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Cefas Environment Report RL 13/09

A report on the investigation of the Cefas monitoring database for incidences of high activities in sediment samples

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A report on the investigation of the Cefas monitoring database for incidences of high activities in sediment samples

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FSA project ERI 0005
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Contents

1. Summary

The Food Standards Agency (FSA) is investigating the possible transfer of radioactive particles from the marine environment to the foodchain. In order to facilitate this investigation, the Centre for Environment, Fisheries and Aquaculture Science (Cefas) has interrogated relevant sections of their monitoring database. This database contains extensive details of the radiological monitoring programme and analytical results undertaken by Cefas on behalf of the FSA and others, culminating in the annually published Radioactivity in Food and the Environment (RIFE) report.

The practice of reporting annual mean sediment concentrations, by substrate and collection location, in RIFE is not sufficient to distinguish the contribution of one high-level concentration from a series of slightly raised concentrations. By comparing individual analyses to a nuclide-dependent screening level, it is intended to identify any high-level concentrations that may indicate the presence of a radioactive 'hot' particle within the sample.

The motivating factor behind the current interest in radioactive particles entering the foodchain is the collection of 'hot' particles found in the vicinity of the Sellafield nuclear site in Cumbria over the past two years. Similar cases of radioactive particles being found on beaches and in the marine environment around nuclear sites have been recorded in the past, including at Sellafield, and so, whilst this report focuses on recent events at Sellafield, the method and analysis could be potentially applied at other locations around the United Kingdom.

2. Background

Beach monitoring trials in November 2006 and January 2007, carried out on Sellafield and Braystones beaches, detected a number of radioactive 'particles' at depths of up to 120 mm. The precise source of the particles is unknown, but appears to be a combination of historic and recent releases (Environment Agency, 2007), although it should be noted that Sellafield is not currently authorised to discharge particulate material from the site. Subsequent monitoring of the beaches on a stretch of coastline from St Bees Head, 13 km north of the Sellafield site, to Ravenglass, 8 km south of the site, is ongoing, and has detected further contaminated particles. The physical nature of these particles varies, from contaminated grains of sand of ~200 micron minimum diameter to stones of a few cm diameter, and a piece of wire of ~3000 microns length by <400 microns diameter.

In order for the FSA to initially assess the risk posed to the public by these particles, via the consumption of fish and shellfish that had in turn consumed a radioactive particle, Cefas produced a report on the size of particles typically consumed by molluscs and crustacea (Beecham, 2008). This report reviewed the literature on the subject and concluded that particles of up to 1 mm (1000 microns) minimum diameter could be consumed, albeit those

particles above ~200 microns were likely to have been inadvertently ingested. The paucity of peer-reviewed data concerning particle size ingestion led the FSA to request further investigation from Cefas in order to supplement this initial report and provide a broader basis for subsequent risk assessments.

It is reasonable to assume that the collection of contaminated objects found to date is not exhaustive, and that due to the nature of the beach monitoring equipment, particles with higher specific activities are more likely to be found. However, there may be radioactivity associated with particles in the marine environment formed from environmental processes, with specific activities considerably lower than those of the hot particles. Depending upon the magnitude of the specific activities, the particulate discharges may be practically indistinguishable from environmentally derived radioactive particles.

3. Cefas' monitoring database

Cefas conducts an annual surveillance programme involving the radioanalysis of a number of marine samples from locations associated with nuclear sites. Samples include fish, crustacea, molluscs, seaweed, sediments and seawater, and these are analysed by radiometric and radiochemical methods to determine the activity concentrations of a range of radionuclides.

Individual analytical results are recorded and maintained on a LIMS database along with collection date and location, and each sample is assigned a unique identification number. The results of this monitoring and analysis programme are then used to derive an annual mean activity concentration for each sample type at each monitoring location, and these data are collated to form an important part of the RIFE series of reports (for example, Environment Agency *et al.*, 2008).

To assist the FSA in their assessment of the risk posed to the foodchain by hot particles in the environment, Cefas were requested to investigate the monitoring database for any anomalously high activity concentrations in sediment samples from the Sellafield area, which may indicate the presence of a contaminated particle. This information, alongside that of the consumption habits of molluscs (Beecham, 2008) could then be used to further quantify the risk posed to seafood consumers by 'hot' particles.

A study of high activity concentrations in mollusc samples has recently been conducted (Jenkinson, 2008). This study concluded that the Cefas database did not contain any evidence of contamination of mollusc samples by a 'hot' particle, although this may be a result of quality control mechanisms designed to re-analyse samples when an erroneous count is suspected.

4. Data Analysis

In order to enable the differentiation of high activity concentrations due to hot particles from those due to temporal and spatial variation, this investigation has focused on four radionuclides. These are: cobalt-60, ruthenium-106, caesium-137 and americium-241, each of which has been detected in particles found on the Sellafield beaches. There are insufficient analysis results for plutonium isotopes in sediments.

Data from the past ten years' sediment sampling and analysis programme were obtained. This was then filtered by radionuclide and substrate. Approximately 250 sample results were available for each of the four nuclides. The different substrates are mud, sandy mud, muddy sand, sand, and turf. Finer-grained substrates typically exhibit higher radionuclide activity concentrations, due in part to the larger surface area available for radionuclide sorption.

The filtered dataset was used to derive a mean activity concentration, excluding results at the limit of detection, over this ten-year period for comparison with individual analyses. In the first instance, a screening level was set that triggers further investigation of individual samples. This initial screening level was set to three times the mean concentration for that nuclide over each substrate, such that if the mean concentration recorded over the ten-year period were, say, 20 Bq kg^{-1} then the screening level would be 3 x 20 = 60 Bq kg^{-1}, and any individual results above this level would be considered possible indicators of particle contamination.

