhog Synergy detection system, the minimum activity present on a particle for it to be included in the estimate of the actual alpha-rich particle population needs to be expressed only in terms of its ^{241}Am activity. If it was assumed that the ratio between the activity of ^{241}Am and the total activity of alpha-emitting isotopes of plutonium is about one then, for a particle to be included in the estimate of the actual alpha-rich particle population, it would need a minimum of about 10 kBq of ^{241}Am activity. It is recognised that, across the population of alpha-rich particles, the ratio between ^{241}Am activity and the activity of alpha-emitting radioisotopes of plutonium does vary.

Consequently, if a particle with a low ^{241}Am activity to total alpha-emitting isotope of plutonium activity were to be ingested, the resulting effective dose may be less than 1 mSv. For a particle with about 10 kBq of ^{241}Am activity, the corresponding detection probability at the surface is approximately 90% and the detection probability integrated to a depth of 0.5 m is about 1%.

To determine the minimum activity which had to be present on a beta-rich particle in order that a dose of 1 mSv would be received following the ingestion of that particle, account had to be made of the contributions of both ^{137}Cs and ^{90}Sr. Following the ingestion of a particle containing equal activities of ^{137}Cs and ^{90}Sr, between 70% and 90% of the effective dose, depending on the age of the individual, comes from exposure to ^{90}Sr. The relative activities of ^{137}Cs and ^{90}Sr on a particle vary considerably although measurements show a median ^{137}Cs:^{90}Sr ratio of approximately 10 with only about 5% of the measured ^{137}Cs:^{90}Sr ratios being greater than 1.25. If it was cautiously assumed that a particle had the same amount of ^{137}Cs and ^{90}Sr activity on it, then at least 8 kBq of ^{137}Cs activity would need to be on that particle for it to be included in the estimate of the actual beta-rich particle population. For a particle with about 8 kBq of ^{137}Cs activity, the corresponding detection probability at the surface is about 95% and the detection probability integrated to a depth of 0.5 m is about 10%.

A significant number of lower activity particles may exist but have not been detected and therefore their contribution to the risk to those who may encounter them are not included in this assessment. The potential implication on the conclusions of this risk assessment if many lower activity objects were to exist is discussed in Section 9.

The factors to account for the number of particles which may be present but which had not been detected vary from beach to beach. Uncertainties associated with this factor depend on the number of particles which were detected and on some beaches this number is relatively low due to, amongst other things, a low area monitored and a low object population being present. In this assessment, therefore, a single factor was used for all beaches to scale the find rate to estimate the actual number of alpha- and beta-rich particles per unit area of beach. Taken across all beaches, the average ratio between the estimated actual particle population per unit area and the find rate measured between 2009 and 2017 was equal to 28 and 5 for alpha- and beta-rich particles respectively. It was assumed that, unless significant changes occur to the characteristics of the detector system, these ratios are appropriate for estimating the actual particle populations into the future.

The risk assessment requires the actual particle population to be expressed in terms of the number of particles per unit mass of sand on each beach. The number of particles per unit mass of sand, N_g (g^{-1}), was estimated using the following equation:

$$N_g = \frac{N_u}{\rho_b}$$

Where ρ_b is the density of material on a beach, taken to be 2 10^6 g m^{-3} which is typical of sand, and N_u is the actual number of particles estimated to be present over 1 m^2 of beach down to a depth of 0.5 m. The number of particles estimated to be present on each beach per unit mass of sand is shown in Table 4. No distribution in the actual particle population was assumed in the risk assessment. This approach was considered appropriate as the particle populations present in any year appears to vary by less than a factor of three with no signs of any long-term trends (see Appendix C). It was also assumed that fragmentation of larger objects would not affect the magnitude of the risk as any increase in the particle population would be offset by an equivalent decrease in the activity present on any particle; this is discussed in Appendix D.

Table 4 Estimated actual particle populations present on the areas of beach considered in the risk assessment

	Northern beaches	Sellafield beach	Southern beaches
Alpha-rich particles			
Find rate of particles per ha	$1.1\ 10^{0}$	$2.1\ 10^{0}$	$2.5\ 10^{-1}$
Actual number of particles per hectare	$3.0\ 10^{1}$	$5.9\ 10^{1}$	$7.0\ 10^{0}$
Actual number of particles per g of sand	$3.0\ 10^{-9}$	$5.9\ 10^{-9}$	$7.0\ 10^{-10}$
Beta-rich particles			
Find rate of particles per ha	$5.0\ 10^{-2}$	$3.0\ 10^{-1}$	$1.0\ 10^{-2}$
Actual number of particles per ha	$2.0\ 10^{-1}$	$1.5\ 10^{0}$	$5.0\ 10^{-2}$
Actual number of particles per g of sand	$2.3\ 10^{-11}$	$1.5\ 10^{-10}$	$4.7\ 10^{-12}$

Between 2009 and 2017, during the time when the Groundhog Synergy detection system was deployed, larger objects were only detected on the beach at Sellafield. In that period, three alpha-rich larger objects and 259 beta-rich larger objects were detected. Using the approach described above, it was estimated that the actual populations of alpha- and beta-rich larger objects on the beach at Sellafield was approximately 0.07 and 1.9 objects per hectare. The actual population of alpha-rich larger objects per unit area of beach was therefore estimated to be nearly a thousand times lower than that of alpha-rich particles. In contrast, the actual population of beta-rich larger objects per unit area of beach was estimated to be similar to that of beta-rich particles.

5.1.2 Habits of beach users

Another key element in the estimation of probabilities of encounter is represented by the habit data. Habit reviews are regularly carried out around all nuclear licensed sites in the UK to collect information about what foods that population consume, where individuals within that population spend time and what activities they participate in. Since 2003, the Centre for Environment, Fisheries and Aquaculture Science (Cefas) has undertaken annual habits reviews around the Sellafield site under a collaborative agreement with FSA, EA and ONR, with the most recent reported review being for 2017 (Clyne et al, 2008; Clyne and Garrod, 2016; Clyne et al, 2010; Clyne et al, 2012; Clyne et al, 2014; Clyne et al, 2011; Clyne et al, 2004; Clyne et al, 2009; Garrod and Clyne, 2017; Garrod et al, 2015b; Moore et al, 2018; Papworth et al, 2013; Tipple, 2006b; Tipple, 2006a; Tipple, 2007). Every five years Cefas also undertake a detailed survey of the habits of a larger number of individuals. The most recent detailed habit surveys were carried out in 2003 (Clyne et al, 2004), 2008 (Clyne et al, 2009) and 2013 (Clyne et al, 2014). Cefas also carried out two additional bespoke habits surveys, in

2007 and 2009 (Clyne, 2008; Clyne et al, 2010), which were used to support the risk assessment described in the report HPA-CRCE-018 (Brown and Etherington, 2011). In this report, the annual habits reviews and the detailed habits surveys are collectively referred to as the habits surveys for simplicity.

Information collected during the annual habits reviews carried out between 2003 and 2017, the detailed habits surveys carried out in 2003, 2008 and 2013, and the bespoke surveys carried out in 2007 and 2009, were all used in this risk assessment as they were considered to represent the situation both now and into the foreseeable future. Older habits surveys were not considered as they are more likely to include information which is no longer relevant.

Habits surveys generally target individuals who are likely to have above average habits since they are used to identify the representative person for use in assessments carried out for permitting and authorisation purposes. The habits used in this assessment are therefore representative of a population of high rate beach users rather than average members of the general population.

As mentioned in Section 4.1, the radiation risks were calculated for three age groups: 1-year-old children (defined as young children), 10-year-old children (defined as children) and adults. Data for few children were included in the habit surveys and therefore, to make best use of the available habits data and to increase the statistical power of the assessment, habits data for individuals between the ages of 0 and 5 years were assigned to the young child age group; data for individuals between the ages of 6 and 15 years were assigned to the child age group; and data for individuals aged 16 years or above[*] were assigned to the adult age group.

The previous assessment identified 3 broad categories of activities that are carried out on Cumbrian beaches: leisure activities (for example playing with sand, building sand castles, paddling, rock pooling and sunbathing); angling activities (for example fishing from the shore and bait digging); and walking activities (for example walking dogs, general walking and beach combing). Leisure activities were assumed to mainly occur during the summer months while angling and walking activities were assumed to occur throughout the whole year. The same categories were adopted for this assessment. It is known that some individuals live in beach chalets at several locations including Braystones. The detailed habits surveys carried out in 2003, 2008 and 2013 included input from members of that population; the risk to individuals living in beach chalets were not therefore considered separately. The habits surveys also recorded observations made on individuals using beaches from further along the Cumbrian coast, including at Parton and Allonby. The observations made during the habits surveys on beaches beyond St Bees in the north and Drigg in the south showed that no beach was used in a way that would warrant the inclusion of additional beach activities in this assessment.

People involved in leisure activities were assumed to wear typical summer clothes (swim wear or shorts and t-shirts) and that significant amounts of sand would come into contact with the skin. Beach anglers were assumed to spend most of their time standing although some bait digging was also assumed to occur; for this assessment only the hands and lower arms of anglers were assumed to come into contact with sand. Although the feet and legs are the

[*] Data for adults include entries reported in the habit surveys as "unknown" age as Cefas confirmed that those individuals were all adults who had declined to give their ages.

main areas of the body exposed to sand when walking, individuals were also assumed to pick up objects which results in the hands and arms also coming into contact with sand.

The total number of people recorded in the habits surveys as participating in each activity on the beaches considered in the assessment is shown in Table 5. Within the habits surveys, some people were identified as carrying out activities over more than one beach, for example walking between St Bees and Drigg; the number of such individuals is included in the 'Multiple areas' row in Table 5. In addition, some people were identified as carrying out more than one activity on a beach, for example sunbathing and walking. In the risk assessment, their total time was divided equally between all appropriate beaches and activities.

The habits surveys showed that adults generally participate in all activities when using beaches along the Cumbrian coast. On Sellafield beach a single adult was observed in 2008 to participate in activities which was recorded in the habit survey as walking and playing. Given the nature of the beach and the likely activities for which people use it for, it was assumed that that individual only took part in activities associated with walking for this risk assessment. It was therefore assumed that Sellafield beach was not used by adults for any leisure activity. The habits surveys also showed that 10-year-old children participate in all types of activity when using beaches, with leisure and walking activities being popular, but that young children only participate in activities associated with leisure or walking. Finally, no children of any age were observed to use Sellafield beach.

Table 5 Number of individuals observed participating in different activities on Cumbrian beaches between 2003 and 2017

Beach	Number of individuals observed on a beach							
	Angling*		Leisure			Walking		
	Adult	Child	Adult	Child	Young child	Adult	Child	Young child
Northern beaches	189	1	34	41	15	160	5	3
Sellafield	46	0	1[#]	0	0	41	0	0
Southern beaches	164	0	35	11	22	312	21	6
Multiple areas[†]	193	15	1	1	0	21	5	2
Total	657	16	71	53	37	649	31	16

* No young children were observed to participate in activities associated with angling.

[#] Individual assumed to participate in walking activities for this assessment.

[†] Individuals who reported making use of more than one beach during the year.

For each age group, Table 6 presents the mean and standard deviations used to define the lognormal distributions of the annual time spent participating in each activity on the three different beach sections considered. These quantities were calculated from the observed annual occupancies reported in the habits surveys. A full discussion of observed beach habits is presented in Appendix E.

Table 6 Quantities used to define lognormal distributions in annual beach occupancy

Beach	Age group	Annual beach occupancy (h y^{-1})					
		Angling		Leisure		Walking	
		Mean	St. dev	Mean	St. dev	Mean	St. dev
Northern beaches	Young child	-	-	$7.6\ 10^1$	$1.1\ 10^2$	$9.2\ 10^1$	$2.0\ 10^2$
	Child	$1.7\ 10^2$	$4.4\ 10^2$	$1.1\ 10^2$	$1.6\ 10^2$	$4.4\ 10^1$	$3.6\ 10^1$
	Adult	$2.3\ 10^2$	$3.5\ 10^2$	$8.7\ 10^1$	$1.7\ 10^2$	$2.1\ 10^2$	$5.6\ 10^2$
Sellafield beach	Young child	-	-	-	-	-	-
	Child	-	-	-	-	-	-
	Adult	$1.7\ 10^2$	$2.9\ 10^2$	-	-	$1.4\ 10^2$	$2.2\ 10^2$
Southern beaches	Young child	-	-	$7.5\ 10^1$	$1.2\ 10^2$	$3.8\ 10^1$	$6.1\ 10^1$
	Child	$5.8\ 10^1$	$1.2\ 10^1$	$8.2\ 10^1$	$1.6\ 10^2$	$1.0\ 10^2$	$1.1\ 10^2$
	Adult	$2.1\ 10^2$	$4.4\ 10^2$	$6.2\ 10^1$	$1.3\ 10^2$	$2.4\ 10^2$	$7.3\ 10^2$

Table 7 presents 2.5th, 50th and 97.5th percentiles of the lognormal distributions of the annual time members of the beach-using population were estimated to spend on each beach using the quantities presented in Table 6. It was estimated that individuals on average used a beach between a few tens and about 100 hours a year. This occupancy rate represents the typical time spent by a holiday maker on Cumbrian beaches during the summer. The 97.5th percentile of the distribution of the annual beach occupancies was estimated to lie between a few hundred and about one thousand hours a year, which correspond to an average of between 1 and 3 hours a day spent on that beach all year round.

Similar to the assessment described in report HPA-CRCE-018, no estimate was made of the risk to a person either removing sand from a beach or making use of sand taken from the beaches as it is difficult to quantify the probability of coming into contact with a radioactive object as a result of those actions. The risk to people removing sand from a beach from any radioactive objects in the sand is unlikely to be greater than that to someone who walks on a beach as both groups would mainly be exposed by sand coming into contact with their hands and arms but a walker will spend far more time on the beach. Risks to children taking part in activities at places which make use of sand removed from the beach (e.g. in children's play areas) are considered to be no greater than those estimated for children playing on the beaches around the Sellafield site.

Table 7 Estimated annual time spent on a beach

Percentile	Annual time spent on a beach (h y^{-1})								
	Northern beaches			Sellafield beach			Southern beach		
	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young child									
2.5^{th}	0.0	$5.5\ 10^{0}$	$2.8\ 10^{0}$	0.0	0.0	0.0	0.0	$4.7\ 10^{0}$	$2.3\ 10^{0}$
50^{th}	0.0	$4.3\ 10^{1}$	$3.9\ 10^{1}$	0.0	0.0	0.0	0.0	$4.0\ 10^{1}$	$2.0\ 10^{1}$
97.5^{th}	0.0	$3.4\ 10^{2}$	$4.9\ 10^{2}$	0.0	0.0	0.0	0.0	$3.4\ 10^{2}$	$1.9\ 10^{2}$
Child									
2.5^{th}	$4.0\ 10^{0}$	$7.7\ 10^{0}$	$8.2\ 10^{0}$	0.0	0.0	0.0	$3.8\ 10^{1}$	$3.7\ 10^{0}$	$1.5\ 10^{1}$
50^{th}	$6.3\ 10^{1}$	$6.3\ 10^{1}$	$3.4\ 10^{1}$	0.0	0.0	0.0	$5.6\ 10^{1}$	$3.9\ 10^{1}$	$7.3\ 10^{1}$
97.5^{th}	$1.0\ 10^{3}$	$5.2\ 10^{2}$	$1.4\ 10^{2}$	0.0	0.0	0.0	$8.4\ 10^{1}$	$4.4\ 10^{2}$	$3.7\ 10^{2}$
Adult									
2.5^{th}	$1.5\ 10^{1}$	$3.5\ 10^{0}$	$4.0\ 10^{0}$	$9.0\ 10^{0}$	0.0	$9.1\ 10^{0}$	$6.4\ 10^{0}$	$2.2\ 10^{0}$	$3.3\ 10^{0}$
50^{th}	$1.2\ 10^{2}$	$4.0\ 10^{1}$	$7.3\ 10^{1}$	$8.9\ 10^{1}$	0.0	$7.6\ 10^{1}$	$8.7\ 10^{1}$	$2.7\ 10^{1}$	$7.1\ 10^{1}$
97.5^{th}	$1.1\ 10^{3}$	$4.3\ 10^{2}$	$1.4\ 10^{3}$	$9.0\ 10^{2}$	0.0	$6.6\ 10^{2}$	$1.1\ 10^{3}$	$3.5\ 10^{2}$	$1.5\ 10^{3}$

Radiological risks to workers who are present on beaches to the north of Sellafield during any potential construction of a new nuclear power station on land adjacent to the Sellafield site were also considered. It was considered that the probability that a worker involved in the construction of the nuclear power plant would come into contact with a radioactive object would be similar to the probability of encountering a radioactive object by an adult walker using the same beach.

5.1.3 Probability of a beach user ingesting an object

5.1.3.1 Inadvertent ingestion of a particle

The method to estimate the probability of inadvertently ingesting a particle is described in Section 6.2 and Appendix F of HPA-CRCE-018 (supplement). In that study, it was cautiously assumed that all particles present on a beach may be inadvertently ingested regardless of their physical size; this assumption is retained in this current assessment. The annual probability of inadvertently ingesting a particle when on a beach, P_{ing} (y^{-1}), was estimated using the following equation:

$$P_{ing} = N_g I_{ing} T$$

Where N_g is the number of radioactive particles per unit mass of sand (g^{-1}), see Table 4, I_{ing} is the inadvertent ingestion rate of sand (g h^{-1}, see Table 8) and T is time spent on the beach (h), see Table 6

A literature review of inadvertent ingestion of soil and geophagia, the deliberate ingestion of earth or soil-like materials, was undertaken for the previous risk assessment and is described in report HPA-CRCE-018 (supplement). That review concluded that it is reasonable to use a representative inadvertent ingestion rate of soil by children of 100 mg d^{-1}. This rate is consistent with the default value recommended for use in RCLEA, a contaminated land assessment model developed for use in the UK (Defra and EA, 2002) and the rate for a 10 year old child recommended in report NRPB-W41 (Smith and Jones, 2003). For a 1 year old child, NRPB-W41 recommends an inadvertent ingestion rate of soil of 300 mg d^{-1}; this rate lies between the upper bound of the soil ingestion rate by a member of the general population of 200 mg d^{-1} recommended by the US EPA (US EPA, 2011) and the 400 mg d^{-1} recommended for use in RCLEA. To account for possible effects of changes in behavior with age, the average ingestion rate of soil by both young children and children was assumed to be 100 mg d^{-1} while the maximum ingestion rates were assumed to be 400 and 200 mg d^{-1} for young children and children respectively.

Few studies appear to have been carried out on the inadvertent ingestion rate of soil by adults in the general population. Instead, the average ingestion rate of soil by an adult was estimated by making use of a formula proposed by (Sedman and Mahmood, 1994). This formula showed that the rate of soil consumption by an adult was approximately one tenth of the child's rate. The mean soil ingestion rate by an adult was therefore assumed to be 10 mg d^{-1}. This rate is the same as that recommended in NRPB-W41 and is similar to that recommended by the US EPA of 20 mg d^{-1}. If the formula proposed by Sedman and Mahmood (Sedman and Mahmood, 1994) was also used to estimate the maximum soil consumption rate by adults it would result in a rate which is below 60 mg d^{-1}, the default rate in the RCLEA tool (Environment Agency, 2011), and the 30 mg d^{-1} high rate recommended in NRPB-W41 (Smith and Jones, 2003). A representative maximum soil ingestion rate by an adult was instead assumed for this assessment to be 50 mg d^{-1}.

None of the papers reviewed specifically relate to the ingestion of sand although some of the reports reviewed by Simon (Simon, 1998) included children who were camping by a beach. As no information could be found on any differences between the consumption rates of soil and sand it was assumed that they are equivalent.

The rates quoted above were based on observations made on individuals who participated in specific activities, for example playing on a river bank, with the assumption that the ingestion rates at other times, that is during times spent away from the observed activity, are low in comparison. In this assessment, it was cautiously assumed that the total mass of material, both soil and sand, ingested over the course of the day would be consumed while the individual was on the beach. Conversion from a daily rate to an hourly rate therefore required an assumption on the amount of time an individual spent on a beach per day. As no information on this quantity was found in the habit surveys it was assumed for this assessment that each visit to a beach lasted on average two hours. It was therefore cautiously assumed that the hourly ingestion rate of sand was equal to half the daily rate. Parameter values used to define a log-normal distribution for the hourly ingestion rate of sand while on a beach are shown in Table 8.

Table 8 Quantities used to define lognormal distributions in the inadvertent ingestion rates of sand when on a beach

		Inadvertent ingestion rate (g h^{-1})		
Activity	**Age group**	**Minimum**	**Mean**	**Maximum**
All	Young child	0.0	5.0 10^{-2}	2.0 10^{-1}
All	Children	0.0	5.0 10^{-2}	1.0 10^{-1}
All	Adult	0.0	5.0 10^{-3}	2.5 10^{-2}

5.1.3.2 Deliberate ingestion of larger objects

Similarly to the previous assessment (Oatway et al, 2011), this assessment considered the deliberate consumption of non-food items assuming the individual had no knowledge that the item may be contaminated. Such individuals may have the rare medical condition known as pica where they persistently ingest non-nutritive substances for a period of time, or may be young children who could put sand in their mouths and subsequently swallow it when they play on the beach. No separate assessment was made of the risk to those who demonstrate such behaviour as insufficient information could be found to quantify any of the required parameters although it is noted that some of the observations made on soil consumption rates, discussed in Section 5.1.3.1, included some element of this behaviour.

In addition to potentially having a higher ingestion rate of soil and sand, individuals exhibiting the behaviours mentioned above may also place larger objects in their mouths. The ICRP's Human Alimentary Tract Model (HATM) (ICRP, 2006) suggests that a value of 70 mm could be used as an upper limit to the size of material that can be put in the mouth of an adult and swallowed. Report HPA-CRCE-018 (supplement) (Oatway et al, 2011) suggested cautious upper limits of the size of an object which could be fitted into the mouth of a 1 or a 10-year-old of 20 mm and 40 mm respectively.

5.1.4 Probability of an object coming into contact with the skin

The probability that an object may come into contact with, and remain in contact with, the skin is inversely proportional to the size of the object. This is because objects with a size much greater than a grain of sand are likely to be too heavy to either become attached to the skin or remain attached to the skin without falling off quickly. Objects much larger than a grain of sand are also likely to be removed rapidly from clothing and shoes because of the discomfort they can cause. It was assumed that any larger object would not remain in contact with the skin without an individual knowing about it and that the only mechanism by which a larger object could come in direct contact with the skin for any length of time was if it was deliberately picked up and held. For this to occur the larger object must be of a sufficiently large size that it could be seen on the beach and it would most likely also need to possess characteristics that would attract the attention of beach users compared with other debris present on the beach. These attributes cannot be quantified and therefore it was not possible to estimate the probability that a larger object may be deliberately collected and held. However, as noted in Section 5.1.1, on any beach there are estimated to be at most two larger objects per hectare, an extremely low rate compared to the number of stones and other items present on beaches along the Cumbrian coast. Additionally, larger objects generally resemble rock fragments (Sellafield Limited, 2018) and hence are assumed to not have characteristics that would attract the attention of people using the beach.

The method used to estimate the probability that a particle could inadvertently come into contact with the skin is described in Section 6.4 and Appendix D, E and H of HPA-CRCE-018 (supplement). The total annual probability that a particle could come into contact with the skin, P_{skin} (y^{-1}), was estimated using the following equation:

$$P_{skin} = P_{body} + P_{nail} + P_{clothes} + P_{shoe}$$

Where P_{body} is the annual probability that a particle could come into contact with the general area of skin on a body; P_{nail} is the annual probability of a particle becoming trapped under a nail; $P_{clothes}$ is the annual probability of a radioactive particle becoming trapped in clothing; and P_{shoe} is the annual probability of having a radioactive object trapped in shoes.

It was assumed that any sand present on the body or in clothing would be continuously refreshed for the duration of the time spent on the beach. The refresh rate is dependent on a number of factors including what the individual was doing, the size of the particle, the location on the body where the particle was attached to, and the material of the clothing. As was done in the previous assessment, the assumption was made that the mass of sand present on the body or in clothing at any time represents the average mass accumulated over an hour spent on the beach. After an hour, any sand in contact with the skin was assumed to be replaced with an equal mass of sand from the beach. This approach is cautious as not all parts of the body, for example clothing worn around the upper body of someone who participates in walking activities, are amenable to a rapid exchange of attached sand with new material.

To estimate the mass of sand that may get onto any part of the body, and hence the annual probability of a particle coming into contact with the skin, the approach described in HPA-CRCE-018 (supplement) (Oatway et al, 2011) divided the body into a number of areas. The areas of the body chosen were selected to account for differences in the dermal loading of sand on different areas of the body and the chance that each area of skin would not covered by clothing. The hands and feet were treated as distinct areas of the body since these areas are likely to be more regularly in contact with sand than other parts of the body and any sand present on them was more likely to be wet. The remaining areas of the body including the legs, chest, arms and head, were assumed to be frequently covered with clothing when on a beach and that any sand present on the skin in those areas would most likely be dry. The total annual probability that a particle may come into contact with the skin was estimated by summing the probabilities that a particle may come into contact with the skin on each of the different areas of the body.

The probability that a particle may be trapped under a nail is related to the volume of sand that may become trapped under a nail rather to the area of skin present. As the probability that a particle may be trapped under a nail cannot be related to the probability of a particle coming into contact with the skin of the body, this probability was estimated explicitly.

The previous assessment cautiously assumed that any particles trapped in clothing or in shoes would be in direct contact with the skin. This is important as the dose rate to the skin from a particle located only a few millimetres from the skin, as is likely to be the case for a particle trapped in loose fitting clothing, is substantially lower than that from a particle which is in contact with the skin. The assumptions made in the previous assessment were retained in this current assessment.

The previous assessment considered the probability that a particle may become trapped against the skin in the ear, the nose and in a wound. The methodology used recognised that many uncertainties are associated with the estimate of the annual probability that a particle may be trapped against the skin in these areas of the body. In the approach adopted, the dermal loading of sand in the ear, nose or a wound was assumed to be no higher than that on any other part of the body. The annual probability that a particle may be trapped was estimated by simply scaling the annual probability that a particle may get onto the skin of the body by the fraction of the skin area of the ears or nose or which could be affected by a wound. The probability that a particle may become trapped against the skin in the ears, nose or in an area affected by a wound was estimated to be at least an order of magnitude lower than the probability that a particle may come into contact with the skin on the other areas of the body. The annual probability that a particle may be trapped in the ear, nose or in an area which could be affected by a wound was not estimated separately in this assessment because it was considered that they would not contribute significantly to the total probability that a particle may come into contact with the skin.

As discussed in Section 7.2.4, it is very unlikely that there would be any adverse health effects from irradiation of the eye from radionuclides present on a particle. No estimate was therefore made of the probability that a particle may be trapped against the eye.

5.1.4.1 Contact of a particle with a general area of skin

The impact of particle size on the ability of material to adhere to the skin was examined by (Sheppard and Evenden, 1994) who found that adhering skin surfaces preferentially selected particles with diameters smaller than 0.1 mm, although particles larger than 50 µm were only found to adhere to the skin if they were associated with wet material. Although radioactive particles detected on beaches range in size from about 100 µm to less than 2 mm, this assessment cautiously assumed that any radioactive particle could adhere to the skin regardless of whether it was associated with wet or dry sand.

The general area of the body was considered to comprise of skin located on the hands, arms, feet, legs, trunk and head except for areas located under nails. The following equation was used to estimate the annual probability of a particle being present on the skin, P_{body} (y^{-1}):

$$P_{body} = N_g \left(F_w M_{sand,w} + \left(1 - F_w\right) M_{sand,c} \right) T$$

Where N_g is the number of radioactive particles per gram of sand (g^{-1}) see Table 4; F_w is the fraction of time spent on the beach in warm weather conditions over a year (dimensionless), see Table 9; $M_{sand,w}$ is the average mass of sand adhering to the skin per hour spent on the beach during warm weather ($g\ h^{-1}$); $M_{sand,c}$ is the average mass of sand adhering to the skin per hour spent on the beach during cold weather ($g\ h^{-1}$); and T is the annual time spent on the beach, ($h\ y^{-1}$), see Table 6.

A triangular distribution was used to represent the fraction of the year assumed to be spent on a beach in warm weather conditions (F_w). The key values of the distributions for each age group were taken from HPA-CRCE-018 (supplement) and are summarised in Table 9.

Table 9 Parameters used to define triangular distributions for the fraction of the year spent by members of the public on beaches in warm weather conditions

		Fraction of year spent on a beach in warm weather		
Age group	**Activity**	**Minimum**	**Mode**	**Maximum**
Young child	All	0.75	1.0	1.0
Children	All	0.50	0.75	1.0
Adult	Leisure	0.50	0.75	1.0
	Walking / Angling	0.25	0.25	0.50

The annual mass of sand that may come into contact with skin in different areas of the body was estimated by multiplying the mass of sand present per unit area of skin (Table 10) by the area of skin exposed during visits to the beach in either warm or cold weather conditions.

Dermal loadings were estimated on the basis of the literature review described in HPA-CRCE-018 (supplement) and additional information given in the Exposures Factors Handbook (US EPA, 2011). The distribution functions and their main parameter values used in this assessment were the same as those used in the previous assessment. For dry sand on the skin of hands and feet a triangular distribution, with a minimum value of 0.1 and a maximum 10 g m^{-2}, with a mode of 1 g m^{-2}, was assumed.

Holmes et al. (Holmes et al, 1999) reported a maximum dermal loading of soil of about 600 g m^{-2} on children playing in mud. This dermal loading is about a factor of 50 higher than the maximum dermal loading of dry sand described above. In the absence of other information, the triangular distribution describing the dermal loading of wet sand was defined by scaling the quantities defining the dermal loading of dry sand by a factor of 50. In line with the assumption made for dry sand, the dermal loading of wet sand on parts of the body other than the hands and feet was taken to be half that on the hands and feet. The values used to define the distributions of dermal loading of sand are summarised in Table 10.

The dermal loadings at the upper end of the ranges given in Table 10 are based on situations, for example children playing in mud, that are likely to result in the highest dermal loadings under any circumstances. It was assumed that any factor which could enhance the dermal loading of sand on a beach, for example the application of sun cream, was accounted for within the distributions defined by the values in Table 10.

Table 10 Parameters defining triangular distributions of the dermal loading of sand on the skin

	Dermal loading ($g\ m^{-2}$)		
Parameters	**Minimum**	**Mode**	**Maximum**
Dermal loading of dry sand on hands/feet	$1.0\ 10^{-1}$	$1.0\ 10^{0}$	$1.0\ 10^{1}$
Dermal loading of dry sand on rest of body	$5.0\ 10^{-2}$	$5.0\ 10^{-1}$	$5.0\ 10^{0}$
Dermal loading of wet sand on hands/feet	$5.0\ 10^{0}$	$5.0\ 10^{1}$	$5.0\ 10^{2}$
Dermal loading of wet sand on rest of body	$2.5\ 10^{0}$	$2.5\ 10^{1}$	$2.5\ 10^{2}$

The skin areas associated with relevant parts of the body considered in this assessment (lower arms, lower legs, hands, palms of the hand and outstretched fingers, feet and soles), as well as the area of skin for the whole body, are presented in Table 11. The total area of skin was taken from ICRP Publication 32 (ICRP, 2002) while the area of individual body locations were estimated using the percentage surface area of body parts recommended by the EPA (US EPA, 2011). Surface areas for the soles of the feet and palms and outstretched fingers were assumed to be 50% of the areas of the feet and hands, respectively.

Table 11 Skin surface areas of various parts of the body

	Skin area (m^2)						
Age group	**Lower arms**	**Lower legs**	**Hands**	**Palms and outstretched fingers**	**Feet**	**Soles of feet**	**Total body**
Young child	$2.6\ 10^{-2}$	$4.9\ 10^{-2}$	$2.8\ 10^{-2}$	$1.4\ 10^{-2}$	$3.7\ 10^{-2}$	$1.9\ 10^{-2}$	$5.3\ 10^{-1}$
Child	$5.9\ 10^{-2}$	$1.3\ 10^{-1}$	$5.9\ 10^{-2}$	$3.0\ 10^{-2}$	$8.5\ 10^{-2}$	$4.3\ 10^{-2}$	$1.1\ 10^{0}$
Adult	$1.1\ 10^{-1}$	$2.4\ 10^{-1}$	$9.9\ 10^{-2}$	$5.0\ 10^{-2}$	$1.3\ 10^{-1}$	$6.5\ 10^{-2}$	$1.9\ 10^{0}$

Table 12 summarises the body areas which were assumed to be covered by sand during each activity taking place when on a beach in warm weather conditions. The corresponding area of skin exposed to sand is given in Table 13.

