Environment Agency

Evidence

Measurement and Assessment of External Radiation Dose Rates to People on Houseboats and using Riverbanks - using the Ribble Estuary as a case study

Report: SC060080/R4

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Miranda Kavanagh

Director of Evidence

Executive summary

This project, *Measurement and Assessment of External Radiation Dose Rates to People on Houseboats and using Riverbanks, using the Ribble Estuary as a Case Study* (SC060080) was undertaken by Enviros Consulting with support from the Environmental Radioactivity Laboratory (ERL) at the University of Stirling.

The study was commissioned by the Environment Agency in response to uncertainties over whether radiological dose assessment methodologies applied to houseboat owners and wildfowlers in the Ribble estuary area accounted for variables such as tidal inundation of channels, shielding from boat hulls and other materials, and what effect the posture of an individual has upon how their external exposure dose is calculated.

The study involved sampling sediments, gamma spectrometry analysis, and measuring beta and gamma dose rate (including in-situ gamma spectrometry). It focused on three field sites in the Ribble estuary: a boatyard where there are houseboats dwellers who are the most exposed critical group in the area; a salt marsh visited by wildfowlers; and a tidal tributary used by pleasure craft.

The study has shown that:

- External gamma dose rate is dominated by caesium-137 arising from historical discharges from the Sellafield Ltd site. The contribution from discharges from the Springfields Fuels Ltd site is minimal.
- Gamma dose rates one metre above sediment were between 35 and 55 nanograys (nGy) per hour (about 30 nGy per hour of which was from natural levels of radioactivity in soils and sediment). Due to variations in topography at the sites visited, the variation in gamma dose with height above sediment was not consistent. However, higher dose rates were often found part way up bank sides where older sediments of higher activity may be exposed.
- Gamma dose rate measurements made adjacent to a tidal channel are influenced by the extent of tidal inundation over the sediment in the channel. At high water they can be around 30 percent lower than those measured at low water. The influence is however quite localised (within five metres of the channel edge) and depends upon the relative contamination of the mobile intertidal sediment and that of the banks and adjacent land areas.
- Boat hulls reduced gamma dose rate by up to 50 percent (for a large boat) compared to that over intertidal sediment. However, for a small boat resting on sediment in a tidal channel there was little attenuation. For a boat in a tidal channel the effective occupancy (i.e. the time the boat was resting on exposed sediments) could be 50 percent or less (with the remaining time afloat). For a boat situated on the top of the bank, little or no time is spent afloat so the time spent resting on sediment is close to 100 percent. Assessments therefore need to take into account site-specific aspects such as size of boat, topography of the area around where it is berthed, the extent of tidal inundation and the proportion of time spent afloat or aground on sediment.
- Variation in gamma dose rate on tidal channel banks of up to 20 nGy per hour was measured, with lower values being recorded at high water. This effect was very localised.
- Overall beta dose rates over sediment were low (of a few 100 nanosieverts (nSv) per hour per square centimetre (cm^2)), the exception being Savick Brook where they were of the order of 2,000 nSv per hour per cm^2. Beta dose rate

decreased by 50 to 75 percent at a one metre height compared to that on the surface. In Savick Brook the elevated beta dose rate was due to discharges from the Springfields Fuels Ltd site to the Ribble estuary. These were however significantly reduced compared to historical measurements.

- It was found that thin or low density materials had little effect on attenuation of the beta emissions. A wax jacket and rubber waders reduced the measured beta skin dose by approximately 20 to 40 percent, while thicker rubber boots did by approximately 80 to 90 percent.

- We suggest a gray (Gy) to sievert (Sv) conversion factor for a wildfowler lying face-down on the sediment of 1.1 Sv Gy^{-1}.

- Based on monitoring data it has not been possible to recommend a specific Sv to Gy^{-1} value for an angler sat low to the ground. We suggest adoption of the generalised value of 0.85 Sv Gy^{-1} unless location-specific information is available.

This study confirmed that houseboat dwellers at the Becconsall Boatyard are the most exposed critical group, receiving around 70 microsieverts (μSv) per year from nuclear site operations. This result is consistent with findings from the statutory monitoring programme undertaken by the Environment Agency and shows that the assessment approach taken for houseboat dwellers is robust. The study has shown that this exposure is primarily due to historical discharges from the Sellafield Ltd site and that there is little contribution from the nearby Springfields Fuels Ltd site. The dose to other boat users is significantly less than that of the houseboat dwellers at Becconsall.

Dose to wildfowlers on the salt marshes are about half that received by houseboat dwellers at Becconsall and are dependent upon assumptions on habits while on the salt marsh. Significantly higher dose rates were measured in dug-out hide pits compared to those over salt marsh, and these may need to be considered in further assessments. Additionally the use of a single sievert to gray conversion factor may not be appropriate to all habits. For example, for time spent lying face-down on the ground surface, an ‘anterior-posterior’ geometry and not a ‘rotational’ geometry is recommended. This in turn would require more detailed information about wildfowler habits - specifically the percentage of time spend standing, sitting, lying down and using dug-out hide pits.

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We would also like to gratefully acknowledge Becconsall Boatyard staff who allowed us access to the boatyard and who were very helpful. We would particularly like to thank the owners of the boats who allowed us access to their vessels.

Further, we would like to thank Dr Richard Wakefield (Atkins) for input and use of background information on radioactivity in the Ribble estuary.

In addition we would like to thank Peter Burgess (Nuvia) for invaluable expert advice on instrumentation for the assessment of beta dosimetry and Mike Wood (University of Liverpool) for supply of additional field instrumentation.