Where samples with activities greater than the screening level were identified, further filtering of the dataset was undertaken in order to compare the high-level sample with samples collected from the same location (as a check on spatial variability between different sampling sites). If the high-level sample had a concentration greater than three times the mean concentration of this subset (excluding the high-level sample), the associated sample was further considered as being possibly contaminated. It should be noted that there is still a possibility that environmental mechanisms (other than hot particles) may be responsible for a sample exceeding both screening methods (such as the influence of historic discharges), and the current methodology cannot differentiate a low-activity 'hot' particle from sediment contaminated by historical (relatively high) authorised liquid discharges.

In the following sections of this report, when a reference is made to a sample being contaminated by a radioactive particle, the implication is that this particle is 'hot' (i.e. a particle discharge from source).

Cobalt-60

The results of 252 cobalt-60 analyses for sediment samples were extracted from the Cefas monitoring database. Twenty-five of these results were below detection limits, and were therefore not included in the subsequent analysis. Table 1 gives a breakdown of these analyses by substrate, and also indicates the number of samples that exceeded the initial and secondary screening levels.

Table 1 – *Breakdown by substrate of cobalt-60 analyses and comparison with screening levels*

Substrate	***No. of samples[a]***	***Mean concentration (Bq kg^{-1}, dry)***	***Samples exceeding screening level:***	
			Initial	***Secondary***
Mud	64	26	2	0
Sandy mud	37	30	0	0
Muddy sand	34	8.3	2	2
Sand	71	4.1	0	0
Turf	21	3.3	0	0

a – Above LoD

Two mud samples exceeded the initial screening level of 78 Bq kg^{-1}, one from Newbiggin in 1998 (86 Bq kg^{-1}) and the other from Carleton Marsh in 2000 (79 Bq kg^{-1}). Neither of these samples, however, exceeded their respective secondary screening levels of 149 Bq kg^{-1} and 108 Bq kg^{-1}, and so these samples were not considered to be potentially contaminated by radioactive particles.

The only other cobalt-60 analyses to exceed the initial screening level were two muddy sand samples collected from Millom in 1998. The activity concentrations of 54 and 46 Bq kg^{-1} were also above the secondary screening level of 30 Bq kg^{-1}, based on the mean concentration of 10 Bq kg^{-1} cobalt-60 in muddy sand samples from this location. Therefore, these samples will be considered further in section 5 as potentially contaminated by radioactive particles.

Ruthenium-106

There are 252 ruthenium-106 results for sediment samples from the Sellafield and Solway area, though 149 of these, particularly those in sand and turf, are recorded as being at the limits of detection. These LoD analyses are not included in the calculation of mean concentrations and screening levels. Table 2 shows the breakdown of the remaining ruthenium-106 analyses by substrate, as well as the mean concentrations and numbers of candidate samples for contamination.

Table 2 – *Breakdown by substrate of ruthenium-106 analyses and comparison with screening levels*

Substrate	***No. of samples[a]***	***Mean concentration (Bq kg^{-1}, dry)***	***Samples exceeding screening level:***	
			Initial	***Secondary***
Mud	45	155	2	1
Sandy mud	36	91	0	0
Muddy sand	19	37	1	1
Sand	3	11	0	0
Turf	0	N/A	0	0

a – Above LoD

Two mud samples exceeded the initial screening level of 465 Bq kg^{-1}, one from Carleton Marsh recording a concentration of 581 Bq kg^{-1} and one from Whitehaven Yacht Basin with 482 Bq kg^{-1}. Both of these samples were taken in 1998. The secondary screening level at the Whitehaven Yacht Basin is 676 Bq kg^{-1}, and so this sample is no longer considered to be potentially contaminated. The mean concentration of ruthenium-106 in mud samples from Carleton Marsh, excluding the sample referred to above, is 140 Bq kg^{-1}. This implies a secondary screening level of 420 Bq kg^{-1}, which is below the activity concentration recorded in the high-level sample from this location. The Carleton Marsh sample is discussed in section 5 as a potential indicator of contamination with a hot particle.

The only other sample to exceed the substrate-dependent initial screening level was a muddy sand sample, with an activity concentration of 179 Bq kg^{-1}. This sample was taken from Millom in 1998. The secondary screening level at this location is 87 Bq kg^{-1}, and so this sample is also considered to be potentially contaminated.

Caesium-137

Two hundred and fifty-two caesium-137 results from sediment samples, taken over the past ten years from the specified locations, were extracted from the Cefas database. All of these samples contained activity concentrations above the limit of detection. Table 3 shows the breakdown of substrates and mean concentrations, as well as the number of samples to exceed the screening levels.

Table 3 – *Breakdown by substrate of caesium-137 analyses and comparison with screening levels*

Substrate	***No. of samples[a]***	***Mean concentration (Bq kg^{-1}, dry)***	***Samples exceeding screening level:***	
			Initial	***Secondary***
Mud	65	448	1	1
Sandy mud	37	284	1	1
Muddy sand	52	164	1	0
Sand	72	80	0	0
Turf	26	573	0	0

a – Above LoD

Three sediment samples were found to have exceeded the initial screening levels, one each for the mud, sandy mud and muddy sand substrates. The muddy sand sample, taken at Millom in 1998, contained 498 Bq kg^{-1} caesium-137. This was only slightly above the initial screening level, and was found to be below the secondary screening level of 546 Bq kg^{-1} for this location and substrate.

The mud sample, taken from Carleton Marsh in 2005, had a notably high concentration of 5150 Bq kg^{-1}, an order of magnitude greater than both the overall mean for that substrate and for this particular location. Hence, this sample comfortably exceeded the secondary screening level of 1390 Bq kg^{-1} and will be considered further in section 5.

The sample of sandy mud which exceeded the initial screening level for caesium-137 had a concentration of 1060 Bq kg^{-1}. This was taken in 2005 at Raven Villa, in the Ravenglass estuary. The secondary screening level for this location is 783 Bq kg^{-1}, and so this sample is also retained for further consideration.

Americium-241

The Cefas monitoring database contains 255 americium-241 results for sediment samples obtained from 1998 to 2007 around Sellafield and the Solway estuary. All but one of these samples recorded activity concentrations above the limit of detection. Table 4 shows the sample numbers and mean concentrations for each substrate.