Table 12 Body areas assumed to be exposed to wet or dry sand during warm weather conditions*

Activity	Material	Minimum	Mean	Maximum
Angling	Wet sand	Hands	Hands and lower arms	Hands and lower arms
	Dry sand#	No skin	No skin	No skin
Leisure	Wet sand	No skin	Hands and feet	25% of total body plus hands and feet
	Dry sand	Hands and lower arms	Lower arms and legs	No skin
Walking	Wet sand	No skin	Hands	Hands and feet
	Dry sand	Hands	Lower arms	Lower arms and legs

* The total mass of sand on the body is the sum of the mass of any wet and dry sand present, noting that the dermal loading of wet sand is greater than that of dry sand.

Only wet sand was assumed to be on the skin of anglers.

Table 13 Parameters used to define the triangular distributions in the area of skin exposed to sand during warm weather conditions*

				Area (m^2)		
Activity	**Material**	**Age group**	**Body area**	**Minimum**	**Mode**	**Maximum**
Angling# ¥	Wet sand	Child	Hand/feet	$5.9\ 10^{-2}$	$5.9\ 10^{-2}$	$5.9\ 10^{-2}$
			Body	0	$5.9\ 10^{-2}$	$5.9\ 10^{-2}$
		Adult	Hand/feet	$9.9\ 10^{-2}$	$9.9\ 10^{-2}$	$9.9\ 10^{-2}$
			Body	0.0	$1.1\ 10^{-1}$	$1.1\ 10^{-1}$
Leisure	Wet sand	Young child	Hand/feet	0.0	$6.5\ 10^{-2}$	$6.5\ 10^{-2}$
			Body	0.0	0.0	$6.8\ 10^{-2}$
		Child	Hand/feet	0.0	$1.4\ 10^{-1}$	$1.4\ 10^{-1}$
			Body	0.0	0.0	$1.4\ 10^{-1}$
		Adult	Hand/feet	0.0	$2.3\ 10^{-1}$	$2.3\ 10^{-1}$
			Body	0.0	0.0	$2.5\ 10^{-1}$
	Dry sand	Young child	Hand/feet	$2.8\ 10^{-2}$	0.0	0.0
			Body	$2.6\ 10^{-2}$	$7.5\ 10^{-2}$	0.0
		Child	Hand/feet	$5.9\ 10^{-2}$	0.0	0.0
			Body	$5.9\ 10^{-2}$	$1.9\ 10^{-1}$	0.0
		Adult	Hand/feet	$9.9\ 10^{-2}$	0.0	0.0
			Body	$1.1\ 10^{-1}$	$3.5\ 10^{-1}$	0.0
Walking	Wet sand	Young child	Hand/feet	0.0	$2.8\ 10^{-2}$	$6.5\ 10^{-2}$
			Body	0.0	0.0	0.0
		Child	Hand/feet	0.0	$5.9\ 10^{-2}$	$1.4\ 10^{-1}$
			Body	0.0	0.0	0.0
		Adult	Hand/feet	0.0	$9.9\ 10^{-2}$	$2.3\ 10^{-1}$
			Body	0.0	0.0	0.0
	Dry sand	Young child	Hand/feet	$2.8\ 10^{-2}$	0.0	0.0
			Body	0.0	$2.6\ 10^{-2}$	$7.5\ 10^{-2}$
		Child	Hand/feet	$5.9\ 10^{-2}$	0 .0	0.0
			Body	0.0	$5.9\ 10^{-2}$	$1.9\ 10^{-1}$
		Adult	Hand/feet	$9.9\ 10^{-2}$	0.0	0.0
			Body	0.0	$1.1\ 10^{-1}$	$3.5\ 10^{-1}$

* The total mass of sand on the body is the sum of mass of wet and dry sand present, noting that the dermal loading of wet sand is greater than that of dry sand.

Only wet sand was assumed to be on the skin of anglers.

¥ No young children were assumed to participate in activities associated with angling

Table 14 summarises the body areas which were assumed to be covered by sand during each activity when on a beach in cold weather conditions. All sand adhering to the body in cold weather conditions was assumed to be wet. The corresponding area of skin exposed to sand is given in Table 15.

Table 14 Parts of the body assumed to be exposed to wet sand during cold weather conditions

Activity	Age group	Minimum	Mean	Maximum
Angling	All ages	Hands	Hands	Hands and lower arms
Leisure	Young child	No skin	25% of one palm	One palm and fingers
	Child / Adult	No skin	Both palms and fingers	Hands
Walking	Young child	No skin	25% of one palm	One palm and fingers
	Child / Adult	No skin	Both palms and fingers	Hands

Table 15 Parameters used to define the triangular distribution in area of skin exposed to sand during cold weather conditions*

			Skin area (m^2)		
Activity	**Age group**	**Body area**	**Minimum**	**Mode**	**Maximum**
Angling#	Child	Hand/feet	$5.9\ 10^{-2}$	$5.9\ 10^{-2}$	$8.9\ 10^{-2}$
	Adult	Hand/feet	$9.9\ 10^{-2}$	$9.9\ 10^{-2}$	$1.5\ 10^{-1}$
Leisure	Young child	Hand/feet	0.0	$1.8\ 10^{-3}$	$7.0\ 10^{-3}$
	Child	Hand/feet	0.0	$3.0\ 10^{-2}$	$5.9\ 10^{-2}$
	Adult	Hand/feet	0.0	$5.0\ 10^{-2}$	$9.9\ 10^{-2}$
Walking	Young child	Hand/feet	0.0	$1.8\ 10^{-3}$	$7.0\ 10^{-3}$
	Child	Hand/feet	0.0	$3.0\ 10^{-2}$	$5.9\ 10^{-2}$
	Adult	Hand/feet	0.0	$5.0\ 10^{-2}$	$9.9\ 10^{-2}$

* The total mass of sand on the body is the sum of mass of wet and dry sand present, noting that the dermal loading of wet sand is greater than that of dry sand.

\# Young children were not assumed to participate in this activity and hence have no skin exposed to sand.

Even though some individuals were identified as bait diggers in the habits surveys, the surveys generally only reported the total time individuals spent angling which was taken to include the time individuals spent digging for bait as well as angling. Individuals recorded as bait diggers generally had lower beach occupancies than those described as anglers. Consequently, the average time spent digging for bait is likely to be lower than the time spent angling. As the fraction of time spent digging for bait could be not derived from observations, a triangular distribution with a representative average value of 13% and minimum and maximum values of 7% and 100% respectively was used in the assessment. These values are the same as those used in previous assessments (Brown and Etherington, 2011; Oatway et al, 2011). The mass of sand present on the skin of anglers during the time when they are not digging for bait was assumed to be the same as that present on the skin of someone participating in walking activities.

5.1.4.2 Particles trapped under a nail

The method used to calculate the annual probability that a particle may become trapped under a nail is the same as that described in HPA-CRCE-018 (supplement). The annual probability of a radioactive particle becoming trapped under a nail, P_{nail} (y^{-1}), was estimated using the following equation:

$$P_{nail} = N_g \left(M_f + F_w M_t \right) T$$

Where N_g is the number of radioactive objects per unit mass of sand (g^{-1}), see Table 4; M_f is the average mass of sand under a fingernail per hour on a beach ($g\ h^{-1}$), see Table 16; M_t is the average mass of sand under a toenail per hour on a beach ($g\ h^{-1}$), see Table 17; F_w is the fraction of time spent on the beach in warm weather conditions (dimensionless), see Table 9 and T is the annual time spent on the beach ($h\ y^{-1}$), see Table 6.

The mass of sand which could be trapped under a nail was assumed to be dependent on the time the nail was in contact with sand and the volume of space under a nail. The approach used to estimate the range in the volume of space under finger and toe nails for each age group, using anatomical data presented in ICRP publication 89 (ICRP, 2002), is described in Section 6.4.2 of HPA-CRCE-018 (supplement). The estimated mass of sand that could become trapped under fingernails and toenails are given in Table 16 and Table 17, respectively. These values were calculated by combining the range in the available volume under a nail and the number of nails assumed to have sand under them.

Table 16 Parameters used to define the triangular distribution in the mass of sand trapped under a fingernail per hour on the beach

	Mass of sand ($g\ h^{-1}$)		
Age group	**Minimum***	**Mode#**	**Maximum‡**
Young child	$1.4\ 10^{-3}$	$3.6\ 10^{-2}$	$3.4\ 10^{-1}$
Children	$2.7\ 10^{-3}$	$7.2\ 10^{-2}$	$6.7\ 10^{-1}$
Adult	$4.5\ 10^{-3}$	$1.2\ 10^{-1}$	$1.1\ 10^{0}$

* Assumes sand is trapped under a single nail of below average dimensions
# Assumes sand is trapped under five nails of average dimensions
‡ Assumes sand is trapped under ten nails of above average dimensions

Table 17 Parameters used to define the triangular distribution in the mass of sand trapped under a toenail per hour on the beach

	Mass of sand (g h^{-1})		
Age group	**Minimum***	**Mode#**	**Maximum‡**
Young child	$4.5\ 10^{-4}$	$1.2\ 10^{-2}$	$1.1\ 10^{-1}$
Children	$9.0\ 10^{-4}$	$2.4\ 10^{-2}$	$2.2\ 10^{-1}$
Adult	$1.5\ 10^{-3}$	$4.0\ 10^{-2}$	$3.7\ 10^{-1}$

* Assumes sand is trapped under a single nail of below average dimensions
# Assumes sand is trapped under five nails of average dimensions
‡ Assumes sand is trapped under ten nails of above average dimensions

5.1.4.3 Particles adhering to clothes

The method used to calculate the annual probability that a particle may become trapped in clothing is the same as that described in HPA-CRCE-018 (supplement). It was assumed that any particle associated with sand which had become trapped in clothing would be able to expose the skin. This is a cautious assumption since a particle would have to be in direct contact with, and remain relatively stationary to, the skin for the duration of that exposure. This situation is unlikely to occur for material trapped in clothes as normally a sizable air gap exists between any trapped material and the skin. The annual probability that a particle becomes trapped in clothes, $P_{clothes}$ (y^{-1}), was estimated using the following equation:

$$P_{clothes} = N_g\, A_c\, M_c\, T$$

Where N_g is the number of particles per unit mass of sand (g^{-1}), see Table 4; A_c is the area of clothing that is exposed to sand (cm^2), see Table 18; M_c is the average mass of sand trapped in clothing per unit time on the beach (g cm^{-2} h^{-1}), see Table 19; and T is the annual time spent on the beach (h y^{-1}), see Table 6.

The surface area of clothing assumed to be exposed to sand during each beach activity is given in Table 18. The area of the body covered by clothing was estimated by scaling the total area of skin on a body by a factor representing the total area of skin different types of clothing covered. For example, the minimum area of skin covered by clothing for people participating in leisure activities represents swimwear, the average area represents individuals wearing shorts and t-shirts, and the maximum area represents someone who is fully clothed with little skin exposed.

Table 18 Parameters used to define the triangular distribution in the area of clothing worn when using a beach

		Area (cm^2)		
Activity	**Age group**	**Minimum**	**Mode**	**Maximum**
Angling	Child	5.6 10^3 *	9.0 10^3 ǂ	1.1 10^4 ¥
	Adult	9.5 10^3 *	1.5 10^4 ǂ	1.9 10^4 ¥
Leisure	Young child	1.0 10^2 #	2.7 10^3 *	5.3 10^3 ¥
	Child	5.0 10^2 #	5.6 10^3 *	1.1 10^4 ¥
	Adult	1.0 10^3 #	9.5 10^3 *	1.9 10^4 ¥
Walking	Young child	2.7 10^3 *	4.2 10^3 ǂ	5.3 10^3 ¥
	Child	5.6 10^3 *	9.0 10^3 ǂ	1.1 10^4 ¥
	Adult	9.5 10^3 *	1.5 10^4 ǂ	1.9 10^4 ¥

* 50% of the total body surface area, representing someone wearing t-shirt and shorts.
# Representative values for a swimming costume.
ǂ 80% of the total body surface area, representing someone wearing t-shirt and trousers.
¥ 100% of the total body surface area, representing someone wearing clothes that cover the entire body.

The mass of sand that could be trapped in clothing depends on both the type and the amount of clothing worn. In the absence of any specific data it was assumed that the loading of sand on clothing was the same as the loading of dry sand on skin other than the hands and feet; values used to define the distribution in the mass of sand assumed to adhere to clothing is given in Table 19.

Table 19 Parameters used to define the triangular distribution of the mass of sand trapped in clothing

	Mass of sand ($g\ cm^{-2}\ h^{-1}$)		
	Minimum	**Mode**	**Maximum**
Mass of sand per unit clothing area	5.0 10^{-6}	5.0 10^{-5}	5.0 10^{-4}

5.1.4.4 Particles trapped in shoes

The method used to calculate the annual probability that a particle could become trapped in shoes is the same as that described in HPA-CRCE-018 (supplement). It was assumed that sand trapped in shoes was located next to the skin and that any particles present in that sand did not move relative to the skin for the duration of the visit to the beach. The annual probability that a radioactive particle could become trapped inside a shoe, P_{shoe} (y^{-1}) was estimated using the following equation:

$$P_{shoe} = N_g M_{shoe} T$$

Where N_g is the number of particles per unit mass of sand (g^{-1}), see Table 4; M_{shoe} is the average mass of sand trapped in shoes per unit time on the beach ($g\ h^{-1}$), see Table 20 and T is the annual time spent on the beach ($h\ y^{-1}$), see Table 6.

The mass of sand which could become trapped in a shoe depends on the type of shoe being worn, the activity the individual participates in and the length of time spent visiting a beach. Values to define the triangular distribution for this quantity, given in Table 20, were taken from a study which assessed the risks posed by fuel fragments on beaches around the Dounreay site (Smith and Bedwell, 2005). These quantities were also used in the previous assessment described in HPA-CRCE-018 (supplement). In the absence of information relating the mass of sand in shoes to the size of shoes or the activity undertaken when using beaches, the same mass of sand was assumed to be present in shoes worn by individuals of any age.

Table 20 Parameters used to define the triangular distribution in the mass of sand trapped in shoes per unit time on a beach

		Mass of sand ($g\ h^{-1}$)		
Beach activity	**Age group**	**Minimum**	**Mode**	**Maximum**
All	All	$1.0\ 10^{0}$	$1.0\ 10^{1}$	$5.0\ 10^{1}$

5.1.5 Probability of inhaling a particle

Very small radioactive objects resuspended through the action of wind can be inhaled by people. Objects which have been inhaled may be exhaled immediately, deposited in the extrathoracic airways, or may penetrate to, and be deposited in, the lungs. With respect to risks to health from the inhalation of radioactive particles, it is the number of particles that deposit in the alveolar-interstitial region of the lungs which is of greatest importance.

The methodology to estimate the probability of inhaling an object is described in Section 6.3 and Appendix G of HPA-CRCE-018 (supplement). As discussed in that report, only objects with a diameter of less than 50 µm are easily suspended by wind action. The ICRP Human Respirable Tract Model (HRTM) (ICRP, 1994) suggests that only particles with an aerodynamic diameter smaller than 10 µm are likely to reach the alveolar-interstitial region of the lungs although objects of tens of micrometres in size may deposit at other points along the respiratory tract.

Sellafield Ltd. only classifies objects in relation to a physical size of 2 mm and all particles analysed to date by scanning electron microscopy have been larger than about 100 µm. No information therefore exists on how many objects are of a size that would allow them to reach the alveolar-interstitial region of the lungs should they be inhaled. To account for the possible presence of an object with a size of the order of about 10 µm, it was very cautiously assumed in the previous assessment that all particles could be suspended by wind action, be inhaled and then reach the alveolar-interstitial region of the lungs. This assumption was retained in this current assessment. The annual probability of inhaling a particle on a beach, $P_{inh,p}$ (y^{-1}), was estimated using the following equation:

$$P_{inh,p} = N_g L_{sand} R_{inh} T$$

Where N_g is the number of radioactive particles per unit mass of sand (g^{-1}) see Table 4; L_{sand} is the sand loading in air ($g\ m^{-3}$), see Table 21; R_{inh} is the inhalation rate ($m^3\ h^{-1}$), see Table 22 and T is the annual time spent on the beach ($h\ y^{-1}$), see Table 6.

A lognormal distribution was assumed for the sand loading in air above a beach. Values to define those distributions were the same as those used in the previous assessment and are based on experimental data, including a number of measurements of atmospheric dust loadings above a range of beach types in Cumbria, described in report NRPB-M462 (Haslam et al, 1994). A summary of the main parameters defining the sand loading log-normal distribution for each age group is presented in Table 21.

Table 21 Parameters used to define the lognormal distribution of sand loading in air

		Sand loading in air ($g\ m^{-3}$)		
Activity	**Age group**	**Minimum**	**Mean**	**Maximum**
All	Young child/Child	$1.0\ 10^{-5}$	$1.0\ 10^{-4}$	$1.0\ 10^{-3}$
All	Adult	$1.0\ 10^{-5}$	$5.0\ 10^{-4}$	$1.0\ 10^{-3}$

In HPA-CRCE-018 a lognormal distribution was also used for the inhalation rates based on data presented in ICRP Publication 66 (ICRP, 1994), in Beals et al (Beals et al, 1996) and in Smith and Bedwell (Smith and Bedwell, 2005). Table 22 summarises the minimum and mean inhalation rates and the standard deviation of the distributions for different age groups used in HPA-CRCE-018 which were also adopted in this assessment.

Table 22 Parameters used to define the lognormal distribution of inhalation rates

		Inhalation rate ($m^3\ h^{-1}$)		
Activity	**Age group**	**Minimum**	**Mean**	**Standard deviation**
Angling	Children	$3.8\ 10^{-1}$	$8.7\ 10^{-1}$	$1.3\ 10^{-1}$
	Adults	$5.4\ 10^{-1}$	$1.7\ 10^{0}$	$2.5\ 10^{-1}$
Leisure	Young child	$1.5\ 10^{-1}$	$4.9\ 10^{-1}$	$7.4\ 10^{-2}$
	Children	$3.1\ 10^{-1}$	$8.7\ 10^{-1}$	$1.3\ 10^{-1}$
	Adults	$4.5\ 10^{-1}$	$1.2\ 10^{0}$	$1.8\ 10^{-1}$
Walking	Young child	$2.2\ 10^{-1}$	$4.9\ 10^{-1}$	$7.4\ 10^{-2}$
	Children	$3.8\ 10^{-1}$	$8.7\ 10^{-1}$	$1.3\ 10^{-1}$
	Adults	$5.4\ 10^{-1}$	$1.2\ 10^{0}$	$1.8\ 10^{-1}$

5.1.6 Annual probability of coming in contact with a radioactive particle by a beach user

Table 23 and Table 24 respectively show the total estimated annual probability of a beach user encountering an alpha- or beta-rich particle when using a beach between St Bees and Drigg. The annual probabilities of encountering a radioactive particle through each exposure pathway are reported in Appendix F.

Over all beaches and beach activities, the highest 97.5th percentile of the annual probability of encountering a particle is of the order of 10^{-4}. It was estimated that the probability that a person would come in contact with an alpha-rich particle on the northern beaches between St Bees and Braystones, on Sellafield beach, and on southern beaches between Seascale and Drigg are factors of about 130, 40 and 150 times greater than the probability that a beta-rich particle would be encountered. These ratios between the annual probability of encountering an alpha- or beta-rich particle are consistent with the differences in the populations of these particles on the different beaches shown in Table 4. The group with the highest annual probability of encountering a particle were adults who used northern beaches or Sellafield beach for activities associated with angling or walking. The most significant contributor to the uncertainty in the annual probability that a particle may be encountered is in the time an individual was assumed to spend on the beach; this is discussed in Appendix G.

Table 23 Estimated annual probability of encountering an alpha-rich particle when using a beach

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$3.8\ 10^{-7}$	$1.7\ 10^{-7}$	0.0	0.0	0.0	0.0	$7.1\ 10^{-8}$	$3.0\ 10^{-8}$
50th	0.0	$3.6\ 10^{-6}$	$2.7\ 10^{-6}$	0.0	0.0	0.0	0.0	$7.7\ 10^{-7}$	$3.4\ 10^{-7}$
97.5th	0.0	$3.2\ 10^{-5}$	$4.1\ 10^{-5}$	0.0	0.0	0.0	0.0	$7.5\ 10^{-6}$	$3.8\ 10^{-6}$
Children									
2.5th	$3.0\ 10^{-7}$	$6.9\ 10^{-7}$	$5.6\ 10^{-7}$	0.0	0.0	0.0	$4.1\ 10^{-7}$	$7.8\ 10^{-8}$	$2.3\ 10^{-7}$
50th	$5.5\ 10^{-6}$	$6.8\ 10^{-6}$	$3.1\ 10^{-6}$	0.0	0.0	0.0	$1.2\ 10^{-6}$	$9.9\ 10^{-7}$	$1.5\ 10^{-6}$
97.5th	$9.8\ 10^{-5}$	$6.8\ 10^{-5}$	$1.6\ 10^{-5}$	0.0	0.0	0.0	$2.5\ 10^{-6}$	$1.3\ 10^{-5}$	$9.0\ 10^{-6}$
Adults									
2.5th	$1.3\ 10^{-6}$	$4.2\ 10^{-7}$	$3.6\ 10^{-7}$	$1.6\ 10^{-6}$	0.0	$1.5\ 10^{-6}$	$1.4\ 10^{-7}$	$6.1\ 10^{-8}$	$7.7\ 10^{-8}$
50th	$1.3\ 10^{-5}$	$5.8\ 10^{-6}$	$7.5\ 10^{-6}$	$1.8\ 10^{-5}$	0.0	$1.5\ 10^{-5}$	$2.2\ 10^{-6}$	$9.1\ 10^{-7}$	$1.7\ 10^{-6}$
97.5th	$1.3\ 10^{-4}$	$7.2\ 10^{-5}$	$1.4\ 10^{-4}$	$2.1\ 10^{-4}$	0.0	$1.5\ 10^{-4}$	$3.1\ 10^{-5}$	$1.3\ 10^{-5}$	$3.8\ 10^{-5}$

Table 24 Estimated annual probability of encountering a beta-rich particle when using a beach

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beach		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$2.8\ 10^{-9}$	$1.3\ 10^{-9}$	0.0	0.0	0.0	0.0	$4.8\ 10^{-10}$	$2.0\ 10^{-10}$
50th	0.0	$2.7\ 10^{-8}$	$2.1\ 10^{-8}$	0.0	0.0	0.0	0.0	$5.3\ 10^{-9}$	$2.3\ 10^{-9}$
97.5th	0.0	$2.4\ 10^{-7}$	$3.1\ 10^{-7}$	0.0	0.0	0.0	0.0	$5.1\ 10^{-8}$	$2.6\ 10^{-8}$
Children									
2.5th	$2.3\ 10^{-9}$	$5.2\ 10^{-9}$	$4.2\ 10^{-9}$	0.0	0.0	0.0	$2.8\ 10^{-9}$	$5.3\ 10^{-10}$	$1.6\ 10^{-9}$
50th	$4.2\ 10^{-8}$	$5.2\ 10^{-8}$	$2.4\ 10^{-8}$	0.0	0.0	0.0	$7.9\ 10^{-9}$	$6.7\ 10^{-9}$	$1.0\ 10^{-8}$
97.5th	$7.3\ 10^{-7}$	$5.1\ 10^{-7}$	$1.2\ 10^{-7}$	0.0	0.0	0.0	$1.7\ 10^{-8}$	$9.1\ 10^{-8}$	$6.1\ 10^{-8}$
Adults									
2.5th	$9.8\ 10^{-9}$	$3.2\ 10^{-9}$	$2.7\ 10^{-9}$	$3.8\ 10^{-8}$	0.0	$3.8\ 10^{-8}$	$9.3\ 10^{-10}$	$4.1\ 10^{-10}$	$5.2\ 10^{-10}$
50th	$1.0\ 10^{-7}$	$4.3\ 10^{-8}$	$5.6\ 10^{-8}$	$4.5\ 10^{-7}$	0.0	$3.7\ 10^{-7}$	$1.5\ 10^{-8}$	$6.2\ 10^{-9}$	$1.1\ 10^{-8}$
97.5th	$9.8\ 10^{-7}$	$5.5\ 10^{-7}$	$1.1\ 10^{-6}$	$5.2\ 10^{-6}$	0.0	$3.7\ 10^{-6}$	$2.1\ 10^{-7}$	$9.0\ 10^{-8}$	$2.6\ 10^{-7}$

5.2 Probability of ingesting a particle by a seafood consumer

Objects in the marine environment may be consumed by marine animals and objects that are consumed by seafood may subsequently be ingested by humans. The risk to health from the possible consumption of a particle when eating seafood was the subject of a specific PHE study published in 2015 (PHE-CRCE-021) (Oatway and Brown, 2015). The main assumptions made in that assessment were retained and are summarised below:

a Only consumption of molluscs and crustaceans was included in the assessment. The potential for a member of the public to ingest a particle when consuming fish was considered to be negligible as fish that are caught commercially are normally gutted at sea followed by the fish being washed; the probability that a particle may be ingested when consuming fish was not estimated in this assessment.

b It was assumed that only particles present in the gut of an animal at the time it was consumed could be ingested by humans and that particles attached to the outside of the animal (for example to the shell) were removed by washing. The probability of a person consuming a particle therefore depends on how much sediment is in the animal’s gut at the time of consumption and how much of the gut content was consumed.

c Most seafood is depurated prior to consumption, especially seafood that is supplied commercially. However, as it is unknown how effective depuration is at removing any particles present in the gut of an animal it was cautiously assumed that the number of particles inside of an animal is not affected by the depuration process.

d Since no information was available to determine the fraction of particles which could be ingested by a mollusc or crustacean, it was cautiously assumed that all radioactive objects classified as particles could be ingested by marine animals. This assumption is likely to be very cautious as crustaceans and molluscs filter what they eat and generally ingest particles no more than a few tens of microns in size, with particles of a few hundred microns in size being rarely found inside such animals (Clyne, 2008; Defossez and Hawkins, 1997).

e It was also assumed that the number of particles present in an animal was directly proportional to the mass of sediment in the gut of the animal. The number of particles in a unit mass of sediment in the gut of an animal was therefore assumed to be the same as the number of particles in a unit mass of sediment in the area where the animal feeds.

The annual probability of ingesting a radioactive particle incorporated into seafood gathered from the West Cumbrian coastline, P_{ing} (y^{-1}) was estimated using the following equation, taken from report PHE-CRCE-021:

$$P_{ing} = M_s N_g$$

Where M_s is the mass of sediment ingested while consuming seafood (g y^{-1}) and N_g is the number of particles per unit mass of sediment (g^{-1}), see Table 4.

A limited programme of sub-sea monitoring using grab sampling was carried out by Sellafield Ltd. between 2011 and 2014. However, that programme did not provide sufficient information to accurately determine the population of objects on the seabed. The approach used in the previous assessment, described in report PHE-CRCE-021, was to assume that the number of particles present in the inter-tidal zone and further off-shore was equivalent to that estimated to be present on the adjacent beach; this approach was used in this current assessment.

The 2017 habit survey (Moore et al, 2018) noted that people obtained molluscs from Nethertown, St Bees, Parton, Tarn Bay and from around Whitehaven, although some molluscs were obtained from Drigg beach. As most of the sites mentioned are to the north of the Sellafield site, the number of particles present per unit mass of sediment inside molluscs was assumed to be equal to that estimated to be present on the northern beaches between St Bees and Braystones. As the estimated population of particles is higher on northern beaches than on southern beaches this approach would not result in any underestimation of the risks to seafood consumers if animals were obtained from elsewhere.

The habit surveys showed that crustaceans are obtained from all along the Cumbrian coastline (Garrod and Clyne, 2017). To retain a suitable level of caution in the assessment as some individuals may obtain all their food from an area smaller than that represented by the coast between St Bees and Drigg, the particle population present in areas where crustaceans were obtained from was assumed to be equal to that present on Sellafield beach.

The mass of sediment ingested annually while consuming seafood, M_s, was estimated using the following equation:

$$M_s = \frac{I_{sf} F_f F_s F_g}{F_e}$$

Where I_{sf} is the annual consumption rate of seafood by people (g y^{-1}), see Table 25; F_f is the mass of material consumed by seafood expressed as a fraction of live weight, see Table 26; F_s is the fraction of material consumed by seafood which is sediment, see Table 27; F_g is the fraction of gut content of seafood consumed by people, see Table 28; and F_e is the fraction of live weight of seafood consumed by people, see Table 29

The distribution in the annual consumption rate of seafood by people, I_{sf}, was derived from the consumption rates observed by habits surveys carried out between 2003 and 2017 (Clyne, 2008; Clyne and Garrod, 2016; Clyne et al, 2010; Clyne et al, 2012; Clyne et al, 2014; Clyne et al, 2011; Clyne et al, 2004; Clyne et al, 2009; Garrod and Clyne, 2017; Garrod et al, 2015a; Moore et al, 2018; Papworth et al, 2013; Tipple, 2006b; Tipple, 2006a; Tipple, 2007). Using this habits data assumes that all the seafood consumed by those interviewed during the habits surveys was sourced from around the Cumbrian coast.

During the review of the seafood consumption rates for this assessment it was noted that the rate of seafood consumption by young children and children observed in 2003 was significantly higher than those rates observed in other years. For example, the average ingestion rate of molluscs and crustaceans by young children reported in the 2003 habits survey was 15.5 kg and 9 kg respectively while the corresponding rates observed between 2004 and 2017 were 0.5 kg and 1 kg. Children associated with observations in 2003 belonged to a family of fishermen who were known to take large quantities of seafood home for consumption but who have since moved away from the area. It was recognised that including data on consumption rates from 2003 may not represent current habits but habits that could be present in the future, and therefore the distribution in the annual seafood consumption rates were cautiously defined using all observed habits made between 2003 and 2017 inclusive. The impact of excluding the 2003 habit data from the assessment is discussed in Appendix H. It is noted that, except for adults consuming crustaceans, the maximum consumption rates of both crustaceans and mollusc for each age group were recorded prior to 2010.

The number of observations made in the habits surveys, especially of young children and children, was too small to derive a probability density function of annual consumption rate of seafood. For this assessment, it was assumed that members of each age group consumed either crustaceans or molluscs with a rate defined by a triangular distribution where the mode and maximum annual rates were taken from the observed rates reported by the habits surveys. As the habits surveys are known to target individuals with above average ingestion rates of seafood, it was assumed that the minimum rates recorded in the habits surveys are substantially higher than that present in the seafood consuming population. To represent individuals who only ingest a very small quantity of locally caught seafood, it was assumed that the minimum annual ingestion rate of seafood was zero.

A summary of the quantities used to define the log-normal distributions in annual consumption rates of seafood used in the risk assessment are presented in Table 25. An ingestion rate equal to the mode given in Table 25 is likely to represent individuals who consume locally caught seafood about once a month if it was assumed that an adult ate about 200 g of mollusc or crustacean during a single meal. The maximum annual consumption rates shown in Table 25 are likely to represent individuals who eat locally caught seafood on most days of the week.

Table 25 Quantities used to define triangular distributions for the annual consumption rate of marine foods

		Consumption rate (g y^{-1})		
Food	**Age group**	**Minimum**	**Mode**	**Maximum**
Crustaceans	Young children	0.0	1.0 10^3	1.2 10^4
	Children	0.0	7.1 10^3	1.2 10^4
	Adults	0.0	2.0 10^3	5.6 10^4
Molluscs	Young children	0.0	1.9 10^4	1.9 10^4
	Children	0.0	1.0 10^2	1.9 10^4
	Adults	0.0	5.0 10^2	5.3 10^4

The distribution functions of the parameters F_f, F_s, and F_e were estimated following a literature search which is described in report PHE-CRCE-021. The probability density function of each of these parameters was assumed to be triangular in form and the values used in report PHE-CRCE-021 to define the density functions were retained for this assessment.

Values selected to define the distribution in parameter F_f, are given in Table 26. For molluscs, no values were found in the literature for the daily mass of material consumed by animals expressed as a fraction of their live weight. The values given in Table 26 were estimated from information on the mass of material consumed by a mollusc and a representative animal live weight. For crustaceans, the maximum representative value was based on a value at the upper end of the range observed in the environment for different species of crustaceans.

Table 26 Parameter values used to define the triangular distribution in the daily mass of material consumed by molluscs and crustaceans expressed as a fraction of live weight, F_f

	Consumption rate (d^{-1})		
Animal	**Minimum**	**Mode**	**Maximum**
Molluscs	3.0 10^{-4}	5.0 10^{-3}	1.0 10^{-2}
Crustaceans	5.0 10^{-2}	1.0 10^{-1}	2.5 10^{-1}

Table 27 provides the values used to define the distribution of the fraction of sediment consumed by molluscs and crustaceans, F_s. As described in report PHE-CRCE-021, for molluscs the minimum and maximum values were based on values found in the literature while the mode was taken to be the midway value. For crustaceans, only a single value was found in the literature which was taken to be the value of the mode while the minimum and maximum values were assumed to be ± 50% of the mode.

