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Health Risk to Seafood Consumers from Radioactive Particles in the Marine Environment near Sellafield

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Health Risk to Seafood Consumers from Radioactive Particles in the Marine Environment near Sellafield

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Abstract

Since 2006 an intensive programme of monitoring for radioactive objects has been carried out on beaches in the vicinity of the Sellafield site in West Cumbria to help assess any potential impacts from on-site activities on the environment and people. These objects comprise particles with sizes smaller than, or similar to, grains of sand (less than 2 mm) and contaminated pebbles and stones. The health risk to people using the beaches along the Cumbrian coast from contaminated objects on those beaches was previously assessed by the Health Protection Agency, a predecessor body to Public Health England (PHE). As part of that assessment, the health risk from contaminated objects that may be ingested through the consumption of locally caught seafood was considered using the results of a conservative scoping study carried out in consultation with the Food Standards Agency.

The Environment Agency (EA) has a programme of work to ensure that the overall monitoring programme, both on the beaches and off-shore, addresses the remaining areas of uncertainty in a prioritised way as well as providing reassurance that the risks remain low. As part of that programme of work, the EA commissioned PHE to provide a best estimate of the health risk to people from ingesting contaminated objects through locally caught seafood and the uncertainties associated with these estimates.

This report describes the approach used in the assessment, the assessed health risk from consumption of local seafood and a discussion of the sensitivity of the health risk to the assumptions made in the assessment. The health risk to commercial fishermen has also been assessed. The overall health risk to both local seafood consumers and commercial fishermen is very low. The highest risks of radiation-induced fatal cancer (97.5th percentile of the distribution) are of the order of 10,000 times smaller than the level of risk that the Health and Safety Executive considers to be the upper limit for an acceptable level of risk. The main uncertainties associated with the estimation of the health risk have also been identified.

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Contents

1 Introduction

Since 2006 an intensive programme of monitoring for radioactive objects has been carried out on beaches in the vicinity of the Sellafield nuclear fuel reprocessing and decommissioning site in West Cumbria to help assess any potential impacts from on-site activities on the environment and people. These objects comprise particles with sizes smaller than, or similar to, grains of sand (less than 2 mm) and contaminated pebbles and stones. The health risk* to people using the beaches or consuming seafood along the Cumbrian coast from the contaminated objects has previously been assessed by the Health Protection Agency, a predecessor body to Public Health England (PHE) (Brown and Etherington, 2011; Etherington et al, 2012). As part of that assessment, the health risk from contaminated objects that may be ingested through the consumption of locally caught seafood was considered using the results of a conservative scoping study carried out in consultation with the Food Standards Agency (Oatway et al, 2011).

The Environment Agency (EA) has a programme of work to ensure that the overall monitoring programme, both on the beaches and off-shore, addresses the remaining areas of uncertainty in a prioritised way as well as providing reassurance that the risks remain low. As part of that programme of work, the EA commissioned PHE to provide a best estimate of the health risk to people from ingesting contaminated objects through locally caught seafood and the uncertainties associated with these estimates.

In addition to assessing the health risk from ingesting radioactive objects through the consumption of local seafood, a scoping assessment has been undertaken to investigate the health risk posed to commercial fishermen from coming into contact with radioactive objects while at work. This has been included on the basis that it is reasonable to assume that commercial fishermen may also consume above-average amounts of local seafood. It is therefore important to investigate the contribution made to their overall health risk from radioactive objects both from handling fishing gear and from consuming seafood to identify if there is a need to improve knowledge of the exposure pathways for this group of people.

This report describes the approach used in the assessment, the assessed health risk and a discussion of the sensitivity of the estimated health risk to the assumptions made in the assessment.

2 Overview of the Assessment Methodology

This section outlines the approach taken to estimate the health risk to seafood consumers† and the main assumptions made. A detailed description of the calculations and parameter values used is given in Appendix A.

The overall health risk to a seafood consumer must take into account the probability that an object may be consumed in seafood and the risk of fatal cancer in the event that the person does consume such an object as well as the activity content of the object. The risk that a

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[*] Health risk is defined as the probability that a person would contract a fatal cancer at some point during their lifetime as a result of consuming a particle when using a beach or when eating seafood over a period of 1 year.

[†] Consumers of seafood caught locally along the Cumbrian coast in the vicinity of the Sellafield site.

radiation-induced fatal cancer from ingestion of seafood could occur during the lifetime of a seafood consumer from 1 year's seafood consumption is calculated by multiplying the probability that a contaminated object is consumed from 1 year's consumption by the risk of dying from radiation-induced cancer over a lifetime if a particle is consumed.

The health risk has been estimated using a statistical approach in order to reflect the large variation in parameter values used to describe the intake of a contaminated object through the consumption of seafood, including the consumption habits of individuals and the level of radioactivity present on different objects. The probabilities of developing fatal cancer from the consumption of an object have been assessed using ranges in the parameter values. The probability distribution of the health risk from ingesting an object in seafood is described in terms of its 2.5th percentile, 50th percentile and 97.5th percentile; 2.5% of seafood consumers have a probability of developing fatal cancer less than the 2.5th percentile, 2.5% of consumers have a probability of developing fatal cancer greater than the 97.5th percentile, and 95% of seafood consumers have a probability of developing fatal cancer which lies between these two percentiles. Equal numbers of seafood consumers have a probability of developing fatal cancer above and below the 50th percentile (the median of the distribution).

The approach adopted has made best use of the available information and the assessment is considered to be adequate for the purpose of determining whether risks to seafood consumers could be significant. However, although care has been taken to select suitable values to define distributions on the values for parameters describing the transfer of particles from the sediment to people from marine animals, there is a paucity of data on these processes. This has meant that the range in many parameter values has been partially based on judgement rather than on extensive experimental research. A sensitivity analysis has therefore been performed to investigate the implications of selecting alternative values for the important parameters used to determine the health risk. Appendix B provides the details and results of this analysis.

2.1 Assessing the health risk to a seafood consumer

The methodology used for the scoping assessment undertaken as part of the earlier study on the health risk to beach users (Oatway et al, 2011) was based on previous work undertaken for assessing the risk to seafood consumers from radioactive fuel fragments in the vicinity of the Dounreay nuclear site (Wilkins et al, 1998). As part of the current study, the opportunity has been taken to undertake a review of the published literature to establish if there is more recent information which could influence the choice of parameter values for describing the transfer of contaminated particles from the marine environment to seafood. Based on this review it was decided that, in order to minimise the assumptions made in interpreting the data into the required parameter values, a slightly modified approach to calculating the transfer of particles from the marine environment to seafood would be used. This new approach estimates the mass of sediment in seafood by combining the mass of material an animal ingests with the fraction of that mass which is likely to be sediment. This is then combined with the number of particles in unit mass of sediment and the amount of sediment a person ingests through the consumption of seafood. Implicit in the methodology is the assumption that only radioactive particles that are in the gut of an animal at the time of consumption are consumed by people; particles attached to the outside of the animal – for example, the shell – are assumed to be removed by washing prior to consumption. The probability of a person consuming a particle therefore depends on how much sediment is in the animal at the time of consumption and how much of the gut content is consumed. The consumption of gut content could occur through the deliberate consumption of parts of the digestive system or through contamination of edible parts of the animal with gut contents during food preparation. The methodology used in this assessment and the range of values used to define each parameter are given in Appendix A.

The most recent habits survey undertaken in the Sellafield area (Clyne et al, 2014) identified the consumption of many different, locally caught species of fish, molluscs and crustaceans. Any mature fish that are caught commercially and consumed will be gutted, usually on a boat off-shore, and so the likelihood that a local person might consume a radioactive particle is extremely small. The consumption of fish has therefore not been considered further. The health risk to individuals who are anglers on a recreational basis was included in the assessment of the health risk to beach users (Brown and Etherington, 2011).

2.1.1 Characteristics of radioactive particles

Sellafield Ltd has undertaken large area beach monitoring around the Sellafield site since 2006 (Sellafield Ltd, 2013). Since 2011, a limited programme of sub-sea monitoring using grab sampling has also been trialled and implemented. An important aim of this ongoing work is to constrain the estimate of the population density of contaminated objects in the sub-sea environment. However, although the grab sampling campaigns have provided valuable data on activity concentrations in sediment off-shore, and have resulted in the retrieval of one particle, there is currently not enough information available to determine the population of contaminated objects on the seabed. The assumption has therefore been made for this assessment that the numbers of objects in the inter-tidal zone and further off-shore are equivalent to that determined for the adjacent beaches.

The Sellafield habits surveys (eg Clyne et al, 2014) have identified that small quantities of winkles are collected from Coulderton and Nethertown, limpets from Nethertown, and mussels from Coulderton and Saltcoats. Only one person has been identified who consumed large quantities of molluscs, which were winkles obtained from Nethertown. Several local individuals have collected winkles commercially in the area, mainly from the boulder scars between Parton and Drigg (Clyne et al, 2014). The monitored beach nearest to Nethertown and Coulderton, where most of the collection of molluscs has occurred, is Braystones. The number of objects estimated to be present on Braystones beach has therefore been used to estimate the health risk from consuming molluscs. For crustaceans (including nephrops*)*, the health risk was estimated based on the number of objects calculated to be present on Sellafield beach. It is recognised that crustaceans may travel and feed along the whole coastline; the use of the data for Sellafield beach, where the highest number of contaminated objects has been found, therefore provides an upper estimate of the numbers of objects that crustaceans could access during feeding. Figure 1 shows the proximity of Braystones and Sellafield beaches to the Sellafield site.

Molluscs and crustaceans appear to primarily ingest particles up to a few tens of micrometres* in size (Defossez and Hawkins, 1997), although particles of a few hundred micrometres are occasionally measured in their guts (Cefas, 2008). Sellafield Ltd has classified any radioactive object recovered that is smaller than 2 mm as a particle; larger objects are classified as

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* One micrometre equals one-thousandth of a millimetre.

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Figure 1: Beach areas in the vicinity of the Sellafield site

stones. As insufficient information was available to allow the particle population to be segregated further based on physical size, it was assumed that all objects classified as particles were available for consumption by marine animals. Within the overriding assumption that the population of particles in off-shore sediment is the same as that on the beaches, this assumption will overestimate the number of particles that could be consumed by molluscs and crustaceans and, consequently, the probability that consumption of an object by a person could occur.

For the purposes of evaluating doses and risks to health, radioactive objects on beaches in the vicinity of the Sellafield site have been classified as either ‘alpha-rich’ or ‘beta-rich’, which is consistent with the way in which the monitoring data is reported by Sellafield Ltd and the approach adopted in Brown and Etherington (2011). An alpha-rich object is one where americium-241 (^{241}Am) has been detected and the ^{241}Am activity is greater than the caesium-137 (^{137}Cs) activity. For the evaluation of doses and risks, ^{241}Am and the alpha emitting isotopes of plutonium (Pu) – ^{238}Pu, ^{239}Pu and ^{240}Pu – are the most important constituents of alpha-rich particles. A beta-rich object is one where ^{137}Cs has been detected and the ^{137}Cs activity is greater than the ^{241}Am activity. The most important constituents of beta-rich particles are ^{137}Cs and strontium-90 (^{90}Sr)*.

Sellafield Ltd has also classified a few objects as being rich in cobalt-60 (^{60}Co). However, as very few of these objects have been found on the beaches, and the health risk would not be higher than those for beta-rich objects, they are not considered further in this assessment.

Information on the radiological and physical characteristics of recovered particles was obtained from a summary spreadsheet provided by Sellafield Ltd (Dalton, 2013) for use in this assessment (version 2.19, last updated 11/12/2013). This spreadsheet has information on every object recovered between 2006 and the end of November 2013, including those particles detected by both the Groundhog Evolution2^{TM} and Groundhog Synergy detection systems. As the distribution of radioactivity on particles has remained essentially the same for both detector systems (NDA, 2013a), the distribution in radioactivity content of particles used in this assessment was determined using information on all particles within that spreadsheet.

2.1.2 Species of seafood consumed

Many species of seafood consumed by the local population are obtained from the Cumbrian coast (Clyne et al, 2009, 2010, 2011, 2012, 2014; Papworth et al, 2013). Some species of animals, including molluscs and crustaceans, obtain their food from or close to the seabed. This could be either from ingesting material within the sediment itself or from ingesting other animals that may themselves ingest sediment. In either case, deliberate or inadvertent consumption of sediment by molluscs and crustaceans is assumed to occur. If radioactive particles are present in the sediment then these could also be consumed by the animal.

Although the consumption of many different species of molluscs and crustaceans was reported in the habits surveys, insufficient information could be found to justify treating different species within these phyla separately. The parameter values for molluscs have therefore been assumed to represent cockles, limpets, mussels, razor shells and winkles, while parameter values for crustaceans have been used to represent brown crab, brown shrimp, common lobster, common prawn and nephrops.

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

2.1.3 Consumption of particles by molluscs and crustaceans

The number of particles in an animal is directly proportional to the mass of sediment in the gut of that animal. The number of particles* in unit mass of sediment in the gut of an animal has been assumed to be the same as the number of particles in unit mass of sediment in the area where the animal feeds. This assumption is similar to that made previously for estimating the health risk to beach users (Brown and Etherington, 2011; Etherington et al, 2012), where it was assumed that the number of radioactive particles present in unit area, volume or mass of beach was constant at any point in time that the beach was used. Implicit in this is the assumption that the population of objects does not change over time. This pragmatic assumption is considered to be acceptable for the purpose of determining whether a significant risk to health is present. As described in Section 2.1.1, the numbers of particles in unit mass of sediment have been assumed to be the same as those on Braystones and Sellafield beaches for molluscs and crustaceans, respectively. From the available information, the mass of sediment inside marine animals appears to be highly variable, not only between different species but also between animals of the same species. For example, Bard and Drinnan (1957) noted that the relative mass of sediment inside mussels with respect to body mass was affected by water temperature, availability of food, amount of sunlight and the state of the tide.

2.1.4 Consumption of particles by people

The content of animal guts has been assumed to be consumed either directly – for example, because the entire animal is ingested – or due to contamination of edible parts of the animal during food preparation. Many factors will affect the amount of gut content consumed, including personal preference and the skill with which meat is extracted from the body without rupturing the digestive system. Depuration of the animal prior to cooking could also significantly affect the amount of sediment inside the animal at the time of consumption (McKay and Fox, 1991). Values have been chosen for the fraction of the gut of molluscs and crustaceans that is consumed; the ranges used to define the distributions have taken into account the variables that could affect this fraction.