Dr Adrian Punt
Project Coordinator

Contents

1 Introduction

This project, '*Measurement and Assessment of External Dose Rates to People on Houseboats and using Riverbanks, using the Ribble Estuary as a Case Study*' (SC060080) was undertaken by Enviros Consulting with support from the Environmental Radioactivity Laboratory (ERL) at the University of Stirling. The aim was to investigate the relationship between measured external beta and gamma dose rates in the Ribble estuary, associated radionuclide activity concentrations in soil and sediments, tidal processes and consequential doses to people who live on houseboats and/or spend time on riverbanks and salt marshes around the estuary.

1.1 Background

The Environment Agency has a statutory power to assess applications for, and authorise, discharges of radioactivity to the environment under the Environmental Permitting Regulations (2010). This is done to ensure protection of the public and the environment. As part of this work, the Environment Agency undertakes routine monitoring around nuclear licensed sites in England and Wales.

The Ribble estuary in Lancashire receives liquid radioactive effluent discharged from the Springfields Fuels Limited site (Springfields), a nuclear licensed site located to the north of the estuary near to Preston. This effluent is discharged under an Environment Agency authorisation. The Springfields site is owned by the Nuclear Decommissioning Authority (NDA) and managed by Westinghouse Electric UK Ltd on their behalf. The site manufactures a range of uranium fuel products for existing nuclear power stations; in future this may be extended to support the fuel needs for prospective new nuclear build. In 2006, the site's Uranium Ore Concentrate purification process was closed. This process provided fuel for the Magnox fleet of reactors, most of which have now ceased operating. As a consequence of the closure, discharges of the short-lived beta-emitting radionuclides thorium-234 (Th-234) and protactinium-234m (Pa-234m) to the Ribble estuary were significantly reduced.

In addition to the discharges from the Springfields site, the Ribble estuary receives some of the radioactivity discharged to the Irish Sea from nuclear fuel reprocessing at the Sellafield Ltd site (Sellafield), which is transported southward down the coast[1],. Radionuclides from nuclear fuel reprocessing at the Sellafield site include caesium-137 (Cs-137), cobalt-60 (Co-60) and americium-241 (Am-241). Over recent years significant abatement processes have been implemented and discharges are now considerably lower.

There are also operational nuclear power stations in the vicinity of the Ribble estuary. Heysham is situated on the coast about mid-way between the Sellafield site and the Ribble, and has two separate nuclear power stations each operated by British Energy (part of the EDF Group). Wylfa is a Magnox nuclear power station located on Anglesey, and is owned by the NDA. The discharges from these stations are very small in comparison to current or historical discharges from the Sellafield site.

Some radionuclides have a tendency to bind with sedimentary particles, particularly in turbid estuarine conditions. Radionuclides with this tendency include isotopes of

[1] This can occur through two key process: i) particles of sediment from the Irish Sea to which radionuclides have adsorbed may be swept into the estuary on the flood tide and may be subsequently deposited in the estuary; and, ii) dissolved phase radionuclides in seawater which enters the estuary on the flood tide may bind to sediment in the estuary, particularly in the upper estuary where suspended sediment concentrations are high and salinity tends to be lower.

thorium, uranium and their decay products from the Springfields site; and Co-60, Cs-137, and, Am-241 from the Sellafield site. These have accumulated over many years in the intertidal sediments of the Ribble estuary, its tributaries (particularly the tidal reaches of the River Douglas) and associated salt marsh areas. This process has resulted in increased radiological exposure to members of the public compared to natural background rates. This exposure and the associated activity concentrations of radionuclides in sediment (and aquatic foodstuffs) are regularly monitored by the Environment Agency and the Food Standards Agency and are reported annually in the Radioactivity in Food and the Environment (RIFE) series[2].

The RIFE report identifies houseboat dwellers, wildfowlers and farmers who spend large amounts of time over the salt marshes of the Ribble, to be the individuals who are most exposed in this area (critical groups). The RIFE report states that the primary exposure route that dominates the critical group dose is via external beta (from Th-234 and Pa-234m decay) and gamma exposure (from Th-234, Pa-234m, Co-60, Cs-137 and Am-241 decay) and so is influenced to different degrees by discharges from the Springfields site and the Sellafield site. This is discussed further in Appendix A1.

The RIFE-12 report (Joint Agencies, 2007) estimated that in 2006, the annual dose to high-occupancy houseboat dwellers in the Ribble estuary was 0.075 millisieverts (mSv), which is less than ten percent of the Public Dose Limit of 1 mSv. This was higher than in 2005, when the annual dose was estimated to be 0.037 mSv because updated information was available, both on the habits of houseboat owners and from additional measurements taken onboard a houseboat[3]. However, the extent of these new measurements was limited.

Dose assessments for estuarine environments are complex because of the geometry of exposure, variable shielding and range of radiations involved. There are several groups of people who are exposed, including houseboat occupiers, anglers who may sit on the banks of the Ribble and wildfowlers who may lie in dugouts and hide pits or on mudflats. Houseboat dwellers may be shielded by the water column, which varies with the state of the tide and also the type / construction of boat. External beta and gamma exposure also depend upon whether houseboat dwellers, anglers or wildfowlers are standing, sitting or lying down and the shielding offered by boat structures and clothing where relevant.

Given the potential complexity of the assessments and the need to assess exposure on a regular basis using monitoring data, it is necessary to review assessment methods from time to time. This review has taken into account: habits and usage of the areas; changes in the radionuclides present; and changes in the beta and gamma dose rates from the mud in the estuary and from historical deposits on adjacent salt marsh areas.