Table 27 Parameter values used to define the triangular distribution in the fraction of material consumed by molluscs and crustaceans that is sediment, F_s

	Fraction of total ingested material that is sediment		
Animal	**Minimum**	**Mode**	**Maximum**
Molluscs	$1.0\ 10^{-1}$	$1.5\ 10^{-1}$	$2.0\ 10^{-1}$
Crustaceans	$1.0\ 10^{-2}$	$2.0\ 10^{-2}$	$3.0\ 10^{-2}$

In the assessment described in report PHE-CRCE-021, the values used to define the distribution in the fraction of animal gut content consumed by people, F_g, were based on a review of food preparation techniques. For molluscs, the entire animal is generally consumed and hence a single value for this parameter of 100% was used. For crustaceans, the range in the values for this parameter could not be defined with certainty as they are dependent on the ability of the person preparing the food. The values used to define the distribution of the fraction of gut content of an animal which could be consumed by humans, given in Table 28, were therefore based on judgement.

Table 28 Values used to define the distribution of the fraction of gut content consumed, F_g

	Fraction of gut content consumed			
Distribution type	**Minimum**	**Mode**	**Maximum**	**Distribution**
Molluscs	$1.0\ 10^{0}$	$1.0\ 10^{0}$	$1.0\ 10^{0}$	Uniform
Crustaceans	0.0	$5.0\ 10^{-2}$	$1.0\ 10^{-1}$	Triangular

Table 29 shows the representative values used to define the distribution in the edible fraction of seafood F_e for use in the assessment.

Table 29 Parameter values used to define the triangular distribution in the edible fraction of molluscs and crustaceans, F_e

	Edible fraction		
Animal	**Minimum**	**Mode**	**Maximum**
Molluscs	$2.0\ 10^{-1}$	$3.0\ 10^{-1}$	$5.0\ 10^{-1}$
Crustaceans	$2.0\ 10^{-1}$	$3.0\ 10^{-1}$	$5.0\ 10^{-1}$

5.2.1 Annual probability of consuming a radioactive particle in seafood

The estimated annual probabilities that an individual may ingest an alpha- or beta-rich particle through consumption of seafood are given in Table 30. The 97.5th percentile in the annual probability of ingesting a radioactive particle when consuming seafood was estimated to be of the order of 10^{-7} y^{-1}. The highest probability of ingesting a particle was associated with adults ingesting an alpha-rich particle when consuming molluscs. The parameter contributing most to the uncertainty in the annual probability that a particle may be ingested when consuming seafood was the annual rate at which seafood was consumed although parameters related to the rate at which molluscs consume material are also important; this is discussed in Appendix G.

Table 30 Estimated annual probability of ingesting a particle when consuming seafood

Percentile	Annual probability of ingesting a particle (y^{-1})					
	Alpha-rich particles			Beta-rich particles		
	Molluscs	Crustaceans	Total*	Molluscs	Crustaceans	Total*
Young children						
2.5th	$1.4\ 10^{-8}$	$6.6\ 10^{-10}$	$2.2\ 10^{-8}$	$1.1\ 10^{-10}$	$1.6\ 10^{-11}$	$2.4\ 10^{-10}$
50th	$8.1\ 10^{-8}$	$7.4\ 10^{-9}$	$9.1\ 10^{-8}$	$6.1\ 10^{-10}$	$1.8\ 10^{-10}$	$8.6\ 10^{-10}$
97.5th	$2.3\ 10^{-7}$	$3.7\ 10^{-8}$	$2.3\ 10^{-7}$	$1.7\ 10^{-9}$	$9.3\ 10^{-10}$	$2.1\ 10^{-9}$
Children						
2.5th	$1.5\ 10^{-9}$	$1.5\ 10^{-9}$	$9.6\ 10^{-9}$	$1.1\ 10^{-11}$	$3.6\ 10^{-11}$	$1.5\ 10^{-10}$
50th	$3.4\ 10^{-8}$	$1.2\ 10^{-8}$	$5.1\ 10^{-8}$	$2.6\ 10^{-10}$	$3.0\ 10^{-10}$	$6.5\ 10^{-10}$
97.5th	$1.5\ 10^{-7}$	$4.5\ 10^{-8}$	$1.7\ 10^{-7}$	$1.2\ 10^{-9}$	$1.1\ 10^{-9}$	$1.7\ 10^{-9}$
Adults						
2.5th	$5.4\ 10^{-9}$	$2.4\ 10^{-9}$	$2.2\ 10^{-8}$	$4.1\ 10^{-11}$	$6.0\ 10^{-11}$	$3.1\ 10^{-10}$
50th	$9.7\ 10^{-8}$	$3.2\ 10^{-8}$	$1.5\ 10^{-7}$	$7.3\ 10^{-10}$	$8.0\ 10^{-10}$	$1.8\ 10^{-9}$
97.5th	$4.2\ 10^{-7}$	$1.7\ 10^{-7}$	$4.9\ 10^{-7}$	$3.2\ 10^{-9}$	$4.3\ 10^{-9}$	$5.7\ 10^{-9}$

* The total probability of ingesting a particle was estimated explicitly using the distributions in the relevant parameter values. The total values given in this table may not therefore equal the sum of the probability of a particle being ingested when molluscs or crustaceans are consumed separately.

6 Estimating the activity present on objects

As indicated in Section 4, risks were calculated separately for alpha- and beta- rich particles making the assumption that only ^{241}Am and isotopes of plutonium were present on alpha-rich particles and only ^{137}Cs and ^{90}Sr were present on beta-rich particles. The impact that the presence of other radionuclides may have on the doses and risks was investigated in the assessment described in report PHE-CRCE-021 (Oatway and Brown, 2015). That assessment showed that assuming ^{137}Cs and ^{90}Sr was present on alpha-rich particles, and ^{241}Am and isotopes of plutonium were present on beta-rich particles, would not affect the estimated risk by more than a few percent due to the much higher activity of ^{241}Am or ^{137}Cs on alpha- and beta-rich particles respectively.

The distribution in the ^{241}Am activity on alpha-rich particles detected using the Groundhog Synergy detection system between September 2009 and the end of 2017 is shown in Figure

2. The ^{241}Am activity on most of the particles was of the order of a few tens of kBq; an activity of over 100 kBq was measured on only 29 of them. The highest ^{241}Am activity measured on an alpha-rich particle was about 250 kBq; this particle was detected by the Groundhog Synergy detection system on the beach at Sellafield in 2010. The average ^{238}Pu and $^{239/240}Pu$ activity on alpha-rich particles was about a third of that of ^{241}Am. Where measured, the activity of ^{241}Pu was found to be significantly higher than that of the alpha-emitting radionuclides. However, as the dose per unit activity from ^{241}Pu is low in comparison to that from the alpha-emitting isotopes of plutonium it was only included in this assessment for completeness.

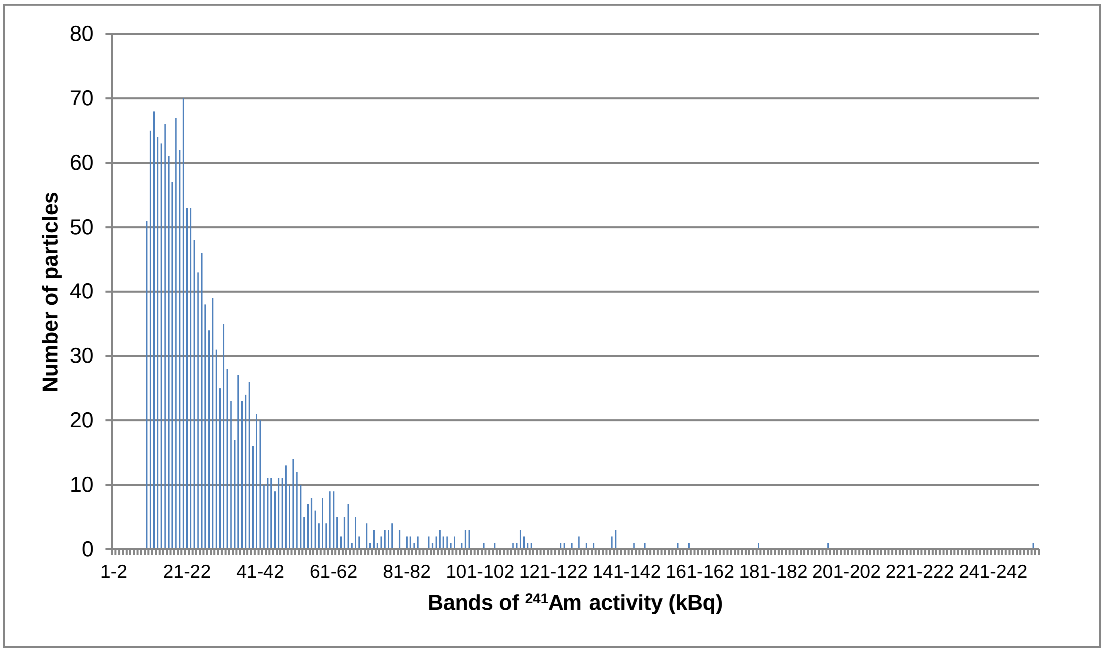

Figure 2 Distribution in ^{241}Am activity on alpha-rich particles detected using the Groundhog Synergy detection system up till the end of 2017. In line with the assumptions made in this assessment, particles with less than 10 kBq activity are not shown.

The distribution in ^{137}Cs activity on beta-rich particles detected by the Groundhog Synergy detection system between September 2009 and the end of 2017 is shown in Figure 3. Figure 3 shows that most beta-rich particles have activities of only a few tens of kBq with a few having ^{137}Cs activities above 100 kBq. The beta-rich particle with the highest ^{137}Cs activity found on the beaches between St Bees and Drigg was detected on the beach at Sellafield in 2017. The activity measured on that particle was about 190 kBq. A beta-rich particle with about 290 kBq of ^{137}Cs activity was detected in 2010 on a beach at Whitehaven, outside the geographical area included in the assessment.

The activity of ^{241}Am present on alpha-rich particles and ^{137}Cs and ^{90}Sr on beta-rich particles were defined as log-normal distributions with the arithmetic mean and standard deviation being estimated from measurements. However, particles with low ^{241}Am or ^{137}Cs activities may not have been detected and hence the mean activity per particle calculated on the population of detected particles is higher than on the particles actually present in the environment. To predict the distribution of activity on the population of particles present in the environment, the detection probability was taken into account. Figure 4 and Figure 5 show the measured distributions in ^{241}Am and ^{137}Cs activity on alpha- and beta-rich particles and the predicted lognormal distributions used in the assessment respectively. Also illustrated in Figure 4 and Figure 5 are the 50th and 97.5th percentile activities of the log-normal distributions.

The activity of plutonium isotopes on alpha-rich particles was not estimated from measurements as only a limited number of particles had been subjected to such analysis. Instead it was assumed that the activity of each isotope of plutonium existed in some ratio with that of ^{241}Am. The ratio between the activity of each isotope of plutonium and ^{241}Am was defined as a normal distribution with an arithmetic mean and standard deviation based on measured quantities. Table 31 shows the values used to estimate the activity of each radionuclide used in this assessment and Table 32 presents the corresponding estimated activities expressed with respect to their percentiles.

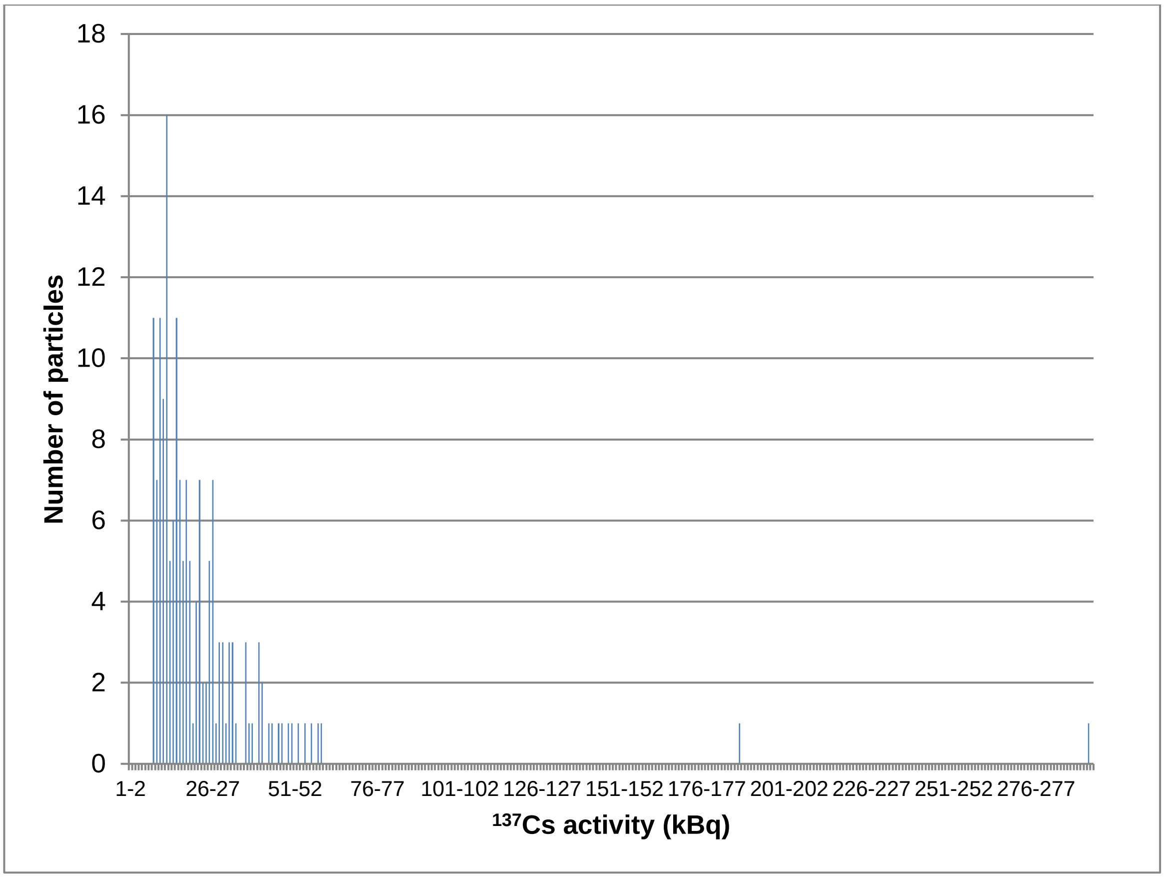

Figure 3 Distribution in ^{137}Cs activity on beta-rich particles detected using the Groundhog Synergy detection system up until the end of 2017. In line with the assumptions made in this assessment, particles with less than 8 kBq activity are not shown.

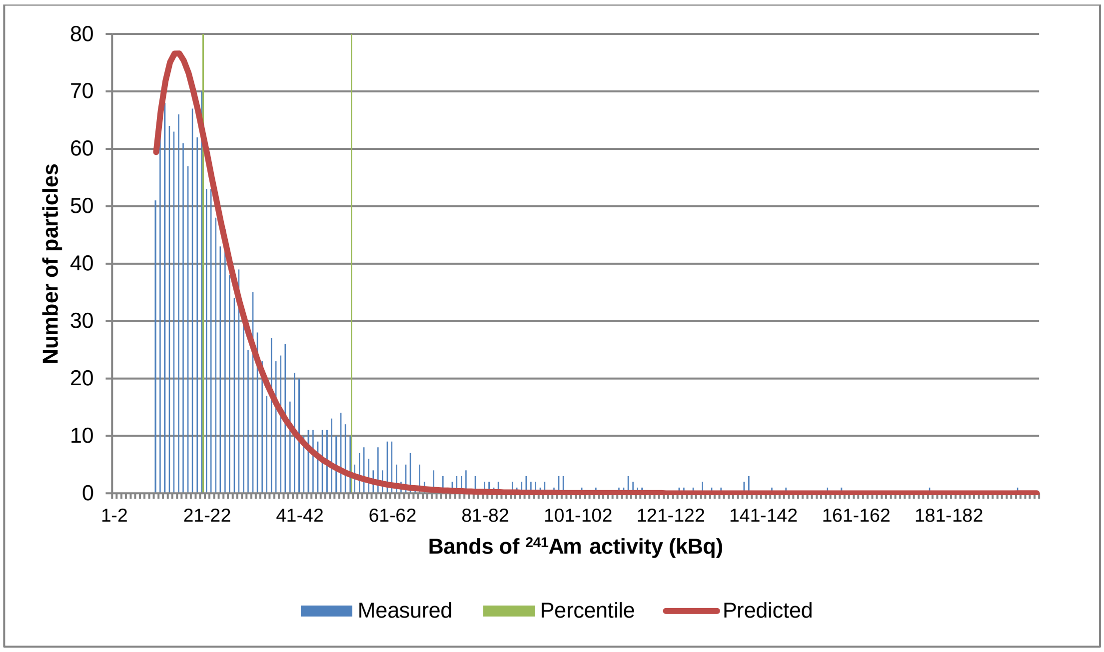

Figure 4 Fit of predicted lognormal distribution of ^{241}Am activity on the true particle population with the distribution in activity on detected particles and the positions of the 50th and 97.5th percentile values

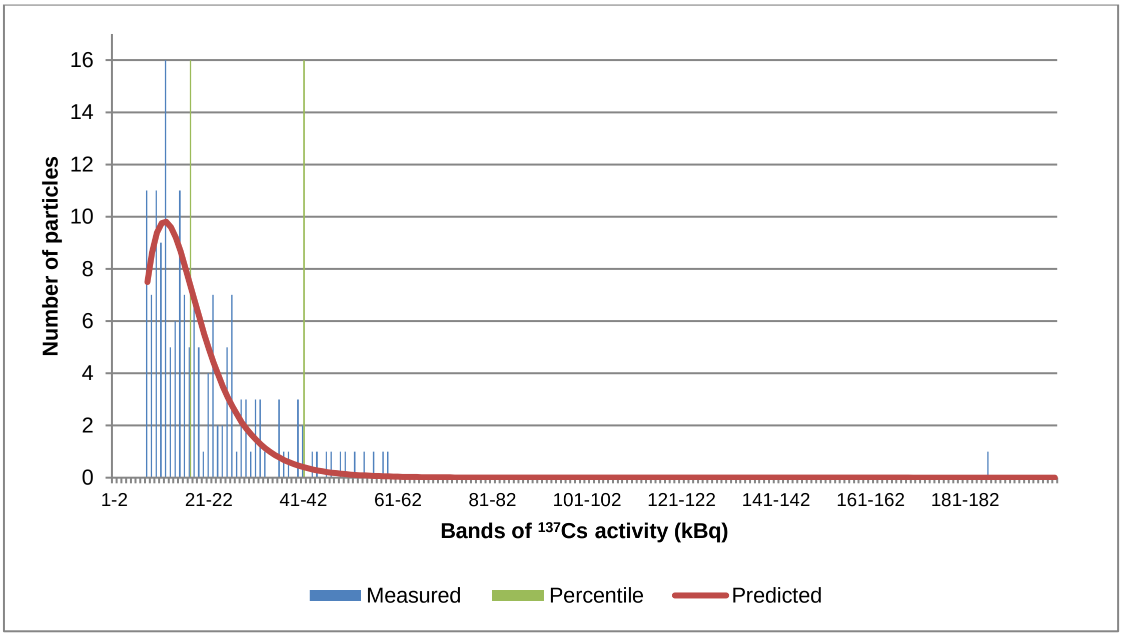

Figure 5 Fit of predicted lognormal distribution of ^{137}Cs activity on the true particle population with the distribution in activity on detected particles and the positions of the 50th and 97.5th percentile values

Table 31 Arithmetic averages and standard deviations used to define the log-normal distribution of radioactivity levels on alpha- or beta-rich particles assumed in this assessment

	Alpha-rich particles				Beta-rich particles	
		Scaling factor for plutonium isotopes*				
	^{241}Am (Bq)	^{238}Pu:Am	$^{239/240}$Pu:Am	^{241}Pu:Am	^{137}Cs (Bq)	^{90}Sr (Bq)*
Average	2.2 10^{4}	0.3	0.3	6	1.7 10^{4}	2.2 10^{4}
Standard deviation	1.2 10^{4}	0.1	0.2	2	9.0 10^{3}	3.6 10^{5}

* These values, which are based on measured quantities, are only intended to be used to define the lognormal distributions of the activity of each radionuclide for use in this assessment. The values presented in this table are not easily interpreted with respect to the relative levels of activity which may be present on a real population of particles.

Table 32 Range in the estimated activity present on a population of alpha- or beta-rich particles

	Activity (Bq)					
	Alpha-rich particles				Beta-rich particles	
Percentile	^{241}Am	^{238}Pu	$^{239/240}$Pu	^{241}Pu	^{137}Cs	^{90}Sr
2.5th percentile	1.1 10^{4}	1.2 10^{3}	1.4 10^{3}	4.5 10^{4}	8.5 10^{3}	1.5 10^{1}
50th percentile	2.0 10^{4}	6.4 10^{3}	5.5 10^{3}	1.1 10^{5}	1.6 10^{4}	1.4 10^{3}
97.5th percentile	5.1 10^{4}	2.1 10^{4}	2.3 10^{4}	3.3 10^{5}	4.1 10^{4}	1.4 10^{5}

7 Assessment of doses from exposure to a radioactive object on the beaches

This section provides information on the doses received by individuals who come in contact with radioactive particles and larger objects found on the beaches near to the Sellafield site. It deals with both stochastic effects for which the probability of occurrence of the effect increases with increasing radiation dose without a threshold, but the severity of the effect is independent of dose (ICRP, 2007), and deterministic effects (tissue reactions), for which the severity of the effect increases with increasing dose once a threshold has been exceeded.

The term dose generally refers to the dosimetric quantities of the absorbed dose to organs, for example the skin, when deterministic effects are considered and the effective dose when stochastic effects are considered. Effective doses provided in this section were used to calculate the radiological risks in this assessment. Effective doses from intakes of radionuclides (ingestion and inhalation) for radiological protection purposes, are calculated by ICRP using biokinetic and dosimetric models for different ages at intake (ICRP, 2007; ICRP, 2015a). These effective doses are integrated to age 70 years following intake by a reference adult (aged 20 years), child (aged 10 years) or young child (aged 1 year) and referred to as committed effective doses (ICRP, 2006a). Committed effective doses provide single values for the control of radiation exposures but conceal, as steps in their calculation, the contributions made by doses to individual organs and tissues and the time-course of dose delivery.

7.1.1 Exposure following the inhalation of a particle

HPA-CRCE-018 (supplement) (Oatway et al, 2011) presents evidence to show that particles with an aerodynamic diameter greater than about 30 µm deposit almost exclusively in the extrathoracic region of the respiratory tract with only particles with an aerodynamic diameter smaller than 10 µm likely to reach the alveolar-interstitial region of the lungs. This is illustrated in Figure 6, which reproduces Figure 14 in HPA-CRCE-018 (supplement), which shows that the estimated equivalent dose to the lung does not increase when particles are larger than about 10 µm. If all particles, defined as objects of less than 2 mm in size, are assumed to behave the same as objects of a few microns in size with respect to their ability to penetrate to the alveolar-interstitial region of the lungs, the estimated risk to health will be significantly overestimated. However, as discussed in Section 5.1.5, this assumption was made to account for the possibility that a population of particles smaller than 100 µm could exist in the environment.

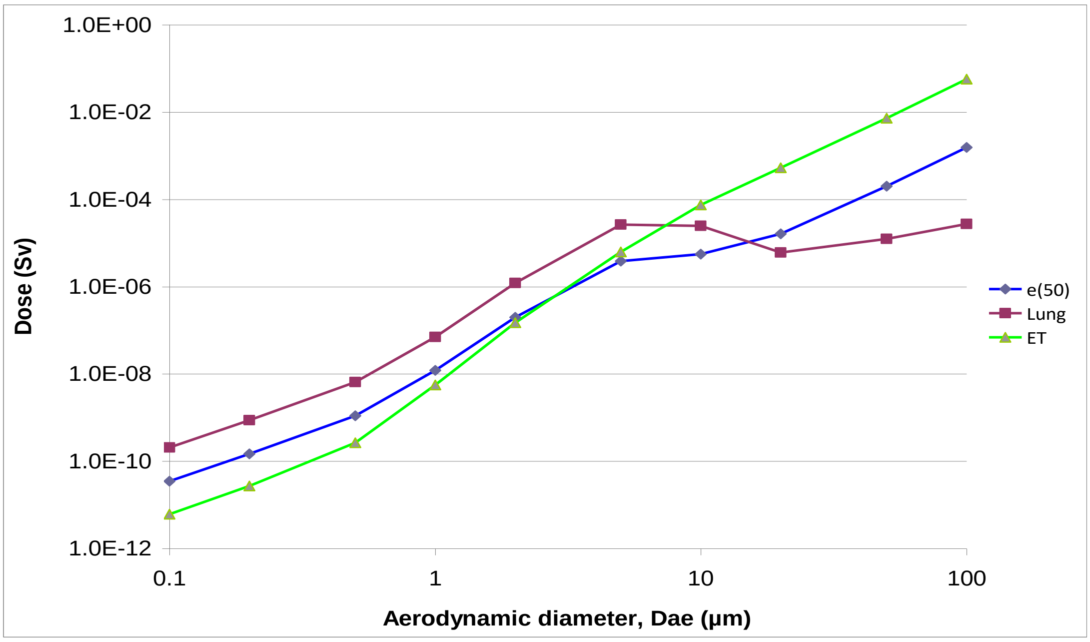

Figure 6 Effective dose and equivalent doses to the lungs and extrathoracic (ET) region, for a population potentially exposed to the inhalation of a single particle of the specified aerodynamic diameter containing ^{241}Am (Type S), as predicted by ICRP's Human Respiratory Tract Model (ICRP, 1994)

HPA-CRCE-018 (supplement) also describes an analysis conducted on a limited number of particles with respect to physical size and radioactivity content (Cowper, 2009). That analysis showed that there is an approximately linear relationship between the ^{241}Am activity present on a particle and the particle volume. Based on that analysis, it was stated in HPA-CRCE-018 (supplement) that "particles with ^{241}Am activities greater than about 10 kBq are likely to have aerodynamic diameters in excess of 200 µm". Report HPA-CRCE-018 (supplement) therefore concluded that "for particle sizes that are likely to be inhaled, the effective dose resulting from the inhalation of a single particle was estimated to be no greater than a few mSv". For this assessment, it was not considered necessary to change the conclusions given in HPA-CRCE-

018 (supplement) with respect to the magnitude of the potential risk to health that may result following the inhalation of an alpha-rich particle.

In HPA-CRCE-018 (supplement) it was noted that the effective dose following the inhalation of a beta-rich particle by a one-year old, the age group which would receive the highest dose, would be no more than about 6 mSv. However, as noted in HPA-CRCE-018 (supplement), the particle on which that estimation was based had an AMAD of about 29 µm and hence it is at the upper end of the range likely to be able to penetrate to the deeper regions of the lungs. That particle was also assumed to have a Cs:Sr activity ratio of about 1.7 which is very high compared to the majority of objects detected. An estimated effective dose of 6 mSv following the inhalation of a beta-rich particle was therefore considered to represent a dose at the upper end of the likely range.

An effective dose of a few millisieverts implies an absorbed dose to the lung of no more than a few Grays from an alpha-rich particle and much less than a Gray from a beta-rich particle. These doses are much less than the 20 Gy dose which is associated with a steeply rising probability of clinical pneumonitis and reduced lung functioning (ICRP, 2012b). It is recognised that this threshold is associated with irradiation of the whole lung rather than just a small part of it as would be the case following the inhalation of a particle; this threshold must therefore be regarded as cautious for use in this situation. The previous assessment concluded that, based on a cautious analysis of the potential magnitude of dose which may be received following the inhalation of a radioactive particle, the likelihood of any deterministic effects is extremely low. As no additional information has been obtained since that analysis, this interpretation of the available information is retained.

7.1.2 Exposure following the ingestion of an object

7.1.2.1 Methodology to estimate the absorbed dose to the colon following the ingestion of a radioactive object

In the previous assessment, HPA-CRCE-018 (supplement), a detailed calculation of the absorbed dose to the colon from the ingestion of a beta-rich particle found on the beach was carried out. The method used was based on the method adopted to estimate absorbed doses to the recto sigmoid colon from ingestion of Dounreay fuel fragments (DFF) (Harrison et al, 2005). The recto sigmoid colon is the region of the GI tract that receives the greatest doses from ingested beta-rich objects because it has the narrowest diameter of the three segments into which the colon is divided and it has the longest transit time.

Two kinds of absorbed doses were computed depending on the path the particle was assumed to take while transiting the colon: expectation doses which represent an average absorbed dose from particles at different radial positions within the lumen, and 'maximum' doses which assumed the worst-case situation where the particle was in contact with the mucosal lining of the recto sigmoid during its entire transit.

The absorbed dose rate to the colon per unit activity present on a particle is shown in Table 33 which is a reproduction of Table 86 of HPA-CRCE-018 (supplement). Transit times used in the calculations were 16 hours for an adult (based on an adult female) and 12 hours for a 1 year old child. The absorbed dose to the colon of a child was not estimated due to insufficient information being available, but it is expected that it would lie between those estimated for a 1 year old child and an adult.

Table 33 Expectation and maximum absorbed doses to the rectosigmoid colon

	Absorbed dose (Gy Bq^{-1})					
	Expectation rectosigmoid dose			Maximum rectosigmoid dose		
Age group	^{137}Cs	^{90}Sr	^{90}Y	^{137}Cs	^{90}Sr	^{90}Y
1-year old child	$5.2\ 10^{-9}$	$2.7\ 10^{-9}$	$3.7\ 10^{-8}$	$5.3\ 10^{-8}$	$5.5\ 10^{-8}$	$1.4\ 10^{-7}$
Adult	$2.0\ 10^{-9}$	$8.8\ 10^{-10}$	$1.3\ 10^{-8}$	$2.6\ 10^{-8}$	$2.7\ 10^{-8}$	$7.1\ 10^{-8}$

Table 34 shows the estimated absorbed dose to the colon following ingestion of a radioactive particle. These values were estimated by multiplying the absorbed dose rate to the recto sigmoid colon given in Table 33 by the distributions of activity on beta-rich particles described in Chapter 6. The highest 97.5th percentile of the absorbed dose to the colon of any individual who may ingest a particle was estimated to be of the order of 28 mGy. The threshold for deterministic effects in the colon is equal to an absorbed dose of 23 Gy. As the maximum estimate 97.5th percentile of the absorbed dose is about a factor of one thousand below the threshold for deterministic effects the threshold would not be exceeded. Severe tissue damage to the colon following the ingestion of a particle is therefore unlikely to occur.

Table 34 Estimated absorbed dose to the colon assuming ingestion of a beta-rich particle

	Absorbed dose (Gy)	
Percentile	Expectation dose	Maximum dose
Young children		
2.5th	$5.3\ 10^{-4}$	$5.6\ 10^{-5}$
50th	$1.4\ 10^{-3}$	$1.7\ 10^{-4}$
97.5th	$2.8\ 10^{-2}$	$5.6\ 10^{-3}$
Adults		
2.5th	$2.6\ 10^{-4}$	$2.1\ 10^{-5}$
50th	$6.8\ 10^{-4}$	$6.1\ 10^{-5}$
97.5th	$1.4\ 10^{-2}$	$2.0\ 10^{-3}$

7.1.2.2 Methodology to estimate the effective dose from ingestion of a particle

The committed effective dose to an individual following ingestion of an object, E_τ, (Sv) was estimated using the following equation:

$$E_\tau = \sum_r A_r\, e_{\tau,r}$$

Where A_r is the activity of radionuclide r on the particle taken into the body through ingestion (Bq) and $e_{T,r}$ is the committed effective dose coefficient for ingestion for radionuclide r (Sv Bq^{-1}).

Americium and plutonium absorbed to blood are distributed to body organs and tissues with long-term retention in the skeleton and liver (ICRP, 2015a). For radioisotopes of plutonium and americium, the liver, bone surfaces and red bone marrow are important contributors to overall dose, contributing a total of 86% of the committed effective dose in the example of ^{239}Pu ingested by adults. Because of the long-term retention of plutonium and americium in body tissues and the long half-lives of their radioisotopes, doses are delivered throughout the integration period although losses by excretion result in decreasing doses. In the example of ingestion of ^{239}Pu by adults, 50% of the committed effective dose is delivered in 20 years and 80% in 35 years. For 1-year-old children, retention times during childhood are shorter and the corresponding figures are 50% in 8 years and 80% in 33 years.

The most important factor in determining the dose per unit intake for ingestion of an alpha-rich particle is the fraction of activity present on the object which is absorbed from the GI tract to the body fluids (f_1). As reported in HPA-CRCE-018 (supplement), *in vivo* and *in vitro* studies showed that most particles retrieved from beaches along the Cumbrian coast have f_1 values ranging from 10^{-7} to 10^{-6} although the maximum measured was about an order of magnitude higher. The approach used in the previous assessment assumed that every particle had an f_1 value equal to the maximum measured rounded up to one significant figure to provide an additional degree of caution given the small number of particles which had been subjected to analysis and to account for possible changes which may occur to the characteristics of the particles in the future. In the previous assessment, a particle uptake fraction of $3\ 10^{-5}$ was assumed for all ages. This approach was also used in this assessment. It is noted that the measured f_1 for particles retrieved from the Cumbrian coast are low compared to the ICRP recommended value of $5\ 10^{-4}$ for unknown compounds of plutonium and americium. The reason for this is likely to be that the uptake fraction for plutonium and americium, which are minor constituents of the particle matrix, is determined by the low particle dissolution fraction of the rather insoluble materials of which the particles are made of.