Table 4 – *Breakdown by substrate of americium-241 analyses and comparison with screening levels*

Substrate	***No. of samples[a]***	***Mean concentration (Bq kg^{-1}, dry)***	***Samples exceeding screening level:***	
			Initial	***Secondary***
Mud	68	858	1	1
Sandy mud	37	660	1	1
Muddy sand	52	182	2	1
Sand	71	204	1	1
Turf	26	272	0	0

a – Above LoD

The sandy mud sample that exceeded the secondary screening level was from Raven Villa, with an activity concentration of 2130 Bq kg^{-1} recorded in a 2005 sample. The mean of all other samples from this location and substrate is 630 Bq kg^{-1}, giving a secondary screening level of 1890 Bq kg^{-1}. This sample is retained as a potential indicator of hot particle contamination. Also retained for further discussion is a sample of muddy sand taken at Millom in 1998. The activity recorded in this sample is 1050 Bq kg^{-1}, compared with a secondary screening level of 820 Bq kg^{-1}.

Finally, a sand sample taken from the Sellafield pipeline in 2003 has an activity concentration of 1890 Bq kg^{-1}, an order of magnitude greater than the mean concentration in sand. This sample also comfortably exceeds the secondary screening level of 550 Bq kg^{-1} and will be considered further in section 5.

5. Discussion

The analysis by dataset filtering identified ten individual sediment analyses that, due to exceeding a secondary location-specific screening level, could be considered as being potentially contaminated by a radioactive particle. A summary of these samples is shown in Table 5, indicating that ten analyses were conducted on just six separate sediment samples. Sample 1998006369, muddy sand from Millom, provided three of the high-level concentrations, and samples 2005001700 and 2005001701, sandy mud from Raven Villa and mud from Carleton Marsh respectively, provided two each. Further details of these analyses, and those exceeding thee initial screening level, can be found in Annex 1.

In determining whether any of the samples listed in Table 5 may indeed have been contaminated by a radioactive particle, as opposed to being a sediment sample which has become associated with a relatively high level of the authorised radioactive discharge, it is useful, although not conclusive, to compare the sample concentrations with the specific activities found in 'hot' particles recovered from the Sellafield beaches. In the absence of a firm definition of what activity level would constitute a 'hot' particle, the results of analysis conducted on the recovered particles provide us with a rough 'fingerprint' against which Cefas' sediment samples can be compared.

Table 5 – *Summary of samples with concentrations exceeding secondary screening levels for one or more of the selected nuclides*

Substrate	***Sample location***	***Sample ID***	***Collection date***	***Nuclide***
Mud	Carleton Marsh	1998001560	22/04/1998	Ru-106
	Carleton Marsh	2005001701	30/11/2005	Cs-137 Am-241
Sandy mud	Raven Villa	2005001700	29/11/2005	Cs-137 Am-241
Muddy sand	Millom	1998006369	14/09/1998	Co-60 Ru-106 Am-241
	Millom	1998007103	12/11/1998	Co-60
Sand	Sellafield pipeline	2003000457	09/01/2003	Am-241

The particles found on the beaches around Sellafield have been analysed by Sellafield's own laboratories as well as the National Physical Laboratory, and found to contain a variety of radionuclides. Dominant amongst these nuclides, in terms of both activity and presence, are caesium-137 and americium-241. High levels of plutonium isotopes have also been found, although in relatively few of the particles recovered thus far. Particles tend to be enhanced in either caesium-137 or americium-241, and plutonium-rich particles typically have high levels of americium-241 as well.

Caesium- and americium-rich particles have been recovered with activities above 10^5 Bq, though 10^3 – 10^4 Bq is more characteristic. Where plutonium isotopes are found to be present, activities of ~10^5 Bq plutonium-241 and ~10^4 Bq plutonium-238 and plutonium-239 are typical. A small number of particles containing high levels of cobalt-60 have been recovered, and these have activities of the order 10^3 Bq. Owing to the high caesium-137 levels in many of the recovered particles, levels of ruthenium-106 are difficult to quantify, and consequently are stated as being below the limit of detection.

An additional factor for consideration when comparing concentrations in sediment samples to levels in 'hot' particles is the method of analysis. The method employed to analyse routine surveillance monitoring samples is not designed to quantitatively identify a highly active point source, owing to differing sample geometries and instrument calibration. All of the sediment samples considered in the current report were analysed using gamma spectroscopy with sample sizes of between 0.25 and 0.5 kg, implying that the specific activities of these samples would be between a quarter and a half of the reported unit weight. Due to the nature of gamma spectroscopy, some self-shielding of the sample can also be expected, particularly for lower energy gamma-emitters such as americium-241, and this will be exacerbated if the activity in the sediment sample is concentrated at a point away from the detector. Consequently, the reported activity concentration of any sediment sample may not accurately reflect the specific activity of a radioactive particle contained therein, but rather assumes a degree of homogeneity across the sample.

Bearing this in mind, we now consider each of the samples in Table 5. Sample 1998001560, a mud sample from Carleton Marsh containing a raised concentration of ruthenium-106, is difficult to classify, as ruthenium levels in Sellafield hot particles have not been accurately determined. The concentration in this sample is 580 Bq kg^{-1}, approximately five times the mean concentration of all ruthenium-106 mud analyses extracted from the database for this report. Significantly, other mud samples taken in 1998 provide the next three highest ruthenium concentrations, which may suggest that deeper layers of sediment, reflecting historic Sellafield discharges, had become exposed prior to this time period. A counter to this argument is the concentration of caesium-137 and americium-241 in this sample – deeper sediments would be expected to have elevated levels of these nuclides, as they were discharged in larger quantities in the 1970s and 1980s, but concentrations show little deviation from the mean for this substrate and location. Additionally, there is no record, to our knowledge, of a radioactive

hot particle displaying elevated activity levels of ruthenium-106 alone, without the presence of either caesium-137 or americium-241. Time-trend data of ruthenium-106 concentrations in *Porphyra* at Seascale, sampled weekly since 1998, shows a marked peak indicative of an increased discharge of this radionuclide around this time. The size of this peak is approximately five times the mean concentration in subsequent years, and so it seems very likely that the raised concentrations found in mud samples in 1998 are simply a reflection of increased inputs to the marine environment from Sellafield.