The annual mass of sediment consumed by a human is directly related to the mass of seafood consumed. In the assessment, the annual consumption rate of marine animals by the population of seafood consumers has been defined by a distribution, the values for which have been based on information collected from local habits surveys (Clyne et al, 2009, 2010, 2011, 2012; Papworth et al, 2013). Only adults and children over 7 years old were reported to consume seafood in these habits surveys; therefore, children below the age of 7 have been assumed not to consume seafood in this assessment. The health risk has been evaluated for 10-year-olds and adult seafood consumers.

Changes in the year-on-year consumption rates of molluscs and crustaceans have been observed within the surveys. For example, between 2008 and 2012 the annual average consumption rate of crustaceans by adults increased by about 70%, while that for molluscs decreased by about the same amount. These changes could be a result of the availability of certain animals, the weather, cost and changes in individual preferences. By basing the

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* The number of particles present in unit area of beach, ie the actual particle population, is different from the number of particles detected, due to the capabilities of the equipment used to detect the objects.

distribution of the annual seafood consumption rate on observations made over a 5-year period, the impact of these short-term variations has been taken into account.

2.2 Assessing the health risk to a commercial fisherman

Commercial fishermen may consume above-average amounts of seafood and it is important to investigate the contribution made to their overall health risk from radioactive objects when handling fishing gear, and to determine if this is likely to be significantly different to that of recreational anglers. In 2012 approximately 400 tonnes of crustaceans and 2100 tonnes of molluscs were caught by ships landing their catches at Whitehaven (MMO, 2013). Some of these catches would have been obtained from areas where particles are present in the environment. Most of the landings went to processing factories or were exported, although small amounts were sold directly by fishermen to the public, local restaurants and hotels (Clyne et al, 2014). In the most recent habits survey (Clyne et al, 2014) four individuals were observed using pots for fishing brown crabs and common lobsters as a full-time occupation; the main fishing areas were from Parton to Nethertown and from Sellafield to Tarn Bay.

Commercial fishermen have been assumed to spend most of their time out at sea where exposure is likely to be restricted to particles in sediment attached to nets or traps as they are hauled back on to the boat. The amount of sediment attached to such equipment is likely to be relatively low due to the action of the water removing any loose sediment and particles quickly. Fishermen have also been assumed to handle equipment when performing general maintenance tasks, which could occur both on a boat and onshore in areas where radioactive objects could be present.

To scope the potential health risk to a commercial fisherman from exposure to radioactive particles in sediment, the methodology described by Oatway et al (2011) to estimate the health risk to an angler has been used. An angler was assumed to spend about 10% of their time on a beach digging for bait and the remainder of their time fishing. The exposure pathways considered were sediment becoming attached to skin and clothing and the inadvertent ingestion and inhalation of sediment. No account was made of the effect of using any protective equipment, such as gloves, due to the difficulty in predicting how effective such clothing would be in reducing exposure. The only change in parameter values to those used in Oatway et al is that the time for which an individual is exposed to sediment has been increased to 1500 hours in a year; this exposure time is approximately equal to the maximum time observed for an individual handling fishing gear in 2012 (Papworth et al, 2013). Given the behavioural differences between anglers using the beach and commercial fishermen, especially the time spent in direct contact with sediment, this approach is considered to be suitably cautious.

3 Results and Discussion

The annual probability of ingesting a particle from the consumption of seafood has been estimated for both alpha- and beta-rich objects. The highest annual probability of encounter (97.5th percentile of the distribution) is for adults consuming molluscs containing an alpha-rich particle and is about $3\ 10^{-7}$ (chance of 1 in 3 million in a year). The probability of an adult encountering a beta-rich particle is about 50 times lower. The probability of ingesting a particle by a 10-year-old child is about a factor of 60 lower than that for adults for molluscs and a factor of 5 lower for crustaceans, reflecting the relatively higher consumption of crustaceans compared to molluscs by children. A summary of the annual probability of ingesting a particle is given in Table 1 and Table 2 for adults and children, respectively; detailed results of the annual probabilities of ingesting a particle from the consumption of seafood are given in Appendix A.

Table 1: Estimated overall risk of fatal cancer for an adult seafood consumer associated with the possible ingestion of alpha- and beta-rich particles

		Effective dose if a particle is ingested* (mSv)	Risk of cancer if a particle is ingested (%)	Annual probability of ingesting a particle*	Overall risk of fatal cancer*
Alpha-rich	Molluscs	3.9	0.04	3 10^{-7}	3 10^{-11}
	Crustaceans			2 10^{-7}	3 10^{-11}
Beta-rich	Molluscs	1.7	0.02	8 10^{-9}	3 10^{-13}
	Crustaceans			3 10^{-9}	2 10^{-13}
Total	Molluscs				3 10^{-11}
	Crustaceans				3 10^{-11}
Total overall risk					6 10^{-11}

* The 97.5th percentile in the overall risk of fatal cancer 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. Therefore the overall risk of fatal cancer presented in this table does not equal the product of the 97.5th percentile risk of fatal cancer if a particle was ingested and the annual probability of ingesting a particle

Table 2: Estimated overall risk of fatal cancer for a child seafood consumer associated with the possible ingestion of alpha- and beta-rich particles

		Effective dose if a particle is ingested* (mSv)	Risk of cancer if a particle is ingested (%)	Annual probability of ingesting a particle*	Overall risk of fatal cancer*
Alpha-rich	Molluscs	4.2	0.04	4 10^{-9}	6 10^{-13}
	Crustaceans			3 10^{-8}	5 10^{-12}
Beta-rich	Molluscs	2.8	0.03	1 10^{-10}	7 10^{-15}
	Crustaceans			6 10^{-10}	5 10^{-14}
Total	Molluscs				6 10^{-13}
	Crustaceans				5 10^{-12}
Total overall risk					6 10^{-12}

* The 97.5th percentile in the overall risk of fatal cancer 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. Therefore the overall risk of fatal cancer presented in this table does not equal the product of the 97.5th percentile risk of fatal cancer if a particle was ingested and the annual probability of ingesting a particle

This implies that the probability a particle would be found in seafood by the routine environmental sampling programme is very low. To date, there have been no conclusive measurements made that would demonstrate the presence of a radioactive particle in seafood of the size and activity of those detected and removed by the beach monitoring programme; while a number of samples did contain activity concentrations that exceeded the arbitrary secondary screening level set, they did not approach the activity levels recorded in analyses of particles found on the beaches (Cefas, 2008; NDA, 2013b).

The overall health risk to seafood consumers has been determined by multiplying the annual probability of ingesting an object by the risk that a person would contract a fatal cancer during their lifetime if consumption of an object did occur. It is justified to multiply the two probabilities together to determine the overall risk since they are independent of each other (ICRP, 2007). The result of this calculation is the probability that the person would contract a fatal cancer at some point during their lifetime as a result of consuming seafood over a period of 1 year.

Table 1 and Table 2 present the 97.5th percentile of the overall health risk. The tables present both the estimated 97.5th percentiles of the annual probability of ingesting an object and the risk of contracting fatal cancer if an object was ingested separately. The product of these values should not be used to estimate the overall health risk as it will lead to an overly conservative estimate. The 97.5th percentile of the overall risk of fatal cancer given in the tables was estimated explicitly from the two distributions.

Figure 2 presents the distribution in the health risk to an adult consumer of molluscs from the presence of alpha-rich particles; the figure also shows the relative position of the 2.5th, 50th and 97.5th percentile values for reference. Although the health risk varies for different combinations of radionuclide, seafood type and age of consumer, the shape of the distribution does not change significantly. Figure 2 highlights the level of conservatism if the 97.5th percentile value of the distribution is used.

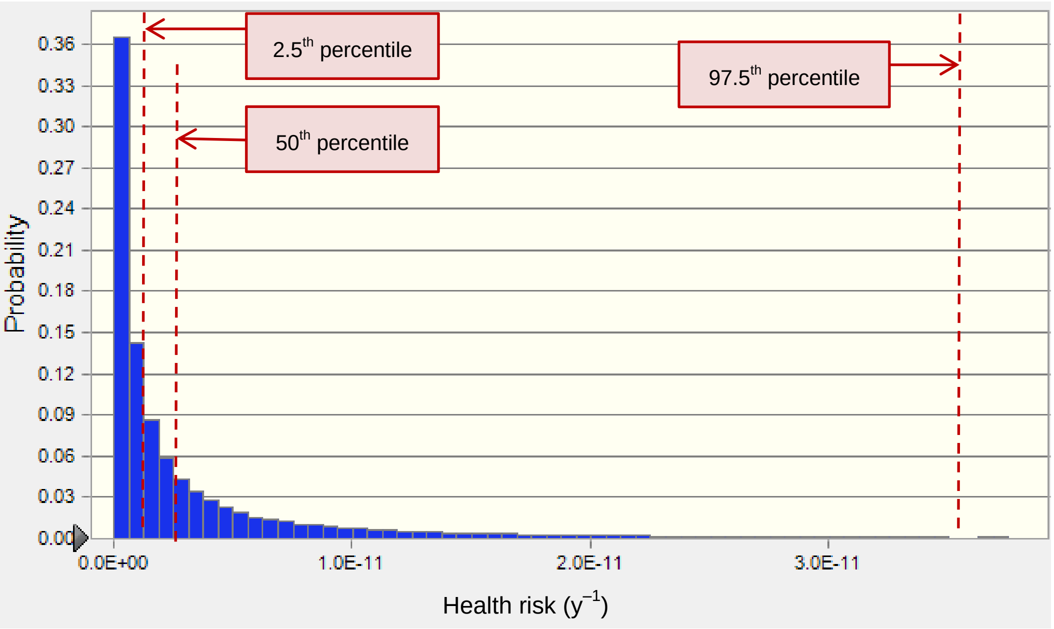

Figure 2: Distribution in the health risk to an adult consumer of molluscs for alpha-rich particles

If it is assumed that, for any individual, the annual mass of molluscs consumed is independent of the mass of crustaceans consumed, then the overall health risk is equal to the sum of the health risks from consuming each type of seafood. In addition, as the health risks from consuming alpha- and beta-rich particles were assessed separately, the total health risk from consuming any particle is the sum of the health risks from consuming either an alpha- or beta-rich particle. The value obtained by summing the 97.5th percentile health risks from consuming alpha- and beta-rich particles in molluscs and crustaceans given in Table 1 and Table 2 gives a conservative estimate of the 97.5th percentile of the overall health risk.

The overall health risk from the consumption of radioactive particles within molluscs and crustaceans is estimated to be very low, with the chance of dying from cancer as a result of 1 year's potential exposure being less than $6\ 10^{-11}$ (1 in 15 billion) (for ingestion of a particle in seafood by an adult). A typical value for all adult seafood consumers (50th percentile value of the distribution) is about an order of magnitude lower at around 1 in 100 billion. Most of this risk is from the consumption of alpha-rich particles. The highest and typical health risks to a child are about an order of magnitude lower than the respective values for adults. The highest estimated health risk is over two orders of magnitude lower than that estimated for seafood consumers by Brown and Etherington (2011).

The risk of radiation-induced fatal cancer for a commercial fisherman operating for 1 year off the West Cumbrian coast from exposure to radioactive particles is estimated to be no more than $3\ 10^{-11}$ (1 in 30 billion). This level of health risk is similar to that estimated for individuals who consume the highest amounts of seafood. However, as the health risk to commercial fishermen was estimated using cautious assumptions it is considered to be an upper bound of the potential risk to this group posed by radioactive particles in the environment.

The risk of radiation-induced fatal cancer for an adult consumer of seafood or for an adult engaging in commercial fishing is estimated to be about 70 times greater than to an adult beach user (Brown and Etherington, 2011). The difference in the health risk between these groups is due to the relative mass of sediment assumed to be ingested. The health risk for a child seafood consumer is estimated to be similar to the highest health risk for young children (1-year-olds) using beaches around the Sellafield site.

To put these estimated risks to health into context, the Health and Safety Executive (HSE, 2001) believes that an annual individual risk of death of 1 in 1,000,000 for both workers and members of the public corresponds to a very low level of risk and should be used as a guideline for the boundary between broadly acceptable and tolerable levels of risk. Based on the information available at the time of this study, the health risk from radioactive particles in seafood, or from exposure to such particles when undertaking commercial fishing, are of the order of 100,000 times smaller than the level of risk that the HSE considers to be the upper limit for an acceptable level of risk; the risks posed by the potential presence of radioactive particles in seafood are therefore very low.

3.1 Sensitivity analysis

For some of the parameters used in the assessment, not enough information could be found to allow the full range of their potential values to be established. For these parameters, the distributions were therefore based on judgement as well as on measurement. In order to judge the sensitivity of the estimated health risk to the choice of the parameter values used, a sensitivity analysis has been carried out. The contribution of the parameters to the overall uncertainty in the health risk has been estimated by evaluating their contribution to the variance* in the health risk. The greater the contribution to the variance, then the greater the contribution of the parameter to the overall uncertainty in the health risk. For those parameters contributing significantly to the uncertainty in the health risk, additional work has been undertaken to investigate how using alternative values may affect the estimated health risk. A detailed description of this sensitivity analysis is given in Appendix B.

The contribution of each parameter to the uncertainty in the health risk is shown in Figure 3 and Figure 4 for molluscs and crustaceans, respectively. The figures show that the density of sediment, the fraction of animal live weight consumed by people and the fraction of material consumed by seafood which is sediment are likely to contribute less than a few per cent to the uncertainty in the health risk. Refinement of the values used to define the distributions for these parameters is unlikely to improve the uncertainty in the estimated health risk significantly. These parameters have therefore not been considered further. Of those parameters which have been estimated to contribute significantly to the uncertainty in the health risk, the distribution of values for the activity content of alpha- and beta-rich particles, the ratio of caesium to strontium activity on beta-rich particles, and the annual consumption rate of seafood were derived using measurements and observations; as they are based on a large quantity of data collected over a number of years, additional information is unlikely to change the distribution used in this assessment significantly.