New dose coefficients for ingestion are being computed by ICRP using the Human Alimentary Tract (HAT) model described in ICRP Publication 100 (ICRP, 2006b). However, as this data has yet to be published this assessment made use of the ICRP Publication 30 model (ICRP, 1982). The corresponding dose coefficients derived using the ICRP Publication 30 model assuming an f_1 of $3\ 10^{-5}$, are shown in Table 35. If the dose coefficient for ingestion were estimated using the HAT model then it is anticipated that they would be lower than those shown in Table 35 although generally by less than a factor of 2.

Table 35 Dose coefficient for ingestion for radionuclides associated with alpha-rich particles estimated using the ICRP Publication 30 model

	Dose coefficient for ingestion (Sv Bq^{-1})		
Radionuclide	**Young child**	**Child**	**Adult**
^{241}Am	$5.4\ 10^{-8}$	$2.3\ 10^{-8}$	$1.7\ 10^{-8}$
^{238}Pu	$5.5\ 10^{-8}$	$2.4\ 10^{-8}$	$1.8\ 10^{-8}$
$^{239/240}Pu$	$5.4\ 10^{-8}$	$2.5\ 10^{-8}$	$1.9\ 10^{-8}$
^{241}Pu	$4.9\ 10^{-10}$	$3.5\ 10^{-10}$	$3.1\ 10^{-10}$

The organ distribution of caesium and strontium are very different to that of americium and plutonium. While caesium is distributed relatively uniformly throughout the soft tissues of the body, strontium is retained principally in the skeleton, with doses to skeletal tissues contributing about 80% of the committed effective dose in the adult. Retention times for caesium are shorter, with more than 90% of the committed effective dose from ^{137}Cs delivered within 1 year of intake. For ^{90}Sr, 30% of the committed effective dose is delivered within 1 year, 50% in 4 years and 80% in 20 years.

As no direct measurements were made of the intestinal absorption of caesium and strontium from beta-rich particles, it was assumed in the assessment described in report HPA-CRCE-018 that the ICRP default gut uptake fractions (f_1) applied to all the activity in the particle and not just the mass fraction of the object that is soluble. This approach is likely to overestimate the effective dose following ingestion of a particle as what little experimental evidence is available shows that particle solubilities are very low (Cowper, 2009). The dose coefficients for ingestion of radionuclides associated with beta-rich particles are presented in Table 36.

Table 36 Dose coefficient for ingestion for radionuclides associated with beta-rich particles estimated using the ICRP Publication 30 model*

	Dose coefficient for ingestion (Sv Bq^{-1})		
Radionuclide	**Young child**	**Child**	**Adult**
^{137}Cs	$1.2\ 10^{-8}$	$1.0\ 10^{-8}$	$1.3\ 10^{-8}$
^{90}Sr	$7.3\ 10^{-8}$	$6.0\ 10^{-8}$	$2.8\ 10^{-8}$
^{90}Y	$2.0\ 10^{-8}$	$5.9\ 10^{-9}$	$2.0\ 10^{-9}$

* f_1 is equal to 1 for caesium; 0.3 for strontium; 0.0001 for yttrium (ICRP, 2012a).

Table 37 presents the estimated committed effective dose assuming a radioactive particle was ingested. The effective doses were calculated using the equation above and distributions of activity on alpha-rich and beta-rich particles given in Table 31. The highest 97.5th percentile of the effective dose following ingestion of a radioactive particle by any individual was estimated to be approximately 13 mSv. The effective dose following ingestion of a beta-rich particle was estimated to be greater than that following the ingestion of an alpha-rich particle at the 97.5th percentile. However, at lower percentiles the effective dose following the ingestion of an alpha-rich object was estimated to be greater than that from the ingestion of a beta-rich particle. The relatively high dose from the ingestion of a high activity beta-rich particle, especially by children and young children, is mainly due to the increased ^{90}Sr activity estimated to be present on such particles.

As explained in Section 5.1.1, a dose of 1 mSv was used to define the minimum of activity which had to be present on an object for it to be included in the estimation of the actual number of objects which may be present in the environment. It is noted that some of the doses presented in Table 37 are below 1 mSv. This is because the activity on an object which would result in a dose of 1 mSv was derived using an assumption on the relative activities of different radionuclides. When the dose from contact with a particle were calculated the activity of each radionuclide was defined using a distribution and therefore some combinations of these distributions resulted in an estimated dose below 1 mSv.

Table 37 Estimated committed effective dose assuming a radioactive particle was ingested

	Effective dose (Sv)	
Percentile	**Alpha-rich particle**	**Beta-rich particle**
Young children		
2.5th	$9.2\ 10^{-4}$	$1.3\ 10^{-4}$
50th	$1.8\ 10^{-3}$	$3.8\ 10^{-4}$
97.5th	$5.0\ 10^{-3}$	$1.3\ 10^{-2}$
Children		
2.5th	$4.1\ 10^{-4}$	$1.1\ 10^{-4}$
50th	$8.1\ 10^{-4}$	$3.0\ 10^{-4}$
97.5th	$2.2\ 10^{-3}$	$9.3\ 10^{-3}$
Adult		
2.5th	$3.0\ 10^{-4}$	$1.3\ 10^{-4}$
50th	$6.1\ 10^{-4}$	$3.1\ 10^{-4}$
97.5th	$1.7\ 10^{-3}$	$4.5\ 10^{-3}$

7.1.3 Radiological impact following the deliberate ingestion of a larger object

As mentioned in Section 5.1.3.2, people with the rare medical condition called pica, and young children who put objects in their mouths as part of learning about their environment, may deliberately ingest sand and possibly large objects. To determine whether this exposure pathway may lead to significant radiological risks the committed effective dose that would result from the ingestion of the most active larger object was estimated. This approach allows an upper bound to be estimated on the potential dose that would result from the ingestion of any larger object. Implicit in this calculation was the assumption that the most active larger object was of a size which could be deliberately ingested by a member of any age group.

The highest ^{241}Am activity measured on an alpha-rich larger object detected between 2009 and 2017 was 620 kBq. This object was found on the beach at Sellafield in 2010. Also measured on that object were significant activities of ^{238}Pu (110 kBq), $^{239/240}$Pu (330 kBq) and ^{241}Pu (4.5 MBq). The estimated effective doses to a young child, a child or an adult who happened to ingest that larger object are shown in Table 38.

The maximum ^{137}Cs activity measured on a beta-rich larger object detected between 2009 and 2017 was about 3.7 MBq. That object was detected on the beach at Sellafield in 2015. The effective dose to the three age groups considered in this assessment from ingestion of that object are also presented in Table 38. As no dose rate measured from a larger object detected to date has indicated that ^{90}Sr may be present at high levels of activity, the estimated doses present in Table 38 are from exposure to ^{137}Cs only. If the highest activities measured on alpha- and beta-rich objects detected up to 2017 are representative of the highest activities likely to be present on any larger object, then it can be concluded that the highest effective dose from ingestion of a larger object would be of the order of a few tens of mSv.

Table 38 Maximum estimated committed effective dose from the ingestion of a larger object

	Effective dose (Sv)	
Age group	**Alpha-rich objects**	**Beta-rich objects**
Young child	$5.5\ 10^{-2}$	$4.5\ 10^{-2}$
Child	$2.5\ 10^{-2}$	$3.7\ 10^{-2}$
Adult	$1.9\ 10^{-2}$	$4.8\ 10^{-2}$

7.2 Exposure to the skin assuming an object is in contact with it

7.2.1 Skin structure and radiation effects

Different tissues and cells are recognised as the primary targets for radiation-induced deterministic and stochastic effects in skin (Charles and Harrison, 2007; Charles, 1990; Hopewell, 1990; NCRP, 1999). The skin consists of two distinct layers, the outermost epidermis and the underlying dermis. The epidermis is continually renewed from a basal layer containing stem cells, and dead cells are sloughed from the skin surface. The epidermis varies in thickness according to body site (ICRP, 2002). The basal layer extends around the skin appendages, notably the shaft and base of the hair follicles that project deep into the dermis. At some sites on the body over 50% of the basal layer stem cells may be associated with the hair follicles. However, it has been suggested (ICRP, 2015b) that the origin of basal cell carcinoma, the main type of skin cancer induced by radiation, may be predominantly a small proportion of intra-follicular basal cells located in the “rete-pegs”, the bases of the undulations in the basal layer. The depth of the undulating intra-follicular basal layer is between 20 μm and 100 μm over most of the body although the soles of the feet and the palms of the hands can have epidermal thicknesses of more than 500 µm. The ICRP and the International Commission on Radiation Units and Measurements (ICRU) use a nominal average value of 70 µm for adults (ICRP, 1977; ICRP, 1991; ICRP, 1992) (ICRP, 2007) (ICRU, 1997), generally interpreted for dosimetric purposes as a depth of 50 to 100 µm.

In publication 89 (ICRP, 2002), ICRP provides reference data for nominal epidermal depths as a function of age as: 45 µm for newborn and for individuals up to age five; 50 µm at age 10; 60 µm at age 15; and 70 µm for adults. However, it has recently been concluded that these data will not be used directly to specify target depths for skin cancer in the development of ICRP dosimetric phantoms. Recognising the substantial variation in epidermal thicknesses with body site and that hair follicles may also contain a proportion of stem cell targets, a simplified scheme will be adopted in which the 50 to 100 µm depth for adults (nominal 70 µm) will also be used at age fifteen and a slightly wider band, of 40 to 100 µm, will be used at age ten and younger (Harrison, 2019).

The dermis is about 1 to 3 mm thick depending on body site. The vascularised papillary dermis is an important target for radiation-induced deterministic effects resulting from high dose cell-killing (Hopewell, 1990; ICRP, 1992; NCRP, 1999). The most important deterministic effect that can be produced by radiations energetic enough to irradiate the dermis is acute ulceration, also referred to as dermal necrosis, which may occur after about two weeks and last several days. While ulceration caused by large area irradiation can be seriously debilitating and may require skin grafting, localised damage caused by particles will be more readily repaired by cell migration from the periphery. Erythema caused by radiation emitted by radionuclides on a particle will be transient, extends over very small areas, and is subject to considerable variability and possible confusion with normal skin blemishes. Ulceration would generally occur within two weeks of irradiation and would heal over a period of several weeks, perhaps leaving a small scar (Hopewell, 1990). For less penetrating radiations, such as low energy beta particles and potentially also including high energy alpha particles, damage is likely to be limited to epidermal necrosis.

In considering doses delivered by radioactive particles and the potential for localised tissue damage, it is necessary to specify an area of irradiation as well as the depth of the target tissue. ICRP and the US National Council on Radiation Protection and Measurements (NCRP) have standardised the control of local skin doses using estimates of the average doses over the most exposed 1 cm^2 of skin at a depth of 70 µm (ICRP, 1991; ICRP, 1992); (NCRP, 1999)). The 1 cm^2 averaging is designed primarily for the control of localised irradiation of a larger area of skin, for which the end-point of concern is moist desquamation rather than acute ulceration. Consequently, the averaging of doses over 1 cm^2 has no direct biological significance in relation to acute dermal ulceration from small particles where the area of exposure is of the order of a few mm^2. However, there is practical merit in being able to set limits that apply generally to radioactive particles and wider field irradiation. Similarly, it has been suggested that doses should be calculated at a depth of 150 µm in evaluating all deterministic end-points for skin, corresponding to energy deposition in the papillary dermis (ICRP, 1992). While this may be scientifically correct, ICRP (ICRP, 1991; ICRP, 2007; ICRU, 1997) and the NCRP (NCRP, 1999) have chosen to calculate and measure doses at the nominal depth of the epidermal basal layer of 70 µm (50 to 100 µm) in the control of both deterministic and stochastic effects.

Unlike cancers which may develop in other tissues and organs, the incidence of cancer in the skin is far from certain to result in a fatality due to the widespread availability in the UK of appropriate medical care. For this reason, this assessment estimated both the risk of skin cancer incidence as well as fatality from skin cancer.

7.2.2 Estimated absorbed dose to the skin

The absorbed dose to the skin from a particle in contact with it, D_s (Gy), was estimated using the following equation:

$$D_s = \sum_r A_r \dot{D}_{s,r} T$$

Where A_r is the activity of a radionuclide on the particle on the skin (Bq), $\dot{D}_{s,r}$ is the absorbed dose rate to the skin from radionuclide r (Gy Bq^{-1} h^{-1}) and T is the length of time the particle is in contact with the skin (h).

As described in Section 8.6.1 in HPA-CRCE-018 (supplement), the range of alpha particles emitted by ^{241}Am and the alpha-emitting isotopes of plutonium is up to about 45 µm in tissue. As this penetration depth is less than the nominal depth of 70 µm recommended by ICRP for radiological protection purposes, the (1 cm^2, 70 µm) dose to the skin from exposure to alpha-particles is effectively zero. However, if shallower skin depths are assumed, particularly if these are much less than 40 µm, then the dose rate to the skin from high energy alpha particles may be significant although to achieve such penetration the alpha particle would have to be emitted perpendicular to the skin surface and that the radionuclide from which it was emitted would have to be in direct contact with the skin, both of which are low probability events.

Skin doses from photon emissions from point sources of the radionuclides present on alpha-rich particles, calculated using Monte Carlo methods (Rohloff and Heinzelmann, 1996), were provided in Table 79 HPA-CRCE-018 (supplement) and are reproduced in Table 39. The dose rates per unit activity presented in Table 39 were used to estimate the absorbed dose to skin from an alpha-rich particle present on it. The contribution to the skin dose of ^{137}Cs detected on a small number of alpha-rich particles was not included as the activity of ^{137}Cs measured on these objects was less than a few tens of Bq. In addition, the effects of self-absorption of 60 keV photons for particles with dimensions of about 1 mm and densities of a few g cm^{-3} were also pessimistically assumed to be negligible for this assessment.

Table 39 Dose rate to the skin from photons emitted by the major radionuclides associated with alpha-rich objects

Radionuclide	Dose rate to the skin (1 cm^2, 70 μm) for a point source (Gy h^{-1} Bq^{-1})
^{238}Pu	$1.99\ 10^{-9}$
^{239}Pu	$7.45\ 10^{-10}$
^{240}Pu	$1.89\ 10^{-9}$
^{241}Pu	$1.17\ 10^{-12}$
^{241}Am	$1.20\ 10^{-8}$

The derivation of an absorbed dose rate to the skin from exposure to ^{137}Cs and ^{90}Sr present on a particle was discussed in Section 9.1 of HPA-CRCE-018 (supplement). Based on direct dose rate measurements on a small number of beta-rich particles and larger objects found between November 2006 and August 2009, the (1 cm^2, 70 µm) dose rates from a particle containing only ^{137}Cs was estimated to be 1.7 10^{-6} Gy h^{-1} Bq^{-1}; this dose rate was also used in this current assessment. HPA-CRCE-018 (supplement) also shows that the (1 cm^2, 70 µm) dose rate from a particle containing only ^{90}Sr is approximately six times higher than that from a particle with the same activity of ^{137}Cs. For this assessment, it was therefore assumed that the (1 cm^2, 70 µm) dose rate from ^{90}Sr was equal to 1 10^{-5} Gy h^{-1} Bq^{-1}. It should be recognised that, as these dose rates are associated with large uncertainties due to the effects of self-absorption and the difficulty of being able to align the particle on a detector, they are only intended to be representative values. A measure of this is illustrated by comparing the (1 cm^2, 70 µm) dose rate from a particle with 100 kBq of ^{90}Sr activity, which has a theoretical dose rate of about 1 Gy h^{-1}, with a rate of 0.8 Gy h^{-1} that was measured from a particle which has about 170 kBq of ^{90}Sr activity (Tanner et al, 2016).

7.2.3 Absorbed dose to the skin when in contact with a particle

The risk of localised ulceration from Dounreay particles was evaluated by (Charles and Harrison, 2007) assuming an ED_{50}, the dose to produce an effect in 50% of exposed individuals, of 10 Gy and a threshold for the observation of any effects of 2 Gy (averaged over 1 cm^2 at 70 µm). An absorbed dose of 2 Gy is also the ED_1 for reactions of human skin to ionising radiation noted by ICRP in publication 118 (ICRP, 2012b). It is noted that this threshold dose only applies for particles in stationary contact with the skin; if the particle moves by a distance much greater than its own size the threshold value would be significantly higher (Harrison et al, 2005).

Table 40 presents the estimated dose rates to skin from an alpha- or beta-rich particle if it was in contact with it. These dose rates were estimated using the approach described in Section 7.2.2 where the activity of each radionuclide on the particle in contact with the skin was estimated using the approached described in Section 6. The absorbed dose rate from beta-rich particles was estimated to be significantly greater than that from alpha-rich particles. For a beta-rich particle in contact with the skin, the 97.5th percentile of the (70 µm, 1 cm^2) absorbed dose rate to the skin was estimated to be 1.4 Gy h^{-1}. If a particle with the activity to produce such a dose rate was to come into contact with the skin, and expose the same area of skin continuously, the threshold for severe tissue damage of 2 Gy may be exceeded in a couple of hours. This situation is considered unlikely to arise as any particle present on the skin is unlikely to expose the same area of skin for such a length of time unless it became trapped as discussed in Section 5.1.4. As discussed in Section 7.2.1, if damage to the skin were to occur it is likely to be limited to epidermal necrosis over an area of skin equal to the size of the particle. Such damage to the skin will not have any effect on the health of the individual and, for most individuals, it is unlikely to be noticed. It is also noted that the threshold dose is defined for practical purposes as the level of dose that results in an effect occurring in only 1% of those exposed at that rate (ICRP, 2012b). This means that, even if the threshold dose was exceeded, there is only a small probability than any individual may experience a reaction unless the absorbed dose received is many times that of the threshold.

Table 40 Estimated absorbed dose to the skin from a radioactive particle

	Absorbed dose (1 cm^2, 70 μm) to the skin (Gy h^{-1})	
Percentile	**Alpha-rich particle**	**Beta-rich particle**
2.5th	1.4 10^{-4}	1.8 10^{-2}
50th	2.7 10^{-4}	5.0 10^{-2}
97.5th	7.0 10^{-4}	1.4 10^{0}

7.2.4 Absorbed dose to the eye

Damage from radiation exposure to the eye may cause cataracts of the lens (ICRP, 2012b). ICRP have recommended that a threshold of 0.5 Gy should be assumed to apply to both acute and protracted irradiation of the eye. However, because particles on the cornea of the eye would be at a minimum distance of 2 to 3 mm from the lens, dose rates would be around two orders of magnitude less than that from a particle which was in direct contact with the organ. Given that the presence of a particle in the eye is likely to cause irritation, it is considered very unlikely that any particle would remain in stationary contact with the eye for sufficient time to cause damage.

7.2.5 Doses to the skin from exposure to a larger object

Larger objects are extended sources of radiation so that any skin in contact with the object is exposed to essentially a uniform radiation field. For skin exposed to an extended source of radiation, the end-point of concern is moist desquamation rather than acute ulceration. For moist desquamation, the ED_{50} and threshold values for exposures lasting several hours are about 30 Gy and 15 Gy, respectively (Edwards and Lloyd, 1996; ICRP, 2012b).

In HPA-CRCE-018 (supplement) (Oatway et al, 2011) it was noted that, as the size of an object increases, the (1 cm^2, 70 µm) skin dose rate becomes more closely related to the activity per unit surface area of the object rather than to the total activity on the object. Based on a small number of measurements it was reported in HPA-CRCE-018 (supplement) that an appropriate factor to determine the (1 cm^2, 70 µm) skin dose rate for objects with surface areas greater than about 13 cm^2 was 0.86 mGy h^{-1} kBq^{-1} cm^{-2}; this factor was corroborated by modelling using the VARSKIN tool, the results of which are also presented in HPA-CRCE-018 (supplement) (Oatway et al, 2011). The derivation of this factor in the VARSKIN tool assumed that only ^{137}Cs and its progeny was present on an object. Analysis conducted since the publication of HPA-CRCE-018 has shown that the median Sr:Cs activity ratio on beta-rich larger objects is about 0.01 (Sellafield Limited, 2018) although the Sr:Cs activity ratio can be as high as about 0.7. For the purpose of this assessment it was considered appropriate to assume that the majority of the activity present on any beta-rich larger object was associated with just ^{137}Cs and the above factor was used to estimate the absorbed dose rate to the skin from exposure to a beta-rich larger object.

The highest ^{137}Cs activity measured on a beta-rich larger object detected to the end of 2017 was about 3.7 MBq. As this object had a surface area of about 38.5 cm^2, the dose rate from that object was estimated to be about 250 mGy h^{-1}. Unlike particles, a larger object is generally too big to be trapped against the body and too heavy to be caught in clothes or in shoes for any length of time. The only plausible mechanism by which a larger object could remain in contact with the skin was if it was held and therefore exposure to radioactivity on a larger object would be very unlikely to occur for more than a couple of hours. The probability that contact with a beta-rich larger object would result in the threshold for deterministic effects to be exceeded was therefore considered to be low.

7.3 Doses from a particle trapped in a wound

Not all the activity present on a particle trapped in a wound will become available for uptake by the body. The fraction of the activity on a particle which is trapped in a wound that can be dissolved into body fluids and become available for uptake by the organs of the body is called the fractional transfer factor, f_w. There is no information on the value of this parameter for radioactivity associated with particles from around the Sellafield site. To estimate the potential magnitude of the effective dose from the uptake of radioactivity from an alpha-rich particle that had become trapped in a wound, two approaches were investigated and discussed in HPA-CRCE-018 (supplement).

The first approach looked at a study which aimed to estimate the uptake of alpha-emitting radionuclides associated with particles trapped in wounds as a result of using land associated with the former nuclear weapons test site at Maralinga in South Australia (Harrison et al, 1990). That approach estimated an f_w of up to 10^{-4}. The maximum alpha activity measured on a particle detected using the Groundhog Synergy detection system was about 300 kBq. If such a particle were to become trapped in a wound on a 1 year old then, using an f_w of 10^{-4} and a dose coefficient for ingestion of alpha emitting radionuclides of 5 10^{-8} Sv Bq^{-1}, which is based on the values given in Table 35, their effective dose would be no more than about 1 mSv. This dose is about an order of magnitude less that the 97.5th percentile of the dose which could be received following the ingestion of an alpha-rich particle as shown in Table 37.

The second approach considered in HPA-CRCE-018 (supplement) was based on the model of wound biokinetics and dosimetry developed by the NCRP (NCRP, 2006). As explained in HPA-CRCE-018 (supplement), use of that tool with the assumption that a particle would only be trapped in a wound for a period of no longer than 10 days resulted in an estimated dose which was of the same magnitude as that estimated using the experimental approach described above for uptake of radioactivity from particles trapped in wounds of those using land at the Maralinga test site.

No studies could be found which considered the uptake of ^{137}Cs or ^{90}Sr into the body following incorporation of a particle in a wound. For this assessment it was therefore assumed that the uptake fractions of ^{137}Cs and ^{90}Sr following ingestion were equal to those recommended by the ICRP in Publication 119 for activity taken into the body by ingestion (ICRP, 2012a). For ^{137}Cs the uptake fraction was therefore equal to 1 while that for ^{90}Sr was 0.3. These uptake fractions are likely to be very cautious as experimental work with alpha-rich particles, described in Section 7.1.2.2, showed that a significant fraction of the activity present on a particle is unavailable for uptake to the body even after the particle had been subjected to the harsh conditions of the stomach.

The potential upper magnitude of the effective dose from uptake of activity from a beta-rich particle trapped in a wound was estimated assuming the particle had on it 170 kBq of ^{90}Sr activity, this being equal to the maximum ^{90}Sr activity measure on any particle detected to the end of 2017. A particle with up to 290 kBq of ^{137}Cs activity has also been detected, but it had a very low activity of ^{90}Sr on it; that particle therefore does not represent the limiting case due to the relative values of the dose coefficients for ingestion for ^{90}Sr and ^{137}Cs. Based on the assumed activity of the beta-rich particle which had become trapped in a wound, and that all of that activity was available for uptake by the body, the upper bound of the effective dose to a 1 year old was estimated to be about 15 mSv. This dose is about the same as the 97.5th percentile of the effective dose that could be received following the ingestion of a beta-rich particle, as is shown in Table 37.

8 Calculation of radiological risks

8.1 Risk coefficients for stochastic effects

Risk coefficients for the purpose of radiological protection have been derived by the International Commission on Radiological Protection (ICRP) using information on cancer incidence and fatality from epidemiological studies of the Japanese survivors of the atomic bombings at Hiroshima and Nagasaki and other studies (ICRP, 2007). In its latest recommendations, ICRP specifies detriment-adjusted nominal risk coefficients which can be used in the calculation of risks for stochastic effects after exposure to radiation at low dose rates that are appropriate for the purposes of radiological protection (ICRP, 2007); these are reproduced in Table 41. Detriment includes lifetime incidence of specific cancers and takes account of the severity of disease in terms of lethality, quality of life and years of life lost. The most significant contribution to the risk factor is from cancer risks with a small contribution accounting for the possibility of hereditary effects. Risk coefficients given by ICRP are average values across populations and so account for exposure to radiation at all ages and both sexes. Value for the whole population (aged between 0 and 84 years at exposure) are somewhat larger than for the working age population (aged between 18 and 64 years at exposure) because cancer risks are generally greater for exposures at younger ages, mainly because of the longer life-spans for expression of risk but also because of greater sensitivity to induction of some cancers.

Table 41 Detriment-adjusted nominal risk coefficients recommended by ICRP (ICRP, 2007)

	Detriment-adjusted nominal risk coefficient (Sv^{-1})		
Exposed population	**Cancer**	**Heritable effects**	**Total**
Whole population	$5.5\ 10^{-2}$	$2.0\ 10^{-3}$	$5.7\ 10^{-2}$
workers	$4.1\ 10^{-2}$	$1.0\ 10^{-3}$	$4.2\ 10^{-2}$

For the calculation of stochastic risks from exposure to particles on the beaches near to the Sellafield site, differences in risk factors between children and adults and also between lifetime risk expressed in terms of fatality or incidence were considered; the risk coefficients recommended by ICRP were therefore not used. Lifetime risk coefficients of fatality and incidence are shown in Table 42 for children, where the same values were assumed to be suitable for individuals exposed at age 1 and 10 years, and adults. These risk coefficients are based on calculations performed in preparation for forthcoming ICRP reports (Harrison, 2019).

For the purposes of this assessment, single value risk coefficients were used although it should be recognised that they are subject to substantial uncertainties. These uncertainties arise because the estimates of stochastic risk given in Table 42 were derived largely from epidemiological studies of the effects of external exposures to gamma rays, principally cancer incidence and mortality data for the Japanese A-bomb survivors. In this assessment, these risk coefficients are applied to doses from intakes of radionuclides, including alpha particle emitters, with highly localised irradiation of tissues. Comparisons of the effects of external and internal exposures are limited but generally support the use of common risk estimates and hence the models used to calculate doses from internal irradiation (Harrison and Muirhead, 2003; Little et al, 2007; Marsh et al, 2014).

Table 42 Estimated lifetime risk coefficients of stochastic effects*

	Lifetime risk coefficients of stochastic effects (Sv^{-1})	
Age group	**Incidence**	**Fatality**
Young child and children	$1.4\ 10^{-1}$	$9.0\ 10^{-2}$
Adult	$4.5\ 10^{-2}$	$3.0\ 10^{-2}$

* Excluding skin cancer which is address separately in Section 8.2

Localised irradiation of skin should also be assumed to present a risk of skin cancer. The population average risk of skin cancer incidence is assumed by ICRP to be 0.1 Gy^{-1} (ICRP, 2007), where the (70µm, 1 cm^2) absorbed dose is averaged over the entire surface area of the skin. The lethality factor assumed by ICRP is $2\ 10^{-3}$ (ICRP, 2007); this reflects skin cancer survival rates being much higher than the survival rates associated with other types of cancer.

8.2 Risk to health to a population of beach users

Table 43 and Table 44 show the estimated lifetime risk of developing fatal cancer to a member of the population, who uses a beach near to the Sellafield site for a year, from ingestion or inhalation with an alpha- or beta-rich particle. Due to the approach used in this assessment, the lifetime risks presented in Table 43 and Table 44 represent those to high rate users of beaches; risks to members of the general population, who make less use of Cumbrian beaches, would be lower. The risks in Table 43 and Table 44 and in other tables in this section are given to two significant figures; this degree of precision is not warranted because of the large uncertainties associated with the calculation of the risks but allows for comparison of the risks. Consequently, in the general discussion of the results of this assessment, risks will be quoted as order of magnitude values only.

Across the population using beaches between St Bees and Drigg for a year, the 2.5th and 97.5th percentiles of the lifetime risk of developing fatal cancer were estimated to be of the order of 10^{-15} and 10^{-11} respectively. The 50th percentile of the estimated lifetime risks from using a beach for a year was estimated to be or the order of 10^{-12}. The group with the highest estimated lifetime risk were young children participating in either leisure or walking activities on beaches between St Bees and Braystones. The exposure pathway contributing most to the lifetime risk was the inadvertent ingestion of alpha-rich particles. Lifetime risks of developing fatal cancer in adults are generally an order of magnitude lower than those for children, mainly due to their relatively low ingestion rate of sand. As the inadvertent ingestion pathway contributed most to the 97.5th percentile of the lifetime risk to members of the beach using population, the very cautious assumption that particles could be inhaled had little impact on the magnitude of the estimated risk.

The number of particles found on the beach at Sellafield was estimated to be higher than on the beaches between St Bees and Braystones. However, the relatively low occupancy of the beach at Sellafield means that the lifetime risk of developing fatal cancer to people using that beach is lower than that to people using the northern beaches. It was estimated that the population using the southern beaches between Seascale and Drigg face the lowest lifetime risks compared to those using any of the beaches considered in this assessment mainly due to the southern beaches having a relatively low particle population density. A breakdown of the estimated risks to a population of high rate beach users with respect to the age of the population, which beach they use and the activities they participate in, is presented in Appendix I. An assessment of the risks to a hypothetical group of young children and children who make use of the beach at Sellafield was also undertaken for completeness and is described in Appendix J.

The parameter contributing most to the uncertainty in the estimated lifetime risk of developing fatal cancer was the annual time individuals were assumed to spend on a beach. Due to the importance of the inadvertent ingestion pathway, variation in the annual inadvertent ingestion rate of sand and the ^{241}Am activity present on particles were also found to contribute significantly to the uncertainty in the estimated lifetime risk; this is discussed in Appendix G.