Another Carleton Marsh mud sample, number 2005001701, contained very high concentrations of both caesium-137 (5.1 kBq kg^{-1}) and americium-241 (8.7 kBq kg^{-1}). Despite the presence of both nuclides in this sample, in contrast to the observed trend for Sellafield beach particles to exhibit contamination by only one of these two nuclides, such high concentrations would be consistent with the presence of a hot particle of typical specific activity. However, the elevated concentrations found in this sample triggered the quality control mechanisms in place in the radioanalytical laboratory at Cefas, and this sample was divided and reanalysed. Each of the divided sub-samples contained comparable levels of caesium-137 and americium-241 activity, and so it was concluded that these levels were representative of the sediment sample as a whole, rather than the presence of a hot particle in one portion of the sample. Low levels of the short-lived nuclide cobalt-60 indicate that this sample was of older sediments that were associated with higher historic discharges of caesium-137 and americium-241.

The procedure of re-analysing samples when an erroneous count is suspected is standard quality control practice. The monitoring and analysis programme is designed to provide a reflection of the prevailing environmental levels of radionuclides that have been released under authorisation from licensed nuclear sites, rather than identify potential contamination by unauthorised, highly active particles. The current climate regarding particle contamination, and the search for hot particles in general, is likely to ensure that any future marine samples displaying activity concentrations above the ‘normal’ range (those that would typically lead to reanalysis) are treated as potentially contaminated by a particle of the type that are being found on the beaches around Sellafield.

The only sample of sandy mud to yield nuclide concentrations in excess of the secondary screening level was from Raven Villa, in the Ravenglass Estuary. This sample, number 2005001700, was collected one day prior to the Carleton Marsh mud sample discussed above. It too had elevated levels of caesium-137 (1.1 kBq kg^{-1}) and americium-241 (2.1 kBq kg^{-1}), but a lower than expected cobalt-60 concentration, indicating older sediments associated with historic Sellafield discharges. It is likely, due to the dynamic environment in which these two samples (2005001700 and 2005001701) were collected, that the samples consisted primarily of sub-surface material, with contamination typical of greater historic discharges from Sellafield. We therefore assume that these samples are not contaminated by a radioactive hot particle.

Activity concentrations in sample 1998006369, muddy sand from Millom, exceeded the secondary screening level for three of the nuclides under consideration. Cobalt-60 (54 Bq kg^{-1}), ruthenium-106 (180 Bq kg^{-1}) and americium-241 (1050 Bq kg^{-1}) were all elevated with respect to the mean concentration for this substrate and location in the current dataset (see Annex 1). The concentration of caesium-137 in this sample exceeded the initial screening level. Of potential significance is that the subsequent sample from this location (1998007103), collected two months later, also contained elevated concentrations of all four nuclides, although only that of cobalt-60 exceeded the secondary screening level (see Table 5). Liquid discharges of cobalt-60 from Sellafield increased in the late 1990s, so it is conceivable that an authorised discharge 'pulse' was transported to the Millom area, where it became associated with the sediment. This could also explain the relatively high levels of the other radionuclides. The fact that raised concentrations of all four nuclides were found in successive samples increases the likelihood that natural processes are responsible, and so we consider the probability that either of these samples is contaminated by a radioactive particle to be very small.

The final sample to provide an activity concentration above a secondary screening level was a sand sample from the Sellafield pipeline area. Gamma spectrometry analysis showed an elevated americium-241 level of almost 1.9 kBq kg^{-1}, some ten times the mean concentration at this location. Levels of the other three nuclides in this sample were unremarkable. After conversation with radioanalytical staff, and confirmation that no re-analysis had been conducted at the time, the sample was recalled from Cefas' storage facility.

The presence of a hot particle was confirmed by dividing the sample and presenting each portion to a small-diameter scintillation probe. Repeating this method, the particle was eventually isolated from the sand (see Figure 1) and subjected to an initial gamma analysis, which confirmed the presence of americium-241 with approximate activity levels of a few kBq. To obtain a more accurate measurement, the gamma detector was recalibrated using an americium-241 point source of similar size to the hot particle. Subsequent analysis revealed an activity of 2.2 kBq from the particle, whilst the concentration of americium-241 in the remainder of the sand sample was now just 170 Bq kg^{-1}.

The presence and amount of plutonium in the hot particle has not been determined, as this would require further radiochemical analysis, although it could potentially be estimated using other plutonium:americium ratios from the Sellafield area.

Subject to the consent of the sample owners, the hot particle will now be offered to those organisations responsible for the investigation of the Sellafield foreshore and the analysis of radioactive items found there.