1.2 Objectives

This aim of this project was to establish a transparent and robust assessment approach for calculating radiological doses to public exposure groups in the Ribble estuary for use in retrospective dose assessments. The specific objectives of the project included:

- elucidating how estuary bank geometry combined with tidal water level affected the radionuclide dependent gamma dose rate in air (air kerma) measured in boats, and how the combination of occupancy and tidal cycles affects the absorbed (effective) dose rates;

[2] e.g. Joint Agencies (2008) Radioactivity in Food and the Environment 2007, RIFE-13
[3] Cefas habit report (Cefas, 2007)

- identifying the key radionuclides contributing to beta/gamma external doses over sediment, and how the dose rates vary with activity concentration within sediment and with distance above the sediment;

- establishing the level of shielding provided by clothes, waterproofs, seats, decking and hulls of boats, and water;

- evaluating how the different geometries of standing, sitting, crouching or lying prostrate affect a person's external exposure, and determining the appropriate height at which beta/gamma dose rate reading should be taken;

- determining the most appropriate conversion factor from gray (Gy) the unit of gamma dose rate in air (air kerma) to sievert (Sv) the effective or absorbed dose, and derive a reasonable figure for natural background dose rate above sediment in the Ribble estuary;

- providing recommendations for the approaches to calculation of external exposure at other estuaries.

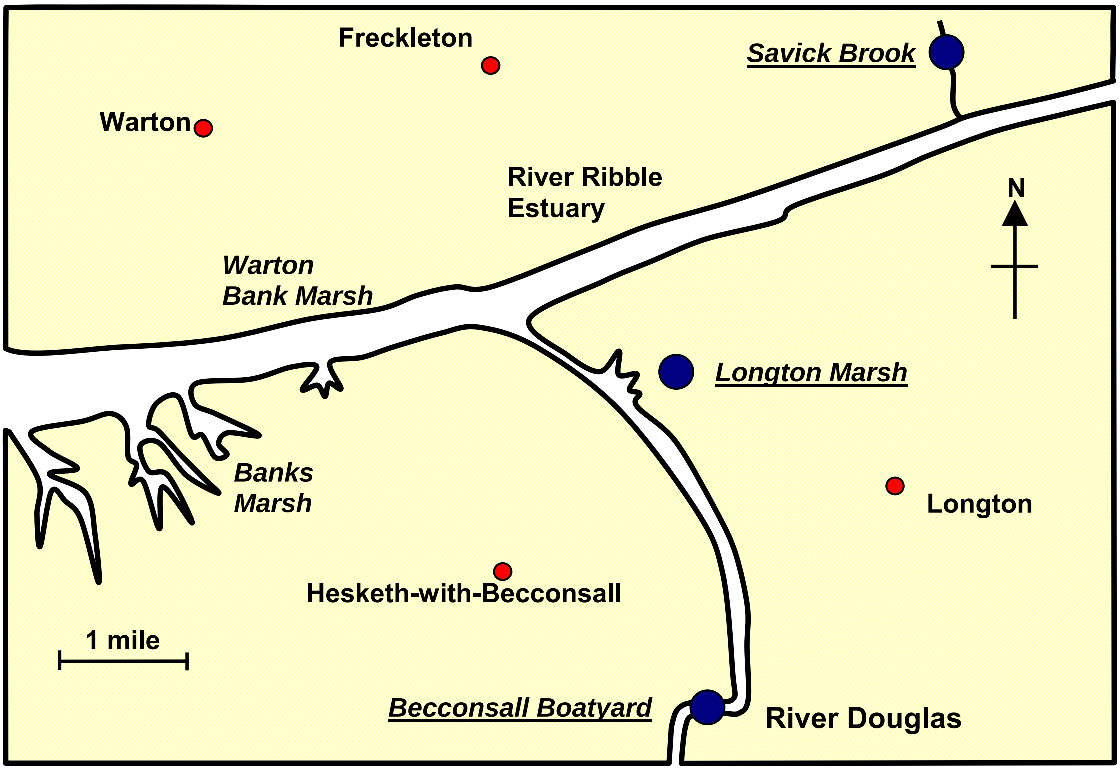
2 Methods

A monitoring and sampling campaign to measure external beta and gamma dose rates was implemented around the estuary (including on and around houseboats), to assess how they varied with tidal inundation, height over sediment and distance to the bank. Measurements made use standard routine monitoring instruments were compared with measurements made using in-situ gamma spectrometry to assess the contribution to gamma dose in air from different radionuclides. Sediment samples were collected to help understand further whether beta and gamma exposure was due to naturally occurring radionuclides or those arising from discharges from the nuclear industry.

Four field visits were undertaken during 2008: 31st July to 1st August; 16th to 17th October; 10th to 11th November; and, 28th November. One of these surveys (October) was timed to coincide with one of the highest tides of the year (in excess of 10 metres). Summary details are provided below and more information given in Appendix A2.

Three sites providing a range of conditions were selected for this study. These were Becconsall Boatyard (towards the tidal limit of the River Douglas), Longton Marsh (situated between the River Douglas and River Ribble) and Savick Brook (to the north of the estuary). The field sites visited are shown in Figure 1.