The sensitivity analysis and investigation carried out for the remaining parameters identified in Figures 3 and 4 are described below and the results summarised in Section 4.

3.1.1 Radionuclide content of particles

Less than 1% of alpha-rich particles recovered to date have had levels of ^{137}Cs activity above the limit of detection and about 10% of beta-rich particles have had measurable levels of ^{241}Am activity. Due to the small number of these particles compared to the total population, the doses and any additional health risk from including these additional radionuclides have not been considered in the assessment or in the earlier health risk assessment for beach users (Brown and Etherington, 2011). To judge the significance of this decision, an estimate of the health risk has been made assuming, as a worst case situation, that all alpha-rich particles contain ^{137}Cs and ^{90}Sr and all beta-rich particles contain ^{241}Am and Pu isotopes. A description of the sensitivity analysis and results are given in Appendix B.

Assuming ^{137}Cs and ^{90}Sr are present on all alpha-rich particles and ^{241}Am and Pu isotopes are present on all beta-rich particles changes the health risk to a seafood consumer by less than 1%. The low effect on the health risk from the presence of these radionuclides is due to their relatively low activity: ^{137}Cs has not been measured on alpha-rich particles with an activity of more than 1% of the ^{241}Am activity, while on beta-rich particles ^{241}Am has not been measured with an activity of more than 6% of the ^{137}Cs activity.

In this assessment it has been assumed that all objects classified as particles are available for consumption by marine animals. The available evidence suggests that only a small fraction of such objects might be consumed by molluscs and crustaceans. This is because any particles would normally be ingested coincidentally to food and most animals have a filtering mechanism

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* Statistical variance gives a measure of how the data distributes itself about the mean or expected value.

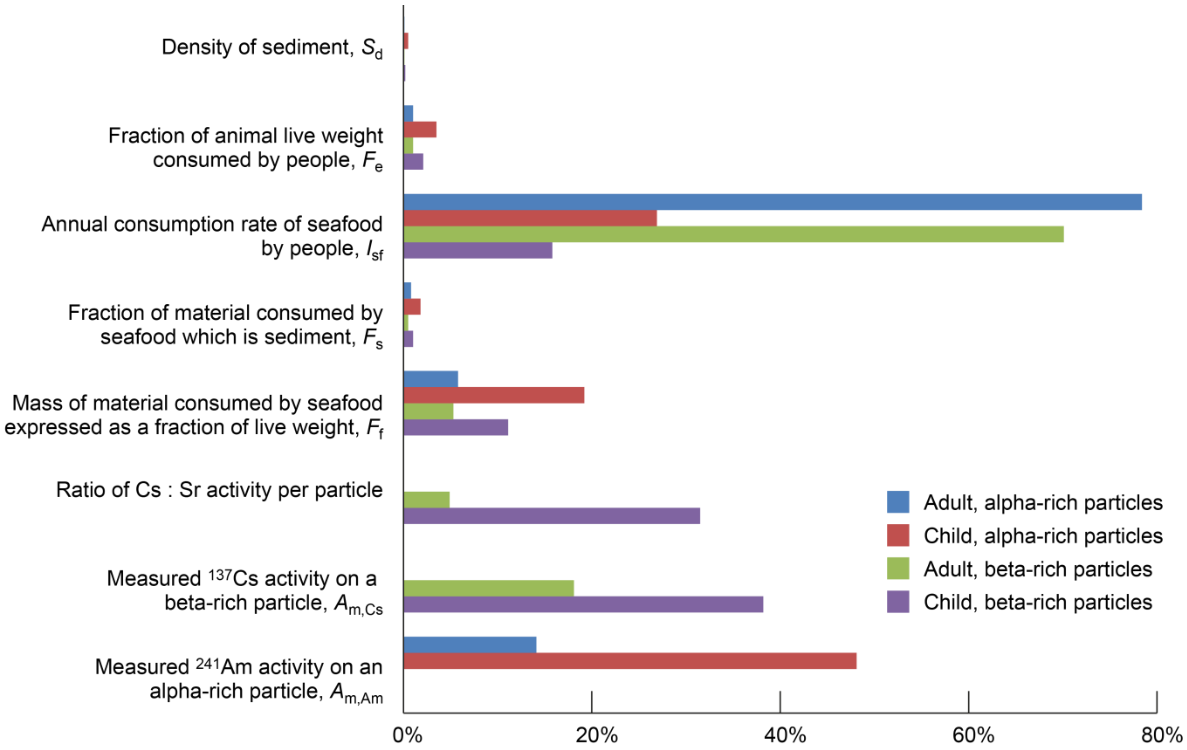

Figure 3: Contribution of different parameters to the uncertainty in the estimated health risk from the ingestion of particles in molluscs

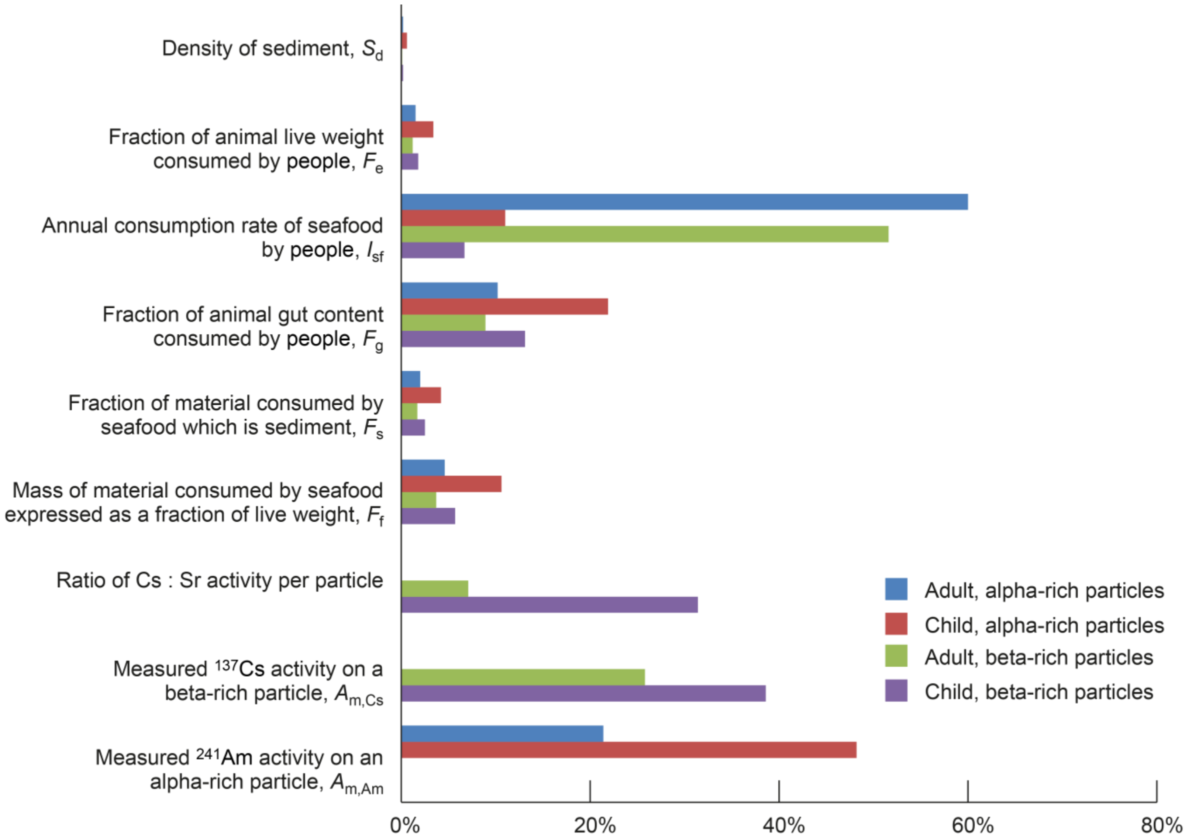

Figure 4: Contribution of different parameters to the uncertainty in the estimated health risk from the ingestion of particles in crustaceans

which will prevent excessive volumes of sediment and particles larger than a few tens of micrometres being ingested (Cefas, 2008; Defossez and Hawkins, 1997). There is some evidence that the ^{241}Am activity on an alpha-rich object is directly related to the object's physical size (Oatway et al, 2011). Assuming that this relationship applies to all alpha-rich particles, then molluscs and crustaceans can be expected to consume only objects with activities towards the lower end of the distribution included in this assessment. The assumption that all objects classified as particles (< 2 mm) could be consumed by molluscs and crustaceans is therefore likely to have led to the health risk being overestimated.

3.1.2 Fraction of animal gut consumed, F_g

The distribution in the fraction of animal gut content which is consumed by people and in the mass of material consumed by marine animals expressed as a fraction of the animals' live weight have been defined using very limited information. Figure 3 and Figure 4 show that these parameters contribute significantly to the uncertainty in the health risk. The impact of the choice of values for these parameters on the health risk has therefore been explored as part of the sensitivity analysis (see Appendix B for details).

The fraction of a crustacean's gut content consumed by people is likely to depend on individual preference and skill when preparing the animal for consumption; consequently the values used to define the distribution in this parameter were based largely on judgement. As the amount of gut content consumed is directly proportional to the health risk, increasing the fraction of gut content consumed would increase the health risk. If it is assumed that up to 70% of the gut content is consumed rather than up to 10%, then the health risk increases proportionally. However, even if a value of 70% is used, the risk to any individual remains very low, no more than about 10^{-10} for 1 year's consumption (1 in 10 billion) for an adult consumer. It should be noted that even if individual animals are prepared in such a way that a higher fraction of gut content is consumed, it is unlikely that the majority of animals consumed would be prepared in this way. In addition, individuals consuming such a large fraction of gut content, should they exist, are likely to be in a minority with respect to the population of crustacean consumers.

3.1.3 Mass of sediment consumed by seafood, F_f

In this assessment the mass sediment in the gut of an animal was estimated from the product of the mass of material consumed by an animal and the fraction of that mass which was sediment. However, measurements of the aluminium and inorganic particulate content of molluscs, reported by McKay and Fox (1991) and McKay and Halliwell (1994), allow the mass of sediment inside molluscs to be estimated using an alternative approach. As McKay and colleagues expressed their measurements in relation to the total shelled weight of the animal rather than with respect to the mass of the animal's gut, their data could not be used directly in this assessment. However, the measurements made by McKay and colleagues could be used to place an upper bound on the mass of sediment likely to be present in the gut of an animal. The estimated 97.5th percentile of the health risk estimated using data from the work of McKay and colleagues is within a factor of about five of the health risk estimated using the methodology described in Appendix A. As expected, the approach using data from McKay and colleagues estimates a higher risk. Given the uncertainties in these calculations, the health risks estimated by these two approaches are in reasonable agreement and the approach used in this assessment can be considered to be robust.

4 Conclusions

The conclusions of this study, based on currently available information, are that the overall health risks to both local seafood consumers and commercial fishermen are very low. The risk of radiation-induced fatal cancer for a commercial fisherman operating for 1 year off the West Cumbrian coast from exposure to radioactive particles, using cautious assumptions, is similar to that estimated for individuals who consume the highest amounts of seafood. The health risk to commercial fishermen is considered to be an upper bound of the potential risk to this group and the risk of ingesting radioactive particles in seafood is likely to dominate the health risk to commercial fishermen if they are also seafood consumers.

The risk of radiation-induced fatal cancer for an adult consumer of seafood or for an adult engaging in commercial fishing is estimated to be about 70 times greater than that to an adult beach user (Brown and Etherington, 2011). The difference in the health risks between these groups is due to the relative mass of sediment assumed to be ingested. The health risk for a child seafood consumer is estimated to be similar to the highest health risk for young children (1-year-olds) using beaches around the Sellafield site.

The highest risk of radiation-induced fatal cancer (97.5th percentile of the distribution) is of the order of 10,000 times smaller than the level of risk that the Health and Safety Executive considers to be the upper limit for an acceptable level of risk (HSE, 2001).

The main uncertainty associated with the estimation of the health risk to seafood consumers is due to the assumption that the number of particles in seabed sediment, where molluscs and crustaceans feed, is the same as that on adjacent beaches and that the distribution of particle activity in these populations is the same. This is particularly the case for crustaceans which feed offshore, away from the intertidal areas of the beaches. The estimated low probability that a particle is likely to be present in seafood implies that it is very unlikely that a particle would be found in seafood by the routine sampling programme. Ongoing seabed characterisation and monitoring activities will assist with confirming whether this assumption is appropriate. It should be noted that the numbers of particles on the seabed would need to be at least 1000 times higher for the health risk from consuming seafood to approach the level of risk that the HSE considers to be the upper limit for an acceptable level of the risk of dying. If evidence becomes available to suggest that the health risk is significantly higher than the current estimate – for example, if a larger population of particles in the offshore environment is found, particularly in areas where molluscs and crustaceans feed and are harvested – then this conclusion should be reviewed.

There is also uncertainty associated with how particles are taken up by marine animals. In order to improve modelling of the transfer of sediment to people through the consumption of seafood, more information on the amount of sediment consumed by various species of molluscs and crustaceans, and the fraction of the animal gut content regularly consumed by people, could be obtained.

Table 3 summarises the main uncertainties in the estimated health risks and identifies possible ways of reducing the uncertainty in the assumptions made in the assessment of risks to health.

Table 3: Summary of key assumptions made in the assessment and potential methods to reduce the uncertainty in their values

Parameter	Assumption	Impact of assumption on uncertainty in health risk	Measures to reduce uncertainty
Object/particle population distribution (numbers) on seabed	Same as beach	High – given likely sources of particles offshore, this may underestimate the risk	Ongoing seabed characterisation programme
Number of particles present with low activities	Particles with less than 3 kBq not included in the assessment	Low – risk of fatal cancer from such particles is low even if they are consumed	Improvements in detector capability for low activity sources
Probability of particle being taken up by molluscs/crustaceans	All particles (< 2 mm) assumed to be available for take up by molluscs/ crustaceans regardless of size	Medium – this assumption will overestimate the risk if there is a relationship between particle activity and size	Studies on maximum particle size taken up by molluscs/ crustaceans
Number of particles in the gut of an animal	Number of particles in unit mass of material inside an animal's gut equals that in the environment	Medium – if animals retain particles preferentially in the gut the number present could be greater than in the environment	Studies on mass of sediment and range in particle size in the gut of molluscs/crustaceans Further evaluation of relationship between particle size and activity content

5 Acknowledgements

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6 References

Bard RH and Drinnan RE (1957). The ratio of shell to meat in *Mytilus* as a function of tidal exposure to air. *J Mar Sci* 22(3), 329–336.