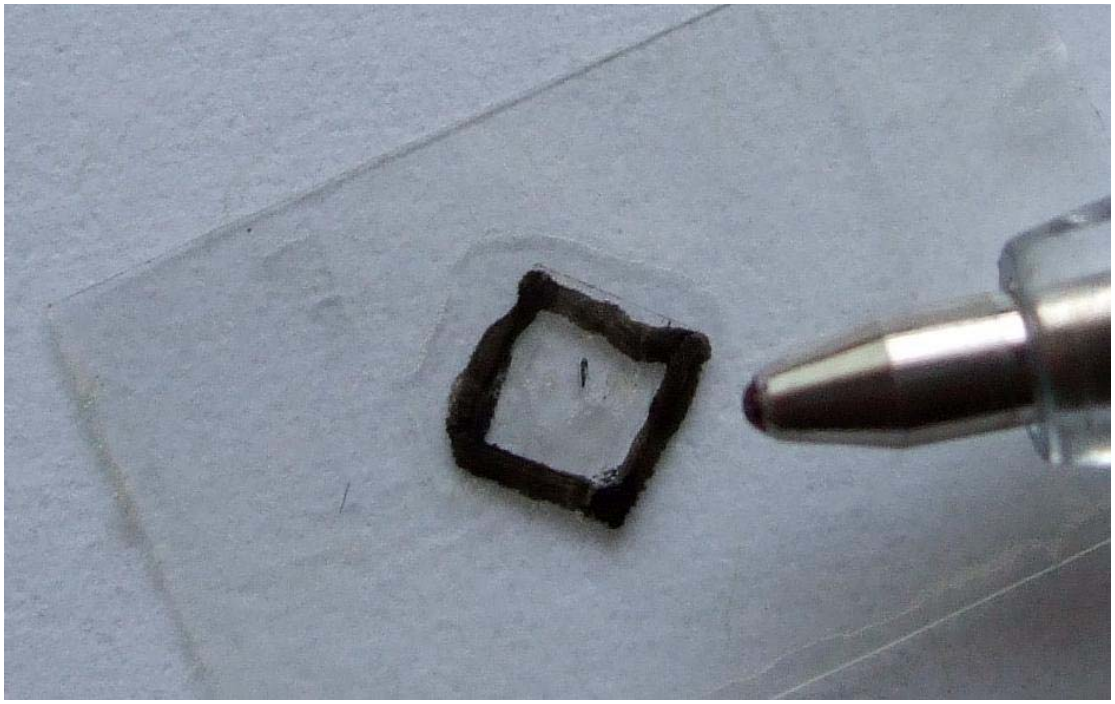

Figure 1 - *Hot particle found in a 2003 sample of sand from the Sellafield pipeline area. The sample was re-analysed as part of this project, and the particle isolated. The particle is the small dark sliver near the centre of the black box. A biro tip is shown alongside to indicate the comparitive size.*

6. References

Beecham, J. (2008). *A literature review on particle assimilation by molluscs and crustaceans*, Cefas Environment Report RL 10/08, Lowestoft.

Environment Agency (2007). *Radioactive particles in the environment around Sellafield*, Environment Agency Progress Report March 2007, Bristol.

Environment Agency, Environment & Heritage Service, Food Standards Agency and Scottish Environment Protection Agency (2008). *Radioactivity in Food and the Environment, 2007 (RIFE 13)*, Bristol, Belfast, London, Stirling.

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Annex 1 – Further details of high-level samples

Further details of all particles exceeding the initial screening level are provided in Tables A1 – A4. The initial screening level is the mean of all analyses above the limit of detection for that nuclide and substrate. The secondary screening level is the mean of all analyses, excluding the sample in question, from that location, as a check on the spatial variation of nuclide concentrations.

Table A1 - *Cobalt-60 analyses exceeding the initial screening level. Highlighted concentrations also exceeded the secondary screening level*

Substrate (Location)	***Sample ID (Collection date)***	***Concentration (Bq kg^{-1}, dry)***	***Initial screening level (Bq kg^{-1})***	***Secondary screening level (Bq kg^{-1})***
Mud (Carleton Marsh)	2000002807 (28/04/2000)	79.4	78.6	104
Mud (Newbiggin)	1998006852 (19/10/1998)	86.8	78.6	121
Muddy sand (Millom)	1998006369 (14/09/1998)	53.8	25	25
Muddy sand (Millom)	1998007103 (12/11/1998)	46.4	25	26

Table A2 - *Ruthenium-106 analyses exceeding the initial screening level. Highlighted concentrations also exceeded the secondary screening level*

Substrate (Location)	***Sample ID (Collection date)***	***Concentration (Bq kg^{-1}, dry)***	***Initial screening level (Bq kg^{-1})***	***Secondary screening level (Bq kg^{-1})***
Mud (Carleton Marsh)	1998001560 (22/04/1998)	581	466	424
Mud (Whitehaven Yacht Basin)	1998001136 (16/02/1998)	482	466	676
Muddy sand (Millom)	1998006369 (14/09/1998)	179	111	87

Table A3 - *Caesium-137 analyses exceeding the initial screening level. Highlighted concentrations also exceeded the secondary screening level*

Substrate (Location)	***Sample ID (Collection date)***	***Concentration (Bq kg^{-1}, dry)***	***Initial screening level (Bq kg^{-1})***	***Secondary screening level (Bq kg^{-1})***
Mud (Carleton Marsh)	2005001701 (30/11/2005)	5150	1350	1390
Sandy mud (Raven Villa)	2005001700 (29/11/2005)	1060	852	783
Muddy sand (Millom)	1998006369 (14/09/1998)	498	493	546

Table A4 - *Americium-241 analyses exceeding the initial screening level. Highlighted concentrations also exceeded the secondary screening level*

Substrate (Location)	***Sample ID (Collection date)***	***Concentration (Bq kg^{-1}, dry)***	***Initial screening level (Bq kg^{-1})***	***Secondary screening level (Bq kg^{-1})***
Mud (Carleton Marsh)	2005001701 (30/11/2005)	8660	2570	3150
Sandy mud (Raven Villa)	2005001700 (29/11/2005)	2130	1980	1880
Muddy sand (Millom)	1998006369 (14/09/1998)	1050	547	817
Muddy sand (Millom)	1998007103 (12/11/1998)	595	547	870
Sand (Sellafield pipeline)	2003000457 (09/01/2003)	1890	613	547

Annex 2 – Figures showing individual analysis results

The data used in this report are presented in Figures A1 – A19, and the initial screening level for each nuclide and substrate is also depicted for comparison. Analysis results below the limit of detection were neglected in this report, and are not shown. There were no positive results (above LoD) for ruthenium-106 in turf.