Figure 1: Map of Site Locations



At each location the following measurements were taken:

- gamma dose rate in air in nanograys per hour (nGy per hr) was measured in houseboats, and at 0.25 metres (m), 0.5 m and 1 m over the sediment surface over a range of tidal conditions using a compensated Geiger Műller Tube and Mini-Instrument and Thermo 6-80 rate meters, all with ISO17025:2005 quality assurance certified calibration. These are standard instruments used by regulators and industry throughout the UK in statutory monitoring programmes around all nuclear licensed sites. Measurements were taken over intertidal sediment and at various distances from intertidal sediment up the bank edge and onto adjacent salt marsh. Measurements were made onboard three boats through a range of different tidal conditions. All measurements were made over a 600 second time period;

- in-situ gamma spectrometry was undertaken using hyper pure sodium iodide (NaI) and germanium (HPGe) detectors at a range of heights over sediment at all three locations and onboard houseboats over a range of different tidal conditions;

- initial trials of standard beta dose rate instruments were undertaken to identify the best instrument for the beta dose rate aspects of the work; the results showed some instruments lacked sufficient sensitivity. Beta dose rate was therefore measured using a ruggedised version of the Thermo Electra BP19RD, a large area probe which had a wide monitoring area of 100 square centimetres (cm^2), coupled to a digital rate meter. A 12 millimetre (mm) Perspex shield was constructed to shield out any beta emissions to enable the gamma contribution to the instrument to be established. The instrument was calibrated by Nuvia. Measurements were made at distances of 0.01 m; 0.05 m; 0.15 m; 0.5 m; and 1 m from the sediment surface. The shielding effects of a range of clothing materials were also assessed;

- sediment samples were collected and returned to the laboratory for high resolution (low background) gamma spectrometry (24 hour count times).

In-situ gamma spectrometry and gamma dose rate in air were measured repeatedly on and around three boats at the boatyard across a range of different tidal conditions. The three boats studied had the following characteristics:

- **Boat 1** – a medium sized boat with a small internal living area and fibreglass hull, ‘dry docked’ on a relatively level terrace which cut into the upper bank of a tidal channel where the area under the boat was only inundated on extreme (equinox) high tides. This is a situation where there may be full time occupancy;

- **Boat 2** – a large, keeled, sailing vessel with fibreglass hull and wooden decking that was moored within a small, relatively steep-sided tidal channel which floods and drains on each cycle of the tide. At low water the keel of the boat rested on the bed sediment and the below-deck areas were flanked to either side by intertidal sediments on the channel banks. At high water the boat was lifted up by the rising tide, not just off the sediment in the channel base, but above the channel sides so that the deck area was around three metres above the level of the adjacent salt marsh at low water. The boat was berthed for the winter months and represents a potential for seasonal (e.g. six month) occupancy;

- **Boat 3** – a small, flat bottomed, fibreglass vessel with a single partly covered cabin area moored in the same tidal channel as Boat 2. As with Boat 2 it was elevated up above the sediment bed and channel sides with the inundating tide. At high water the area within the boat was approximately level with that of the adjacent salt marsh. This was a small boat, unsuitable for accommodation, but typical of that used for inshore angling or day pleasure cruises. Nonetheless, it represents a potential scenario where the boat could become stranded over intertidal areas during a single tidal cycle. In this instance the small size of the boat, limited hull shielding and proximity to sediment are likely to make it the most conservative scenario assessed with respect to dose rate received but not duration of exposure.

All gamma dose rate in air measurements reported in this document are based on Ra-226 calibration. Instrument calibration based on Cs-137 was also investigated, but was found to over-predict the gamma dose rate in air by 30 percent compared to in-situ gamma spectrometry measurements. Reported values have all been corrected for the contribution from intrinsic and cosmic radiation (a total of approximately 60 nGy hr^{-1}). The gamma dose rate in air values quoted include naturally occurring radionuclides in the sediment and those which may be derived or enhanced by human activities (see Section 3.3 for details).

In-situ gamma spectrometry was used to determine the contribution from naturally occurring radionuclides and from anthropogenic radionuclides that have been discharged from the Springfields site and the Sellafield site. Site-specific background rates were derived for naturally occurring levels of radionuclides (around 30 nGy hr^{-1}). This terrestrial background rate has been subtracted as part of the effective dose calculation.

3 Potential Exposure around the Ribble

The results of the monitoring and sampling are discussed in this section. Further information on the study results is given in Appendices A3 and A4. Appendix A5 provides more detail on the subtraction of background dose rates and calculation of effective dose. All gamma dose rate in air measurements have had the intrinsic count rate of the instrument and cosmic background subtracted, but include the contribution from naturally occurring radionuclides in the environment.

3.1 Houseboat Dwellers

Three boats in or next to a tidal channel adjacent to the Becconsall Boatyard were surveyed to assess the likely levels of external exposure under different potential houseboat use scenarios. A detailed discussion is given in Appendix A3 and summary results provided below.

3.1.1 Sediment Activity Concentrations

Activity concentrations of Cs-137 were typically around 300 Bequerels per kilogram (Bq kg^{-1}, dry weight) and of Am-241 were around 200 Bq kg^{-1} (dry weight) in sediments around the boats at Becconsall Boatyard. The activity concentrations of Co-60 were very low (a few Bq kg^{-1} dry weight). These results were consistent over time. Activity concentrations of Th-234 and Pa-234m varied by over an order of magnitude; the highest concentrations in the channel bed sediment were up to around 1,000 Bq kg^{-1} (dry weight). Those on higher areas of the bank were of the order of a 100 Bq kg^{-1} (dry weight)[4]. Activity concentrations of the other uranium and thorium decay chain products were much more consistent, typically between 25 to 30 Bq kg^{-1} (dry weight) per radionuclide.

3.1.2 Gamma Dose Rate in Air

Average gamma dose rate in air measurements (excluding intrinsic and cosmic radiation of 60 nGy hr^{-1}, but inclusive of natural background) given in Table 1 for on the bank edge, over intertidal sediment and within the boats. The measurements taken within the boats have been broadly separated into ‘lower water’ (LW) when the bed sediment was exposed and ‘higher water’ (HW) when the channel was partly or completely inundated.

Gamma dose rate in air ranged from 40 to 50 nGy hr^{-1} underneath the boat hulls. The gamma dose rate in air in each boat reduced with increased tidal inundation of the channel. This was most extreme (by a factor of 5) in Boat 2. At low water there appeared to be little difference in gamma dose rate measured above and below deck.