Table 43 Estimated lifetime risks of developing fatal cancer from the possible ingestion or inhalation of an alpha-rich particle when using a beach for a year

	Lifetime risk of developing fatal cancer (y^{-1})								
	Northern beaches			Sellafield beach*			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$9.4\ 10^{-14}$	$4.8\ 10^{-14}$	0.0	0.0	0.0	0.0	$1.7\ 10^{-14}$	$8.2\ 10^{-15}$
50th	0.0	$1.0\ 10^{-12}$	$8.7\ 10^{-13}$	0.0	0.0	0.0	0.0	$2.2\ 10^{-13}$	$1.1\ 10^{-13}$
97.5th	0.0	$1.2\ 10^{-11}$	$1.7\ 10^{-11}$	0.0	0.0	0.0	0.0	$2.7\ 10^{-12}$	$1.4\ 10^{-12}$
Children									
2.5th	$3.8\ 10^{-14}$	$6.8\ 10^{-14}$	$7.0\ 10^{-14}$	0.0	0.0	0.0	$5.4\ 10^{-14}$	$8.0\ 10^{-15}$	$3.0\ 10^{-14}$
50th	$7.0\ 10^{-13}$	$7.1\ 10^{-13}$	$3.9\ 10^{-13}$	0.0	0.0	0.0	$1.4\ 10^{-13}$	$1.0\ 10^{-13}$	$1.9\ 10^{-13}$
97.5th	$1.3\ 10^{-11}$	$7.1\ 10^{-12}$	$2.2\ 10^{-12}$	0.0	0.0	0.0	$4.6\ 10^{-13}$	$1.3\ 10^{-12}$	$1.3\ 10^{-12}$
Adults									
2.5th	$7.3\ 10^{-15}$	$1.5\ 10^{-15}$	$1.7\ 10^{-15}$	$8.6\ 10^{-15}$	0.0	$7.0\ 10^{-15}$	$7.6\ 10^{-16}$	$2.0\ 10^{-16}$	$3.4\ 10^{-16}$
50th	$7.9\ 10^{-14}$	$2.0\ 10^{-14}$	$3.8\ 10^{-14}$	$1.1\ 10^{-13}$	0.0	$7.4\ 10^{-14}$	$1.2\ 10^{-14}$	$3.3\ 10^{-15}$	$8.6\ 10^{-15}$
97.5th	$8.6\ 10^{-13}$	$2.8\ 10^{-13}$	$8.1\ 10^{-13}$	$1.4\ 10^{-12}$	0.0	$9.1\ 10^{-13}$	$2.0\ 10^{-13}$	$5.3\ 10^{-14}$	$2.2\ 10^{-13}$

* No young children or children have been observed to use the beach at Sellafield for any purpose

Table 44 Estimated lifetime risks of developing fatal cancer from the possible ingestion or inhalation of a beta-rich particle when using a beach for a year

Percentile	Lifetime risk of developing fatal cancer (y^{-1})								
	Northern beaches			Sellafield beach*			Southern beaches		
	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$1.2\ 10^{-16}$	$6.5\ 10^{-17}$	0.0	0.0	0.0	0.0	$2.1\ 10^{-17}$	$1.0\ 10^{-17}$
50th	0.0	$1.9\ 10^{-15}$	$1.7\ 10^{-15}$	0.0	0.0	0.0	0.0	$3.6\ 10^{-16}$	$1.8\ 10^{-16}$
97.5th	0.0	$9.5\ 10^{-14}$	$1.1\ 10^{-13}$	0.0	0.0	0.0	0.0	$2.0\ 10^{-14}$	$9.5\ 10^{-15}$
Children									
2.5th	$1.0\ 10^{-16}$	$1.8\ 10^{-16}$	$1.5\ 10^{-16}$	0.0	0.0	0.0	$1.0\ 10^{-16}$	$1.9\ 10^{-17}$	$6.5\ 10^{-17}$
50th	$2.5\ 10^{-15}$	$2.2\ 10^{-15}$	$1.2\ 10^{-15}$	0.0	0.0	0.0	$3.8\ 10^{-16}$	$3.0\ 10^{-16}$	$5.5\ 10^{-16}$
97.5th	$1.3\ 10^{-13}$	$1.0\ 10^{-13}$	$4.0\ 10^{-14}$	0.0	0.0	0.0	$1.1\ 10^{-14}$	$1.4\ 10^{-14}$	$1.6\ 10^{-14}$
Adults									
2.5th	$4.6\ 10^{-17}$	$8.8\ 10^{-18}$	$9.8\ 10^{-18}$	$1.8\ 10^{-16}$	0.0	$1.4\ 10^{-16}$	$4.3\ 10^{-18}$	$1.1\ 10^{-18}$	$1.8\ 10^{-18}$
50th	$4.8\ 10^{-16}$	$1.2\ 10^{-16}$	$2.3\ 10^{-16}$	$2.2\ 10^{-15}$	0.0	$1.5\ 10^{-15}$	$7.0\ 10^{-17}$	$1.8\ 10^{-17}$	$4.5\ 10^{-17}$
97.5th	$7.0\ 10^{-15}$	$2.3\ 10^{-15}$	$6.2\ 10^{-15}$	$3.5\ 10^{-14}$	0.0	$2.5\ 10^{-14}$	$1.4\ 10^{-15}$	$3.7\ 10^{-16}$	$1.5\ 10^{-15}$

* No young children or children have been observed to use the beach at Sellafield

Table 45 and Table 46 respectively show the estimated lifetime risk of developing skin cancer based on the annual probability that a particle may come into contact with the skin and the dose from a particle assuming the particle remained in contact with the skin for an hour. Over all age groups and beaches, the highest 97.5th percentile of the lifetime risk of skin cancer incidence per hour that a particle was on the skin was estimated to be of the order of 10^{-12}; this risk was associated with an adult angler on Sellafield beach being exposed to beta-rich particles. As it is unlikely that a particle would remain in contact with the skin for more than a few hours, even if it became trapped, the 97.5th percentile of the annual risk of skin cancer incidence was estimated to be of the order of 10^{-11}. For skin cancer, the lethality rate is about 500 times lower than the incidence rate (ICRP, 2007). The highest 97.5th percentile of the annual risk that fatal skin cancer may develop because of using a beach for a year was therefore estimated to be of the order of 10^{-14}. The annual risk of developing fatal skin cancer was estimated to be about three orders of magnitude lower than the risk of developing fatal cancer as a result of ingesting a particle when using a beach.

Table 45 Estimated lifetime risk of developing skin cancer per hour that an alpha-rich particle is in contact with the skin

	Lifetime risk of developing fatal cancer (y^{-1})								
	Northern beaches			Sellafield beach*			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5^{th}	0.0	$9.8\ 10^{-16}$	$4.6\ 10^{-16}$	0.0	0.0	0.0	0.0	$1.8\ 10^{-16}$	$8.0\ 10^{-17}$
50^{th}	0.0	$1.1\ 10^{-14}$	$8.3\ 10^{-15}$	0.0	0.0	0.0	0.0	$2.3\ 10^{-15}$	$1.0\ 10^{-15}$
97.5^{th}	0.0	$1.2\ 10^{-13}$	$1.4\ 10^{-13}$	0.0	0.0	0.0	0.0	$2.8\ 10^{-14}$	$1.3\ 10^{-14}$
Children									
2.5^{th}	$7.0\ 10^{-16}$	$1.5\ 10^{-15}$	$1.3\ 10^{-15}$	0.0	0.0	0.0	$8.5\ 10^{-16}$	$1.7\ 10^{-16}$	$5.2\ 10^{-16}$
50^{th}	$1.4\ 10^{-14}$	$1.7\ 10^{-14}$	$7.8\ 10^{-15}$	0.0	0.0	0.0	$2.8\ 10^{-15}$	$2.5\ 10^{-15}$	$3.9\ 10^{-15}$
97.5^{th}	$2.7\ 10^{-13}$	$1.9\ 10^{-13}$	$5.2\ 10^{-14}$	0.0	0.0	0.0	$9.8\ 10^{-15}$	$3.6\ 10^{-14}$	$2.8\ 10^{-14}$
Adults									
2.5^{th}	$5.7\ 10^{-16}$	$1.9\ 10^{-16}$	$1.5\ 10^{-16}$	$6.6\ 10^{-16}$	0.0	$6.7\ 10^{-16}$	$6.4\ 10^{-17}$	$2.6\ 10^{-17}$	$3.3\ 10^{-17}$
50^{th}	$6.6\ 10^{-15}$	$2.8\ 10^{-15}$	$3.6\ 10^{-15}$	$9.1\ 10^{-15}$	0.0	$7.4\ 10^{-15}$	$1.1\ 10^{-15}$	$4.4\ 10^{-16}$	$8.2\ 10^{-16}$
97.5^{th}	$7.8\ 10^{-14}$	$4.0\ 10^{-14}$	$8.4\ 10^{-14}$	$1.2\ 10^{-13}$	0.0	$9.3\ 10^{-14}$	$1.7\ 10^{-14}$	$7.8\ 10^{-15}$	$2.1\ 10^{-14}$

* No young children or children have been observed to use the beach at Sellafield for any purpose

Table 46 Estimated lifetime risk of developing skin cancer per hour that a beta-rich particle is in contact with the skin

	Lifetime risk of developing fatal cancer (y^{-1})								
	Northern beaches			Sellafield beach*			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5^{th}	0.0	$1.2\ 10^{-15}$	$5.4\ 10^{-16}$	0.0	0.0	0.0	0.0	$2.0\ 10^{-16}$	$8.5\ 10^{-17}$
50^{th}	0.0	$1.7\ 10^{-14}$	$1.4\ 10^{-14}$	0.0	0.0	0.0	0.0	$3.3\ 10^{-15}$	$1.5\ 10^{-15}$
97.5^{th}	0.0	$7.6\ 10^{-13}$	$7.4\ 10^{-13}$	0.0	0.0	0.0	0.0	$1.6\ 10^{-13}$	$6.6\ 10^{-14}$
Children									
2.5^{th}	$8.7\ 10^{-16}$	$1.9\ 10^{-15}$	$1.4\ 10^{-15}$	0.0	0.0	0.0	$8.2\ 10^{-16}$	$2.0\ 10^{-16}$	$5.2\ 10^{-16}$
50^{th}	$2.3\ 10^{-14}$	$2.6\ 10^{-14}$	$1.2\ 10^{-14}$	0.0	0.0	0.0	$3.7\ 10^{-15}$	$3.6\ 10^{-15}$	$5.6\ 10^{-15}$
97.5^{th}	$1.3\ 10^{-12}$	$1.3\ 10^{-12}$	$4.2\ 10^{-13}$	0.0	0.0	0.0	$1.1\ 10^{-13}$	$1.8\ 10^{-13}$	$1.8\ 10^{-13}$
Adults									
2.5^{th}	$7.0\ 10^{-16}$	$2.3\ 10^{-16}$	$2.0\ 10^{-16}$	$2.7\ 10^{-15}$	0.0	$2.7\ 10^{-15}$	$7.3\ 10^{-17}$	$2.9\ 10^{-17}$	$3.6\ 10^{-17}$
50^{th}	$1.0\ 10^{-14}$	$4.7\ 10^{-15}$	$6.1\ 10^{-15}$	$4.9\ 10^{-14}$	0.0	$3.9\ 10^{-14}$	$1.5\ 10^{-15}$	$6.4\ 10^{-16}$	$1.3\ 10^{-15}$
97.5^{th}	$4.4\ 10^{-13}$	$2.2\ 10^{-13}$	$3.9\ 10^{-13}$	$2.0\ 10^{-12}$	0.0	$1.8\ 10^{-12}$	$8.6\ 10^{-14}$	$3.7\ 10^{-14}$	$9.1\ 10^{-14}$

* No young children or children have been observed to use the beach at Sellafield

8.3 Risk to health to a population of seafood consumers

Table 47 presents the estimated lifetime risks of developing fatal cancer from the possible inadvertent ingestion of radioactive particles in seafood, caught near to the Sellafield site, when eating seafood over the course of a year. The 2.5^{th} and 97.5^{th} percentiles of the lifetime risk of a seafood consumer developing fatal cancer was estimated to be 10^{-13} and 10^{-11} respectively, with the 50^{th} percentile of the risk being approximately a factor of five below the 97.5^{th} percentile value. The highest lifetime risks were associated with young children consuming alpha-rich particles within molluscs. Young children face the highest risks as, although adults consume the most seafood, young children have a much higher lifetime risk per unit activity ingested.

Table 47 Estimated lifetime risk of developing fatal cancer from the possible ingestion of radioactive particles in seafood caught near to the Sellafield site over the course of a year

Percentile	Lifetime risk of developing fatal cancer (y^{-1})				
	Alpha rich particles		Beta-rich particle		
	Molluscs	Crustaceans	Molluscs	Crustaceans	Total*
Young child					
2.5th	2.1 10^{-12}	4.6 10^{-16}	2.8 10^{-15}	4.6 10^{-16}	3.2 10^{-12}
50th	1.3 10^{-11}	7.1 10^{-15}	2.2 10^{-14}	7.1 10^{-15}	1.5 10^{-11}
97.5th	5.7 10^{-11}	3.3 10^{-13}	7.4 10^{-13}	3.3 10^{-13}	6.3 10^{-11}
Child					
2.5th	1.1 10^{-13}	1.0 10^{-13}	3.0 10^{-16}	8.2 10^{-16}	6.1 10^{-13}
50th	2.5 10^{-12}	9.1 10^{-13}	7.7 10^{-15}	9.1 10^{-15}	3.8 10^{-12}
97.5th	1.6 10^{-11}	4.9 10^{-12}	2.8 10^{-13}	3.0 10^{-13}	1.9 10^{-11}
Adult					
2.5th	9.5 10^{-14}	3.9 10^{-14}	3.3 10^{-16}	4.7 10^{-16}	3.7 10^{-13}
50th	1.8 10^{-12}	6.0 10^{-13}	7.2 10^{-15}	8.0 10^{-15}	2.8 10^{-12}
97.5th	1.1 10^{-11}	4.4 10^{-12}	1.2 10^{-13}	1.5 10^{-13}	1.3 10^{-11}

* The total estimated annual effective dose was estimated explicitly using the distributions in the annual probability of consuming a particle and in the risk of cancer assuming a particle was ingested. The total annual risk of fatal cancer presented in this table does therefore not equal the sum of the annual risk following the consumption of different marine animals or of the ingestion of different particle classes

When estimating the lifetime risks presented in Table 47 it is acknowledged that several cautious assumptions were made. These include the assumption that particles are of a size which could be ingested by marine animals despite most particles detected to date being too large, and the assumption that normal food preparation techniques, such as depuration, are not followed. In addition, the lifetime risks presented in Table 47 were estimated using habits observed between 2003 and 2017 and included some annual consumption rates which are markedly higher than those generally observed. The impact on the estimated lifetime risks of not including the annual consumption rates from 2003, the year in which most of the exceptionally high consumption rates are seen, is presented in Appendix H.

The parameter contributing most to the uncertainty in the estimated lifetime risk of developing fatal cancer from the possible ingestion of a particle when consuming seafood was the annual rate at which molluscs were consumed. As the possible ingestion of an alpha-rich particle contributed more to the lifetime risk than ingestion of a beta-rich particle, the variation in the ^{241}Am activity on particles was also found to contribute significantly to the uncertainty in the estimated lifetime risk; this is discussed in Appendix G.

8.4 Comparison of estimated risks with previous studies

Where possible the approach used in this risk assessment followed that used in previous assessments as described in reports HPA-CRCE-018 (Brown and Etherington, 2011), HPA-CRCE-038 (Etherington et al, 2012) and PHE-CRCE-021 (Oatway and Brown, 2015). However, due to the availability of more information, for this assessment changes were made to the methodology used to estimate the actual number of objects which could be present in the environment. In addition, this assessment also made use of a larger set of data with respect to object find rates and the habits of the exposed populations. This assessment also made a more realistic assessment of the risks by assigning distributions to the activity present on objects rather than just assuming an encounter would be with the object with the highest activity. Despite these differences, the 97.5th percentile of the lifetime risks of developing fatal cancer estimated in this assessment are in broad agreement with those estimated in previous assessments.

In the previous assessment, it was estimated that the probability that deterministic effects would arise in the unlikely situation that an object was encountered would be low. This assessment confirmed that deterministic effects would not arise if an object were to be ingested. As far as the skin is concerned, the current assessment estimated that the dose rate from some particles may be sufficiently high that the threshold for deterministic effects to the skin may be exceeded if such a particle happened to remain in continuous contact with the skin for several hours, a situation which is unlikely to occur. It is noted, however, that even if the threshold were to be exceeded the resulting physical damage is likely to be a blister over an area equal to the size of the particle (i.e. a few mm^2).

9 Conclusions

9.1 Estimated risk to health from the encounter with a radioactive object

This report described the approach used to estimate the lifetime risk to the health of individuals from an annual exposure to radioactive objects which are present on the beaches near the Sellafield site. To estimate that risk, a statistical approach was used to account for the variability in the habits of individuals using the beaches or consuming seafood caught off the Cumbrian coast and in the characteristics (e.g. measured activity) of those objects. The lifetime risks were estimated using information on objects that were detected between September 2009 and 2017 and habits observed between 2003 and 2017. It was assumed that this information represents the current situation and that into the foreseeable future.

Parameter values were generally determined using information from the literature and were selected to be cautious to maintain suitable robustness in the assessment. The approach used in this assessment is similar to the approach used in the assessment of doses to the representative person and focussed on individuals who are likely to receive the highest risks from exposure to objects on the beach. The risks to members of the general population are likely to be lower than those estimated in this assessment because, compared to the individuals considered in this assessment, members of the general population spend less time on Cumbrian beaches and consume less seafood.

The 97.5th percentile of the lifetime risk that a high rate beach user or seafood consumer may develop fatal cancer from a possible encounter with a radioactive object was estimated to be of the order of 10^{-11}. The 50th percentile lifetime risks were estimated to be approximately an order of magnitude lower than the 97.5th percentile risk. The group with the highest estimated lifetime risk of developing fatal cancer following use of a beach for a year were young children participating in either leisure or walking activities on northern beaches between St Bees and Braystones. The exposure pathway contributing most to the lifetime risk was inadvertent ingestion of alpha-rich particles. The highest lifetime risks from consumption of seafood for a year were associated with young children inadvertently ingesting an alpha-rich particle when eating molluscs.

The approach used in this assessment excluded particles which had very low levels of activity as they are only detected at very low probabilities; see Section 5.1.1. To account for the possible presence of large numbers of very low activity particles, this assessment assumed that all higher activity particles could be either inhaled by beach users or be ingested by marine animals, despite them being too large for these pathways. The 97.5th percentile of the annual probability of encountering a higher activity particle was estimated to be of the order of 10^{-7}. Even if the number of very low activity particles exceeded the number of higher activity particles by several orders of magnitude it is very unlikely that anyone using a beach or consuming seafood for a year would come into contact with one. Consequently, the conclusions of this risk assessment would not be affected by the possible presence of a significant population of very low activity particles in the environment.

The 97.5th percentile of the lifetime risk from the possible encounter with a radioactive object were estimated to be more than 100 thousand times less than the level of risk where regulatory control of a hazard may be required. For example, the following extract from Health and Safety Executive (HSE) guidance (HSE, 2001) states that for a risk of death of one in a million per year (10^{-6} y^{-1}) for both workers and the public:

'Risks falling into this region are generally regarded as insignificant and adequately controlled. We, as regulators, would not usually require further action to reduce risks unless reasonably practicable measures are available. The levels of risk characterising this region are comparable to those that people regard as insignificant or trivial in their daily lives. They are typical of the risk from activities that are inherently not very hazardous or from hazardous activities that can be, and are, readily controlled to produce very low risks. Nonetheless, we would take into account that duty holders must reduce risks wherever it is reasonably practicable to do so or where the law so requires it.'

An annual risk of death to a member of the public of one in a million per year (10^{-6} y^{-1}) is also the risk at which regulatory control is applied to manage the disposal of radioactive waste by the Environment Agency (BEIS et al, 2018).

The ratio between rates of cancer incidence and fatality is unlikely to be more than a factor of two for most cancers. As the difference in the risk of cancer incidence and fatality is likely to be substantially less than any uncertainty present in the estimated quantities, the lifetime risk of cancer incidence and fatality are not presented separately in this report. The exception to this is skin cancer where incidence rates are higher than rates of fatality by a factor of about 500. As the overall risk of developing fatal skin cancer was estimated to be two to three orders of magnitude lower than that of developing fatal cancer from the possible ingestion of a particle, the risk of skin cancer incidence is therefore likely to be no higher than the risk of developing fatal cancer following the ingestion of a particle.

This assessment also estimated whether an encounter with a radioactive object may result in tissue damage to either the skin or colon, the organs most likely to be exposed to radiation from an object. This assessment showed that that severe tissue damage to the colon is unlikely to occur as the highest estimated absorbed dose is about a factor of 100 lower than the threshold dose.

It was estimated that the threshold for tissue damage may potentially be exceeded if a particle with more than about 100 kBq of ^{90}Sr activity remained in direct contact with the skin for several hours. However, it is acknowledged that the dose rate to the skin per unit activity used in this assessment is likely to be cautious to compensate for the difficulty of accounting for self-absorption of the emitted radiation by a particle. It is therefore possible that no particle could cause the threshold dose to the skin to be exceeded if it remained in contact with the skin for a realistic period of time. It is also noted that any damage to the skin would be limited to the formation of a small blister with no significant or long-term health consequences.

Based on the results of this assessment, PHE concludes that the risk to health from radioactive objects on the beaches near the Sellafield site is very low. As the risk to health from radioactive objects is very low, PHE suggests that measures to control those risks, for example remedial measures that remove objects from the environment or the addition of signage on the beaches, are not warranted on public health grounds.

9.2 Impact of the risk assessment on the future monitoring programme

The current monitoring programme was designed to detect and recover objects with the aim to improve knowledge of the potential hazard they pose. As discussed in this assessment, there is no evidence which suggests that there have been significant changes with time in either the find rate or in the characteristics of the objects that are being detected and this situation is likely to continue into the foreseeable future. Based on the very low risk posed by objects in the environment near to the Sellafield site, PHE is of the opinion that there is little justification to continue with the current beach monitoring programme on public health grounds and suggests that the current monitoring programme could be replaced with one that is reduced in scope and whose aim is to collect information to provide reassurance that the assumptions made in this risk assessment remain valid.

This assessment showed that there is little difference in the magnitude of the estimated risk to individuals who use the beaches between St Bees and Sellafield. In broad terms, the magnitude of the risks associated with using beaches between St Bees and Braystones was due to the relatively high occupancy while the risks associated with using the beach at Sellafield was due to the relatively high particle population present on that beach. The risks to health to those using beaches between Seascale and Drigg were estimated to be lower than on the other beaches considered mainly as they had a much lower particle population. Consequently, a programme of routine monitoring should continue to focus on areas of higher find rate or occupancy as has largely been the case to date.

9.3 Impact on the intervention plan

The EA has developed an intervention plan with the other organisations involved in protecting the public from the hazards posed by radioactive objects (EA., 2017). That plan sets out a procedure to respond to the detection of unusual radioactive objects, both in relation to the characteristics on a single find or to an overall change in the find rate.

Trigger levels included in the intervention plan are used to identify particles with unusually high levels of activity that require further detailed analysis. As the trigger levels are based on cautious assumptions with respect to the potential risk to health any particle may pose, the detection of a particle that exceeds the trigger level for further analysis does not automatically mean that the risk posed by that particle is not acceptable nor that urgent action is needed to reduce the hazard. The protocol does not include trigger levels for larger objects as they pose a much lower risk to health compared with particles. Instead, decisions on submitting larger objects for further analysis are made on a case by case basis.

The intervention plan also includes trigger levels for intervention that are intended to be compared against the find rate of particles either on the beaches or off-shore. As trigger levels for intervention are based on estimated lifetime risks of developing fatal cancer from annual use of a beach or consumption of seafood, they should not be compared against results of monitoring carried out over relatively small areas or over short time periods. This is because the results of such monitoring are unlikely to reflect the situation over an entire year or over most of a beach.

Sections 9.3.1 to 9.3.5 describe a review of the existing trigger levels considering the risks to health estimated in this assessment.

9.3.1 Trigger levels associated with the activity on alpha-rich particles

The existing protocol includes a trigger level for further analysis related to a measured ^{241}Am activity of 5 MBq on any individual particle. This trigger level corresponds to an effective dose to a child of about 550 mSv which was described in HPA-CRCE-018 (supplement) as being borderline of acceptable. To make the protocol more robust in identifying particles that should be sent for further analysis, it is suggested that the existing trigger level is replaced with one that corresponds to a specific radiological criterion. Public Health England suggests that an activity of alpha emitting radionuclides on a particle that corresponds to an effective dose of 100 mSv, equal to the highest dose recommended for use as a reference level by ICRP (ICRP, 2007), is appropriate for use as a trigger level. An effective dose of 100 mSv would be received if the ingested particle had about 1.8 MBq of alpha emitting radionuclide activity on it, noting that the dose coefficient for ingestion of ^{241}Am and the alpha emitting isotopes of plutonium are broadly equivalent.

As the preliminary analysis conducted on objects detected on the beaches only measures the activity of ^{241}Am, it is suggested that any particle with more than 1 MBq of ^{241}Am activity should be subjected to further analysis. This value is based on the observation that, on particles detected until the end of 2017, on average about 60% of the total alpha activity was ^{241}Am with the remaining 40% being a mixture of ^{238}Pu and $^{239/240}$Pu. If further analysis shows that the total alpha emitting radionuclide activity on the particle is greater than 1.8 MBq then appropriate action should be taken as specified in the finds characterisation protocol. Since the highest ^{241}Am activity measured on any particle detected to the end of 2017 was about 0.6 MBq, the proposed change in the value of the trigger level will not result in an increase in the number of particles being sent for further analysis.

The aim of any further analysis on alpha-rich particles that meet the above criterion should be to establish an accurate measure of the activity present on that particle. In addition, the gut uptake fraction from that particle should be determined. A decision on whether an evaluation of the lifetime risk posed by a population of such particles is required should be taken on a case by case basis taking into account both the activity available for uptake to the body and the number of such particles that may exist in the environment. The detection of particles with high levels of activity may also affect the monitoring programme; see Section 9.3.5.

9.3.2 Trigger levels associated with the activity on beta-rich particles

The existing intervention protocol includes a trigger level for analysis of beta-rich particles in terms of a field estimated equivalent skin dose rate from a particle of more than 300 mGy h^{-1}. The purpose of this trigger level is to identify particles that have a sufficiently high dose rate to exceed the threshold for deterministic effects to the skin if exposure lasts longer than about seven hours, which represents a cautious length of time for which a particle may be trapped against the skin. Since no changes in either the threshold for deterministic effects to the skin or the time for which a particle may be trapped against the skin were established in this assessment, PHE recommends that this trigger level remains.

To enable preliminary measurement on particles in the field, it is important to express this dose rate in terms of a contact dose rate rather than a dose rate to the skin. Skin to contact dose rate conversion factors were given in HPA-CRCE-018 (supplement) (Oatway et al, 2011) for SmartIon and TLD detectors of 95 and 0.18 respectively. Using these factors, order of magnitude contact dose rates corresponding to a skin dose rate of 300 mGy h^{-1} are 1 mGy h^{-1} for the SmartIon detector and 1000 mGy h^{-1} for the TLD detector.

For beta-rich particles, an additional trigger level for further analysis was included in the existing protocol related to a laboratory gamma analysis indicating that more than 100 kBq of ^{137}Cs activity is present on a particle. This trigger level was intended to identify those particles that should be sent for further analysis to determine the activity of any ^{90}Sr that may be present due to the difficulty of measuring ^{90}Sr compared to ^{137}Cs and the possibility that the particle may possess a high Cs:Sr activity ratio. However, the trigger level related to a dose rate greater than 300 mGy h^{-1} should identify any particle with more than either about 30 kBq of ^{90}Sr activity or about 180 kBq of ^{137}Cs activity on it. The effective dose from ingestion of a particle with these activities would be about 10 mSv. The use of a trigger level related to an equivalent skin dose rate therefore provides a means to identify particles that have the potential to cause effective doses that may be of concern should they be ingested, as well as dose rates that may lead to deterministic effects. For these reasons, PHE suggests that the trigger level for further analysis related to the measurement of more than 100 kBq of ^{137}Cs activity on a particle should be removed from the protocol.

The aim of further analysis of a beta-rich particle which exceeds the above criterion is to provide an accurate measure of both the total activity that is present on the particle and the contact dose rate from the particle. A decision on whether a risk assessment is required to evaluate the lifetime risk posed by a population of such particles, and the potential for deterministic effects to arise, should be taken on a case by case basis. That decision should take into account both the potential dose from exposure to such a particle and the number of such particle that may exist in the environment. The detection of particles with high levels of activity may also affect the monitoring programme; see Section 9.3.5.

9.3.3 Trigger levels associated with find rates on beaches

The current trigger level for intervention in relation to the find rate of alpha-rich particles is 10^3 particles per hectare. Across beaches between Sellafield and St Bees, where the highest risks were estimated, a find rate of about 1 alpha-rich particle per hectare corresponds to a 97.5th percentile of the lifetime risk of developing fatal cancer from using a beach for a year of about 10^{-11} y^{-1}. To meet the risk criterion of 10^{-6} y^{-1}, the find rate would need to be of the order of 10^5 alpha-rich particles per hectare. When deriving the current trigger level for intervention, an additional factor of ten was used to provide a further degree of caution. If this factor of 10 was included, a suitable trigger level for intervention would be a find rate of 10^4 alpha-rich particles per hectare.

The current trigger level for the find rate if beta-rich particles is set at 2 10^4 particles per hectare. The current find rate on the northern beaches is 0.05 particles per hectare and corresponds to a 97.5th percentile of the lifetime risk of developing fatal cancer from using a beach for a year of about 10^{-13} y^{-1}. To meet the risk criterion of 10^{-6} y^{-1}, the find rate would need to be of the order of 5 10^5 particles per hectare. Inclusion of a safety factor of 10 to provide a further degree of caution means that a suitable trigger level for intervention would be a find rate of 5 10^4 beta-rich particles per hectare.

The trigger levels for intervention discussed above are many orders of magnitude higher than the current find rates. Public Health England therefore suggest that current trigger levels for intervention are not suitable and that a different approach, based on a qualitative review of the overall find rate, should be used to determine whether changes to the monitoring programme are necessary. Public Health England suggests that a change in the find rate over large areas and sustained periods of at least an order of magnitude should be used. Based on the find rates reported between 2009 and 2017, order of magnitude trigger levels for intervention for alpha- and beta-rich particles of 10 and 1 particles per hectare are suggested. As these find rates are dependent on the equipment used, they should be reviewed if a change in detection equipment occurs.

9.3.4 Trigger levels associated with find rates off-shore

To aid off-shore monitoring the intervention plan also includes trigger levels related to the number of particles per unit mass of sand. As mentioned in Section 1 an offshore monitoring programme was trialled between 2011 and 2014. However, offshore monitoring was deemed not to represent Best Available Technique (BAT) and the programme was stopped. Recognising that this situation may change in the future, a re-evaluation of the trigger levels associated with off-shore monitoring has also been undertaken.

The current trigger levels for intervention for offshore particles are 20 and 50 alpha or beta-rich particles per tonne of sediment respectively. The existing protocol states that the trigger level for intervention with respect to off-shore monitoring should be determined assuming a detection probability of 100%. This approach was taken as it was considered preferable to derive that trigger level without accounting for the detection probability as it was not known what technique would be applied to offshore monitoring in the future.

Tables 4 and 47 show that, for ingestion of particles in molluscs obtained from an area with an estimated population of respectively 3 10^{-9} and 2.3 10^{-11} alpha- and beta-rich particles per gram of sediment, the respective highest 97.5th percentile of the lifetime risks are 5.7 10^{-11} and 7.4 10^{-13} per year. To expose the seafood consuming population to a risk no greater than 10^{-6} per year, the actual population of alpha- or beta-rich particles would need to be less than about 50 or 30 particles per tonne of sediment respectively. Inclusion of a safety factor of 10 reduces these actual particle populations to 5 and 3 particles per tonne of sediment for alpha- and beta-rich particles, respectively

9.3.5 Trigger levels for high activity particles

The current intervention plan includes trigger levels for how many high activity particles may be found before a review of the risk assessment should be undertaken. With regards to alpha-rich particles, the current trigger level is 40 particles per hectare where those particles have more than 1 MBq of alpha activity on them. In this report, it is suggested that the trigger level for further analysis of alpha-rich particles should change to 1 MBq of ^{241}Am activity. It is therefore suggested that this level is now used to define a high activity alpha-rich particle. Although a change in the definition of a high activity particle is suggested, it is noted that no particles detected to the end of 2017 possess a level of activity that would exceed either the current or the suggested criterion. As the maximum activity assumed to be present on an alpha-rich particle in this assessment was below both the current and suggested trigger levels, it is impossible to derive from this risk assessment a find rate of high activity alpha-rich particles above which the risk assessment should be reviewed.

Although finding a single high activity alpha-rich particle would represent an unusual situation, it would not affect the risk posed by the population of particles due to the very low chance that someone may encounter that particle. However, finding several such particles within a short period of time would provide justification to review the situation as it may indicate that the situation may have changed from that assumed in the risk assessment. It is therefore suggested that a review of the situation should be undertaken if 2 or more alpha-rich particles, with an activity of more 1 MBq of ^{241}Am activity, are detected on a single beach within a single calendar year. To account for limited monitoring occurring on some beaches, it is also suggested that finding 2 or more high activity alpha-rich particles within any sequentially monitored 10 ha area on a single beach should also be regarded as providing justification to review the situation.

A high activity beta-rich particle is defined as one from which the dose rate to the skin exceeds 300 mGy h^{-1}. It is suggested that a review should be carried out if the annual probability of encountering a high activity beta-rich particle exceeds 10^{-6}. On the southern beaches, a find rate of 0.01 beta-rich particles per hectare resulted in an estimated 97.5th percentile of the annual probability of encounter with a beta-rich particle on the skin of the order of 10^{-7}. However, the distribution of activity on beta-rich particles used in this assessment assumed that only about 10% of beta-rich particles had more than 30 kBq of ^{90}Sr on them, the level of activity estimated to produce a dose rate of 300 mGy h^{-1} assuming no ^{137}Cs was present, noting that the dose rate from ^{90}Sr is greater than that from ^{137}Cs. If 10% of the detected beta-rich particles had an equivalent skin dose rate that exceeded 300 mGy h^{-1}, then a find rate of

1 high activity beta-rich particle per hectare represents a suitable trigger level to prompt a review as it implies the situation may have exceeded the assumptions made in this assessment. The corresponding find rates on northern and Sellafield beaches are respectively about 5 and 3 high activity beta-rich particles per hectare. To keep the application of the protocol simple it is suggested that only a single trigger level, of 1 beta-rich particle per hectare with a field estimated equivalent skin dose rate that exceeds 300 mGy h^{-1}, is used for all beaches. To account for limited monitoring occurring on some beaches, it is suggested that finding 1 high activity beta-rich particle within any sequentially monitored 10 ha area on a single beach should be regarded as providing justification to review the situation

9.4 Review of recommendations made in previous risk assessments

A number of recommendations were made as a result of the assessments described in report HPA-CRCE-018 (Brown and Etherington, 2011) aimed at both reducing uncertainties in the risk assessment and demonstrating that protection of the public was adequate.