Brown J and Etherington G (2011). Health Risks from Radioactive Objects on Beaches in the Vicinity of the Sellafield Site. Chilton, HPA-CRCE-018.

Cefas (2008). Literature Review on Particle Assimilation by Molluscs and Crustaceans. RL 10/08. Lowestoft, Cefas.

Clyne FJ, Tipple JR, Garrod CJ and Jeffs TM (2009). Radiological Habits Survey: Sellafield, 2008. RL 02/09. Lowestoft, Cefas.

Clyne FJ, Garrod CJ and Elliot J (2010). Radiological Habits Survey: Sellafield Review, 2009. Shellfish consumption and intertidal occupancy review. RL 07/10. Lowestoft, Cefas.

Clyne FJ, Garrod CJ, Rumney P, Smedley CA and Ly VE (2011). Radiological Habits Survey: Sellafield Review, 2010. Shellfish consumption and intertidal occupancy review. RL 13/11. Lowestoft, Cefas.

Clyne FJ, Garrod CJ, Ly VE and Rumney P (2012). Radiological Habits Survey: Sellafield Review, 2011. Shellfish consumption and intertidal occupancy review. RL 05/12. Lowestoft, Cefas.

Clyne FJ, Garrod CJ and Papworth GP (2014). Radiological Habits Survey: Sellafield 2013. RL 02/14. Lowestoft, Cefas.

Dalton A, Sellafield Ltd, UK (2013). Personal communication.

Defossez J-M and Hawkins AJS (1997). Selective feeding in shellfish: size-dependent rejection of large particles within pseudofaeces from *Mytilus edulis, Ruditapes philippinarum* and *Tapes decussatus*. *Mar Biol* 129, 139–147.

Etherington GE, Youngman MJ, Brown J and Oatway W (2012). Evaluation of the Groundhog Synergy Beach Monitoring System for Detection of Alpha-rich Objects and Implications for Health Risks to Beach Users. Chilton, HPA-CRCE-038.

HSE (2001). Reducing Risks, Protecting People. HSE's Decision-making Process. HSE Books.

ICRP (2007). Recommendations of the ICRP. ICRP Publication 103. *Ann ICRP* 37(2–4).

McKay WA and Fox AA (1991). Particulate associated nuclides in Cumbrian winkles implications for assessment of dose to man. *J Environ Radioact* 14, 1–21.

McKay WA and Halliwell CM (1994). The levels of particulate-associated nuclides in Irish Sea shellfish and the implications for dose assessment. *J Radiol Prot* 14(1), 43–53.

MMO (2013). UK Sea Fisheries Annual Statistics 2012. Underlying dataset by port. Marine Management Organisation, UK Sea Fisheries Annual Statistics. Available at www.gov.uk/government/statistical-data-sets/uk-sea-fisheries-annual-statistics-2012

NDA (2013a). Particles in the Environment. Annual Report for 2012/2013 and Forward Programme. Nuclear Decommissioning Authority. SSEM/2013/16.

NDA (2013b). Investigation into Quarter 1, 2013 G33 Mussel Sample Actinide Data. Nuclear Decommissioning Authority. SSEM/2013/28.

Oatway W, Brown J, Etherington G, Anderson T, Fell T, Eslava-Gomez A, Hodgson A, Pellow P and Youngman M (2011). Supporting Information for the Assessment of the Health Risks from Radioactive Objects on Beaches in the Vicinity of the Sellafield Site. HPA-CRCE-018 (supplement).

Papworth GP, Clyne FJ, Garrod CJ, Ly VE and Dewer A (2013). Radiological Habits Survey: Sellafield Review 2012. RL 04a/13. Lowestoft, Cefas.

Sellafield Ltd (2013). Monitoring our Environment. Discharges and Monitoring in the United Kingdom. Annual Report 2012.

Wilkins BT, Fry FA, Burgess PH, Fayers CA, Haywood SM, Bexon AP and Tournette C (1998). Radiological Implications of the Presence of Fragments of Irradiated Fuel in the Sub-tidal Zone at Dounreay. Chilton, NRPB-M1005.

Appendix A Methodology to Assess the Health Risk to a Seafood Consumer

The overall health risk to a seafood consumer must take into account the probability that an object may be consumed in seafood and the risk of fatal cancer in the event that the person does consume such an object as well as the activity content of the objects. The risk that a radiation-induced fatal cancer from ingestion of seafood could occur during the lifetime of a seafood consumer from 1 year's seafood consumption is calculated by multiplying the probability that a contaminated object is consumed from 1 year's consumption by the risk of dying from radiation-induced cancer over a lifetime if a particle is consumed. The distribution in the health risk associated with ingesting a radioactive particle when consuming seafood by an adult or a child has been estimated using the following equation:

$$HR_{\mathrm{SF}} = D_{\mathrm{eff}}\, R\left(P_{\mathrm{ing,C}} + P_{\mathrm{ing,m}}\right)$$

where HR_{SF} = risk of radiation-induced fatal cancer from 1 year's seafood ingestion

D_{eff} = committed effective dose from the ingestion of a particle which has an activity within the range measured on particles to date (Sv)

R = risk of radiation-induced fatal cancer per Sv if a particle was ingested

$P_{\mathrm{ing,C}}$ = annual probability of ingesting a particle when consuming crustaceans (y^{-1})

$P_{\mathrm{ing,m}}$ = annual probability of ingesting a particle when consuming molluscs (y^{-1})

ICRP Publication 103 (ICRP, 2007) does not give risk coefficients for children and so specific calculations were carried out for a 1-year-old child and a 20-year-old adult (Brown and Etherington, 2011). The calculations took account of protraction of the received dose over the lifetime of the individual, ie the committed dose, and the increase in age of the individual over the time of the exposure. For this study, additional calculations have been carried out for 10-year-old children (Haylock, 2014). The risks of radiation-induced fatal cancer that would result from an intake giving rise to a committed effective dose of 1 Sv have been estimated to be 9% for both the 10-year-old child and the adult (Haylock, 2014). It may be noted that the adult value differs from ICRP's nominal risk coefficient for lethality-adjusted cancer risk for adult workers of 4.1% Sv^{-1} (ICRP, 2007) mainly because ICRP's value is averaged over ages between 18 and 64 years and risks decrease with age due to decreasing life expectancy. Uncertainties on these risk coefficients are likely to be large, particularly for children.

For this assessment the statistical computer tool 'Crystal Ball' (Oracle, 2014) has been used to estimate the distribution of health risks to seafood consumers using distributions on the input parameter values.

A1 Estimating the effective dose assuming a particle is ingested

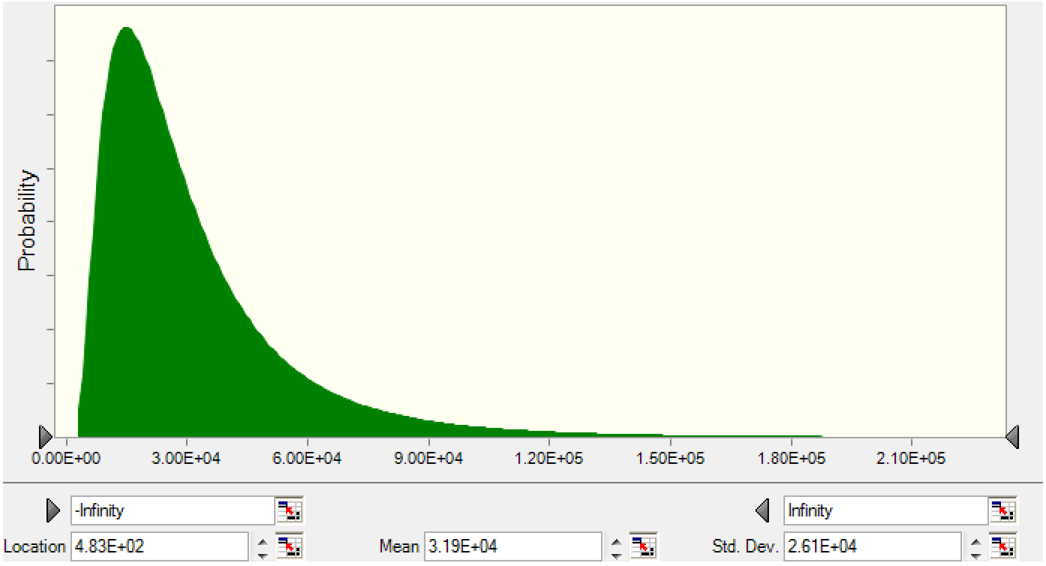
A1.1 Alpha-rich particles

Although only about 20% of the alpha-rich particles recorded in the finds summary spreadsheet have measurable levels of plutonium isotopes (^{238}Pu and $^{239/240}$Pu), it was cautiously assumed that all alpha-rich particles contain both ^{241}Am and the Pu isotopes. Crystal Ball has been used to fit a distribution to the measured ^{241}Am activities on alpha-rich particles recorded in the finds summary spreadsheet. Parameter values used to define the distribution for ^{241}Am activity on alpha-rich particles are given in Table A1 and the distribution is shown in Figure A1.

Table A1: Values to define the distribution* of ^{241}Am activity associated with alpha-rich particles

Parameter	Distribution	Minimum (location)	Mean	Standard deviation
$A_{\text{m,Am}}$	Lognormal	$4.83\ 10^{2}$	$3.19\ 10^{4}$	$2.61\ 10^{4}$

* The terminology used in this table matches that used in Crystal Ball to define the distribution. In Crystal Ball ‘location’ is used to define the minimum value within a distribution



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Infinity

Location 4.83E+02

Mean 3.19E+04

Std. Dev. 2.61E+04

Figure A1: Distribution of ^{241}Am activity associated with alpha-rich particles, parameter $A_{\text{m,Am}}$ (the x-axis gives the activity in Bq)

The effective dose from ingesting an alpha-rich particle was estimated using the following equation:

$$D_{\text{eff},\alpha} = A_{\text{m,Am}}\ F_{\text{Pu}}\ DC_{\text{A}}$$

where $A_{\text{m,Am}}$ = measured ^{241}Am activity on an alpha-rich particle, see Table A1 (Bq)
F_{Pu} = factor to account for any Pu isotopes present on a particle (value of 2)
DC_{A} = dose coefficient for ingestion of actinides, see Table A2 (Sv Bq^{-1})

Where both ^{241}Am and Pu isotopes have been measured on a particle, on average about 60% of the total activity is due to ^{241}Am. For the purpose of estimating the dose if an alpha-rich particle is consumed, the activity of any Pu isotopes present on a particle has been accounted for by increasing the ^{241}Am activity by a factor of two. This simple approach is justified as the dose coefficients for americium and plutonium are similar. Using this approach means that all health risks associated with alpha-rich particles are directly related to measured ^{241}Am activities.

The dose coefficients for ingestion used in this assessment are given in Table A2. For simplicity, the dose coefficient for ingestion for ^{239}Pu has been used to estimate the dose from all alpha emitting radionuclides as it is generally the highest. No distribution in the value of the dose coefficient for ingestion has been used. The dose coefficients for ingestion have been obtained from Oatway et al (2011); these have been used in preference to those published by the ICRP as they are estimated from in vivo studies on particles recovered from Sellafield beaches.

Table A2: Dose coefficient for ingestion (Sv Bq^{-1})

Parameter	Adult*	Child†
DC_A, actinides‡	1.9 10^{-8}	2.1 10^{-8}
DC_{Cs}, caesium-137	1.3 10^{-8}	1.0 10^{-8}
DC_{Sr}, strontium-90	2.8 10^{-8}	6.0 10^{-8}

* From Oatway et al (2011)

† The dose coefficient for ingestion for a child has been estimated by scaling the value for an adult presented in Oatway et al (2011) by the ratio of adult to child dose coefficient for ingestion given in ICRP (2012)

‡ Values are for ^{239}Pu; used to estimate the dose following intake of Am and Pu isotopes. For comparison, the adult dose coefficient for ingestion of ^{241}Am and ^{238}Pu are 1.7 10^{-8} and 1.8 10^{-8}, respectively, while for children they are 5.4 10^{-8} and 5.5 10^{-8}, respectively

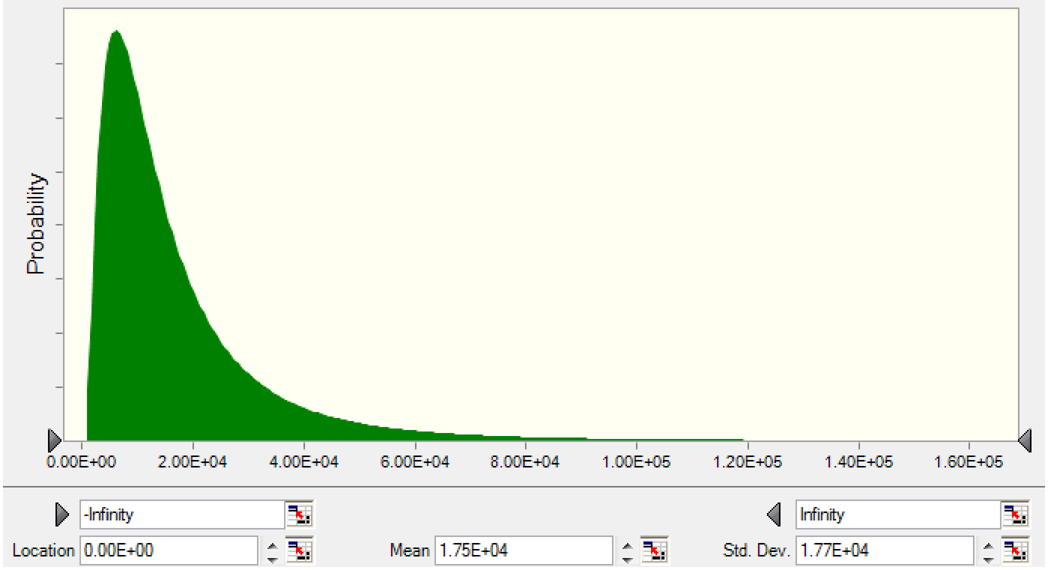
A1.2 Beta-rich particles

Crystal Ball has been used to fit a distribution to the measured ^{137}Cs activities on beta-rich particles recorded within the finds summary spreadsheet. Parameter values used to define the distribution for ^{137}Cs activity on beta-rich particles are given in Table A3 and the distribution is shown in Figure A2.