Within a houseboat, particularly when moored in a tidal channel, the concept of a planar source of gamma radiation from the bed sediment being sequentially attenuated by the hull, internal structures and then by the upper decking, is not appropriate. Throughout a range of tidal conditions a boat occupant may be exposed from gamma

[4] Note the Th-234 and Pa-234m are much reduced compared to pre-2006 when activity concentrations were ~100,000 Bq kg^{-1} or more at some locations.

emitters on the channel sides or adjacent salt marsh, not just from the sediment under the boat (see Figures A3.1, A3.8 and A3.15 in Appendix 3 for illustration).

Table 1: Gamma Dose Rate in Air (nGy hr^{-1})

	Average Gamma dose rate in Air (nGy hr^{-1})				Gamma dose rate Ratios		
Boat	On Bank Edge	Below Hull	In Boat (below deck)	In Boat (above deck)	Bank Edge : In Boat	Below Hull: Below Deck	Below Hull: Above Deck
Boat 1	Not measured	50 (LW)	12 (HW) – 18 (LW)	4 (HW) - 18 (LW)	Not applicable	0.36	0.36
Boat 2	36 (LW)	40 (LW)	4 (HW) - 25 (LW)	5 (HW) - 25(LW)	0.69	0.63	0.63
Boat 3	28 (HW) – 37 (LW)	44 (LW)	11 (HW) – 34 (LW)	Not measured	0.92	0.77	Not applicable

Note – values reported have had intrinsic and cosmic radiation (ca. 60 nGy hr^{-1}) subtracted, but include dose rates from naturally occurring radionuclides in the environment. To calculate the gamma dose rate in air due to anthropogenic activities subtraction of a dose rate of 30 nGy h^{-1} is recommended (see Section 3.3 and Appendix 5).

The gamma dose rate in air (minus intrinsic and cosmic background of 60 nGy hr^{-1}) for each of the boats, accounting for position and tidal dynamics were:

- Boat 1: dose rates varied from 20 to 30 nGy hr^{-1} depending upon position in the boat, but across a broad range of tidal conditions. Low water dose rates in the boat were 40 to 60 percent of those measured over sediment;

- Boat 2: dose rates varied from around 30 nGy hr^{-1} at low water to near to zero at high water. The rate averaged over the tidal cycle derived from multiple points within the boat was 11 nGy hr^{-1} (around 30 percent of the low water value). Low water dose rates in the boat were about 75 percent of those over sediment;

- Boat 3: dose rates varied from 40 nGy hr^{-1} at low water to 10 nGy hr^{-1} at high water. The rate averaged over the tidal cycle was 23 nGy hr^{-1}, based on a reading in the centre of the boat (about 50 percent of the low water value). Low water dose rates in the boat were comparable to those measured over sediment.

3.1.3 Primary Contributors to the Gamma Dose Rate

The results from in-situ gamma spectrometry within boats or over surrounding soils and sediments found that about a quarter of the net gamma dose rate in air from terrestrial sources was from naturally occurring potassium-40 (K-40) and about a quarter from uranium-238 (U-238) and its associated decay chain. Cs-137 was the primary dose contributor, accounting for at times in excess of a quarter of the total gamma dose rate in air. At low water Am-241 provided virtually no contribution to the gamma dose rate in air and only very low levels were from excess Th-234 and Pa-234m (less than one percent of the total measured rate). There was no measurable contribution from Co-60. At high water the gamma dose rate in air (minus intrinsic and cosmic radiation) can approach zero, but this depends upon the size of the boat and its position relative to bank areas (lower gamma dose rate in air measurements were found on the larger boat particularly when elevated above the sediment and away from the adjacent channel sides).

3.1.4 Beta Skin Dose

Beta skin doses were low, typically only detectable over intertidal sediment with values around 100 nanosieverts per hour per square centimetre (nSv hr^{-1} per cm^2).

3.2 Anglers and Wildfowlers

Sediment samples were taken, and beta and gamma dose rate measured on salt marshes and bank edges at Longton Marsh near to the east side of the River Douglas and in the tidal reaches of Savick Brook. This was done to assess how exposure varied with distance from channel edge, height over sediment and shielding by different clothing materials[5]. Further details are provided in Appendix A4.

3.2.1 Sediment Activity Concentrations

Activity concentrations of Cs-137 in surface sediment were typically around 300 Bq kg^{-1} (dry weight) while that of Am-241 was around 200 Bq kg^{-1} (dry weight). Only very low activity concentrations of Co-60 (of a few Bq kg^{-1} dry weight) were detected. These results are consistent with those found at the Becconsall Boatyard.

Activity concentrations of Th-234 and Pa-234m were again variable, here by up to two orders of magnitude. The sampling position relative to the extent of tidal inundation (and hence frequency of sediment supply) appears to be the dominant factor. The measurement ranges also differed significantly between the two sites, with those in Savick Brook (just upstream of the Springfields site) being higher; up to around 4,000 Bq kg^{-1} (dry weight) within intertidal sediment of the channel base.

Activity concentrations of other uranium and thorium decay chain products were much more consistent, typically between 25 to 30 Bq kg^{-1} (dry weight). Comparison of surface measurements with those derived from the base of a core sample indicated that activity concentrations in surface sediment are only marginally elevated over historical levels which pre-date UK nuclear industry activities.

3.2.2 Gamma Dose Rate in Air

At Savick Brook and Longton Marsh the gamma dose rate in air (minus intrinsic and cosmic radiation contribution of 60 nGy hr^{-1}, but inclusive of all terrestrial sources) ranged from between 30 to 60 nGy hr^{-1}. There was no consistent relationship between gamma dose rate in air and height above sediment. This may have been due to reduction in the instrument field of view when lowered down, and also the complex topography of banks and channel sides and local heterogeneity of sediment deposits. In addition there was little clear relationship with distance away from exposed intertidal sediment; this is particularly true where the channel was bordered by tidally inundated salt marsh upon which sediment and radioactivity has also been deposited.