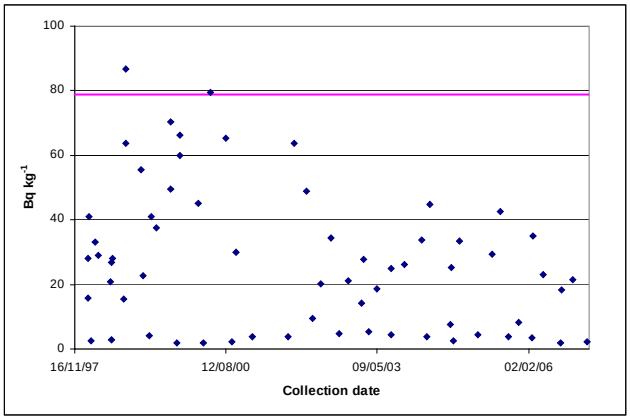

Figure A1 – Cobalt-60 concentrations in mud samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

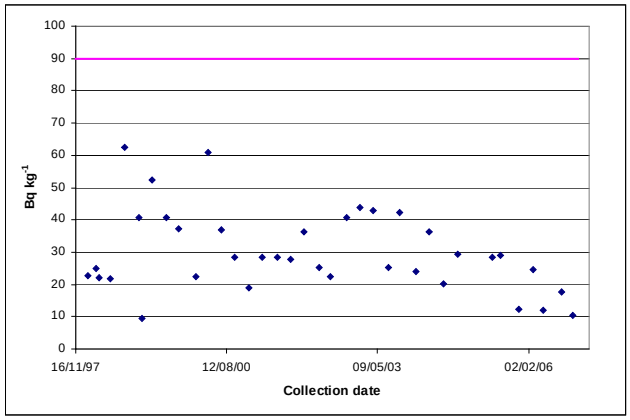

Figure A2 – Cobalt-60 concentrations in sandy mud samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

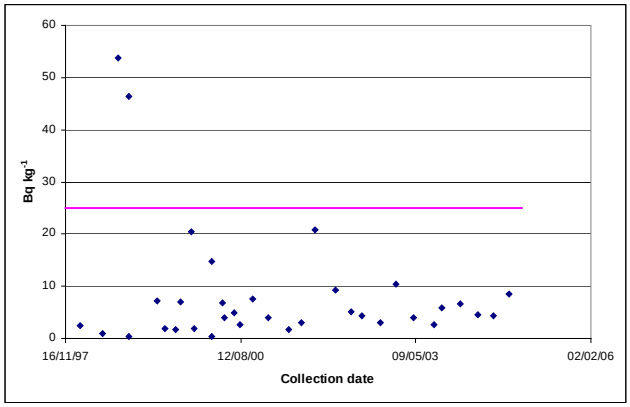

Figure A3 – Cobalt-60 concentrations in muddy sand samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

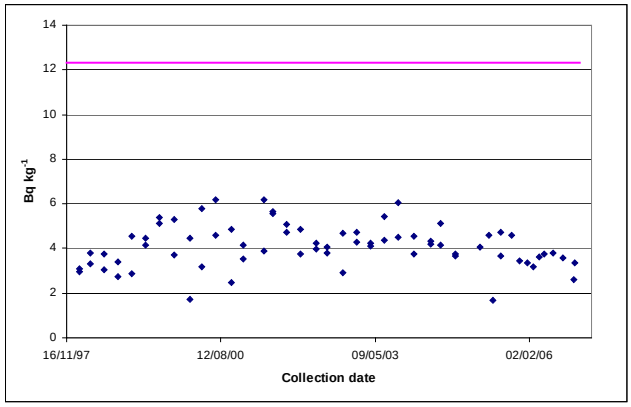

Figure A4 – Cobalt-60 concentrations in sand samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

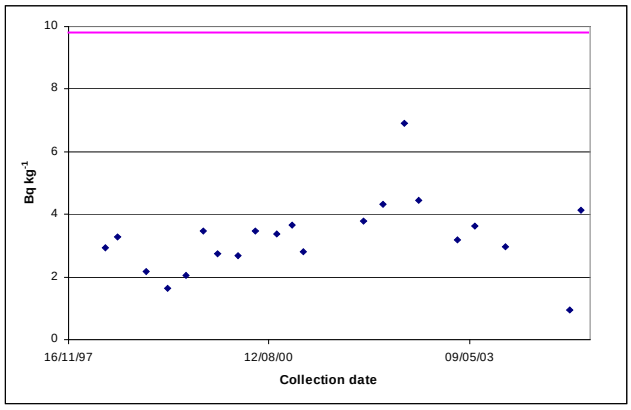

Figure A5 – Cobalt-60 concentrations in turf samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

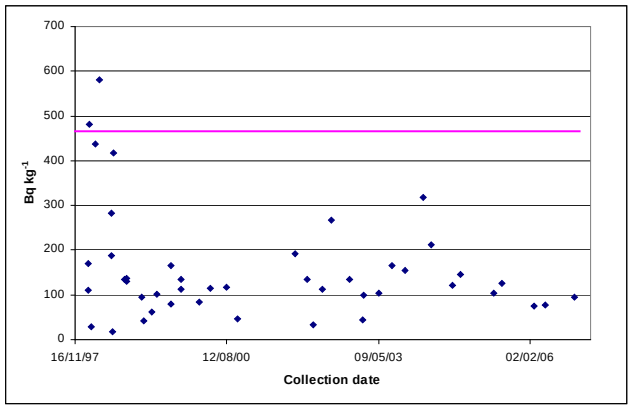

Figure A6 – Ruthenium-106 concentrations in mud samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