Since the publication of HPA-CRCE-018, several more years of monitoring have been carried out on beaches along the Cumbrian coast, both close to the Sellafield site and at a few beaches further afield. The monitoring has focussed on beaches that are expected to have relatively high object populations based on the conceptual site model (Atkins Limited, 2018), and on beaches that have been shown by habits surveys to be frequently used by members of the public. This additional monitoring satisfies the first recommendation made in HPA-CRCE-018 that regular monitoring of Sellafield beach and one or two other beaches with high public occupancy should continue to provide reassurance to the regulators and the public that the risks remain low. As shown by this current risk assessment, the additional information collected since 2011 has resulted in very little change in the magnitude of the estimated risk. As suggested in Section 9.2, one of the aims of any future routine monitoring programme should be to collect information to provide reassurance that the assumptions made in this risk assessment remain valid and that the risks to health remain extremely low. It is therefore suggested that monitoring in the future should focus on beaches where the risks are likely to be greatest due to either high object populations or high public use.

The second recommendation made in HPA-CRCE-018 was for the development of a detection system that would detect objects with more than 400 kBq of ^{90}Sr activity on the assumption that some objects may exist with very low Cs:Sr activity ratios. From an analysis of some of the particles detected to the end of 2017 it seems that there is little correlation between the activities of ^{137}Cs and ^{90}Sr on objects and that most objects have far more ^{137}Cs activity than ^{90}Sr. Consequently, the ability to detect objects that have very low Cs:Sr activity ratios is not as important as it was once thought. This is because any object which is likely to have sufficiently high levels of ^{90}Sr to potentially cause an unacceptable risk to health would most likely also have levels of ^{137}Cs activity, which are readily detectable. While further development of the detector system should be encouraged, it is considered that detection of objects with very low Cs:Sr activities is not of prime concern.

A recommendation was made in HPA-CRCE-018 that large volume air sampling over beaches should be performed to determine if a large population of inhalable particles exist. Such monitoring is undertaken as part of the routine monitoring programme conducted by Sellafield Ltd. In addition, studies have been undertaken around the Sellafield site that have investigated the importance of the sea-to-land transfer of radionuclides following the routine discharge of radioactivity to the marine environment (Bryan et al, 2004). As those studies included the analysis of ^{137}Cs and plutonium isotopes in soil along the coast, they should also be able to identify any enhanced levels of radioactivity caused by the movement of small particles off the beaches. Neither the routine monitoring programme nor the sea-to-land transfer studies have identified any particles that were of a respirable size and had unusually high levels of radioactivity associated with them. Respirable beach particles are likely to form part of the general mass of respirable particulates that are present in the environment and would be detected by the regular monitoring programme carried out by Environment Agency (Environment Agency et al, 2018). The potential long-term impact on the risk to health posed by object fragmentation is described in Appendix D of this report.

It was suggested in HPA-CRCE-018 that systems that allowed better detection of alpha-rich objects should be considered for use on beaches near to the Sellafield site. In 2009, the Groundhog Synergy detection system was deployed on beaches around the Sellafield site that had an enhanced ability to detect radiation emitted from ^{241}Am. It was recommended in HPA-CRCE-018 that, following the introduction of Groundhog Synergy, a review should be undertaken to assess its impact. That review was described in HPA-CRCE-038 (Etherington et al, 2012) and concluded that any increase in the alpha-rich object find rate was likely due to improvements in the detection system and not in any change in the number of objects actually present in the environment. This current assessment also made use of information related to objects detected by the Groundhog Synergy detection system. Publication of HPA-CRCE-038 and this report are considered to satisfy the requirement of the recommendation made in HPA-CRCE-018.

It was noted in HPA-CRCE-018 that monitoring on some beaches, particularly Drigg beach, only covered a relatively small fraction of available area and that as a result there were likely to be significant uncertainties in the actual population of objects estimated to be present on those beaches. Although the area monitored annually on some beaches has remained low, uncertainties in the calculated risks were reduced in the current assessment by adopting a more robust methodology based on the pooling of available monitoring data over larger beach areas. Public Health England suggest that there is no longer a need to increase the area monitored on Drigg beach to reduce uncertainties in the risk assessment further.

HPA-CRCE-018 also noted that, at the time of its publication, little information existed on the depth profile of objects on beaches and suggested that effort should be made to better understand how the number of objects present on a beach varied with depth. Since the publication of HPA-CRCE-018, a review of the morphology of beaches along the Cumbrian coast has been undertaken (CH2M Hill, 2016) which showed that sand on Cumbrian beaches was well mixed and any radioactive objects present should be assumed to be evenly distributed down to a depth of at least 0.5 m. This assumption was included in this assessment when estimating the actual number of objects likely to be present per unit area of beach.

The last area for improvement suggested in HPA-CRCE-018 regarded the technique used to measure the $\dot{H}_P$ (0.07) dose rate to skin from a particle in contact with it. Since publication of HPA-CRCE-018, work carried out under contract by PHE has reviewed two techniques that could be used for this purpose: radiochromic film (RCF) and thermoluminescence extremity dosemeters (EXTRAD®) (TLD). That work has shown that neither of these techniques is able to provide the most reliable measurement of the dose rate in all circumstances, although they often produce results that are in good agreement. It is therefore suggested that if a screening measurement of dose rate indicates that further investigation of this quantity is warranted, where practical both the RCF and TLD techniques should be used to provide a more accurate measurement of the $\dot{H}_P$ (0.07) dose rate to skin. Use of both techniques also provides a means of validating any measurement obtained, thereby reducing uncertainty.

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Appendix A Summary of significant decisions

Table A1 provides a summary of the decisions made in this risk assessment with respect to both the methodology and data used.

Table A1 Summary of key decisions made in the risk assessment

Topic	Decision	Comment
Minimum activity on an object	Activity linked to an effective dose following ingestion of 1 mSv	It was necessary to include this cut-off dose to prevent estimated risks being overly dependent on unconfirmed number of low activity objects being present. It was decided that the minimum activity which would be assumed to be present on an object would be linked to a dose. It was decided that an appropriate dose criterion was 1 mSv. This dose is the dose criterion recommended by the IAEA for exemption from regulatory control for low probability events, i.e. events with a probability of occurrence of less than 10^{-2} y^{-1}. The dose criterion corresponds to alpha-rich particles with an ^{241}Am activity of 10 kBq with plutonium isotopes assumed to be present in equal amounts. This corresponds to an integrated probability of detection down to a depth of 0.5 m of 1%. The dose criterion corresponds to beta-rich particles having a minimum ^{137}Cs activity of 8 kBq with ^{90}Sr present at 10 kBq. This corresponds to an integrated probability of detection down to a depth of 0.5 m of 10%.
Find data associated with specific detector systems	Groundhog Synergy detection system	The Groundhog Evolution2^{TM} detection system was used between 2006 and August 2009 during the early beach monitoring programme at Sellafield. The focus during the time that system was employed was to find as many objects as possible rather than to employ the system in a systematic manner. The conditions under which objects were detected are therefore not known with confidence. The Groundhog Synergy detection system was employed in a more systematic manner through, for example, better control of detector speed and height. There is therefore higher confidence in the conditions under which objects were detected. Only objects detected using the Groundhog Synergy detection system are therefore included in this assessment.
Depth of beach mixing	0.5 m	Average mixing depth used in this assessment was 0.5 m, which is the value reported by the beach morphology review for most beaches. The number of objects per unit mass of sand was taken to be a constant down to this depth. The impact of this assumption is discussed in Appendix B.
Estimated particle populations	Single value	No distribution in the population of particles present on the beaches was assumed in the risk assessment. This approach was used as there does not appear to be any significant trends in particle population with time, recognising that there is considerable uncertainty in this estimate for many beaches due to low find rates.
Area of beach where objects are present	Entire beach	Insufficient information was available to determine object populations for specific areas of beach. It was assumed that the estimated object population per unit area of beach was constant over the entire area of beach.

Topic	Decision	Comment
Habits data available	2003-2017	Beach occupancies and seafood consumption rates were based on observations made between 2003 and 2017 as the annual survey in 2003 was the first to include observations on beach use and seafood consumption together. Some of the consumption rates recorded for 2003 appear to be unusually high. It was decided that all data on consumption rates collected between 2003 and 2017 would be used in the assessment, but that an analysis would also be made of the potential impact on the estimated risk of including only seafood consumption rates recorded between 2004 and 2017; this is discussed in Appendix H.
Assessed population	High rate beach use/seafood consuming population	The data collected in the habits surveys is not representative of the habits of the general population because the surveys are carried out for the purpose of identifying the representative person and therefore target people who are likely to be most highly exposed
Inclusion of children on Sellafield beach	Not present	Information gathered by habits surveys conducted around the Sellafield site for identifying the representative person indicates that only adults make use of the beach at Sellafield. The assessment therefore did not include calculation of risks to children or young children making use of the beach at Sellafield. An analysis of the potential risks to children if they were to be present on Sellafield beach was undertaken to improve the robustness of the assessment conclusions; this is described in Appendix J.
Size of objects ingested by marine animals	All particles	Information collected by the monitoring programme does not allow an estimate of how many particles may be in the environment which could be ingested by molluscs or crustaceans. It was therefore assumed that all objects classified as particles were available for consumption by marine animals
Beach areas	Three beach areas between St Bees and Drigg	As the assessment described in HPA-CRCE-018 showed that the magnitude of the risks to health were similar to those using beaches at either St Bees or Braystones or at either Seascale or Drigg, the risks associated with using three areas of beach were considered in this assessment: North of Sellafield (between St Bees and Braystones; Sellafield; south of Sellafield (between Seascale and Drigg).

Appendix B Impact of changing the beach mixing volume

As reported in the main part of this report, for this risk assessment it was assumed that particles present on the beaches are evenly mixed within the volume of sand to a depth of 0.5 m and that the number of particles per unit mass of sand is a constant across a particular beach.

To investigate how sensitive the calculation of the number of particles present on the beach is to a variation in the mixing depth, the particle population per unit mass of sand was estimated assuming two mixing depths: 0.5 m and 0.1 m. The alpha- and beta-rich particle populations estimated on each beach between St Bees and Drigg using these two mixing depths are shown in Table B1. The difference in the estimated particle populations was estimated to be less than a factor of 2 on all beaches except for beta-rich particles on St Bees beach. This difference may indicate that the sand on St Bees beach is not mixed as much as the sand on other beaches.

Table B1 Estimated number of particles per unit mass of sand on different beaches for mixing depths of 0.1 m and 0.5 m are assumed

	Particles per gram of sand				
	St Bees	**Braystones**	**Sellafield**	**Seascale**	**Drigg**
Alpha-rich particles					
Mixing depth of 0.1 m	$3.4\ 10^{-9}$	$5.1\ 10^{-9}$	$8.2\ 10^{-9}$	$1.0\ 10^{-9}$	$9.2\ 10^{-10}$
Mixing depth of 0.5 m	$2.3\ 10^{-9}$	$3.6\ 10^{-9}$	$5.9\ 10^{-9}$	$7.3\ 10^{-10}$	$6.3\ 10^{-10}$
Beta-rich particles					
Mixing depth of 0.1 m	$2.2\ 10^{-11}$	$6.0\ 10^{-11}$	$2.5\ 10^{-10}$	$1.1\ 10^{-11}$	-
Mixing depth of 0.5 m	$5.7\ 10^{-12}$	$3.7\ 10^{-11}$	$1.5\ 10^{-10}$	$6.7\ 10^{-12}$	-

Appendix C Trends in the probability of encountering a particle

Figure C1 and C2 show respectively the annual number of alpha- and beta-rich particles estimated to be present per unit area of each beach around the Sellafield site between 2009 and 2017. These particle populations were estimated from the number of particles detected by the Groundhog Synergy detection system. As the actual particle populations shown in Figures C1 and C2 were estimated from the reported find rates, no particle populations could be estimated for those years in which no particles were detected on a beach. The absence of an estimated particle population in Figures C1 and C2 does not therefore imply that particles were absent from any beach between 2009 and 2017. It is also noted that the actual particle populations estimated to be present on each beach in 2009 were based only on particles detected between September and the end of that year due to the timeframe in which the Groundhog Synergy detection system was employed.

Figures C1 and C2 show that there are no clear trends in either the actual alpha- or beta-rich particle populations with time on any beach between St Bees and Drigg.

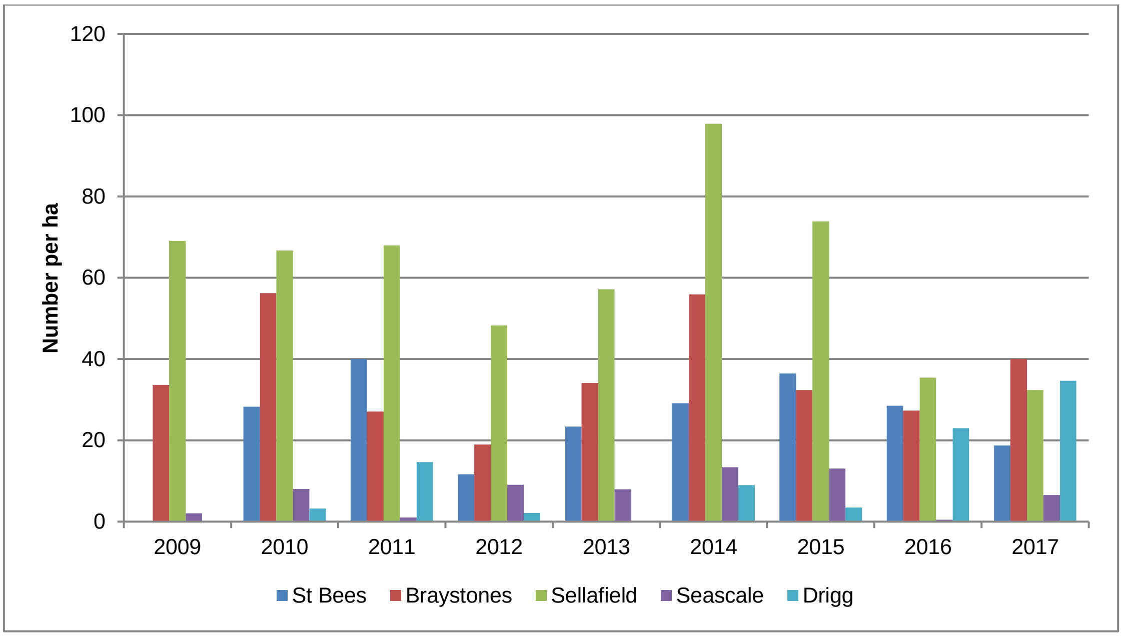

Figure C1 Estimated population of alpha-rich particles present on different beaches

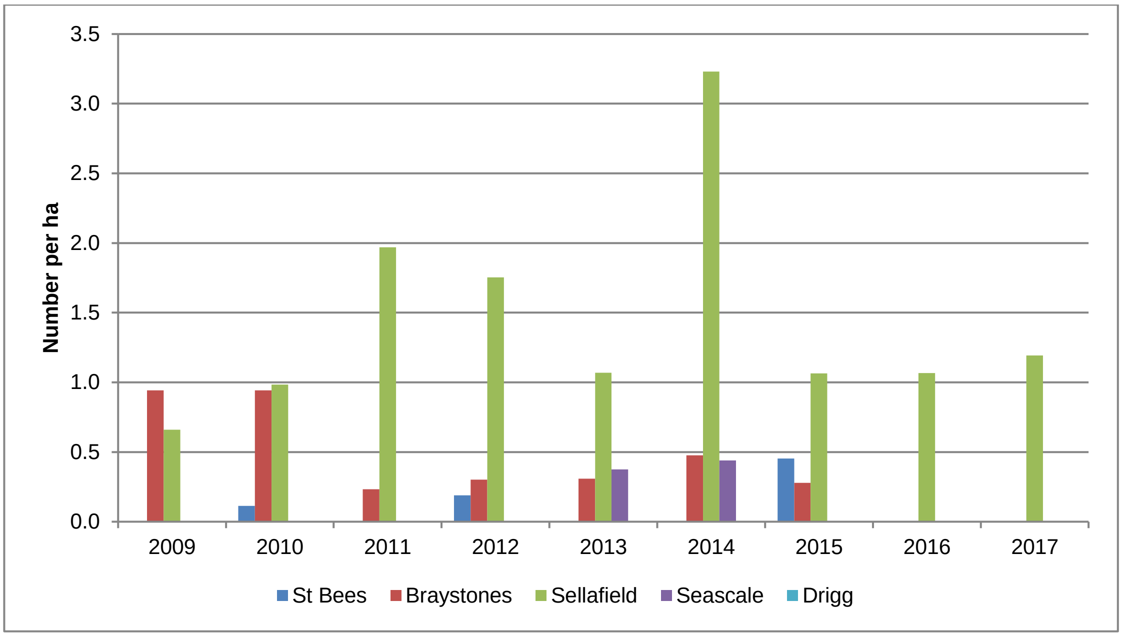

Figure C2 Estimated population of beta-rich particles present on different beaches

Appendix D Impact of the fragmentation of objects on the estimated risk

Fragmentation is the process by which a large object breaks up into smaller objects through the action of environmental processes such as wave action. Fragmentation may affect the probability that a person may come in contact with an object as it can change the number of objects present in the environment and their physical size. Fragmentation may also change the activity present on individual objects and the dose which may be received from exposure to radioactivity on that object.

The fragmentation process does not result in a significant change in the number of objects which may be present over a whole beach although it may affect the population present within smaller areas of a few square metres. Fragmentation is likely to be already occurring on the beaches around Sellafield and, since the number of objects and their activities estimated in this assessment were based on monitoring results, the effects of fragmentation should have been accounted for. It is possible that fragmentation is occurring on timescales of several decades and hence its effects may not have been seen yet. However, as the rate of fragmentation would be low if it occurred on such timescales, any variation in the find rates over an entire beach that is recorded by the monitoring programme is likely to be caused by processes such as storms moving large volumes of sediment around rather than fragmentation.

It is extremely difficult to quantify the effect of fragmentation on the estimated risks; it would depend on the number of new objects created and the how the activity on the original object is distributed amongst the new ones. In general, an increase in the probability of encounter with an object, due to the fact that fragmentation causes more objects to be present on a beach, would be balanced by a decrease in the dose from contact with these objects because of the lower activity present on the objects. The likelihood that the risks would be significantly affected by fragmentation is therefore low.

If a larger object were to fragment into several particles it is possible that the risk to health to someone using that small area of beach may increase as additional routes of exposure would become possible. For example, exposure to radioactivity on a larger object may only occur if it is deliberately picked up while a particle may deliver a dose through inadvertent contact with the skin or when becoming attached to clothing. However, it is considered that any increase in the risk would be transitory as any particles created would be rapidly dispersed and that the impact of possible fragmentation of larger objects on the estimated lifetime risk from using a beach over the course of a year would be very low.

Appendix E Detailed analysis of beach use habits

E1 Number of individuals observed in the habits surveys

The number of adults recorded in the habits surveys taking part in angling, leisure or walking activities on beaches along the Cumbrian coastline are shown in Table E1, Table E2 and Table E3 respectively. From the information recorded in the habits surveys it is apparent that adults participate in all activities on a regular basis over the period covered by the surveys. The only exception is the beach at Sellafield where no adults were recorded to participate in leisure activities.

Table E1 Number of adults recorded in the habits surveys participating in angling activities on beach over the period 2003 to 2017

	Number of individuals					
Year	Braystones	St Bees	Sellafield	Drigg	Seascale	Multiple areas
2003	5	10	5	19	5	88
2004	9	-	1	6	1	-
2005	3	3	1	1	-	3
2006	7	-	-	2	-	2
2007	10	1	1	4	2	6
2008	13	4	3	10	3	14
2009	7	-	-	1	-	5
2010	9	2	-	2	2	3
2011	12	-	4	1	1	3
2012	11	12	5	15	2	37
2013	13	7	12	15	10	31
2014	11	-	1	10	-	1
2015	14	-	8	9	7	-
2016	15	1	5	12	7	-
2017	8	2	-	11	6	-

Table E2 Number of adults recorded in the habits surveys participating in leisure activities on beach over the period 2003 to 2017

	Number of individuals					
Year*	Braystones	St Bees	Sellafield	Drigg	Seascale	Multiple areas
2003	-	5	-	4	10	-
2007	1	-	-	-	-	-
2008	3	4	1#	-	4	1
2009	2	-	-	-	-	-
2010	2	-	-	-	1	-
2011	2	2	-	-	-	-
2012	3	3	-	3	9	2
2013	-	5	-	1	3	2
2014	2	-	-	-	-	-

*Years when no observations were made are excluded

This individual was recorded as using a beach for both leisure and walking. In this assessment, this individual was assumed to use Sellafield beach for walking only

Table E3 Number of adults recorded in the habits surveys participating in walking activities on beach over the period 2003 to 2017

	Number of individuals					
Year	Braystones	St Bees	Sellafield	Drigg	Seascale	Multiple areas
2003	6	15	4	27	23	-
2004	4	1	-	5	4	2
2005	-	2	1	1	2	-
2006	4	1	-	1	-	-
2007	2	-	-	4	-	3
2008	10	13	5	37	50	4
2009	3	3	2	1	1	6
2010	8	1	4	4	11	6
2011	8	5	3	3	-	3
2012	11	9	3	38	16	15
2013	3	14	4	23	26	17
2014	6	-	3	4	2	4
2015	5	3	4	-	5	-
2016	6	8	4	5	7	-
2017	6	4	4	5	7	-

The number of children and young children recorded in the habits surveys participating in angling, leisure or walking activities on beaches along the Cumbrian coastline are shown in Table E4 and Table E5. Data for years when no observations were made of children and young children using the beaches near the Sellafield site are not reported in the tables.

Table E4 Number of children recorded in the habits surveys participating in activities associated with angling (A), leisure (L) and walking (W) on each beach*

	Number of individuals										
	Braystones		St Bees		Drigg		Seascale		Multiple areas		
Year	A	L	L	W	L	W	L	W	A	L	W
2003	-	-	-	-	-	1	1	-	-	1	-
2007	-	3	-	-	-	-	-	-	1	-	-
2008	-	4	-	4	-	3	-	8	2	-	1
2009	-	4	-	-	-	-	-	-	4	-	-
2010	-	4	-	-	-	-	2	3	1	-	1
2011	-	8	-	-	-	-	-	-	4	-	2
2012	-	7	3	1	4	2	4	2	3	-	1
2013	1	-	3	-	-	-	-	2	-	-	-
2014	-	5	-	-	-	-	-	-	-	-	-
Total	1	35	6	5	4	6	7	15	15	1	5

* Years when no activity was observed have been excluded.

Table E5 Number of young children recorded to participate in activities associated with leisure and walking on each beach* along the Cumbrian coast

		Number of individuals					
Year	Activity	2007	2008	2011	2012	2013	Total
Braystones	Leisure	1	4	1	1	-	7
	Walking	-	-	-	-	-	-
St Bees	Leisure	-	2	2	1	3	8
	Walking	-	3	-	-	-	3
Drigg	Leisure	-	-	-	2	2	4
	Walking	-	1	-	-	-	1
Seascale	Leisure	-	3	-	9	6	18
	Walking	-	5	-	-	-	5
Multiple areas	Walking	-	2	-	-	-	2

* Years when no activity was observed have been excluded.

E2 Detailed habits of beach users

Table E6, Table E7 and Table E8 summarise information on the observed length of time adults, children and young children participate in different activities when using beaches near the Sellafield site.

Table E6 Annual time adults were recorded to spend on Cumbrian beaches

		Annual time spent on a beach (h y^{-1})		
Beach		**Angling**	**Leisure**	**Walking**
Braystones	Minimum	5	5	4
	Median	149	31	71
	Maximum	1450	228	875
St Bees	Minimum	6	2	2
	Median	122	35	116
	Maximum	750	374	1191
Sellafield	Minimum	0	-	5
	Median	122	-	69
	Maximum	1068	-	330
Drigg	Minimum	4	2	2
	Median	120	24	122
	Maximum	750	75	912
Seascale	Minimum	4	2	2
	Median	101	30	122
	Maximum	588	198	912
Multiple areas	Minimum	18	12	4
	Median	263	12	189
	Maximum	1524	104	1582

Table E7 Annual time children were observed to spend on Cumbrian beaches

		Annual time spent on a beach (h y^{-1})		
Beach		**Angling**	**Leisure**	**Walking**
Braystones	Minimum		8	-
	Median	12*	148	-
	Maximum		269	-
St Bees	Minimum	-	30	24
	Median	-	35	74
	Maximum	-	104	117
Drigg	Minimum	-	30	24
	Median	-	56	74
	Maximum	-	75	120
Seascale	Minimum	-	22	6
	Median	-	30	78
	Maximum	-	120	269
Multiple areas	Minimum	108		108
	Median	136	105*	108
	Maximum	231		159

* Only a single observation was made of individuals participating in this activity

Table E8 Annual time young children were recorded to spend on Cumbrian beaches

		Annual time spent on a beach (h y^{-1})	
Beach		**Leisure**	**Walking**
Braystones	Minimum	18	-
	Median	24	-
	Maximum	258	-
St Bees	Minimum	18	20
	Median	28	20
	Maximum	274	74
Drigg	Minimum	30	
	Median	38	74*
	Maximum	52	
Seascale	Minimum	2	6
	Median	30	20
	Maximum	250	74
Multiple areas	Minimum	-	
	Median	-	12*
	Maximum	-	

* Only a single observation was made of individuals participating in this activity

Appendix F Detailed estimates of the annual probability of coming into contact with a particle on beaches around the Sellafield site

This appendix presents the estimated annual probability of encountering a radioactive particle when using beaches by each exposure pathway. The total estimated probability of encountering an alpha- or beta-rich particle when using a beach are shown in Table 23 and Table 24 of the main text respectively.

For each exposure pathway, the estimated annual probability of encountering a particle is presented separately for beaches to the north of Sellafield (represented by beaches at St Bees and Braystones), the beach at Sellafield, and beaches to the south of Sellafield (represented by beaches at Seascale and Drigg). Probabilities are given for the 3 different types of activities on the beach considered in the assessment (angling, leisure and walking).

F1 Probability of inhaling a particle when using a beach

Table F1 and Table F2 present the estimated annual probability of inhaling a particle when using beaches near the Sellafield site. Using the assumptions made in this assessment, the highest 97.5th percentile of the probability of inhaling a particle was estimated to be of the order of 10^{-8} per year. The probability of inhaling an alpha-rich particle was estimated to be higher than the probability of inhaling a beta-rich particle by a factor of about 50. The highest probability of inhaling a particle on a beach was estimated to be associated with adults participating in angling activities on Sellafield beach. The probability that particles are inhaled by young children or children was estimated to be about an order of magnitude lower than that for adults.

Table F1 Estimated annual probability of inhaling an alpha-rich particle

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$3.9\ 10^{-13}$	$2.3\ 10^{-13}$	0.0	0.0	0.0	0.0	$7.6\ 10^{-14}$	$4.2\ 10^{-14}$
50th	0.0	$6.7\ 10^{-12}$	$5.8\ 10^{-12}$	0.0	0.0	0.0	0.0	$1.4\ 10^{-12}$	$7.1\ 10^{-13}$
97.5th	0.0	$1.4\ 10^{-10}$	$1.9\ 10^{-10}$	0.0	0.0	0.0	0.0	$3.4\ 10^{-11}$	$1.8\ 10^{-11}$
Children									
2.5th	$5.8\ 10^{-13}$	$1.0\ 10^{-12}$	$8.7\ 10^{-13}$	0.0	0.0	0.0	$5.8\ 10^{-13}$	$1.2\ 10^{-13}$	$3.8\ 10^{-13}$
50th	$1.8\ 10^{-11}$	$1.7\ 10^{-11}$	$9.3\ 10^{-12}$	0.0	0.0	0.0	$3.5\ 10^{-12}$	$2.4\ 10^{-12}$	$4.6\ 10^{-12}$
97.5th	$6.4\ 10^{-10}$	$3.6\ 10^{-10}$	$1.5\ 10^{-10}$	0.0	0.0	0.0	$3.9\ 10^{-11}$	$7.3\ 10^{-11}$	$7.0\ 10^{-11}$
Adults									
2.5th	$3.3\ 10^{-11}$	$5.9\ 10^{-12}$	$6.5\ 10^{-12}$	$4.0\ 10^{-11}$	0.0	$2.8\ 10^{-11}$	$3.3\ 10^{-12}$	$8.1\ 10^{-13}$	$1.3\ 10^{-12}$
50th	$3.2\ 10^{-10}$	$7.2\ 10^{-11}$	$1.3\ 10^{-10}$	$4.3\ 10^{-10}$	0.0	$2.6\ 10^{-10}$	$5.0\ 10^{-11}$	$1.2\ 10^{-11}$	$2.9\ 10^{-11}$
97.5th	$3.1\ 10^{-9}$	$9.0\ 10^{-10}$	$2.6\ 10^{-9}$	$4.9\ 10^{-9}$	0.0	$2.7\ 10^{-9}$	$7.4\ 10^{-10}$	$1.6\ 10^{-10}$	$7.2\ 10^{-10}$

Table F2 Estimated annual probability of inhaling a beta-rich particle

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$2.9\ 10^{-15}$	$1.8\ 10^{-15}$	0.0	0.0	0.0	0.0	$5.2\ 10^{-16}$	$2.9\ 10^{-16}$
50th	0.0	$5.0\ 10^{-14}$	$4.4\ 10^{-14}$	0.0	0.0	0.0	0.0	$9.2\ 10^{-15}$	$4.8\ 10^{-15}$
97.5th	0.0	$1.1\ 10^{-12}$	$1.4\ 10^{-12}$	0.0	0.0	0.0	0.0	$2.3\ 10^{-13}$	$1.2\ 10^{-13}$
Children									
2.5th	$4.3\ 10^{-15}$	$7.8\ 10^{-15}$	$6.5\ 10^{-15}$	0.0	0.0	0.0	$4.0\ 10^{-15}$	$8.2\ 10^{-16}$	$2.6\ 10^{-15}$
50th	$1.4\ 10^{-13}$	$1.3\ 10^{-13}$	$7.0\ 10^{-14}$	0.0	0.0	0.0	$2.4\ 10^{-14}$	$1.7\ 10^{-14}$	$3.1\ 10^{-14}$
97.5th	$4.8\ 10^{-12}$	$2.7\ 10^{-12}$	$1.1\ 10^{-12}$	0.0	0.0	0.0	$2.6\ 10^{-13}$	$5.0\ 10^{-13}$	$4.7\ 10^{-13}$
Adults									
2.5th	$2.5\ 10^{-13}$	$4.4\ 10^{-14}$	$4.9\ 10^{-14}$	$9.8\ 10^{-13}$	0.0	$6.9\ 10^{-13}$	$2.3\ 10^{-14}$	$5.5\ 10^{-15}$	$8.8\ 10^{-15}$
50th	$2.4\ 10^{-12}$	$5.4\ 10^{-13}$	$1.0\ 10^{-12}$	$1.1\ 10^{-11}$	0.0	$6.5\ 10^{-12}$	$3.4\ 10^{-13}$	$7.8\ 10^{-14}$	$2.0\ 10^{-13}$
97.5th	$2.4\ 10^{-11}$	$6.8\ 10^{-12}$	$1.9\ 10^{-11}$	$1.2\ 10^{-10}$	0.0	$6.8\ 10^{-11}$	$5.0\ 10^{-12}$	$1.1\ 10^{-12}$	$4.9\ 10^{-12}$

F2 Probability of ingesting a particle when using a beach

Table F3 and Table F4 present the estimated annual probability that a beach user would inadvertently ingest an alpha- or beta-rich particle respectively. The highest 97.5th percentile of the annual probability of ingesting a radioactive particle was estimated to be of the order of 10^{-7}; the probability that an alpha-rich particle is ingested is generally at least an order of magnitude higher than that of ingesting a beta-rich particle. The beach activity associated with the highest probability of ingesting a particle was angling, with adults and children having a higher probability of encounter when on Sellafield and northern beaches respectively. The probability that a radioactive particle is ingested is slightly higher for children than for adults due to the relative quantities of sediment assumed to be ingested by these age groups.