Table A3: Values to define the distribution* of ^{137}Cs activity on beta-rich particles

Parameter	Distribution	Minimum (location)	Mean	Standard deviation
$A_{m,Cs}$	Lognormal	0	1.75 10^4	1.77 10^4

* The terminology used in this table matches that used in Crystal Ball to define the distribution. In Crystal Ball 'location' is used to define the minimum value within a distribution



-Infinity

Infinity

Location 0.00E+00

Mean 1.75E+04

Std. Dev. 1.77E+04

Figure A2: Distribution of ^{137}Cs activity associated with alpha-rich particles, parameter $A_{m,Cs}$ (the x-axis gives the activity in Bq)

No objects have been detected directly through measurement of their ^{90}Sr* content. However, measurements of the ^{90}Sr activity have been made on objects selected for radiochemical analysis and the contribution of ^{90}Sr to radiation doses was considered in the assessment of doses and risks to health for beach users and in the scoping assessment for seafood consumers (Oatway et al, 2011). The ^{90}Sr activity associated with beta-rich particles, $A_{\mathrm{E,Sr}}$, has been estimated using the following equation:

$$A_{\mathrm{E,Sr}} = \frac{A_{\mathrm{m,Cs}}}{\left(A_{\mathrm{m,Cs}}/A_{\mathrm{m,Sr}}\right)}$$

where $A_{\mathrm{E,Sr}}$ = estimated ^{90}Sr activity on a particle (Bq)
$A_{\mathrm{m,Cs}}$ = measured ^{137}Cs activity on a beta-rich particle (Bq)
$A_{\mathrm{m,Cs}}/A_{\mathrm{m,Sr}}$ = ratio of ^{137}Cs to ^{90}Sr activity measured on beta-rich particles

The ratio of measured strontium to caesium activity has been obtained from Serco (2009, 2010) and Desmond (2013). Using these measured activities, the values used to define the distribution in the ratio of ^{137}Cs to ^{90}Sr activity in this assessment are given in Table A4 and the distribution is shown in Figure A3.

The effective dose from ingesting a beta-rich particle has been estimated using the following equation:

$$D_{\mathrm{eff},\beta} = \left(A_{\mathrm{m,Cs}}\, DC_{\mathrm{Cs}}\right) + \left(A_{\mathrm{E,Sr}}\, DC_{\mathrm{Sr}}\right)$$

where $A_{\mathrm{m,Cs}}$ = distribution in measured ^{137}Cs activity present on a beta-rich particle (Bq)
$A_{\mathrm{E,Sr}}$ = estimated ^{90}Sr activity present on beta-rich particles expressed as a function of measured ^{137}Cs activity (Bq)
DC = dose coefficient for ingestion of the radionuclides identified by the suffix, see Table A2 (Sv Bq^{-1})

A2 Probability of encountering a particle when consuming seafood

Although the consumption of many different species of molluscs and crustaceans has been reported in the habits surveys, insufficient information could be found to justify treating different species within these phyla separately in this assessment. The parameter values for molluscs have therefore been assumed to represent cockles, limpets, mussels, razor shells and winkles, while parameter values for crustaceans have been used to represent brown crab, brown shrimp, common lobster, common prawn and nephrops (also known as Norway lobster or Dublin Bay prawns).

The probability distribution for ingesting a radioactive particle incorporated into seafood gathered from the West Cumbrian coastline has been estimated using the following equation:

$$P_{\mathrm{ing}} = M_{\mathrm{s}}\, N_{\mathrm{g}}$$

where P_{ing} = annual probability of ingesting a particle in either a crustacean or mollusc
M_{s} = mass of sediment ingested while consuming seafood (g y^{-1})
N_{g} = number of particles per gram of sediment

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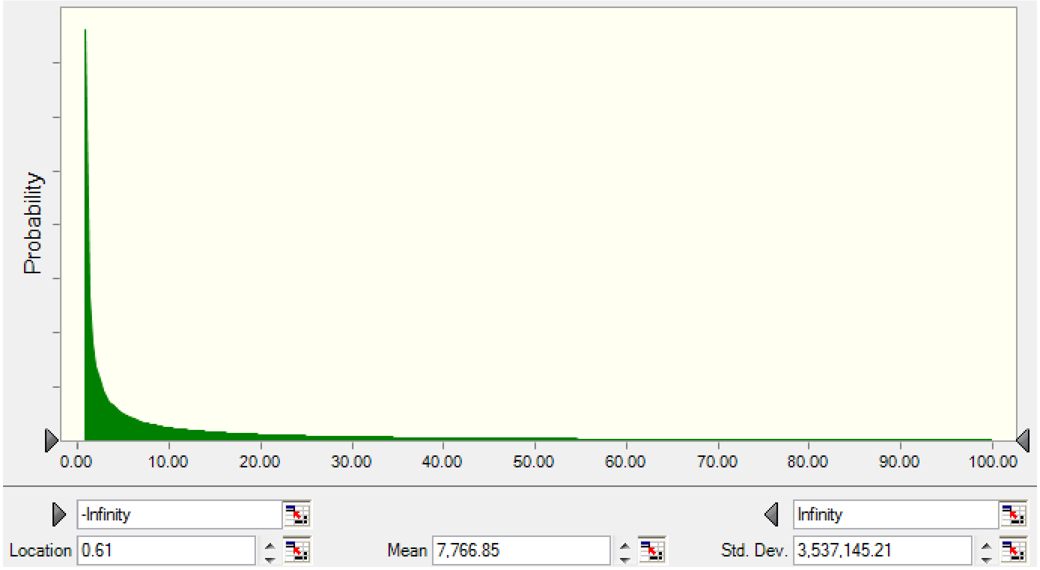
* Strontium-90 is present in equilibrium with its radioactive progeny, yttrium (^{90}Y).

Table A4: Values to define the distribution in the ratio of ^{137}Cs to ^{90}Sr activity*

Parameter	Distribution	Minimum (location)	Mean	Standard deviation
$A_{m,Cs}/A_{m,Sr}$	Lognormal	0.61	7.8 10^3	3.5 10^6

* The terminology used in this table matches that used in Crystal Ball to define the distribution. In Crystal Ball ‘location’ is used to define the minimum value within a distribution. It is recognised that the mean value in the distribution predicted by Crystal Ball is much higher than the mean of the measured values (380). The fitted distribution is unlikely to be very reliable at high Cs : Sr ratios beyond the range of the limited measurement data. However, for particles with a high Cs : Sr ratio, very little of the ingestion dose would be from strontium.
The unreliability of the distribution is therefore not significant, as using the distribution shown in Figure A3 leads to a greater frequency of low ratio values



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Infinity

Location 0.61

Mean 7,766.85

Std. Dev. 3,537,145.21

Figure A3: Distribution in the ratio of ^{137}Cs to ^{90}Sr activity, parameter $A_{m,Cs}/A_{m,Sr}$

The mass of sediment ingested annually while consuming seafood has been estimated using the following equation:

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

where I_{sf} = annual consumption rate of seafood by people (g y^{-1})
F_f = mass of material consumed by seafood expressed as a fraction of live weight
F_s = fraction of material consumed by seafood which is sediment
F_g = fraction of animal gut content consumed by people
F_e = fraction of animal live weight consumed by people

The values used to define the ranges for the above parameters are summarised in Table A5. It is noted that most of the parameters shown in Table A5 are likely to have significant variability as they relate to biological systems. The distributions chosen are judged to be the most likely based on the available information. In a number of cases, judgement has been used to determine the distribution in the parameter values.

Table A5: Parameter values used to estimate how much sediment is annually consumed*

Parameter	Distribution type	Minimum (location)	Mean (standard deviation)†	Maximum
Molluscs				
F_f	Triangular	0.0003	0.005	0.01
F_s	Triangular	0.1	0.15	0.2
F_g	Triangular	1	1	1
F_e	Triangular	0.2	0.3	0.5
I_{sf} (g y^{-1})‡ adult	Lognormal	(6.5)	8,069 (35,175)	49,100
I_{sf} (g y^{-1})‡ child	Lognormal	(40)	120 (496)	1,200
Crustaceans				
F_f	Triangular	0.05	0.1	0.25
F_s	Triangular	0.01	0.02	0.03
F_g	Triangular	0	0.05	0.1
F_e	Triangular	0.2	0.3	0.5
I_{sf} (g y^{-1})‡ adult	Exponential	Rate = 0.000097		53,000
I_{sf} (g y^{-1})‡ child	Lognormal	(1,500)	2,700 (3022)	10,300

* The terminology used in this table matches that used by Crystal Ball to define the distribution. In Crystal Ball 'location' is used to define the minimum value within a distribution

† The distribution in the consumption rate of seafood by children could not be defined using Crystal Ball as insufficient observations were reported in the habits surveys; this distribution was therefore assumed to be lognormal and defined using the minimum, mean and standard deviation of the values reported in the habits surveys

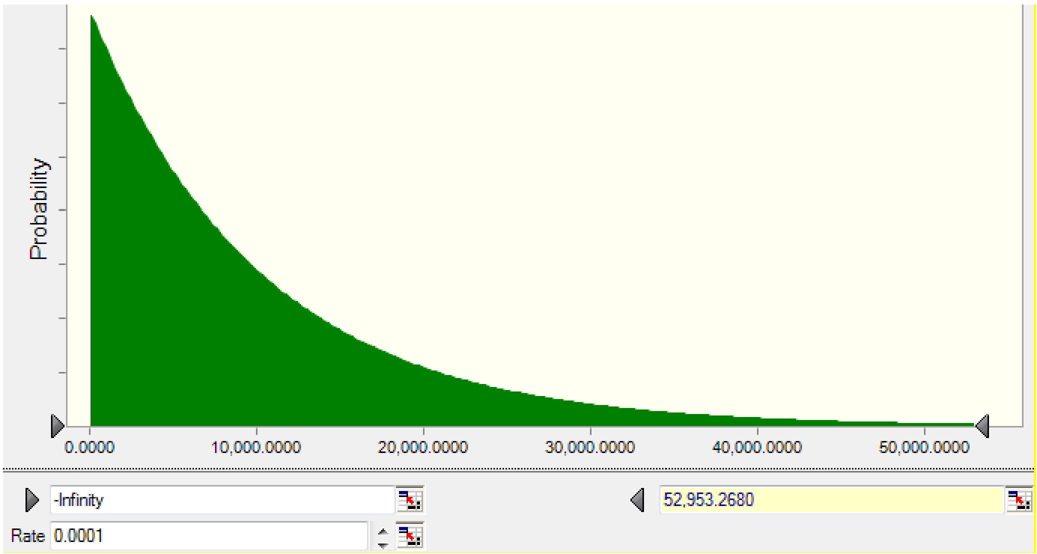
‡ Distribution relates to the summed consumption rate over all appropriate species. The maximum rate observed in the habits surveys, which is given in this table, was used as the maximum rate allowed in the assessment

A2.1 Annual consumption of seafood by people, I_{sf}

The distribution in the annual consumption rate of seafood by people, I_{sf}, has been estimated from the consumption rates reported in the habits surveys (Clyne et al, 2009, 2010, 2011, 2012; Papworth et al, 2013). These surveys were carried out between 2007 and 2012.

For each consumer identified in the habits surveys, the annual consumption rate of all species of molluscs and crustaceans have been summed within each phyla, the resulting values then being used to define the distribution in the annual consumption rate. As the annual consumption rate of seafood is defined by a distribution, there exists the mathematical possibility that very high rates could be included in the assessment, albeit with a very low probability. Such high rates are considered not to be realistic in terms of what people actually eat; the maximum consumption rate permitted in the distribution has therefore been constrained to be the maximum rate observed in the habits surveys. If a consumer eats double the maximum quantity of seafood that has been assumed, the health risk would still be very low (see Section 3.1 of the main report).

The values used to define the distributions for adult and child consumption rates are given in Table A5, while the shape of the distributions for adult consumption rates of molluscs and crustaceans are shown in Figures A4 and A5, respectively. The shapes of the distributions for child consumption rates are similar to those for adults.

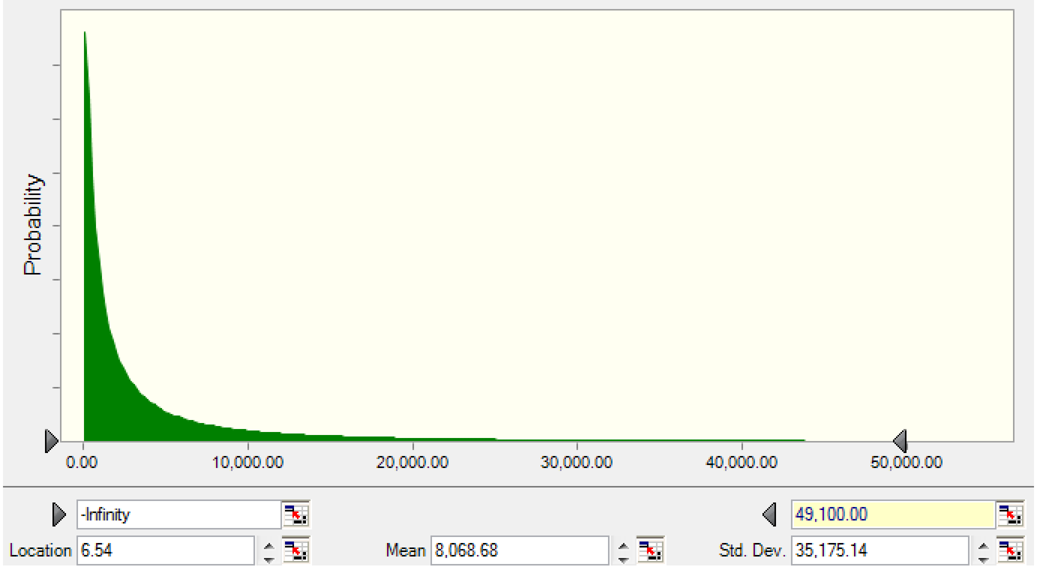


-Infinity

52,953.2680

Rate 0.0001

Figure A4: Distribution in the annual adult consumption rate of crustaceans (the *x*-axis gives the rate in g y^{-1})



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49,100.00

Location 6.54

Mean 8,068.68

Std. Dev. 35,175.14

Figure A5: Distribution in the annual adult consumption rate of molluscs (the *x*-axis gives the rate in g y^{-1})

A2.2 Mass of material consumed by molluscs and crustaceans, F_f

The distribution of values for the mass of material consumed by molluscs and crustaceans, and the fraction of that material that is sediment, has been estimated from information in the literature. This information indicates that the amount of food ingested by an animal is related to a number of factors, including how much food is present in the environment; when the animal last consumed something; the size of the animal; the salinity of the water; the water temperature; and the stage of life of the animal. In addition, information has only been found for a few species of animals, most of which are not found along the Cumbrian coast – for example, Jørgensen and Spiridonov (2013), like many other authors, report findings made on King crabs which are normally found in arctic waters. The paucity of information has led to a simplifying approach being taken in this assessment and the assumption made that the behaviour of all species of molluscs and crustaceans is similar. A summary of information found on the daily intake of material by molluscs and crustaceans, together with the values selected to define the distribution in parameter F_f, is given in Table A6.