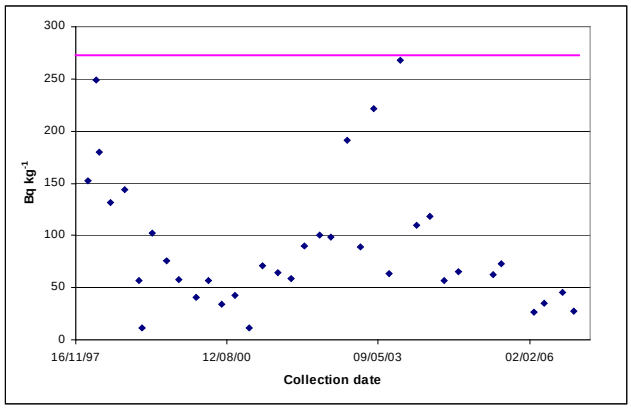

Figure A7 – Ruthenium-106 concentrations in sandy mud samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

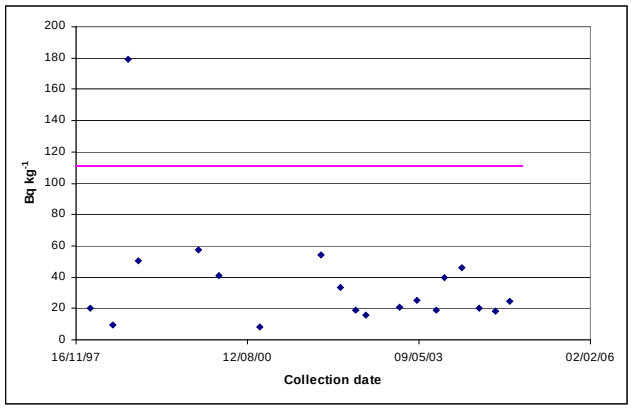

Figure A8 – Ruthenium-106 concentrations in muddy sand samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

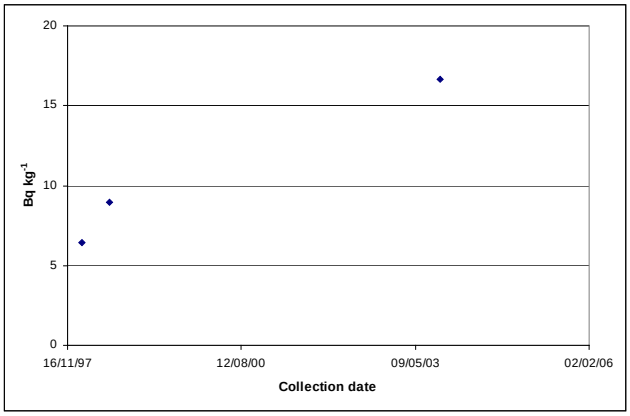

Figure A9 – Ruthenium-106 concentrations in sand samples from the Sellafield area, 1998 – 2007. The initial screening level is not applicable to a dataset of this size

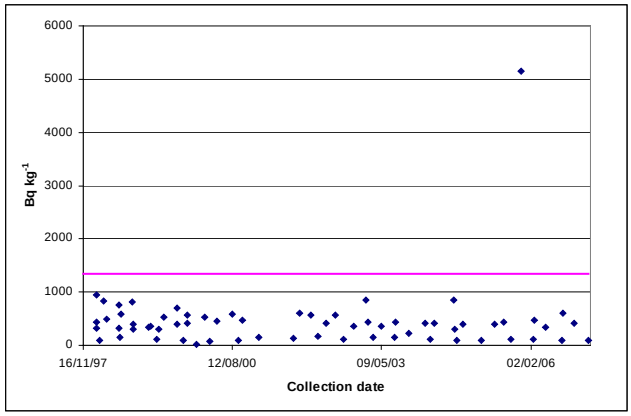

Figure A10 – Caesium-137 concentrations in mud samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

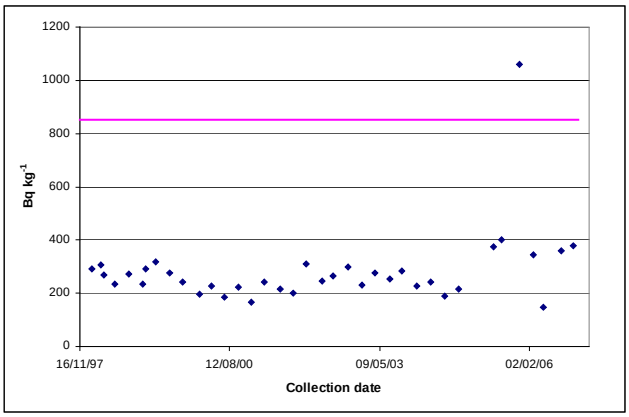

Figure A11 – Caesium-137 concentrations in sandy mud samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

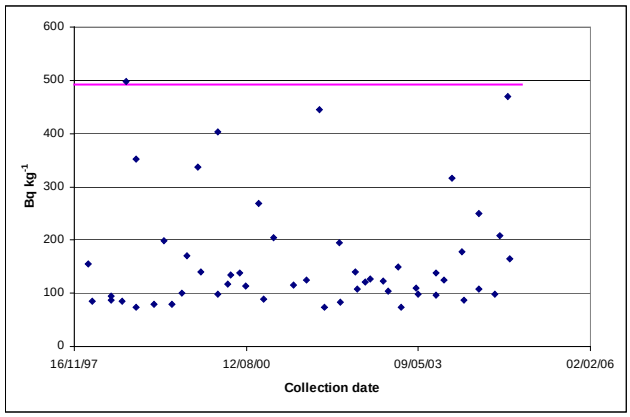

Figure A12 – Caesium-137 concentrations in muddy sand samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

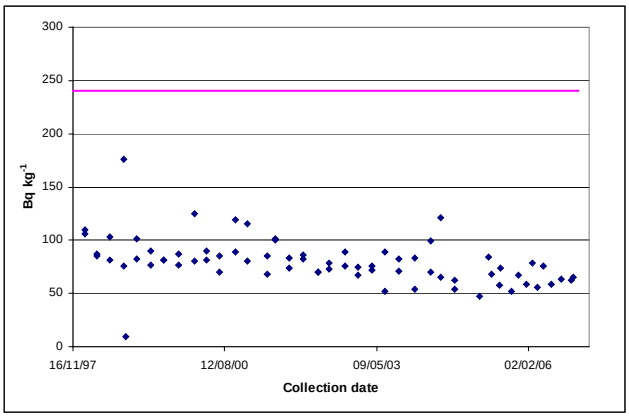

Figure A13 – Caesium-137 concentrations in sand samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