Table F3 Estimated annual probability of inadvertently ingesting an alpha-rich particle

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$6.6\ 10^{-10}$	$3.2\ 10^{-10}$	0.0	0.0	0.0	0.0	$1.2\ 10^{-10}$	$5.9\ 10^{-11}$
50th	0.0	$5.9\ 10^{-9}$	$5.2\ 10^{-9}$	0.0	0.0	0.0	0.0	$1.3\ 10^{-9}$	$6.3\ 10^{-10}$
97.5th	0.0	$5.8\ 10^{-8}$	$7.8\ 10^{-8}$	0.0	0.0	0.0	0.0	$1.3\ 10^{-8}$	$7.4\ 10^{-9}$
Children									
2.5th	$5.6\ 10^{-10}$	$1.1\ 10^{-9}$	$1.1\ 10^{-9}$	0.0	0.0	0.0	$1.0\ 10^{-9}$	$1.2\ 10^{-10}$	$4.6\ 10^{-10}$
50th	$9.2\ 10^{-9}$	$9.1\ 10^{-9}$	$5.0\ 10^{-9}$	0.0	0.0	0.0	$1.9\ 10^{-9}$	$1.3\ 10^{-9}$	$2.5\ 10^{-9}$
97.5th	$1.5\ 10^{-7}$	$8.2\ 10^{-8}$	$2.3\ 10^{-8}$	0.0	0.0	0.0	$3.5\ 10^{-9}$	$1.6\ 10^{-8}$	$1.3\ 10^{-8}$
Adults									
2.5th	$1.4\ 10^{-10}$	$3.6\ 10^{-11}$	$3.9\ 10^{-11}$	$1.6\ 10^{-10}$	0.0	$1.8\ 10^{-10}$	$1.6\ 10^{-11}$	$4.6\ 10^{-12}$	$8.2\ 10^{-12}$
50th	$1.6\ 10^{-9}$	$4.9\ 10^{-10}$	$9.4\ 10^{-10}$	$2.2\ 10^{-9}$	0.0	$1.9\ 10^{-9}$	$2.6\ 10^{-10}$	$8.1\ 10^{-11}$	$2.1\ 10^{-10}$
97.5th	$1.8\ 10^{-8}$	$6.9\ 10^{-9}$	$2.0\ 10^{-8}$	$2.8\ 10^{-8}$	0.0	$2.3\ 10^{-8}$	$4.0\ 10^{-9}$	$1.3\ 10^{-9}$	$5.2\ 10^{-9}$

Table F4 Estimated annual probability of inadvertently ingesting a beta-rich particle

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	4.9 10^{-12}	2.4 10^{-12}	0.0	0.0	0.0	0.0	7.8 10^{-13}	4.0 10^{-13}
50th	0.0	4.4 10^{-11}	3.9 10^{-11}	0.0	0.0	0.0	0.0	8.8 10^{-12}	4.3 10^{-12}
97.5th	0.0	4.3 10^{-10}	5.8 10^{-10}	0.0	0.0	0.0	0.0	8.9 10^{-11}	5.0 10^{-11}
Children									
2.5th	4.2 10^{-12}	8.5 10^{-12}	8.2 10^{-12}	0.0	0.0	0.0	7.1 10^{-12}	8.3 10^{-13}	3.1 10^{-12}
50th	7.0 10^{-11}	6.9 10^{-11}	3.8 10^{-11}	0.0	0.0	0.0	1.3 10^{-11}	9.0 10^{-12}	1.7 10^{-11}
97.5th	1.1 10^{-9}	6.2 10^{-10}	1.7 10^{-10}	0.0	0.0	0.0	2.4 10^{-11}	1.1 10^{-10}	9.0 10^{-11}
Adults									
2.5th	1.1 10^{-12}	2.7 10^{-13}	3.0 10^{-13}	4.0 10^{-12}	0.0	4.6 10^{-12}	1.1 10^{-13}	3.1 10^{-14}	5.6 10^{-14}
50th	1.2 10^{-11}	3.7 10^{-12}	7.1 10^{-12}	5.5 10^{-11}	0.0	4.6 10^{-11}	1.8 10^{-12}	5.5 10^{-13}	1.5 10^{-12}
97.5th	1.3 10^{-10}	5.2 10^{-11}	1.5 10^{-10}	6.9 10^{-10}	0.0	5.7 10^{-10}	2.7 10^{-11}	8.8 10^{-12}	3.6 10^{-11}

F3 Probability of a particle being trapped in clothing when using a beach

Table F5 and Table F6 present the estimated annual probability that an alpha- or beta-rich particle becomes trapped in clothing. The highest 97.5th percentile of the annual probability of a particle becoming trapped in clothing was estimated to be of the order of 10^{-5}, the probability that an alpha-rich particle is trapped is at least an order of magnitude higher than that of a beta-rich particle. The beach activity associated with the highest probability of a particle becoming trapped in clothing was angling, with adults and children having higher probability of encounter when on Sellafield and northern beaches respectively. The probability that a radioactive particle becomes trapped is slightly higher for adults than it is for children due to the relative quantities of clothing assumed to be worn and the relative amount of time members of each age group were assumed to spend on the beach.

Table F5 Estimated annual probability of an alpha-rich particle being trapped in clothing

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young child									
2.5th	0.0	2.6 10^{-9}	3.1 10^{-9}	0.0	0.0	0.0	0.0	5.6 10^{-10}	5.7 10^{-10}
50th	0.0	4.9 10^{-8}	6.7 10^{-8}	0.0	0.0	0.0	0.0	1.0 10^{-8}	8.5 10^{-9}
97.5th	0.0	6.0 10^{-7}	1.2 10^{-6}	0.0	0.0	0.0	0.0	1.5 10^{-7}	1.2 10^{-7}
Child									
2.5th	9.5 10^{-9}	8.8 10^{-9}	1.4 10^{-8}	0.0	0.0	0.0	8.9 10^{-9}	9.3 10^{-10}	6.2 10^{-9}
50th	2.5 10^{-7}	1.5 10^{-7}	1.3 10^{-7}	0.0	0.0	0.0	5.4 10^{-8}	2.2 10^{-8}	6.5 10^{-8}
97.5th	5.1 10^{-6}	2.0 10^{-6}	9.4 10^{-7}	0.0	0.0	0.0	1.6 10^{-7}	3.5 10^{-7}	5.1 10^{-7}
Adult									
2.5th	5.4 10^{-8}	8.1 10^{-9}	1.8 10^{-8}	6.5 10^{-8}	0.0	6.3 10^{-8}	5.5 10^{-9}	1.1 10^{-9}	3.2 10^{-9}
50th	8.2 10^{-7}	1.6 10^{-7}	4.8 10^{-7}	1.1 10^{-6}	0.0	9.8 10^{-7}	1.3 10^{-7}	2.6 10^{-8}	1.1 10^{-7}
97.5th	1.1 10^{-5}	2.9 10^{-6}	1.1 10^{-5}	1.6 10^{-5}	0.0	1.2 10^{-5}	2.2 10^{-6}	4.8 10^{-7}	2.8 10^{-6}

Table F6 Estimated annual probability of a beta-rich particle being trapped in clothing

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young child									
2.5th	0.0	2.0 10^{-11}	2.4 10^{-11}	0.0	0.0	0.0	0.0	3.8 10^{-12}	3.8 10^{-12}
50th	0.0	3.7 10^{-10}	5.1 10^{-10}	0.0	0.0	0.0	0.0	6.9 10^{-11}	5.7 10^{-11}
97.5th	0.0	4.5 10^{-9}	9.3 10^{-9}	0.0	0.0	0.0	0.0	1.0 10^{-9}	7.9 10^{-10}
Child									
2.5th	7.2 10^{-11}	6.6 10^{-11}	1.0 10^{-10}	0.0	0.0	0.0	6.0 10^{-11}	6.3 10^{-12}	4.2 10^{-11}
50th	1.9 10^{-9}	1.1 10^{-9}	9.9 10^{-10}	0.0	0.0	0.0	3.7 10^{-10}	1.5 10^{-10}	4.4 10^{-10}
97.5th	3.8 10^{-8}	1.5 10^{-8}	7.1 10^{-9}	0.0	0.0	0.0	1.1 10^{-9}	2.4 10^{-9}	3.5 10^{-9}
Adult									
2.5th	4.1 10^{-10}	6.1 10^{-11}	1.3 10^{-10}	1.6 10^{-9}	0.0	1.6 10^{-9}	3.7 10^{-11}	7.4 10^{-12}	2.2 10^{-11}
50th	6.2 10^{-9}	1.2 10^{-9}	3.6 10^{-9}	2.7 10^{-8}	0.0	2.4 10^{-8}	9.0 10^{-10}	1.8 10^{-10}	7.4 10^{-10}
97.5th	8.0 10^{-8}	2.2 10^{-8}	8.6 10^{-8}	4.0 10^{-7}	0.0	3.0 10^{-7}	1.5 10^{-8}	3.3 10^{-9}	1.9 10^{-8}

F4 Probability of a particle being trapped in shoes when using a beach

Table F7 and Table F8 respectively presents the estimated annual probability that an alpha- or beta-rich particle becomes trapped in shoes. The highest 97.5th percentile of the annual probability of a radioactive particle becoming trapped in shoes was estimated to be of the order of 10^{-4}, with the probability that an alpha-rich particle is trapped being at least an order of magnitude higher than that of a beta-rich particle. The beach activity associated with the highest probability of a particle becoming trapped in shoes was angling, with adult and child anglers having higher probability of encounter when on Sellafield and northern beaches respectively. The probability that a radioactive particle becomes trapped is slightly higher for adults than it is for children due to the relative amount of time members of each age group was assumed to spend on each beach.

Table F7 Estimated annual probability of an alpha-rich particle being trapped in shoes

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$2.0\ 10^{-7}$	$1.1\ 10^{-7}$	0.0	0.0	0.0	0.0	$3.8\ 10^{-8}$	$2.0\ 10^{-8}$
50th	0.0	$2.3\ 10^{-6}$	$2.0\ 10^{-6}$	0.0	0.0	0.0	0.0	$5.0\ 10^{-7}$	$2.5\ 10^{-7}$
97.5th	0.0	$2.3\ 10^{-5}$	$3.4\ 10^{-5}$	0.0	0.0	0.0	0.0	$5.3\ 10^{-6}$	$3.0\ 10^{-6}$
Children									
2.5th	$1.6\ 10^{-7}$	$2.8\ 10^{-7}$	$2.5\ 10^{-7}$	0.0	0.0	0.0	$1.6\ 10^{-7}$	$3.2\ 10^{-8}$	$1.1\ 10^{-7}$
50th	$3.3\ 10^{-6}$	$3.3\ 10^{-6}$	$1.9\ 10^{-6}$	0.0	0.0	0.0	$7.3\ 10^{-7}$	$4.9\ 10^{-7}$	$8.9\ 10^{-7}$
97.5th	$6.3\ 10^{-5}$	$3.8\ 10^{-5}$	$1.0\ 10^{-5}$	0.0	0.0	0.0	$1.9\ 10^{-6}$	$6.9\ 10^{-6}$	$5.7\ 10^{-6}$
Adults									
2.5th	$4.8\ 10^{-7}$	$1.3\ 10^{-7}$	$1.6\ 10^{-7}$	$6.0\ 10^{-7}$	0.0	$6.2\ 10^{-7}$	$5.7\ 10^{-8}$	$1.8\ 10^{-8}$	$3.3\ 10^{-8}$
50th	$6.7\ 10^{-6}$	$2.1\ 10^{-6}$	$3.8\ 10^{-6}$	$9.1\ 10^{-6}$	0.0	$7.8\ 10^{-6}$	$1.1\ 10^{-6}$	$3.4\ 10^{-7}$	$8.7\ 10^{-7}$
97.5th	$7.6\ 10^{-5}$	$3.0\ 10^{-5}$	$7.7\ 10^{-5}$	$1.2\ 10^{-4}$	0.0	$8.5\ 10^{-5}$	$1.6\ 10^{-5}$	$4.8\ 10^{-6}$	$2.1\ 10^{-5}$

Table F8 Estimated annual probability of a beta-rich particle being trapped in shoes

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$1.5\ 10^{-9}$	$8.4\ 10^{-10}$	0.0	0.0	0.0	0.0	$2.6\ 10^{-10}$	$1.3\ 10^{-10}$
50th	0.0	$1.7\ 10^{-8}$	$1.5\ 10^{-8}$	0.0	0.0	0.0	0.0	$3.4\ 10^{-9}$	$1.7\ 10^{-9}$
97.5th	0.0	$1.7\ 10^{-7}$	$2.5\ 10^{-7}$	0.0	0.0	0.0	0.0	$3.6\ 10^{-8}$	$2.1\ 10^{-8}$
Children									
2.5th	$1.2\ 10^{-9}$	$2.1\ 10^{-9}$	$1.9\ 10^{-9}$	0.0	0.0	0.0	$1.1\ 10^{-9}$	$2.2\ 10^{-10}$	$7.5\ 10^{-10}$
50th	$2.5\ 10^{-8}$	$2.5\ 10^{-8}$	$1.4\ 10^{-8}$	0.0	0.0	0.0	$5.0\ 10^{-9}$	$3.3\ 10^{-9}$	$6.0\ 10^{-9}$
97.5th	$4.7\ 10^{-7}$	$2.8\ 10^{-7}$	$7.9\ 10^{-8}$	0.0	0.0	0.0	$1.3\ 10^{-8}$	$4.7\ 10^{-8}$	$3.9\ 10^{-8}$
Adults									
2.5th	$3.7\ 10^{-9}$	$1.0\ 10^{-9}$	$1.2\ 10^{-9}$	$1.5\ 10^{-8}$	0.0	$1.5\ 10^{-8}$	$3.9\ 10^{-10}$	$1.2\ 10^{-10}$	$2.3\ 10^{-10}$
50th	$5.0\ 10^{-8}$	$1.6\ 10^{-8}$	$2.9\ 10^{-8}$	$2.2\ 10^{-7}$	0.0	$1.9\ 10^{-7}$	$7.2\ 10^{-9}$	$2.3\ 10^{-9}$	$5.9\ 10^{-9}$
97.5th	$5.7\ 10^{-7}$	$2.2\ 10^{-7}$	$5.8\ 10^{-7}$	$2.9\ 10^{-6}$	0.0	$2.1\ 10^{-6}$	$1.1\ 10^{-7}$	$3.2\ 10^{-8}$	$1.4\ 10^{-7}$

F5 Probability of a particle being trapped under a nail when using a beach

Table F9 and Table F10 present the estimated annual probability that an alpha- or beta-rich particle becomes trapped under a nail. The highest 97.5th percentile of the annual probability of a radioactive particle becoming trapped was estimated to be of the order of 10^{-6}, with the probability that an alpha-rich particle is trapped being at least an order of magnitude higher than that of a beta-rich particle. Adult walkers on Sellafield beach were estimated to have the highest probability of having a particle trapped under a nail although this was only slightly higher than that for a child angling on northern beaches.

Table F9 Estimated annual probability of an alpha-rich particle being trapped under a nail

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5^{th}	0.0	$1.8\ 10^{-9}$	$9.8\ 10^{-10}$	0.0	0.0	0.0	0.0	$3.3\ 10^{-10}$	$1.7\ 10^{-10}$
50^{th}	0.0	$1.9\ 10^{-8}$	$1.6\ 10^{-8}$	0.0	0.0	0.0	0.0	$4.1\ 10^{-9}$	$2.1\ 10^{-9}$
97.5^{th}	0.0	$1.8\ 10^{-7}$	$2.6\ 10^{-7}$	0.0	0.0	0.0	0.0	$4.2\ 10^{-8}$	$2.3\ 10^{-8}$
Children									
2.5^{th}	$1.5\ 10^{-9}$	$4.4\ 10^{-9}$	$4.0\ 10^{-9}$	0.0	0.0	0.0	$1.4\ 10^{-9}$	$5.2\ 10^{-10}$	$1.7\ 10^{-9}$
50^{th}	$3.9\ 10^{-8}$	$5.1\ 10^{-8}$	$2.8\ 10^{-8}$	0.0	0.0	0.0	$8.7\ 10^{-9}$	$7.4\ 10^{-9}$	$1.4\ 10^{-8}$
97.5^{th}	$8.1\ 10^{-7}$	$5.2\ 10^{-7}$	$1.5\ 10^{-7}$	0.0	0.0	0.0	$2.5\ 10^{-8}$	$1.0\ 10^{-7}$	$9.3\ 10^{-8}$
Adults									
2.5^{th}	$8.5\ 10^{-9}$	$4.0\ 10^{-9}$	$3.3\ 10^{-9}$	$1.0\ 10^{-8}$	0.0	$1.5\ 10^{-8}$	$9.1\ 10^{-10}$	$5.1\ 10^{-10}$	$6.7\ 10^{-10}$
50^{th}	$1.3\ 10^{-7}$	$5.3\ 10^{-8}$	$8.5\ 10^{-8}$	$1.7\ 10^{-7}$	0.0	$1.7\ 10^{-7}$	$2.1\ 10^{-8}$	$8.7\ 10^{-9}$	$1.9\ 10^{-8}$
97.5^{th}	$1.7\ 10^{-6}$	$7.6\ 10^{-7}$	$1.9\ 10^{-6}$	$2.5\ 10^{-6}$	0.0	$2.0\ 10^{-6}$	$3.6\ 10^{-7}$	$1.4\ 10^{-7}$	$4.8\ 10^{-7}$

Table F10 Estimated annual probability of a beta-rich particle being trapped under a nail

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5^{th}	0.0	$1.3\ 10^{-11}$	$7.4\ 10^{-12}$	0.0	0.0	0.0	0.0	$2.2\ 10^{-12}$	$1.2\ 10^{-12}$
50^{th}	0.0	$1.4\ 10^{-10}$	$1.2\ 10^{-10}$	0.0	0.0	0.0	0.0	$2.8\ 10^{-11}$	$1.4\ 10^{-11}$
97.5^{th}	0.0	$1.4\ 10^{-9}$	$2.0\ 10^{-9}$	0.0	0.0	0.0	0.0	$2.8\ 10^{-10}$	$1.6\ 10^{-10}$
Children									
2.5^{th}	$1.2\ 10^{-11}$	$3.3\ 10^{-11}$	$3.0\ 10^{-11}$	0.0	0.0	0.0	$9.5\ 10^{-12}$	$3.6\ 10^{-12}$	$1.2\ 10^{-11}$
50^{th}	$2.9\ 10^{-10}$	$3.9\ 10^{-10}$	$2.1\ 10^{-10}$	0.0	0.0	0.0	$5.9\ 10^{-11}$	$5.0\ 10^{-11}$	$9.4\ 10^{-11}$
97.5^{th}	$6.1\ 10^{-9}$	$3.9\ 10^{-9}$	$1.2\ 10^{-9}$	0.0	0.0	0.0	$1.7\ 10^{-10}$	$7.0\ 10^{-10}$	$6.3\ 10^{-10}$
Adult									
2.5^{th}	$6.4\ 10^{-11}$	$3.0\ 10^{-11}$	$2.5\ 10^{-11}$	$2.5\ 10^{-10}$	0.0	$3.6\ 10^{-10}$	$6.2\ 10^{-12}$	$3.5\ 10^{-12}$	$4.5\ 10^{-12}$
50^{th}	$9.8\ 10^{-10}$	$4.0\ 10^{-10}$	$6.4\ 10^{-10}$	$4.2\ 10^{-9}$	0.0	$4.3\ 10^{-9}$	$1.4\ 10^{-10}$	$5.9\ 10^{-11}$	$1.3\ 10^{-10}$
97.5^{th}	$1.2\ 10^{-8}$	$5.7\ 10^{-9}$	$1.5\ 10^{-8}$	$6.1\ 10^{-8}$	0.0	$4.9\ 10^{-8}$	$2.4\ 10^{-9}$	$9.4\ 10^{-10}$	$3.3\ 10^{-9}$

F6 Probability of a particle being present on the skin when using a beach near the Sellafield site

Table F11 and Table F12 present the estimated annual probability that an alpha- or beta-rich particle comes into contact with the skin. The highest 97.5th percentile of the annual probability of a radioactive particle coming into contact with the skin was estimated to be of the order of 10^{-4}. The probability that an alpha-rich particle comes into contact with the skin was estimated to be at least an order of magnitude higher than that associated with a beta-rich particle. Adult anglers on Sellafield beach were estimated to have the highest probability of having a particle coming into contact with their skin although this was only slightly higher than that for an adult or a child undertaking activities on other beaches.

Table F11 Estimated annual probability of an alpha-rich particle being present on the skin

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beach		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	5.4 10^{-8}	1.7 10^{-8}	0.0	0.0	0.0	0.0	1.1 10^{-8}	2.8 10^{-9}
50th	0.0	9.0 10^{-7}	4.5 10^{-7}	0.0	0.0	0.0	0.0	1.9 10^{-7}	5.6 10^{-8}
97.5th	0.0	1.1 10^{-5}	9.1 10^{-6}	0.0	0.0	0.0	0.0	2.6 10^{-6}	8.3 10^{-7}
Children									
2.5th	5.3 10^{-8}	1.7 10^{-7}	7.7 10^{-8}	0.0	0.0	0.0	5.0 10^{-8}	1.7 10^{-8}	3.3 10^{-8}
50th	1.4 10^{-6}	2.6 10^{-6}	8.6 10^{-7}	0.0	0.0	0.0	3.1 10^{-7}	3.6 10^{-7}	4.2 10^{-7}
97.5th	2.9 10^{-5}	3.4 10^{-5}	6.7 10^{-6}	0.0	0.0	0.0	9.7 10^{-7}	6.6 10^{-6}	3.7 10^{-6}
Adults									
2.5th	3.0 10^{-7}	1.3 10^{-7}	6.9 10^{-8}	3.6 10^{-7}	0.0	2.7 10^{-7}	3.4 10^{-8}	1.7 10^{-8}	1.7 10^{-8}
50th	4.5 10^{-6}	2.7 10^{-6}	2.3 10^{-6}	6.1 10^{-6}	0.0	4.6 10^{-6}	7.1 10^{-7}	4.1 10^{-7}	4.9 10^{-7}
97.5th	5.6 10^{-5}	4.4 10^{-5}	5.5 10^{-5}	9.0 10^{-5}	0.0	5.8 10^{-5}	1.2 10^{-5}	8.1 10^{-6}	1.5 10^{-5}

Table F12 Estimated annual probability of a beta-rich particle being present on the skin

	Annual probability (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	4.1 10^{-10}	1.3 10^{-10}	0.0	0.0	0.0	0.0	7.5 10^{-11}	1.9 10^{-11}
50th	0.0	6.8 10^{-9}	3.4 10^{-9}	0.0	0.0	0.0	0.0	1.3 10^{-9}	3.8 10^{-10}
97.5th	0.0	8.6 10^{-8}	6.8 10^{-8}	0.0	0.0	0.0	0.0	1.8 10^{-8}	5.6 10^{-9}
Children									
2.5th	4.0 10^{-10}	1.3 10^{-9}	5.8 10^{-10}	0.0	0.0	0.0	3.4 10^{-10}	1.2 10^{-10}	2.2 10^{-10}
50th	1.0 10^{-8}	1.9 10^{-8}	6.5 10^{-9}	0.0	0.0	0.0	2.1 10^{-9}	2.5 10^{-9}	2.8 10^{-9}
97.5th	2.2 10^{-7}	2.5 10^{-7}	5.0 10^{-8}	0.0	0.0	0.0	6.6 10^{-9}	4.5 10^{-8}	2.5 10^{-8}
Adults									
2.5th	2.2 10^{-9}	9.5 10^{-10}	5.2 10^{-10}	8.9 10^{-9}	0.0	6.7 10^{-9}	2.3 10^{-10}	1.2 10^{-10}	1.1 10^{-10}
50th	3.4 10^{-8}	2.0 10^{-8}	1.7 10^{-8}	1.5 10^{-7}	0.0	1.1 10^{-7}	4.8 10^{-9}	2.8 10^{-9}	3.3 10^{-9}
97.5th	4.2 10^{-7}	3.3 10^{-7}	4.1 10^{-7}	2.2 10^{-6}	0.0	1.4 10^{-6}	8.5 10^{-8}	5.5 10^{-8}	1.0 10^{-7}

F7 Probability that a particle becomes trapped in the eye, ear or a wound

Table F13 presents the estimated annual probability that an alpha- or beta-rich particle becomes trapped in either the eye, the ear or in a wound. These annual probabilities were estimated using assumptions rather than being estimated explicitly due to the many variables associated with them. Methodologies to estimate these probabilities were described in HPA-CRCE-018 (supplement); values in Table B13 were taken from the same report and apply to all age groups. The highest estimated annual probability of an alpha-rich particle becoming trapped in one of these areas is of the order of 10^{-6}. The annual probability of a beta-rich particle becoming trapped in one of these locations was estimated to be about an order of magnitude lower than that for an alpha-rich particle.

Table F13 Estimated annual probability of a particle being trapped in the eye, ear, or in a wound

Area of the body	Annual probability (y^{-1})	
	Alpha-rich particle	Beta-rich particle
Eye	10^{-7}	10^{-8}
Ear	10^{-6}	10^{-7}
Wound	10^{-8}	10^{-9}

Appendix G Sensitivity in the estimated annual probability of encountering a particle and in the lifetime risk of fatal cancer

The contribution of different parameters to the sensitivity in the estimated annual probability of encountering a particle or in the estimated lifetime risk of developing fatal cancer was evaluated by assessing each parameter's contribution to the variance in that quantity, where variance provides a measure of how the data are distributed around the mean value. It is important to note that only those parameters defined as probability density functions could contribute to the variance; parameters such as the actual particle population present on a beach were therefore not included in this exercise.

Figure G1 shows the contribution to the variance in the annual probability of coming into contact with a particle when using a beach. The parameter contributing most significantly to the variance was the annual time spent on the beach. The exposure pathway contributing most to the annual probability of encountering a particle was material being trapped in a shoe. The mass of sand assumed to be present in a shoe per hour spent on the beach was therefore also found to contribute significantly to the variance in the annual probability of encountering a particle when using a beach.

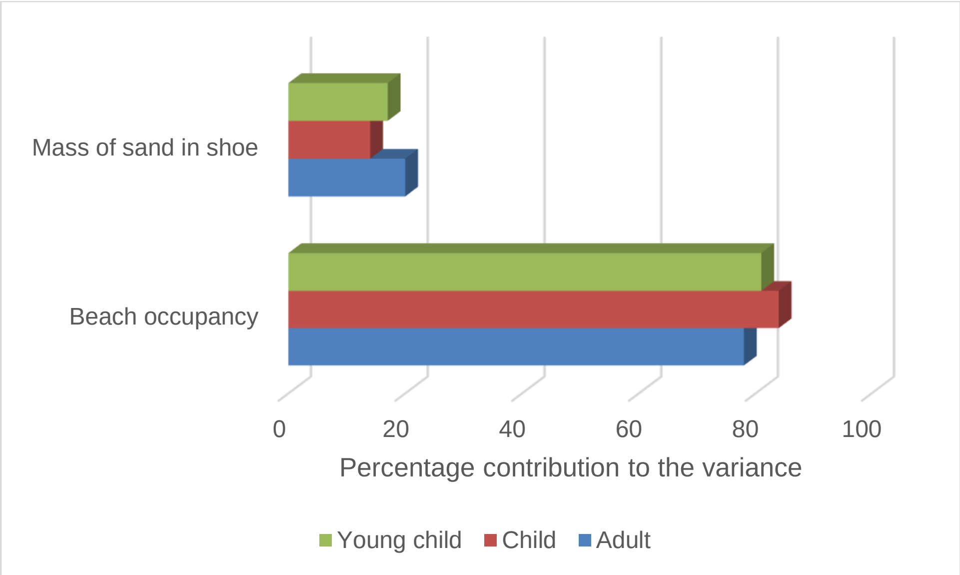

Figure G1 Contribution to the variance in the annual probability of encountering a particle when using a beach (only parameters contributing more than 1% are shown)

Figure G2 shows the contribution to the variance of the maximum lifetime risk of fatal cancer to members of each age group when using a beach. For adults and children, this risk is associated to angling activities on Sellafield and northern beaches respectively, while for young children this risk is associated with walking activities on northern beaches. The parameter providing the largest contribution to the variance in the lifetime risk was the time spent on a beach. For all age groups and beach activities, the exposure pathway contributing most to the lifetime risk was the inadvertent ingestion of alpha-rich particles; the inadvertent ingestion rate of sand and the ^{241}Am activity on particles were therefore also found to contribute significantly to the variance of the lifetime risk of fatal cancer to users of a beach.

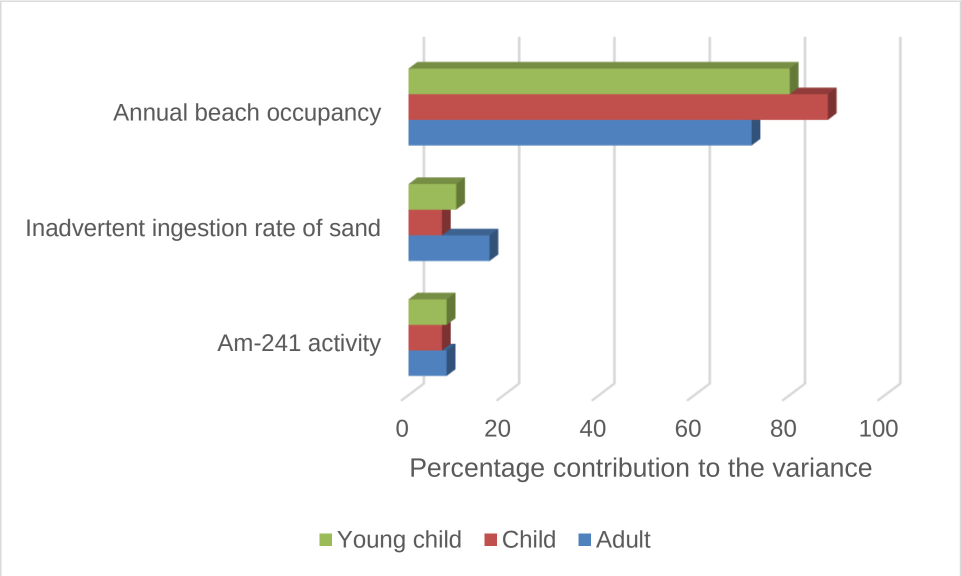

Figure G2 Contribution to the variance in the lifetime risk of developing fatal cancer when using a beach (only parameters contributing more than 1% are shown)

Figure G3 shows the contribution to the variance in the annual probability of inadvertently ingesting a particle when consuming seafood. The exposure pathway providing the largest contribution to the annual probability of ingesting a particle when consuming seafood was the ingestion of an alpha-rich particle when eating molluscs. The parameters that contributed the most to the variance were the annual mass of seafood consumed and the mass of sediment consumed by molluscs.

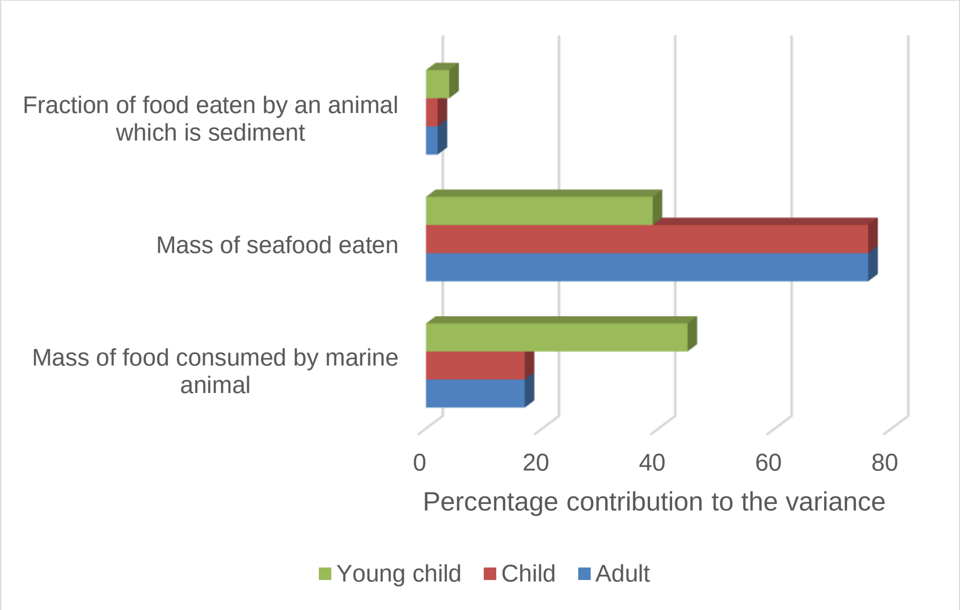

Figure G3 Contribution to the variance in the annual probability of ingesting a particle when consuming seafood (only parameters contributing more than 1% are shown)

Figure G4 shows the variance in the maximum lifetime risk of developing fatal cancer from the possible ingestion of a particle when consuming seafood. For all age groups, this risk was associated with the potential ingestion of alpha-rich particles when eating molluscs. The largest contributor to the variance in the risk when consuming seafood was the annual rate at which seafood was consumed. Other important contributors included parameters related to how much sediment the mollusc consumed and the distribution of ^{241}Am activity on a particle.