The study has shown that on channel sides, particularly where terraces cut into the bank profile, gamma dose rate in air can be up to 15 nGy hr^{-1} higher than that at the bank top or base (potentially due to exposure of historical sediments with higher activity concentrations). Equally, exposure immediately adjacent to a fully inundated area may be 30 percent lower than measurements made at low water. This effect is relatively localised, within about five metres of the waters edge.

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[5] Shielding was only assessed with respect to beta dose rate.

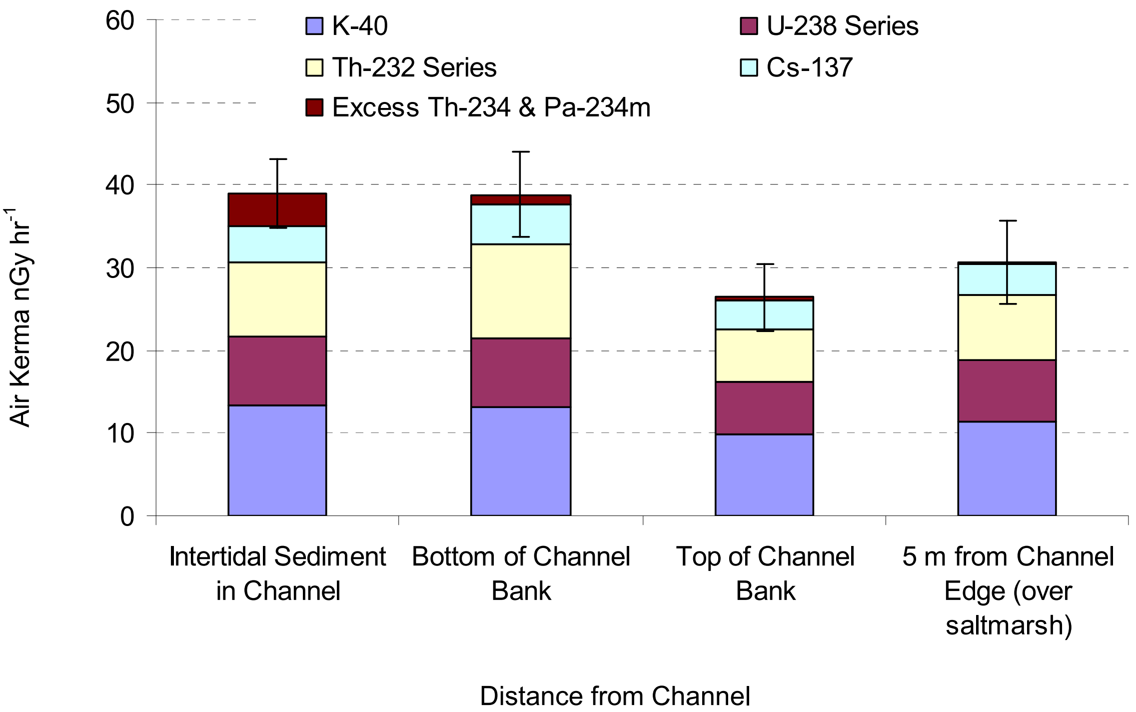
Further gamma dose rate measurements were made in dug-out hide pits on Longton Marsh. These pits measured approximately one metre by one metre by one metre (1 cubic metre, m^3). The gamma dose rate, measured at a central point in one pit was 116 nGy h^{-1} (compared to an average of 61 nGy h^{-1} at 1 m above the surrounding ground adjacent to the pit). A gamma dose rate reading of 88 nGy h^{-1} was taken in a second, wood lined pit with a wooden trap door covering the entrance.

3.2.3 Primary Contributors to Gamma Dose Rate

In-situ gamma spectrometry over sediment and salt marsh determined that primary dose contributor was Cs-137 arising from discharges from Sellafield. At both sites, there was virtually no contribution to the gamma dose rate in air from Am-241 and there was no measurable contribution from Co-60. This is consistent with the findings presented for Becconsall Boatyard. The contribution from excess Th-234 and Pa-234m (from discharges from Springfields) varied depending upon the site. At its highest, this contributed around 10 to 15 percent of the observed gamma dose rate at Savick Brook.

An example of the application of in-situ gamma spectrometry deployed in Savick Brook is given in Figure 2.

Figure 2: Air Kerma at Savick Brook (HPGe Detector)



3.2.4 Beta Skin Dose

Dose rates at a height of 1 centimetre (cm) above the intertidal sediment surface at Savick Brook were approximately 2,000 nSv hr^{-1} per cm^2, significantly higher than those measured at Becconsall. Dose rates appeared relatively constant up to a height of 0.2 metres above the sediment surface, and then decreased linearly with increasing height. At 1 metre, beta skin dose was between 50 and 75 percent of that measured at 0.01 metres.

Attenuation of beta skin dose by clothing materials was assessed by placing different materials over the detector surface. Results are given in Table 2.

Table 2 Beta Skin Dose Attenuation by Clothing

Garment	Height over Sediment (m)	
	0.05	0.5
Rubber Boot	0.79	0.91
Waterproof (breathable) Jacket	No measurable attenuation	0.05
Woollen Jumper	0.04	No measurable attenuation
Plastic sheeting	0.05	0.06
Wax Jacket	0.30	0.22
Rubber Wader	0.32	0.39

The results show that there was effectively no attenuation of the beta emissions for thin materials such as plastic sheeting and light weight waterproofs, and also for thicker, (but low density) materials, such as a woollen jumper. Wax jacket and rubber waders resulted in an approximate 20 to 40 percent reduction in the measured beta skin dose, while thicker rubber boots reduced the dose by approximately 80 to 90 percent.