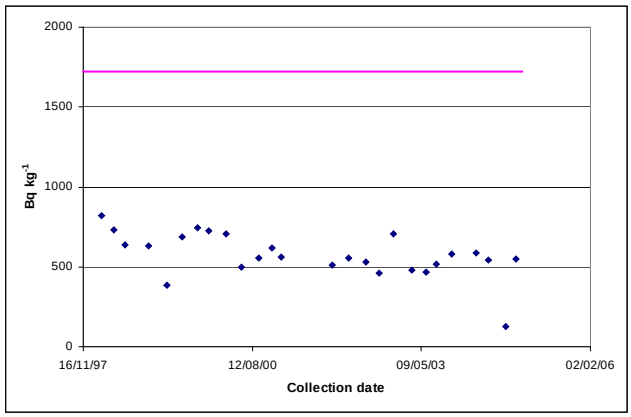

Figure A14 – Caesium-137 concentrations in turf samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

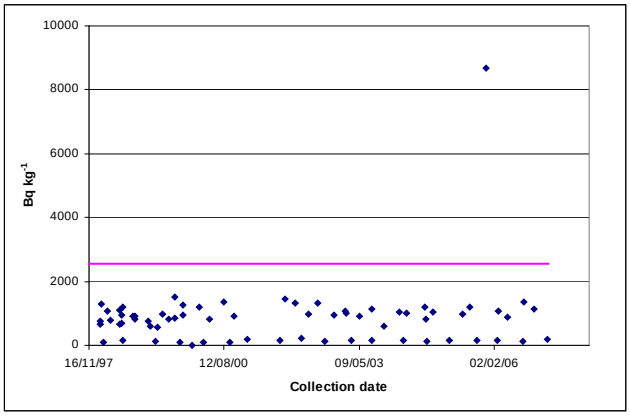

Figure A15 – Americium-241 concentrations in mud samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

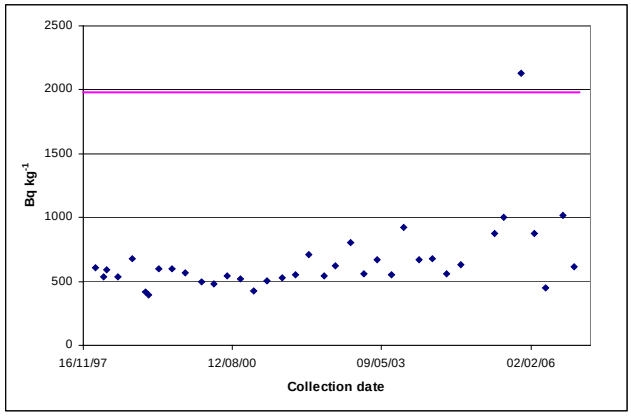

Figure A16 – Americium-241 concentrations in sandy mud samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

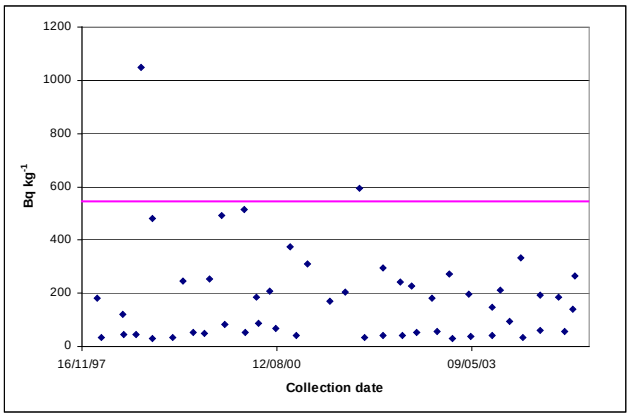

Figure A17 – Americium-241 concentrations in muddy sand samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

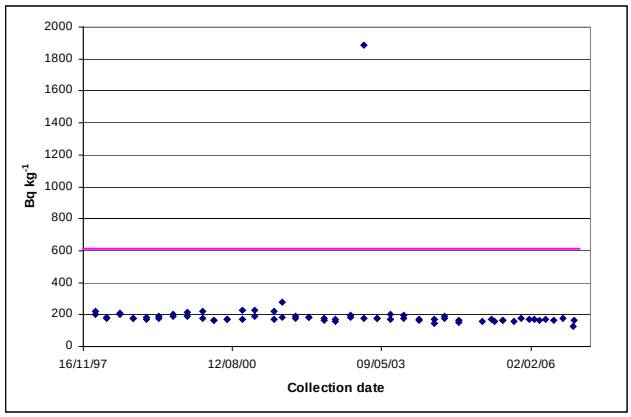

Figure A18 – Americium-241 concentrations in sand samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

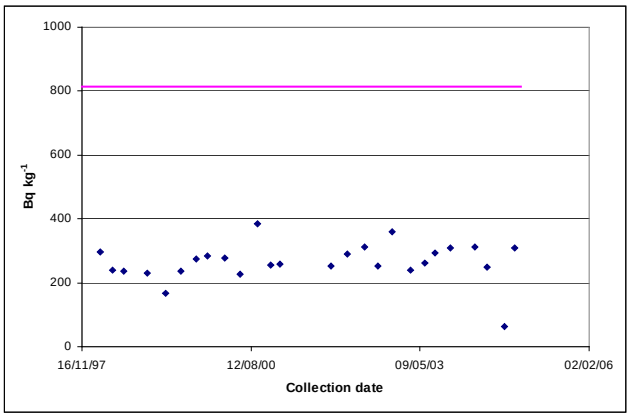

Figure A19 – Americium-241 concentrations in turf samples from the Sellafield area, 1998 – 2007. Initial screening level for this substrate also shown

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