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 A6 have therefore been estimated from information on the mass of material consumed per animal and

Table A6: Daily mass of material consumed by molluscs and crustaceans expressed as a fraction of live weight, F_f

Animal	Minimum	Average	Maximum
Molluscs*			
Winkle[†]	–	0.004	–
Periwinkle[‡]	0.0003	–	0.003
Representative values	**0.0003**	**0.005**	**0.01**
Crustaceans			
King/Snow crabs[§]	0.05	0.1	0.12
Lobsters[¶]	–	–	0.66
Nephrops[#]	–	–	0.25
Representative values	**0.05**	**0.1**	**0.25**

* The values for molluscs were estimated using an average live body weight of winkles of 6 g (Wilkins et al, 1998). Although other species of molluscs can have a greater live weight – Jaeschke et al (2015) reported experiments which used mussels with a 12 g live weight, for example – use of the potentially lower winkle body weight to derive the fractions in this table is cautious

† From Vives et al (2006), estimated from an ingestion rate of 26 mg per day and the average body weight

‡ From Watson (1985), estimated from an ingestion rate of 2–16 mg per day and the average body weight

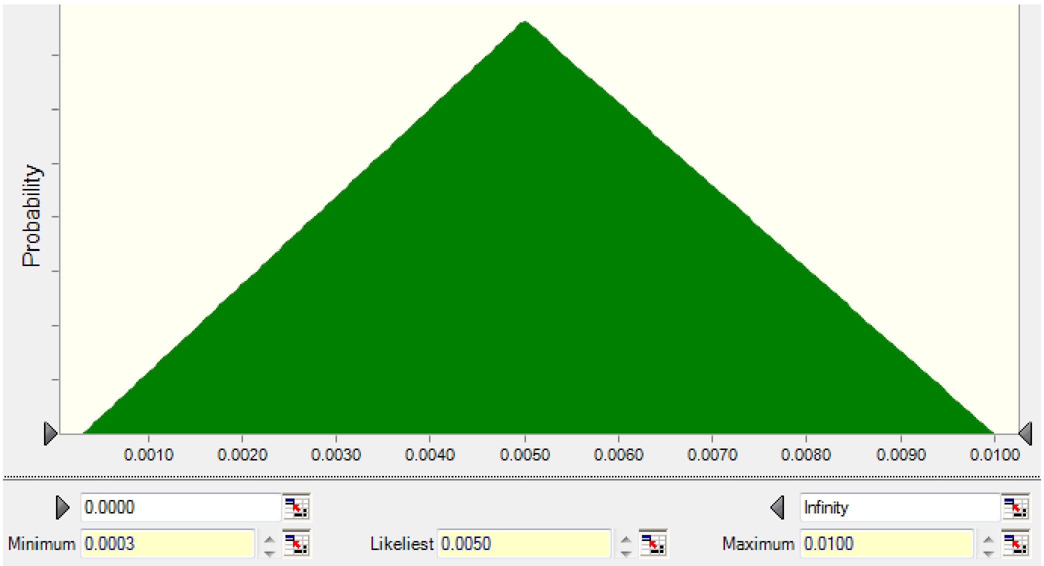
§ From Jørgensen and Spiridonov (2013)

¶ From Factor (1995), where it was stated that the production of 80,000 1-lb lobsters requires about 24 metric tons of foodstuffs per day, noting that some unspecified fraction of this food would not be consumed and therefore wasted

\# From Sarda and Valladares (1990)

a representative animal live weight. Given the sparse data, there is no clear indication of a maximum value for the range and a value has been chosen taking into account the range of live weights for molluscs.

For crustaceans, the minimum and average representative values given in Table A6 were based on limited observations on crabs (it should be noted that these species of crabs are not found around the Sellafield site). The maximum representative value was selected to be based on a value at the upper end of the range observed in the environment for different species of crustaceans. The distributions for the parameter F_f are shown in Figures A6 and A7 for molluscs and crustaceans, respectively.



0.0000

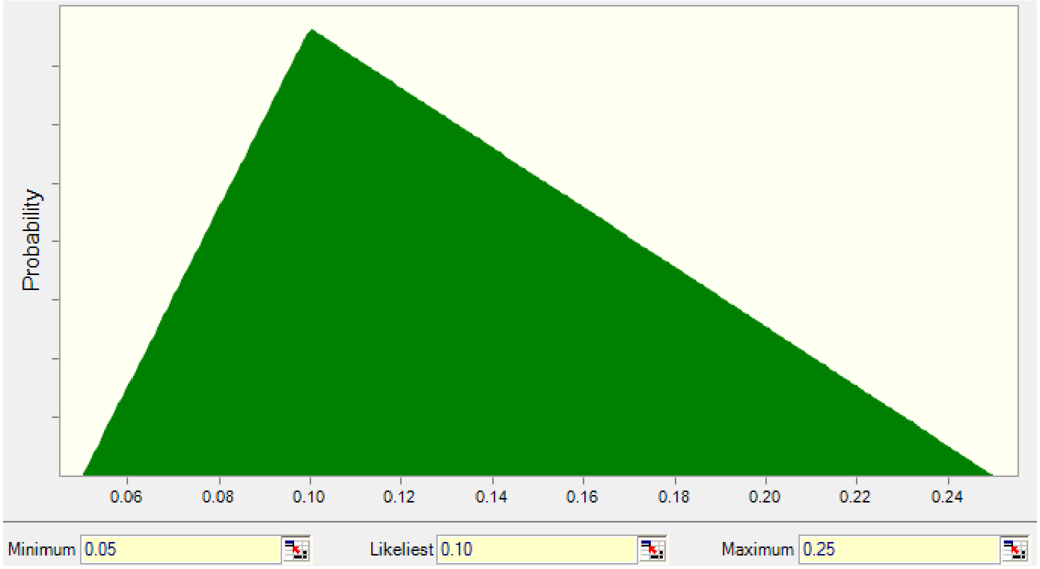
Infinity

Minimum 0.0003

Likeliest 0.0050

Maximum 0.0100

Figure A6: Distribution in the amount of material consumed daily by molluscs, expressed as a fraction of the animal's body mass, F_f



Minimum 0.05

Likeliest 0.10

Maximum 0.25

Figure A7: Distribution in the amount of material consumed daily by crustaceans, expressed as a fraction of the animal's body mass, F_f

A2.3 Fraction of material consumed by molluscs and crustaceans that is sediment, F_s

Table A7 summarises information from the literature used to derive the distribution on the fraction of material consumed by molluscs and crustaceans which comprises sediment rather than food, F_s. For molluscs, the minimum and maximum values were based on values found in the literature. The average value was assumed to be midway between the minimum and maximum values. For crustaceans, only a single value was found in the literature which was assumed to be representative of an average value. As no information was found regarding the potential range F_s could take for crustaceans it was assumed that this would be similar to that found in molluscs, equivalent to about ±50% of the average.

Table A7: Fraction of material consumed by molluscs and crustaceans that is sediment, F_s

Animal	Minimum	Average	Maximum
Molluscs			
Winkles*	0.1	–	0.2
Representative values	**0.1**	**0.15**	**0.2**
Crustaceans			
Spiny lobster†	–	0.02	–
Representative values	**0.01**	**0.02**	**0.03**

* From Beecham (2008)

† From Goes and Lins-Oliveira (2009)

A2.4 Fraction of gut consumed by people, F_g

The distribution in the fraction of animal gut content consumed by people, F_g, was based on a review of food preparation techniques. For molluscs, it has been assumed that the entire gut is consumed and F_g has a value of one with no associated distribution. For crustaceans, it has been assumed that only some of the gut content is consumed, although many factors, including personal preference and the skill with which the meat is extracted from the body without rupturing the digestive system, affect this value. Judgement has been used to account for these factors and to define the distribution in F_g for crustaceans, given in Table A8.

Table A8: Values used to define the distribution* of the fraction of gut content consumed, F_g

Distribution type	Minimum	Mean	Maximum
Crustaceans	0	0.05	0.1

* The terminology used in this table matches that used by Crystal Ball to define the distribution

A2.5 Fraction of live weight of animals consumed by people, F_e

The fraction of an animal which is edible, F_e, depends on the species and whether all or only some of the available meat is consumed. Tables A9 and A10 show, respectively, the values found in the literature for this parameter for molluscs and crustaceans. Based on the published data, a set of representative values has been used to define the distribution in F_e for use in the assessment; these values are also given in Tables A9 and A10. The distribution in F_e for crustaceans is given in Figure A8; the shape of the distribution for molluscs is very similar.

Table A9: Edible fraction* of molluscs, F_e

Animal	Minimum	Average	Maximum
Mussel†	0.2	–	0.5
Mussel‡	–	0.3	–
Mussel§	–	–	0.6
Clam§	0.25	–	0.3
Winkle¶	0.27	–	0.29
Winkle#	0.21	0.23	0.25
Representative values	**0.2**	**0.3**	**0.5**

* The edible fraction of molluscs has been assumed to be composed of every part of the animal except the shell

† From http://cooking.stackexchange.com/questions/27215/what-is-the-proportion-of-edible-meat-in-whole-live-mussels

‡ From www.streetdirectory.com/food_editorials/cooking/seafood_recipes/mussels_a_wonderful_delicay_in_belgium.html

§ From www.sallybernstein.com/food/columns/harlow/mussels.htm

¶ From Vives et al (2005)

From Wilkins et al (1998)

A2.6 Validation of approach for calculating the mass of sediment, M_s

The approach described above to estimate the mass of sediment inside marine animals, M_s, from the product of F_s and F_f, made best use of the available information. However, the mass of sediment in different animals is known to be highly variable, with its value depending on many characteristics of both the animals and their environment (Bard and Drinnan, 1957). The above approach, using the product of parameters F_s and F_f, has been validated against an alternative approach for molluscs.

McKay and Fox (1991) and McKay and Halliwell (1994) measured the amount of inorganic material and aluminium inside molluscs and expressed that quantity as a percentage of the shelled weight of the animal; McKay and Fox stated that these materials could be used to give an indication of the mass of sediment inside the animals. As the inorganic content and aluminium fraction measured were expressed as a fraction of the total shelled weight, and not the mass of the animal's gut, the measurements in the paper could not be used directly in the assessment. However, that data can be used to place an upper bound on the mass of sediment in the animal's gut.

Table A10: Edible fraction of crustaceans, F_e

Animal	Minimum	Average	Maximum
Crab*	0.4	0.44	0.48
Crab[†] (meat)	–	0.25	–
Crab[‡] (meat)	–	0.25	–
Crab[§] (meat)	–	0.25	–
Lobster*	0.27	0.3	0.36
Lobster[¶] (meat)	–	0.2	–
Lobster[#] (meat)	0.16	–	0.66
Prawn[‖] (meat)	–	0.5	–
Shrimp[Δ] (meat)	–	0.5	–
Representative values	**0.2**	**0.3**	**0.5**

* From Wilkins et al (1998)

† From http://forums.egullet.org/topic/129657-how-much-crab-meat-in-a-crab/

‡ From www.ifish.net/board/showthread.php?t=267659

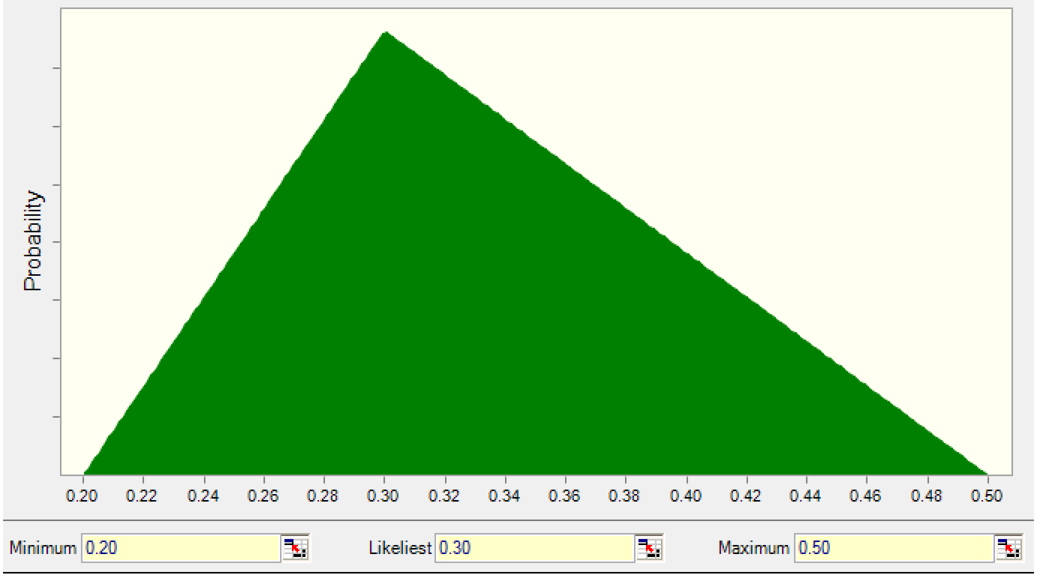
§ From www.scod.com/cities/crabs/crabfacts.html

¶ From www.discusscooking.com/forums/f16/lobster-meat-question-21971.html

From www.bayleys.com/seafood-facts.php

‖ From www.coles.com.au/our-range/our-products/fish-and-seafood/how-to-buy-and-cook-seafood/how-to-buy-and-cook-prawns

Δ From http://chowhound.chow.com/topics/866293



Minimum 0.20 Likeliest 0.30 Maximum 0.50

Figure A8: Distribution in the edible fraction of crustaceans, F_e

From the information presented in McKay and Fox (1991) and McKay and Halliwell (1994), the mass of sediment ingested when consuming molluscs, M_s, was estimated using the following equation:

$$M_s = I_{sf} F_a$$

where I_{sf} = annual consumption rate of seafood by people (g y^{-1})
F_a = fraction of consumed animal mass that is sediment

Based on measurements reported by McKay and colleagues, the parameter F_a was defined with the values given in Table A11.