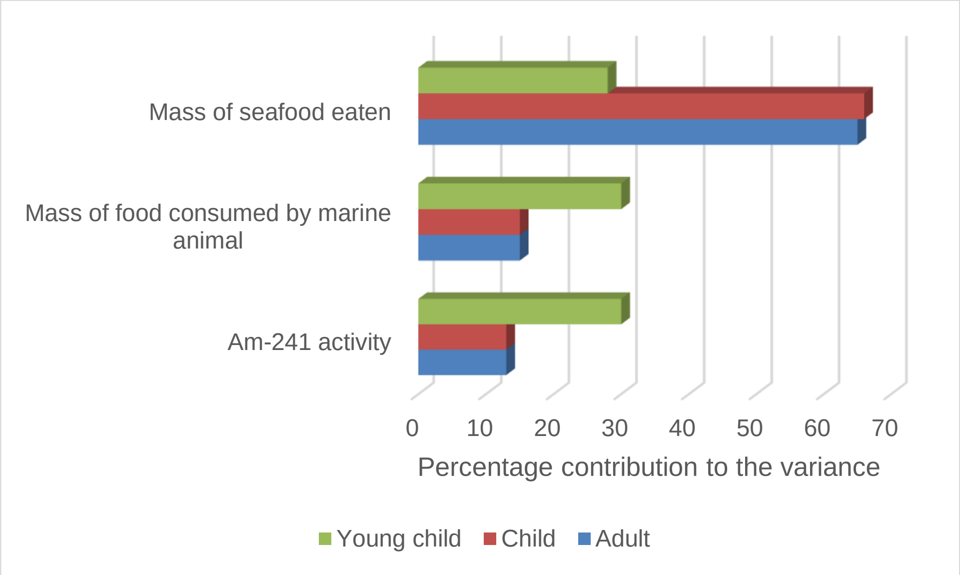

Figure G4 Contribution to the variance to the lifetime risk of developing fatal cancer when consuming seafood (only parameters contributing more than 1% are shown)

Appendix H Estimated lifetime risks to seafood consumers based on habits observed between 2004 and 2017

As discussed in Section 5.2 of the main text, the annual consumption rates of seafood were taken from habits surveys conducted between 2003 and 2017. Some of the annual seafood consumption rates of young children and children, recorded in 2003, were substantially higher than the rates reported for other years. The children belonged to a family who moved away from the area after 2003.

To investigate the effect of using seafood consumption rates recorded for 2003, an additional assessment of the lifetime risks to seafood consumers was undertaken using consumption rates recorded between 2004 and 2017.

Table H1 presents the quantities used to define the distributions in the annual seafood consumption rates derived using habits data collected between 2004 and 2017 inclusive. The omission of the 2003 data only affected the distribution of consumption rates of young children and children and resulted in a decrease in the maximum annual consumption rate of both molluscs and crustaceans by more than a factor of 10 and in the mode of the distribution of the consumption rate of molluscs for young children by more than a factor of thirty. The reason why the mode changed is that only seven observations were recorded on the habits of this age group over the entire period with the three highest observations being made in 2003; the ingestion rates recorded in 2003 were at least a factor of twenty higher than any rate recorded after that year.

Table H1 Quantities used to define triangular distributions for the annual consumption rate of marine foods, based on habit surveys carried out between 2003 and 2017 inclusive

		Consumption rate (g y^{-1})		
Food	**Age group**	**Minimum**	**Mode**	**Maximum**
Crustacean	Young children	0	1.0 10^3	1.0 10^3
	Children	0	7.1 10^3	1.0 10^4
	Adult	0	2.0 10^3	5.6 10^4
Molluscs	Young children	0	5.0 10^2	6.0 10^2
	Children	0	1.0 10^2	1.2 10^3
	Adult	0	5.0 10^2	5.3 10^4

Table H2 presents the estimated annual risks of developing fatal cancer to consumers of seafood due to the presence of radioactive objects in the environment near the Sellafield site based on habits data collected between 2004 and 2017 inclusive. Across all age groups, the highest 97.5th percentile of the annual risk was estimated to be of the order of 10^{-11}. This annual risk is of the same order of magnitude as the highest 97.5th percentile of the annual risks shown in Table 47 which were estimated using seafood ingestion rates collected between 2003 and 2017. In both sets of estimated annual risks, the highest risks were associated with the ingestion of an alpha-rich particle when eating molluscs. With the inclusion of the 2003 habits data, the group with the highest risks were young children while adults were the group with the highest risks if the habits data from 2003 were omitted. This change was due to the reduction in the annual consumption rate of seafood by children.

Table H2 Estimated lifetime risk of developing fatal cancer from the ingestion of radioactive particles in seafood caught near the Sellafield site over the course of a year, based on habit surveys carried out between 2003 and 2017 inclusive

	Lifetime risk of developing fatal cancer (y^{-1})				
	Alpha rich particles		Beta-rich particle		
Percentile	Molluscs	Crustaceans	Molluscs	Crustaceans	Total*
Young children					
2.5th	$5.5\ 10^{-14}$	$1.1\ 10^{-16}$	$7.5\ 10^{-17}$	$1.1\ 10^{-16}$	$1.7\ 10^{-13}$
50th	$3.9\ 10^{-13}$	$1.3\ 10^{-15}$	$6.3\ 10^{-16}$	$1.3\ 10^{-15}$	$6.7\ 10^{-13}$
97.5th	$1.6\ 10^{-12}$	$4.4\ 10^{-14}$	$2.2\ 10^{-14}$	$4.4\ 10^{-14}$	$2.4\ 10^{-12}$
Children					
2.5th	$1.6\ 10^{-14}$	$1.0\ 10^{-13}$	$4.1\ 10^{-17}$	$7.9\ 10^{-16}$	$2.2\ 10^{-13}$
50th	$1.8\ 10^{-13}$	$8.5\ 10^{-13}$	$5.4\ 10^{-16}$	$8.6\ 10^{-15}$	$1.1\ 10^{-12}$
97.5th	$1.0\ 10^{-12}$	$4.5\ 10^{-12}$	$1.7\ 10^{-14}$	$2.9\ 10^{-13}$	$5.4\ 10^{-12}$
Adults					
2.5th	$8.7\ 10^{-14}$	$3.7\ 10^{-14}$	$3.1\ 10^{-16}$	$4.3\ 10^{-16}$	$3.9\ 10^{-13}$
50th	$1.8\ 10^{-12}$	$6.2\ 10^{-13}$	$7.1\ 10^{-15}$	$8.1\ 10^{-15}$	$2.8\ 10^{-12}$
97.5th	$1.1\ 10^{-11}$	$4.4\ 10^{-12}$	$1.3\ 10^{-13}$	$1.5\ 10^{-13}$	$1.4\ 10^{-11}$

* The total estimated annual effective dose was estimated explicitly using the distributions in the annual probability of consuming a particle and in the risk of cancer assuming a particle was ingested. The total annual risk of fatal cancer presented in this table does therefore not equal the sum of the annual risk following the consumption of different marine animals or of the ingestion of different particle classes

Appendix I Detailed estimates of the risks to health to beach users

This appendix provides detailed estimated annual risks of developing fatal cancer to beach users due to the presence of radioactive objects. For each exposure pathway, the 2.5^{th}, 50^{th} and 97.5^{th} percentiles of the annual risk of developing fatal cancer estimated for people using beaches to the north of Sellafield (represented by beaches at St Bees and Braystones), the beach at Sellafield, and beaches to the south of Sellafield (represented by beaches at Seascale and Drigg) are presented. The risks to young children and children using the Sellafield beach were not included in the assessment described in the main part of this report since there are no data reported for these groups in the habits surveys, but an assessment of potential risks to hypothetical groups of children using the Sellafield beach is provided in Appendix J of this report.

I1 Risks to health from inhaling a particle when using a beach

The estimated risks to beach users from inhaling an alpha- or beta-rich particle are shown in Table I1 and Table I2 respectively. The highest annual 97.5^{th} percentile of the lifetime risk from the inhalation of a radioactive particle is of the order of 10^{-12} and is associated with adults using the beach at Sellafield for either angling or walking activities. The risk to young children or children was estimated to be about an order of magnitude less than that to an adult. The risks associated with the presence of beta-rich particles was estimated to be at least an order of magnitude less than the risks associated with the presence of alpha-rich particles.

Table I1 Estimated lifetime risk of developing fatal cancer from the inhalation of an alpha-rich particle when using a beach for a year

	Lifetime risk of developing fatal cancer (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5^{th}	0.0	$1.7\ 10^{-16}$	$1.1\ 10^{-16}$	0.0	0.0	0.0	0.0	$3.4\ 10^{-17}$	$1.9\ 10^{-17}$
50^{th}	0.0	$3.0\ 10^{-15}$	$2.6\ 10^{-15}$	0.0	0.0	0.0	0.0	$6.1\ 10^{-16}$	$3.2\ 10^{-16}$
97.5^{th}	0.0	$6.4\ 10^{-14}$	$8.6\ 10^{-14}$	0.0	0.0	0.0	0.0	$1.5\ 10^{-14}$	$8.0\ 10^{-15}$
Children									
2.5^{th}	$2.6\ 10^{-16}$	$4.7\ 10^{-16}$	$3.9\ 10^{-16}$	0.0	0.0	0.0	$2.6\ 10^{-16}$	$5.4\ 10^{-17}$	$1.7\ 10^{-16}$
50^{th}	$8.2\ 10^{-15}$	$7.7\ 10^{-15}$	$4.2\ 10^{-15}$	0.0	0.0	0.0	$1.6\ 10^{-15}$	$1.1\ 10^{-15}$	$2.0\ 10^{-15}$
97.5^{th}	$2.9\ 10^{-13}$	$1.6\ 10^{-13}$	$6.6\ 10^{-14}$	0.0	0.0	0.0	$1.7\ 10^{-14}$	$3.3\ 10^{-14}$	$3.1\ 10^{-14}$
Adults									
2.5^{th}	$5.0\ 10^{-15}$	$8.8\ 10^{-16}$	$9.8\ 10^{-16}$	$6.0\ 10^{-15}$	0.0	$4.2\ 10^{-15}$	$5.0\ 10^{-16}$	$1.2\ 10^{-16}$	$1.9\ 10^{-16}$
50^{th}	$4.8\ 10^{-14}$	$1.1\ 10^{-14}$	$2.0\ 10^{-14}$	$6.5\ 10^{-14}$	0.0	$4.0\ 10^{-14}$	$7.6\ 10^{-15}$	$1.7\ 10^{-15}$	$4.4\ 10^{-15}$
97.5^{th}	$4.7\ 10^{-13}$	$1.4\ 10^{-13}$	$3.8\ 10^{-13}$	$7.3\ 10^{-13}$	0.0	$4.1\ 10^{-13}$	$1.1\ 10^{-13}$	$2.4\ 10^{-14}$	$1.1\ 10^{-13}$

Table I2 Estimated lifetime risk of developing fatal cancer from the inhalation of a beta-rich particle when using a beach for a year

	Lifetime risk of developing fatal cancer (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5^{th}	0.0	$1.3\ 10^{-18}$	$8.0\ 10^{-19}$	0.0	0.0	0.0	0.0	$2.3\ 10^{-19}$	$1.3\ 10^{-19}$
50^{th}	0.0	$2.3\ 10^{-17}$	$2.0\ 10^{-17}$	0.0	0.0	0.0	0.0	$4.2\ 10^{-18}$	$2.2\ 10^{-18}$
97.5^{th}	0.0	$4.9\ 10^{-16}$	$6.5\ 10^{-16}$	0.0	0.0	0.0	0.0	$1.0\ 10^{-16}$	$5.4\ 10^{-17}$
Children									
2.5^{th}	$2.0\ 10^{-18}$	$3.5\ 10^{-18}$	$2.9\ 10^{-18}$	0.0	0.0	0.0	$1.8\ 10^{-18}$	$3.7\ 10^{-19}$	$1.2\ 10^{-18}$
50^{th}	$6.2\ 10^{-17}$	$5.8\ 10^{-17}$	$3.2\ 10^{-17}$	0.0	0.0	0.0	$1.1\ 10^{-17}$	$7.4\ 10^{-18}$	$1.4\ 10^{-17}$
97.5^{th}	$2.2\ 10^{-15}$	$1.2\ 10^{-15}$	$5.0\ 10^{-16}$	0.0	0.0	0.0	$1.2\ 10^{-16}$	$2.2\ 10^{-16}$	$2.1\ 10^{-16}$
Adults									
2.5^{th}	$3.7\ 10^{-17}$	$6.7\ 10^{-18}$	$7.4\ 10^{-18}$	$1.5\ 10^{-16}$	0.0	$1.0\ 10^{-16}$	$3.4\ 10^{-18}$	$8.3\ 10^{-19}$	$1.3\ 10^{-18}$
50^{th}	$3.6\ 10^{-16}$	$8.1\ 10^{-17}$	$1.5\ 10^{-16}$	$1.6\ 10^{-15}$	0.0	$9.8\ 10^{-16}$	$5.1\ 10^{-17}$	$1.2\ 10^{-17}$	$3.0\ 10^{-17}$
97.5^{th}	$3.5\ 10^{-15}$	$1.0\ 10^{-15}$	$2.9\ 10^{-15}$	$1.8\ 10^{-14}$	0.0	$1.0\ 10^{-14}$	$7.5\ 10^{-16}$	$1.6\ 10^{-16}$	$7.3\ 10^{-16}$

I2 Risks to health from ingesting a particle when using a beach

Table I3 and Table I4 present the estimated annual risk of developing fatal cancer from the inadvertent ingestion of an alpha- or beta-rich particle when using a beach. The highest 97.5^{th} percentile of the lifetime risk to health from the inadvertent ingestion of a particle was estimated to be of the order of 10^{-11} per year. The risk from ingesting an alpha-rich particle is at least an order of magnitude higher than the risk from the ingestion of a beta-rich particle. The highest risks from inadvertently ingesting a particle are associated with young children using beaches to the north of Sellafield for leisure of walking activities.

Table I3 Estimated lifetime risk of developing fatal cancer from the inadvertent ingestion of an alpha-rich particle when using a beach for a year

	Lifetime risk of developing fatal cancer (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$9.3\ 10^{-14}$	$4.8\ 10^{-14}$	0.0	0.0	0.0	0.0	$1.7\ 10^{-14}$	$8.2\ 10^{-15}$
50th	0.0	$1.0\ 10^{-12}$	$8.7\ 10^{-13}$	0.0	0.0	0.0	0.0	$2.2\ 10^{-13}$	$1.1\ 10^{-13}$
97.5th	0.0	$1.2\ 10^{-11}$	$1.7\ 10^{-11}$	0.0	0.0	0.0	0.0	$2.7\ 10^{-12}$	$1.4\ 10^{-12}$
Children									
2.5th	$3.8\ 10^{-14}$	$6.7\ 10^{-14}$	$7.0\ 10^{-14}$	0.0	0.0	0.0	$5.4\ 10^{-14}$	$8.0\ 10^{-15}$	$3.0\ 10^{-14}$
50th	$7.0\ 10^{-13}$	$7.0\ 10^{-13}$	$3.8\ 10^{-13}$	0.0	0.0	0.0	$1.4\ 10^{-13}$	$1.0\ 10^{-13}$	$1.8\ 10^{-13}$
97.5th	$1.3\ 10^{-11}$	$6.9\ 10^{-12}$	$2.1\ 10^{-12}$	0.0	0.0	0.0	$4.4\ 10^{-13}$	$1.3\ 10^{-12}$	$1.2\ 10^{-12}$
Adults									
2.5th	$2.3\ 10^{-15}$	$6.1\ 10^{-16}$	$6.9\ 10^{-16}$	$2.7\ 10^{-15}$	0.0	$2.9\ 10^{-15}$	$2.6\ 10^{-16}$	$8.2\ 10^{-17}$	$1.4\ 10^{-16}$
50th	$3.1\ 10^{-14}$	$9.5\ 10^{-15}$	$1.8\ 10^{-14}$	$4.2\ 10^{-14}$	0.0	$3.5\ 10^{-14}$	$4.9\ 10^{-15}$	$1.6\ 10^{-15}$	$4.1\ 10^{-15}$
97.5th	$4.0\ 10^{-13}$	$1.4\ 10^{-13}$	$4.2\ 10^{-13}$	$6.4\ 10^{-13}$	0.0	$5.0\ 10^{-13}$	$9.0\ 10^{-14}$	$2.9\ 10^{-14}$	$1.1\ 10^{-13}$

Table I4 Estimated lifetime risk of developing fatal cancer from the possible inadvertent ingestion of a beta-rich particle when using a beach for a year

	Lifetime risk of developing fatal cancer (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$1.2\ 10^{-16}$	$6.4\ 10^{-17}$	0.0	0.0	0.0	0.0	$2.1\ 10^{-17}$	$1.0\ 10^{-17}$
50th	0.0	$1.8\ 10^{-15}$	$1.7\ 10^{-15}$	0.0	0.0	0.0	0.0	$3.5\ 10^{-16}$	$1.8\ 10^{-16}$
97.5th	0.0	$9.5\ 10^{-14}$	$1.1\ 10^{-13}$	0.0	0.0	0.0	0.0	$1.9\ 10^{-14}$	$9.5\ 10^{-15}$
Children									
2.5th	$9.8\ 10^{-17}$	$1.8\ 10^{-16}$	$1.5\ 10^{-16}$	0.0	0.0	0.0	$1.0\ 10^{-16}$	$1.8\ 10^{-17}$	$6.4\ 10^{-17}$
50th	$2.4\ 10^{-15}$	$2.2\ 10^{-15}$	$1.2\ 10^{-15}$	0.0	0.0	0.0	$3.6\ 10^{-16}$	$2.9\ 10^{-16}$	$5.3\ 10^{-16}$
97.5th	$1.3\ 10^{-13}$	$1.0\ 10^{-13}$	$3.9\ 10^{-14}$	0.0	0.0	0.0	$1.1\ 10^{-14}$	$1.4\ 10^{-14}$	$1.6\ 10^{-14}$
Adults									
2.5th	$9.0\ 10^{-18}$	$2.2\ 10^{-18}$	$2.4\ 10^{-18}$	$3.1\ 10^{-17}$	0.0	$3.4\ 10^{-17}$	$8.7\ 10^{-19}$	$2.7\ 10^{-19}$	$4.4\ 10^{-19}$
50th	$1.3\ 10^{-16}$	$4.1\ 10^{-17}$	$7.5\ 10^{-17}$	$5.8\ 10^{-16}$	0.0	$4.9\ 10^{-16}$	$1.8\ 10^{-17}$	$5.8\ 10^{-18}$	$1.5\ 10^{-17}$
97.5th	$3.5\ 10^{-15}$	$1.3\ 10^{-15}$	$3.3\ 10^{-15}$	$1.6\ 10^{-14}$	0.0	$1.5\ 10^{-14}$	$6.9\ 10^{-16}$	$2.0\ 10^{-16}$	$7.7\ 10^{-16}$

I3 Total risks to health associated with particles on the skin

Table I5 and Table I6 present the estimated risks of developing fatal cancer of the skin from the presence of an alpha- or beta-rich particle being in contact with the skin for an hour when using a beach for a year. To estimate these risks, the annual probability that a particle comes into contact with the skin was taken to be equal to the sum of the annual probabilities of a particle coming into direct contact with the skin and being trapped in clothing, in a shoe or under a nail. These risks assume a particle remains in contact with the skin for an hour. It is noted that this approach is cautious as a particle is trapped in clothing or in shoes is not likely to be in direct contact with the skin for any significant length of time.

The highest 97.5th percentile of the annual risk of developing fatal skin cancer from the use of a beach for a year was estimated to be of the order of 10^{-15} per year. As the risk factor for incidence of skin cancer is estimated to be a factor of 500 times greater than that of skin cancer fatality, the highest 97.5th percentile of the annual risk of skin cancer incidence was estimated to be of the order of 10^{-12}. The highest risks are associated with exposure of the skin from beta-rich particles trapped in the shoes of an adult undertaking angling activities on Sellafield beach.

Table I5 Estimated lifetime risk of fatal cancer from an alpha-rich particle in contact with the skin when using a beach for a year*

	Lifetime risk of developing fatal cancer (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$2.0\ 10^{-18}$	$9.2\ 10^{-19}$	0.0	0.0	0.0	0.0	$3.7\ 10^{-19}$	$1.6\ 10^{-19}$
50th	0.0	$2.1\ 10^{-17}$	$1.7\ 10^{-17}$	0.0	0.0	0.0	0.0	$4.6\ 10^{-18}$	$2.0\ 10^{-18}$
97.5th	0.0	$2.3\ 10^{-16}$	$2.8\ 10^{-16}$	0.0	0.0	0.0	0.0	$5.6\ 10^{-17}$	$2.6\ 10^{-17}$
Children									
2.5th	$1.4\ 10^{-18}$	$2.9\ 10^{-18}$	$2.5\ 10^{-18}$	0.0	0.0	0.0	$1.7\ 10^{-18}$	$3.4\ 10^{-19}$	$1.0\ 10^{-18}$
50th	$2.8\ 10^{-17}$	$3.4\ 10^{-17}$	$1.6\ 10^{-17}$	0.0	0.0	0.0	$5.7\ 10^{-18}$	$4.9\ 10^{-18}$	$7.8\ 10^{-18}$
97.5th	$5.4\ 10^{-16}$	$3.8\ 10^{-16}$	$1.0\ 10^{-16}$	0.0	0.0	0.0	$2.0\ 10^{-17}$	$7.3\ 10^{-17}$	$5.7\ 10^{-17}$
Adults									
2.5th	$1.1\ 10^{-18}$	$3.8\ 10^{-19}$	$3.0\ 10^{-19}$	$1.3\ 10^{-18}$	0.0	$1.3\ 10^{-18}$	$1.3\ 10^{-19}$	$5.3\ 10^{-20}$	$6.6\ 10^{-20}$
50th	$1.3\ 10^{-17}$	$5.5\ 10^{-18}$	$7.3\ 10^{-18}$	$1.8\ 10^{-17}$	0.0	$1.5\ 10^{-17}$	$2.1\ 10^{-18}$	$8.8\ 10^{-19}$	$1.6\ 10^{-18}$
97.5th	$1.6\ 10^{-16}$	$8.0\ 10^{-17}$	$1.7\ 10^{-16}$	$2.3\ 10^{-16}$	0.0	$1.9\ 10^{-16}$	$3.5\ 10^{-17}$	$1.6\ 10^{-17}$	$4.2\ 10^{-17}$

* Assumes a particle remains in contact with the skin for an hour

Table I6 Estimated lifetime risk of fatal cancer from a beta-rich particle in contact with the skin when using a beach for a year*

	Lifetime risk of developing fatal cancer (y^{-1})								
	Northern beaches			Sellafield beach			Southern beaches		
Percentile	Angling	Leisure	Walking	Angling	Leisure	Walking	Angling	Leisure	Walking
Young children									
2.5th	0.0	$2.4\ 10^{-18}$	$1.1\ 10^{-18}$	0.0	0.0	0.0	0.0	$4.0\ 10^{-19}$	$1.7\ 10^{-19}$
50th	0.0	$3.4\ 10^{-17}$	$2.8\ 10^{-17}$	0.0	0.0	0.0	0.0	$6.6\ 10^{-18}$	$3.0\ 10^{-18}$
97.5th	0.0	$1.5\ 10^{-15}$	$1.5\ 10^{-15}$	0.0	0.0	0.0	0.0	$3.1\ 10^{-16}$	$1.3\ 10^{-16}$
Children									
2.5th	$1.7\ 10^{-18}$	$3.8\ 10^{-18}$	$2.7\ 10^{-18}$	0.0	0.0	0.0	$1.6\ 10^{-18}$	$3.9\ 10^{-19}$	$1.0\ 10^{-18}$
50th	$4.7\ 10^{-17}$	$5.3\ 10^{-17}$	$2.4\ 10^{-17}$	0.0	0.0	0.0	$7.5\ 10^{-18}$	$7.2\ 10^{-18}$	$1.1\ 10^{-17}$
97.5th	$2.5\ 10^{-15}$	$2.6\ 10^{-15}$	$8.5\ 10^{-16}$	0.0	0.0	0.0	$2.2\ 10^{-16}$	$3.6\ 10^{-16}$	$3.7\ 10^{-16}$
Adults									
2.5th	$1.4\ 10^{-18}$	$4.6\ 10^{-19}$	$4.0\ 10^{-19}$	$5.4\ 10^{-18}$	0.0	$5.3\ 10^{-18}$	$1.5\ 10^{-19}$	$5.7\ 10^{-20}$	$7.3\ 10^{-20}$
50th	$2.1\ 10^{-17}$	$9.3\ 10^{-18}$	$1.2\ 10^{-17}$	$9.8\ 10^{-17}$	0.0	$7.7\ 10^{-17}$	$3.1\ 10^{-18}$	$1.3\ 10^{-18}$	$2.5\ 10^{-18}$
97.5th	$8.9\ 10^{-16}$	$4.3\ 10^{-16}$	$7.7\ 10^{-16}$	$4.0\ 10^{-15}$	0.0	$3.6\ 10^{-15}$	$1.7\ 10^{-16}$	$7.4\ 10^{-17}$	$1.8\ 10^{-16}$

* Assumes a particle remains in contact with the skin for an hour

Appendix J Risks to health to young children and children on Sellafield beach

No children or young children were recorded in the habits surveys to make use of the beach at Sellafield and so only the risks to adults using that beach were assessed in this study. However, as the habits recorded in the surveys may not entirely represent those making infrequent use of Cumbrian beaches, for completeness a scoping assessment of the risks to a hypothetical group of children and young children who made use of the beach at Sellafield was also carried out and is summarised in this Appendix.

The only beach activity considered in the assessment was walking. The information in the habit surveys indicates that adults do not use the Sellafield beach for leisure activities, and the beach itself is not considered to be amenable to such activities, and therefore it was assumed that neither young children nor children would take part in leisure activities. Angling was also excluded since there are no data to indicate that children of any age take part in angling activities on any of the beaches immediately adjacent to the Sellafield site.

As beaches to the north of Sellafield offer the best route to reach the beach at Sellafield it was considered that the occupancy rates of children and young children walking on the Northern beaches (Braystones and St. Bees) would best represent the habits of members of these age groups who may use the Sellafield beach.

Table J1 presents the estimated annual probability that a young child or child encounters a radioactive particle while using the beach at Sellafield. The 97.5th percentile of the annual probability of encountering either an alpha- or beta-rich particle, summed over all exposure pathways, was estimated to be of the order of 10^{-4} and 10^{-6} respectively. The most likely route of encountering a particle by a young child or child was through sand getting into their shoes.

Table J2 presents the estimated annual risk of developing fatal cancer to a young child or child who used the beach at Sellafield. The highest 97.5th percentile of the annual risk to members of these age groups who used the beach at Sellafield was estimated to be of the order of 10^{-11}. The pathway contributing most to the annual risk was estimated to be the inadvertent ingestion of alpha-rich particles. The annual risk to young children and children who potentially used the beach at Sellafield from exposure to alpha-rich particles was estimated to be about an order of magnitude greater than that from exposure to beta-rich particles.

Table J1 Annual probability that a hypothetical group of young children or children would encounter a particle on Sellafield beach

		Annual probability of encountering a particle (y^{-1})			
		Young children		Children	
Exposure pathway	Percentile	Alpha-rich	Beta-rich	Alpha-rich	Beta-rich
Inhalation	2.5th	$4.7\ 10^{-13}$	$1.2\ 10^{-14}$	$1.8\ 10^{-12}$	$4.5\ 10^{-14}$
	50th	$1.2\ 10^{-11}$	$2.9\ 10^{-13}$	$1.8\ 10^{-11}$	$4.5\ 10^{-13}$
	97.5th	$3.6\ 10^{-10}$	$9.0\ 10^{-12}$	$2.7\ 10^{-10}$	$6.8\ 10^{-12}$
Inadvertent ingestion	2.5th	$6.6\ 10^{-10}$	$1.6\ 10^{-11}$	$2.3\ 10^{-9}$	$5.7\ 10^{-11}$
	50th	$1.0\ 10^{-8}$	$2.6\ 10^{-10}$	$9.8\ 10^{-9}$	$2.4\ 10^{-10}$
	97.5th	$1.7\ 10^{-7}$	$4.1\ 10^{-9}$	$4.1\ 10^{-8}$	$1.0\ 10^{-9}$
Trapped in clothing	2.5th	$6.1\ 10^{-9}$	$1.5\ 10^{-10}$	$2.9\ 10^{-8}$	$7.1\ 10^{-10}$
	50th	$1.4\ 10^{-7}$	$3.4\ 10^{-9}$	$2.7\ 10^{-7}$	$6.7\ 10^{-9}$
	97.5th	$2.6\ 10^{-6}$	$6.4\ 10^{-8}$	$1.6\ 10^{-6}$	$3.9\ 10^{-8}$
Trapped in shoes	2.5th	$2.1\ 10^{-7}$	$5.2\ 10^{-9}$	$5.0\ 10^{-7}$	$1.2\ 10^{-8}$
	50th	$4.0\ 10^{-6}$	$9.9\ 10^{-8}$	$3.6\ 10^{-6}$	$9.0\ 10^{-8}$
	97.5th	$6.5\ 10^{-5}$	$1.6\ 10^{-6}$	$1.9\ 10^{-5}$	$4.8\ 10^{-7}$
Trapped under a nail	2.5th	$1.9\ 10^{-9}$	$4.7\ 10^{-11}$	$8.6\ 10^{-9}$	$2.1\ 10^{-10}$
	50th	$3.3\ 10^{-8}$	$8.2\ 10^{-10}$	$5.6\ 10^{-8}$	$1.4\ 10^{-9}$
	97.5th	$5.5\ 10^{-7}$	$1.4\ 10^{-8}$	$3.0\ 10^{-7}$	$7.5\ 10^{-9}$
Skin contact	2.5th	$3.2\ 10^{-8}$	$7.8\ 10^{-10}$	$1.6\ 10^{-7}$	$4.1\ 10^{-9}$
	50th	$8.9\ 10^{-7}$	$2.2\ 10^{-8}$	$1.6\ 10^{-6}$	$4.1\ 10^{-8}$
	97.5th	$1.8\ 10^{-5}$	$4.5\ 10^{-7}$	$1.2\ 10^{-5}$	$3.0\ 10^{-7}$
All pathways	2.5th	$3.3\ 10^{-7}$	$8.1\ 10^{-9}$	$1.2\ 10^{-6}$	$3.0\ 10^{-8}$
	50th	$5.5\ 10^{-6}$	$1.4\ 10^{-7}$	$6.1\ 10^{-6}$	$1.5\ 10^{-7}$
	97.5th	$8.4\ 10^{-5}$	$2.1\ 10^{-6}$	$3.1\ 10^{-5}$	$7.6\ 10^{-7}$

Table J2 Lifetime risk of developing fatal cancer to a hypothetical group of young children and children using the Sellafield beach for a year

		Lifetime risk of developing fatal cancer (y^{-1})			
		Young children		Children	
Exposure pathway	Percentile	Alpha-rich	Beta-rich	Alpha-rich	Beta-rich
Inhalation	2.5th	$2.1\ 10^{-16}$	$5.3\ 10^{-18}$	$8.2\ 10^{-16}$	$2.0\ 10^{-17}$
	50th	$5.2\ 10^{-15}$	$1.3\ 10^{-16}$	$8.2\ 10^{-15}$	$2.0\ 10^{-16}$
	97.5th	$1.6\ 10^{-13}$	$4.1\ 10^{-15}$	$1.2\ 10^{-13}$	$3.1\ 10^{-15}$
Inadvertent ingestion	2.5th	$9.9\ 10^{-14}$	$4.4\ 10^{-16}$	$1.4\ 10^{-13}$	$1.1\ 10^{-15}$
	50th	$1.8\ 10^{-12}$	$1.1\ 10^{-14}$	$7.3\ 10^{-13}$	$7.5\ 10^{-15}$
	97.5th	$3.2\ 10^{-11}$	$7.2\ 10^{-13}$	$4.2\ 10^{-12}$	$2.6\ 10^{-13}$
Skin exposure	2.5th	$1.8\ 10^{-18}$	$7.5\ 10^{-18}$	$4.9\ 10^{-18}$	$1.9\ 10^{-17}$
	50th	$3.3\ 10^{-17}$	$1.7\ 10^{-16}$	$3.0\ 10^{-17}$	$1.5\ 10^{-16}$
	97.5th	$6.0\ 10^{-16}$	$9.7\ 10^{-15}$	$1.9\ 10^{-16}$	$5.3\ 10^{-15}$
All pathways	2.5th	$9.9\ 10^{-14}$	$4.5\ 10^{-16}$	$1.4\ 10^{-13}$	$1.1\ 10^{-15}$
	50th	$1.8\ 10^{-12}$	$1.1\ 10^{-14}$	$7.4\ 10^{-13}$	$7.7\ 10^{-15}$
	97.5th	$3.2\ 10^{-11}$	$7.3\ 10^{-13}$	$4.4\ 10^{-12}$	$2.6\ 10^{-13}$