3.3 Background Rate Subtraction

All gamma dose rate in air measurements have had the intrinsic count rate of the instrument and cosmic background subtracted, but include the contribution from naturally occurring radionuclides in the environment. Cosmic background, determined over a large body of water was found to be between 42 and 48 nGy hr^{-1} (mean value 45 nGy hr^{-1}). A value of 60 nGy hr^{-1}, inclusive of intrinsic and this cosmic background has been subtracted from all gamma dose rate in air measurements reported (see Section A5.1.2).

As discussed in Appendix A5, the terrestrial background from naturally occurring levels of radioactivity can be both site and substrate specific. Based on a single salt marsh core collected from the area adjacent to Savick Brook, the contribution from natural levels of radioactivity in sediment has been calculated as approximately 30 nGy hr^{-1}. This is however highly dependent upon soil moisture content and may not be fully applicable across all areas of the estuary. Nonetheless, the value of 70 nGy hr^{-1}, typically applied in statutory monitoring programmes to account for terrestrial, e.g. 30 nGy hr^{-1} and cosmic background, e.g. 40 nGy hr^{-1} (but excluding intrinsic rate of the instrument) appears to be appropriate (albeit slightly conservative).

Use of the 70 nGy hr^{-1} value may not be appropriate in all situations. For measurements made in a boat, particularly when situated up near the high water mark (e.g. Boat 1), some of the terrestrial component of the background radiation will be shielded by the boat hull (rates measured in the boat were 40 to 60 percent of those over sediment). In this instance, a background rate subtraction of around 60 nGy hr^{-1} (i.e. an average rate of 45 nGy hr^{-1} for cosmic background and a rate of 15 nGy hr^{-1} for terrestrial background) should be applied to measurements taken within the boat (not underneath). For other boat related scenarios, particularly where the boat sits in a tidal channel, this effect will be less significant and a total (cosmic and terrestrial) background value of 70 nGy hr^{-1} may be applicable (but again slightly conservative). This value is also applicable when there isn't a structure present that provides shielding from terrestrial sources of radiation, e.g. for wildfowlers and anglers.

3.4 Gray to Sievert Conversion

Calculation of the effective dose in sieverts from gamma dose rate in air measurements depends upon the geometry of exposure and the energy of emissions of radionuclides in the sediment. These have been assessed and results are given in Appendix A5.

Two exposure geometries have been considered; the Anterior-Posterior (AP) geometry which applies to when a person is lying face-down on the sediment and the Rotational (ROT) geometry which applies to when a person is standing on the sediment. In both the AP and the ROT geometries, the exposure arises from a planar source from activity deposited to sediment. A third geometry exists, the Isostatic (ISO) geometry where an individual is fully immersed in a gamma radiation field. Although exposure of an individual, particularly when in a channel, may be from multiple directions; this does not represent a uniform exposure field and this geometry has not been considered further. The ROT geometry is typically applied to gamma dose rate in air measurements made at one metre over sediment as reported in statutory monitoring programmes.

Based on in-situ gamma spectrometry measurements made around the Ribble, the ROT geometry conversion factor (for gamma dose rate in air measurements at one metre) was found to vary from 0.83 to 0.84 Sv Gy^{-1}. The value of 0.85 Sv Gy^{-1} used in statutory monitoring programmes is therefore considered appropriate (albeit slightly conservative). However, a ROT geometry is not considered suitable when an individual is lying face-down on the sediment. In this case, using an AP geometry and a Sv Gy^{-1} value of 1.1 is more appropriate and again should be applied to measurements made at one metre over the sediment surface.

Calculation of geometries for seated positions over sediment has not been possible based on measurements of gamma dose rate in air with distance over sediment. Many of the sites assessed were characterised by banks and complex topography and did not represent a level planar surface. The dose rate measured may have been more influenced by adjacent sediment deposits, not just those directly below the instrument.

4 Assessment of Effective Dose

Assessments of effective dose for a number of hypothetical exposure scenarios are given below.

There are a number of variables that may influence the dose (in terms of effective dose) that a member of the public may receive around the Ribble estuary. Insufficient data exist on site-specific habits of these people to fully assess the ranges of actual exposure. Therefore five main hypothetical exposure situations have been derived, relating to the three boats studied, an angler and a wildfowler.

In each instance the effective dose, H_E (nSv hr^{-1}) is calculated according to:

$H_E = D_S - D_B * R * T * G$

Where:

Ds Measured gamma dose in air (nGy hr^{-1}) over sediment minus intrinsic and cosmic background;

D_B Gamma dose in air (nGy hr^{-1}) over sediment due to natural levels of radioactivity in the sediment;

R Ratio between gamma dose in air over sediment and in boat (unitless);

T Ratio between gamma dose in air at low water to that integrated over a tidal cycle; and,

G Conversion factor between Gy to Sv (Sv Gy^{-1}).

and:

Exposure Scenario	R	T	Geo-metry	Sv Gy^{-1} ratio
Medium sized houseboat towards high water mark (Boat 1)	0.5	1	ROT	0.85
Large houseboat in tidal channel (Boat 2)	0.75	0.3	ROT	0.85
Small boat in tidal channel (Boat 3)	1	0.5	ROT	0.85
Angler sat on bank	N/A	N/A	ROT	0.85
Wildfowler lying on sediment	N/A	N/A	AP	1.1
Wildfowler in hide pit	N/A	N/A	ROT	0.85

Annual exposure (in terms of effective dose) has been calculated by multiplying the predicted hourly exposure rate by the anticipated annual exposure in hours per year (hr yr^{-1}).