Table A11: Values used to define the distribution* in the fraction of consumed mollusc mass that was sediment, F_a

Distribution type	Minimum	Mean	Maximum
Triangular	$1\ 10^{-5}$	0.01	0.03

* The terminology used in this table matches that used by Crystal Ball to define the distribution

A2.7 Number of particles per gram of sediment, N_g

The number of objects per gram of sediment, N_g, was calculated using the following equation:

$$N_g = \frac{N_m}{D\ R\ S_d}$$

where N_g = number of particles per gram of sediment
N_m = number of particles per m^2 of beach
D = depth of sediment in which the particle population was assumed to be evenly distributed (0.15 m and 0.4 m for alpha- and beta-rich particles, respectively – Oatway et al, 2011)
R = packing ratio of sediment
S_d = density of sediment (g m^{-3})

The number of particles in unit area of beach, given in Table A12, was obtained from Etherington et al (2012), where the number of alpha- and beta-rich particles in unit area of beach were estimated by scaling the number of detected particles by the probability of detecting each particle. The probability of detecting a particle depends on its radionuclide content and activity and on its location. When estimating the particle population it has been assumed that the number density of particles remains constant down to a depth equivalent to that where there is about a 0.1% probability of detection; this is about 0.15 m and 0.4 m for alpha- and beta-rich particles, respectively. Due to the large uncertainties associated with low detection probabilities, particles with an activity of less than 3 kBq were not considered when estimating the number of particles present in unit area; this is consistent with the approach adopted for estimating the number of particles on beaches in Etherington et al (2012). The number of particles in unit area of beach has been assumed to have no distribution.

Table A12: Estimated number of particles in unit area of beach, N_m

		Braystones	Sellafield
Alpha-rich	Particles per ha*	6	15
	Particles per m^2	$6.0\ 10^{-4}$	$1.5\ 10^{-3}$
Beta-rich	Particles per ha	0.43	0.67
	Particles per m^2 †	$4.3\ 10^{-5}$	$6.7\ 10^{-5}$

* From Etherington et al (2012)
† From Oatway et al (2011)

The distribution in values used to define the packing ratio and the density of sediment has been obtained from information in Wilkins et al (1998) and SEPA (2007), respectively. Both of these distributions have been assumed to be triangular. The values used to define the distribution for these parameters are given in Table A13.

Table A13: Values used to define the distribution* in the packing ratio of sand, *R*, and the density of sediment, S_d

Parameter	Distribution	Minimum	Likeliest	Maximum
R, packing ratio of sand†	Triangular	0.55	0.56	0.6
S_d, density of sediment (g m^{-3})‡	Triangular	$1.44\ 10^6$	$1.79\ 10^6$	$2.08\ 10^6$

* The terminology used in this table matches that used by Crystal Ball to define the distribution
† From Wilkins et al (1998)
‡ From SEPA (2007)

A3 Detailed results

Table A14 presents the estimated health risk from the consumption of radioactive particles in seafood; the 2.5th, 50th and 97.5th percentiles are given for adults and children. Table A15 presents the total health risk from consuming radioactive particles assuming that the mass of sediment inside an animal was estimated using the measurements made by McKay and Fox (1991) and McKay and Halliwell (1994). As expected, the health risks estimated using the measurements of McKay and colleagues are up to a factor of five higher than those given in Table A14; however, the health risks estimated using the two approaches can be considered to be broadly consistent.

Table A16 presents the estimated probability of consuming a particle; the 2.5th, 50th and 97.5th percentiles of the distribution are given for adults and children.

Table A17 presents the effective dose that would be received if a particle is consumed in seafood; the 2.5th, 50th and 97.5th percentiles of the distribution in the results are given for adults and children.

Table A14: Health risk* from consuming either an alpha- or beta-rich particle in seafood

		Alpha-rich particles		Beta-rich particles	
	Percentile	Molluscs	Crustaceans	Molluscs	Crustaceans
Adult	2.5th	$3.0\ 10^{-14}$	$4.4\ 10^{-14}$	$1.7\ 10^{-16}$	$1.6\ 10^{-16}$
	50th	$1.2\ 10^{-12}$	$1.9\ 10^{-12}$	$8.0\ 10^{-15}$	$7.7\ 10^{-15}$
	97.5th	$3.4\ 10^{-11}$	$2.5\ 10^{-11}$	$3.0\ 10^{-13}$	$1.5\ 10^{-13}$
Child	2.5th	$6.7\ 10^{-15}$	$8.0\ 10^{-14}$	$2.5\ 10^{-17}$	$2.0\ 10^{-16}$
	50th	$5.0\ 10^{-14}$	$6.9\ 10^{-13}$	$3.2\ 10^{-16}$	$2.7\ 10^{-15}$
	97.5th	$5.7\ 10^{-13}$	$5.3\ 10^{-12}$	$6.9\ 10^{-15}$	$4.9\ 10^{-14}$

* The distribution in health risk was estimated explicitly using the distributions in the probability of consuming a particle and in the dose assuming a particle was ingested

Table A15: Health risk from consuming either an alpha- or beta-rich particle in seafood using an alternative approach for the mass of sediment in the guts of molluscs

	Percentile	Alpha-rich	Beta-rich
Adult	2.5th	$1.6\ 10^{-13}$	$8.6\ 10^{-16}$
	50th	$6.6\ 10^{-12}$	$4.4\ 10^{-14}$
	97.5th	$1.9\ 10^{-10}$	$1.7\ 10^{-12}$
Child	2.5th	$3.4\ 10^{-14}$	$1.3\ 10^{-16}$
	50th	$2.8\ 10^{-13}$	$1.7\ 10^{-15}$
	97.5th	$3.3\ 10^{-12}$	$3.9\ 10^{-14}$

Table A16: Probability of consuming either an alpha- or beta-rich radioactive particle in seafood

		Alpha-rich particles		Beta-rich particles	
	Percentile	Molluscs	Crustaceans	Molluscs	Crustaceans
Adult	2.5th	$4.7\ 10^{-10}$	$6.7\ 10^{-10}$	$1.3\ 10^{-11}$	$1.1\ 10^{-11}$
	50th	$1.4\ 10^{-8}$	$2.3\ 10^{-8}$	$3.8\ 10^{-10}$	$3.9\ 10^{-10}$
	97.5th	$2.9\ 10^{-7}$	$1.9\ 10^{-7}$	$7.8\ 10^{-9}$	$3.2\ 10^{-9}$
Child	2.5th	$1.2\ 10^{-10}$	$1.4\ 10^{-9}$	$3.3\ 10^{-12}$	$2.3\ 10^{-11}$
	50th	$5.3\ 10^{-10}$	$7.7\ 10^{-9}$	$1.4\ 10^{-11}$	$1.3\ 10^{-10}$
	97.5th	$4.4\ 10^{-9}$	$3.4\ 10^{-8}$	$1.2\ 10^{-10}$	$5.7\ 10^{-10}$

Table A17: Effective dose received assuming an alpha- or beta-rich particle is consumed in seafood (mSv)*

	Percentile	Alpha-rich particle	Beta-rich particle
Adult	2.5th	0.24	0.04
	50th	0.94	0.23
	97.5th	3.9	1.7
Child	2.5th	0.26	0.03
	50th	1.0	0.23
	97.5th	4.2	2.8

* The distribution in the activity content across the particle population was used to calculate the distribution in doses

A4 References

Bard RH and Drinnan RE (1957). The ratio of shell to meat in Mytilus as a function of tidal exposure to air. *J Mar Sci* 22(3), 329–336.

Beecham J (2008). Literature Review on Particle Assimilation by Molluscs and Crustaceans. RL 10/08. Lowestoft, Cefas.

Brown J and Etherington G (2011). Health Risks from Radioactive Objects on Beaches in the Vicinity of the Sellafield Site. Chilton, HPA-CRCE-018.

Clyne FJ, Tipple JR, Garrod CJ and Jeffs TM (2009). Radiological Habits Survey: Sellafield, 2008. RL 02/09. Lowestoft, Cefas.

Clyne FJ, Garrod CJ and Elliot J (2010). Radiological Habits Survey: Sellafield Review, 2009. Shellfish consumption and intertidal occupancy review. RL 07/10. Lowestoft, Cefas.

Clyne FJ, Garrod CJ, Rumney P, Smedley CA and Ly VE (2011). Radiological Habits Survey: Sellafield Review, 2010. Shellfish consumption and intertidal occupancy review. RL 13/11. Lowestoft, Cefas.

Clyne FJ, Garrod CJ, Ly VE and Rumney P (2012). Radiological Habits Survey: Sellafield Review, 2011. Shellfish consumption and intertidal occupancy review. RL 05/12. Lowestoft, Cefas.

Desmond J, Sellafield Ltd (2013). Personal communication.

Etherington GE, Youngman MJ, Brown J and Oatway W (2012). Evaluation of the Groundhog Synergy Beach Monitoring System for Detection of Alpha-rich Objects and Implications for Health Risks to Beach Users. Chilton, HPA-CRCE-018.

Factor IR (1995). Biology of the Lobster *Homanus americanus*. Academic Press.

Goes CA and Lins-Oliveira JE (2009). Natural diet of the spiny lobster, *Panulirus echinatus* Smith, 1869 (Crustacea: Decapoda: Palinuridae), from São Pedro and São Paulo Archipelago, Brazil. *Braz J Biol* 69(1), 143–148.

Haylock P, PHE (2014). Personal communication.

ICRP (2007). Recommendations of the ICRP. ICRP Publication 103. *Ann ICRP* 37(2–4).

ICRP (2012). Compendium of Dose Coefficients based on ICRP Publication 60. ICRP Publication 119. Ann ICRP 41(suppl).

Jaeschke BC, Lind OC, Bradshaw C and Salbu B (2015). Retention of radioactive particles and associated effects in the filter-feeding marine mollusc *Mytilus edulis*. *Sci Total Environ* 502, 1–7.

Jørgensen LL and Spiridonov V (2013). Effect from the king- and snow crab on Barents Sea benthos. Results and conclusions from the Norwegian-Russian Workshop in Tromsø 2010. Fisken og Havet nr. 8/2013. Institute of Marine Research, Bergen, Norway, 41pp.

McKay WA and Fox AA (1991). Particulate associated nuclides in Cumbrian winkles implications for assessment of dose to man. *J Environ Radioact* 14, 1–21.

McKay WA and Halliwell CM (1994). The levels of particulate-associated nuclides in Irish Sea shellfish and the implications for dose assessment. *J Radiol Prot* 14(1), 43-53.

Oatway W, Brown J, Etherington G, Anderson T, Fell T, Eslava-Gomez A, Hodgson A, Pellow P and Youngman M (2011). Supporting Information for the Assessment of the Health Risks from Radioactive Objects on Beaches in the Vicinity of the Sellafield Site. Chilton, HPA-CRCE-018 (supplement).

Oracle (2014). Crystal Ball fusion edition. Release 11.1.2.3.000 (32-bit) (build 11.1.3436.0 on 23.5.2013).

Papworth GP, Clyne FJ, Garrod CJ, Ly VE and Dewer A (2013). Radiological Habits Survey: Sellafield Review, 2012. RL 04a/13. Lowestoft, Cefas.

Sarda F and Valladares FJ (1990). Gastric evacuation of different foods by *Nephrops norvegicus* (Crustacea: Decapoda) and estimation of soft tissue ingested, maximum food intake and cannibalism in captivity. *Mar Biol* 104(1), 25–30.

SEPA (2007). Strategy for the assessment of the potential impact of Sellafield radioactive particles on Southwest Scotland, December 2007. SEPA.

Serco (2009). Analysis of beach monitoring finds – final report issue 2. Report to Sellafield Ltd. Serco/TAS/002037/1. Warrington, Serco.

Serco (2010). Analysis of beach monitoring finds – second tranche. Report to Sellafield Ltd. ESR 78. Warrington, Serco.

Vives I Batlle J, Wilson RC, McDonald P and Parker TG (2005). Uptake and depuration of ^{131}I by the edible periwinkle *Littorina littorea*: uptake from seawater. *J Environ Radioact* 78, 51–67.

Vives I Batlle j, Wilson RC, McDonald P and Parker TG (2006). A biokinetic model for the uptake and depuration of radioiodine by the edible periwinkle *Littorina littorea*. *Radioact Environ* 8, 449–462.

Watson DC (1985). Dietary preferences of the common periwinkle *Littorina littorea*. *J Exp Mar Biol Ecol* 88, 193–211.

Wilkins BT, Fry FA, Burgess PH, Fayers CA, Haywood SM, Bexon, AP and Tournette C (1998). Radiological Implications of the Presence of Fragments of Irradiated Fuel in the Sub-tidal Zone at Dounreay. Chilton, NRPB-M1005.

Appendix B Details of the Sensitivity Analysis

For some of the parameters used in the assessment, not enough information could be found to allow the full range of their potential values to be established. For these parameters, the distributions were therefore based on judgement as well as on measurement. In order to judge the sensitivity of the estimated health risk on the parameter values chosen, a sensitivity analysis has been carried out. Details of the approach used in this sensitivity analysis, and the estimated health risk, are presented in this appendix.

B1 Presence of caesium/strontium on alpha-rich particles

Less than 1% of alpha-rich particles recovered to date contain measurable activities of ^{137}Cs. Due to the small number of these particles compared to the total population, the dose and any additional health risk from including these additional radionuclides have not been considered in the assessment. To judge the significance of this decision, an estimate of the health risk has been made assuming, as a worst case situation, that all alpha-rich particles contain ^{137}Cs and ^{90}Sr. The equations in Appendix A have been modified as detailed in this section.

The effective dose from ingesting an alpha-rich particle which also contains ^{137}Cs and ^{90}Sr has been estimated using the following equation:

$$D_{\mathrm{eff},\alpha} = \left(A_{\mathrm{m,Am}}\, F_{\mathrm{Pu}}\, DC_{\mathrm{A}}\right) + \left(A_{\mathrm{E,Cs}}\, DC_{\mathrm{Cs}}\right) + \left(A_{\mathrm{E,Sr}}\, DC_{\mathrm{Sr}}\right)$$

where $A_{\mathrm{m,Am}}$ = measured ^{241}Am activity of an alpha-rich particle (Bq), see Appendix A
F_{Pu} = factor to account for any Pu isotopes present on a particle, equal to 2
DC = dose coefficient for ingestion of the radionuclides identified by the suffix ($\mathrm{Sv\ Bq^{-1}}$), see Table A2
$A_{\mathrm{E,Cs}}$ = estimated ^{137}Cs activity present on an alpha-rich particle as a function of ^{241}Am activity (Bq)
$A_{\mathrm{E,Sr}}$ = estimated ^{90}Sr activity present on an alpha-rich particle as a function of ^{241}Am activity (Bq)

The ^{137}Cs activity associated with an alpha-rich particle was estimated by first calculating the ratio of ^{137}Cs to ^{241}Am activity for all the alpha-rich particles where both radionuclides have been measured with above minimum detectable levels of radioactivity. Due to the small number of particles meeting this criterion, a distribution could not be fitted to the resulting Cs : Am ratios. As a result, it has been assumed that all alpha-rich particles have a ^{137}Cs activity equal to the ^{241}Am activity scaled by the maximum ratio of ^{137}Cs to ^{241}Am activity, that is:

$$A_{\mathrm{E,Cs}} = R_{\mathrm{Cs:Am}}\, A_{\mathrm{m,Am}}$$

where $A_{\mathrm{E,Cs}}$ = estimated ^{137}Cs activity present on alpha-rich particles (Bq)
$R_{\mathrm{Cs:Am}}$ = maximum measured ratio of ^{137}Cs to ^{241}Am activity on alpha-rich particles (0.005)
$A_{\mathrm{m,Am}}$ = measured activity of ^{241}Am on alpha-rich particles (Bq)

Table B1 presents the estimated health risk from the consumption of alpha-rich particles in seafood assuming that all particles contain ^{241}Am, Pu isotopes, ^{137}Cs and ^{90}Sr. Comparing Tables B1 and A14 shows the difference in the health risk – with ^{137}Cs and ^{90}Sr either present or not present on alpha-rich particles – is less than about 2% at the 97.5th percentile, although at lower percentiles this difference is up to about 10%.

Table B1: Health risk from consuming an alpha-rich particle in seafood, assuming the additional presence of ^{137}Cs and ^{90}Sr

	Percentile	Molluscs	Crustaceans
Adult	2.5th	$3.1\ 10^{-14}$	$4.4\ 10^{-14}$
	50th	$1.2\ 10^{-12}$	$1.9\ 10^{-12}$
	97.5th	$3.4\ 10^{-11}$	$2.5\ 10^{-11}$
Child	2.5th	$7.0\ 10^{-15}$	$8.3\ 10^{-14}$
	50th	$5.1\ 10^{-14}$	$7.1\ 10^{-13}$
	97.5th	$5.7\ 10^{-13}$	$5.4\ 10^{-12}$

B2 Presence of americium/plutonium on beta-rich particles

About 10% of beta-rich particles recovered to date contain ^{241}Am with activities above the limits of detection. Due to the small number of such particles compared to the population of beta-rich particles, the assessment has not considered the effects on the doses and health risk from ^{241}Am and Pu isotopes on beta-rich particles. To judge the significance of the decision, an estimate of the health risk has been made assuming, as a worst case situation, that all beta-rich particles contain ^{241}Am and Pu isotopes.

The effective dose from ingesting a beta-rich particle containing ^{241}Am and Pu isotopes was estimated using the following equation:

$$D_{\mathrm{eff},\beta} = \left(A_{\mathrm{E,Am}}\, F_{\mathrm{Pu}}\, DC_{\mathrm{Am}}\right) + \left(A_{\mathrm{E,Sr}}\, DC_{\mathrm{Sr}}\right) + \left(A_{\mathrm{m,Cs}}\, DC_{\mathrm{Cs}}\right)$$

where $A_{\mathrm{E,Am}}$ = estimated ^{241}Am activity present on a beta-rich particle as a function of ^{137}Cs activity (Bq)

F_{Pu} = factor to account for any Pu isotopes present on a particle, equal to 2

DC = dose coefficient for ingestion of the radionuclides identified by the suffix (Sv Bq^{-1}), see Table A2

$A_{\mathrm{m,Cs}}$ = measured ^{137}Cs activity on beta-rich particles (Bq), see Appendix A

$A_{\mathrm{E,Sr}}$ = estimated ^{90}Sr activity present on a beta-rich particle as a function of ^{137}Cs activity (Bq)

The ^{241}Am activity associated with beta-rich particles was estimated using the following equation:

$$A_{\mathrm{E,Am}} = \left(\frac{A_{\mathrm{m,Am}}}{A_{\mathrm{m,Cs}}}\right) A_{\mathrm{m,Cs}}$$

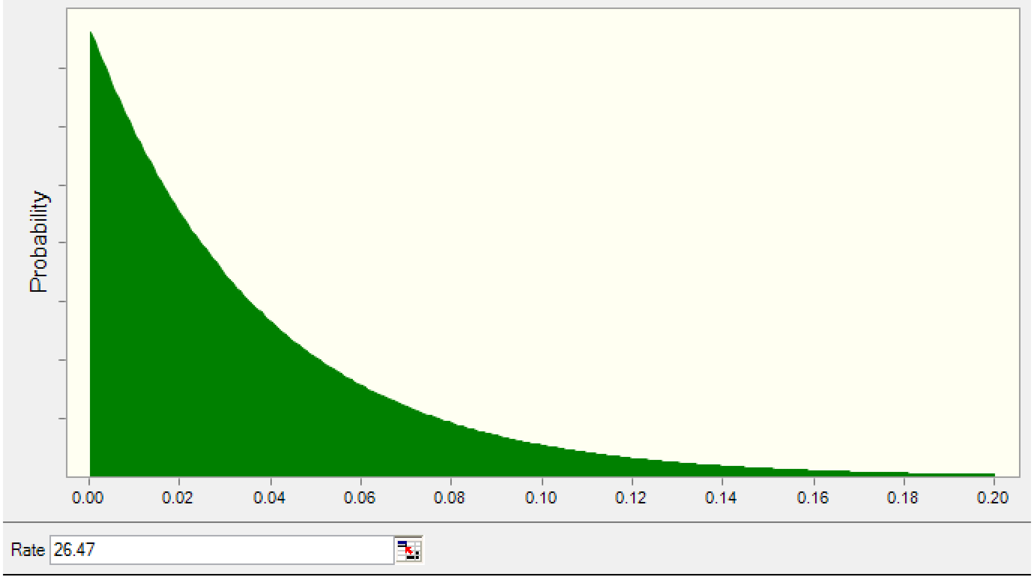
where $A_{E,Am}$ = estimated ^{241}Am activity present on beta-rich particles (Bq)
$A_{m,Am}$ = measured ^{241}Am activity present on alpha-rich particles (Bq)
$A_{m,Cs}$ = measured ^{137}Cs activity present on beta-rich particles (Bq)

The distribution for the parameter $A_{m,Cs}$ is given in Table A3, while that for the ratio of ^{241}Am to ^{137}Cs is given in Table B2 and shown in Figure B1.

Table B2: Values used to define the distribution* of ^{241}Am to ^{137}Cs activity associated with beta-rich particles, $A_{E,Am}$

Distribution type	Rate
Exponential	26.47

* The terminology used in this table matches that used by Crystal Ball to define the distribution



Rate 26.47

Figure B1: Distribution in the ratio of ^{241}Am to ^{137}Cs activity associated with beta-rich particles, $A_{E,Am}$

Table B3 presents the estimated health risk from consumption of beta-rich particles in seafood, assuming that all particles contain ^{241}Am, Pu isotopes, ^{137}Cs and ^{90}Sr. Comparing Tables B3 and A14 shows the difference in the health risk – with ^{241}Am and Pu isotopes either present or not present on beta-rich particles – is less than about 2% at the 97.5th percentile. At the 97.5th percentile, ^{137}Cs and ^{90}Sr are present at much higher activities than ^{241}Am and Pu isotopes and so dominate the dose. However, at lower percentiles of the distribution, inclusion of ^{241}Am and Pu isotopes on beta-rich particles is estimated to increase the health risk by up to 17%. This is because ^{241}Am and Pu isotopes are present with relatively high activities compared to ^{137}Cs and ^{90}Sr and the contribution to the dose from ^{241}Am and Pu isotopes relative to that from ^{137}Cs and ^{90}Sr is higher.

Table B3: Health risk from consuming a beta-rich particle in seafood, assuming the additional presence of ^{241}Am and Pu isotopes

	Percentile	Molluscs	Crustaceans
Adult	2.5th	$1.8\ 10^{-16}$	$1.6\ 10^{-16}$
	50th	$8.7\ 10^{-15}$	$8.3\ 10^{-15}$
	97.5th	$3.3\ 10^{-13}$	$1.6\ 10^{-13}$
Child	2.5th	$2.8\ 10^{-17}$	$2.2\ 10^{-16}$
	50th	$3.5\ 10^{-16}$	$2.9\ 10^{-15}$
	97.5th	$7.3\ 10^{-15}$	$5.0\ 10^{-14}$

B3 Fraction of crustacean gut contents consumed by people, F_g

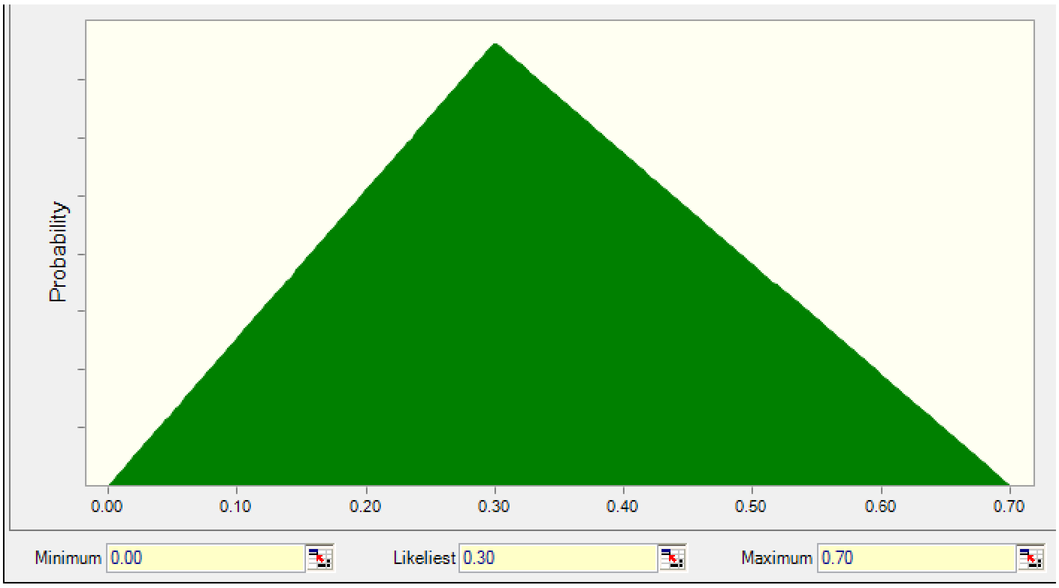
In Table A8, the values used to define the distribution in the fraction of gut content consumed for crustaceans, F_g, were based on a review of food preparation practices. However, individual preference and skill may affect this parameter significantly and previous assessments – see, for example, Wilkins et al (1998) – used higher values, although the basis for those values is not clear. A sensitivity analysis has therefore been undertaken to assess the impact on the health risk assuming that a far greater fraction of the gut content is consumed. This could occur through contamination of meat by poor preparation practices or by deliberate consumption of larger parts of the gut. For the sensitivity analysis, the distribution in F_g for crustaceans has been assumed to be defined using the values in Table B4, as shown in Figure B2.

Table B4: Values used to define the distribution* in the fraction of sediment ingested when consuming crustaceans, F_g

Distribution type	Minimum	Mean	Maximum
Triangular	0	0.3	0.7

* The terminology used in this table matches that used by Crystal Ball to define the distribution

Table B5 presents the estimated health risk when consuming a cautiously high fraction of crustacean gut content. Comparing the values of the estimated health risk in Table B5 with those in Table A14 shows that the health risk increases by a factor directly proportional to the amount of gut content consumed – for example, increasing the maximum fraction from 10% to 70% increases the 97.5th percentile health risk by up to a factor of about seven.



Minimum 0.00

Likeliest 0.30

Maximum 0.70

Figure B2: Distribution in the fraction of sediment ingested when consuming crustaceans, F_g

Table B5: Health risk from consuming either an alpha- or beta-rich particle in seafood, assuming a higher fraction of crustacean gut content is consumed

	Percentile	Alpha-rich particle	Beta-rich particle
Adult	2.5th	2.9 10^{-13}	1.0 10^{-15}
	50th	1.2 10^{-11}	5.0 10^{-14}
	97.5th	1.7 10^{-10}	1.0 10^{-12}
Child	2.5th	5.2 10^{-13}	1.2 10^{-15}
	50th	4.7 10^{-12}	1.7 10^{-14}
	97.5th	3.6 10^{-11}	3.2 10^{-13}

B4 Reference

Wilkins BT, Fry FA, Burgess PH, Fayers CA, Haywood SM, Bexon AP and Tournette C (1998). Radiological Implications of the Presence of Fragments of Irradiated Fuel in the Sub-tidal Zone at Dounreay. Chilton, NRPB-M1005.