4.1 Scenario 1: Boat 1

Scenario 1 represents a houseboat situated near the very extreme of the tidal limit and is occupied by the residents for virtually all of the time throughout the year. The gamma dose rate in air, from natural terrestrial and anthropogenic sources within the sediment under the boat, is around 50 nGy hr^{-1} (of which 30 nGy hr^{-1} is assumed to be from natural levels of radionuclides). Measurements within the boat, averaged across the different areas of the boat at low water, are about half the value of the gamma dose rate over sediment. The effect of typical tidal variations are negligible. A typical ROT

Gy to Sv conversion rate is applied. Under this scenario, the effective dose due to anthropogenic sources of radioactivity is 8.5 nanosieverts per hour (nSv hr^{-1}). If the boat is occupied on a near-full time basis (e.g. 8,300 hours per year) the resulting dose is approximately 70 microsieverts per year (μSv yr^{-1}), which is less than ten percent of the Public Dose Limit:

Dose Rate over Sediment (nGy hr^{-1})	Terrestrial Background (nGy hr^{-1})	R	T	Geo-metry	Sv Gy^{-1} ratio	Dose (nSv hr^{-1})
50	30	0.5	0.1	ROT	0.85	8.50

4.2 Scenario 2: Boat 2

Scenario 2 represents a houseboat situated in a small tidal channel, which is occupied by residents virtually all of the time, but only through the winter season (assumed to be over six months of the year). The gamma dose rate in air from the natural terrestrial and anthropogenic sources in sediment under the boat is around 40 nGy hr^{-1} (30 nGy hr^{-1} assumed to be from natural levels of radionuclides). Measurements within the boat, averaged across the different areas of the boat at low water, are about 75 percent of the value of the gamma dose rate over sediment. The effect of typical tidal variations results in a tidally integrated dose rate in the boat, which is about 30 percent of that at low water. A typical ROT Gy to Sv conversion rate is applied. Under this scenario the effective dose due to anthropogenic sources of radioactivity is 1.9 nSv hr^{-1}. Where the boat is occupied on a near full time basis for six months of the year (about half that in Scenario 1, that is 4,150 hours per year) the resulting dose is approximately 8 μSv yr^{-1}, which is less than one percent of the Public Dose Limit:

Dose Rate over Sediment (nGy hr^{-1})	Terrestrial Background (nGy hr^{-1})	R	T	Geo-metry	Sv Gy^{-1} ratio	Dose (nSv hr^{-1})
40	30	0.75	0.3	ROT	0.85	1.91

4.3 Scenario 3: Boat 3

Scenario 3 represents a small boat (potentially out on a fishing trip) that remains at one location within a channel area over a full tidal cycle (approximately 12 hours) – so the boat spends some time afloat and some resting on sediment. Gamma dose rate in air from natural terrestrial and anthropogenic source in sediment under the boat is around 40 nGy hr^{-1} (30 nGy hr^{-1} assumed to be from natural levels of radionuclides). Dose rates in the boat are effectively the same as those over sediment. The effect of typical tidal variations results in a tidally integrated dose rate that is about 50 percent of that at low water. A typical ROT Gy to Sv conversion rate is applied. Under this scenario the effective dose due to anthropogenic sources of radioactivity is 4.3 nSv hr^{-1}. The resulting dose over the 12 hour period is approximately 0.1 μSv yr^{-1}, around 0.01 percent of the Public Dose Limit:

Dose Rate over Sediment (nGy hr^{-1})	Terrestrial Background (nGy hr^{-1})	R	T	Geo-metry	Sv Gy^{-1} ratio	Dose (nSv hr^{-1})
40	30	1	0.5	ROT	0.85	4.25

4.4 Scenario 4: Angler

Scenario 4 is applicable to an angler who spends time immediately adjacent to a channel, sitting or standing over intertidal or salt marsh sediment. Their total annual occupancy is assumed to be 250 hours per year based on Cefas habit observations. However, the habits data do not provide a breakdown of activities within this overall period. It has therefore been assumed that 50 percent of the time (125 hours per year) is located on a mid bank terrace, over a range of tidal conditions other than high water, so the angler receives higher dose rates (approximately 55 nGy hr^{-1}). The remaining 50 percent of the time is assumed to be spent at the top of the bank adjacent to a fully inundated channel (when the dose rates are lower, approximately 35 nGy hr^{-1}). In each instance 30 nGy hr^{-1} is assumed to be from natural levels of radionuclides and a typical ROT Gy to Sv conversion rate is applied. Under this scenario the effective dose due to anthropogenic sources of radioactivity ranges from 4.25 to 21.3 nSv hr^{-1} depending upon position on the bank. The resulting dose received over the total exposure period is approximately 3 μSv yr^{-1}, which is less than one percent of the Public Dose Limit:

Dose Rate over Sediment (nGy hr^{-1})	Terrestrial Background (nGy hr^{-1})	R	T	Geo-metry	Sv Gy^{-1} ratio	Dose (nSv hr^{-1})
55	30	N/A	N/A	ROT	0.85	21.3
35	30	N/A	N/A	ROT	0.85	4.25

4.5 Scenario 5 Wildfowler

Scenario 5 is applicable to a wildfowler who spends time over salt marsh sediment. Their total annual occupancy is assumed to be 390 hours per year based on Cefas habit data, but again this data does not provide a breakdown of activities within the overall period. It has therefore been assumed that during this period 50 percent of the time (185 hours per year) is spent lying down on the salt marsh surface (particularly on bank sides) where dose rates may be higher, approximately 55 nGy hr^{-1}. Of the remaining time, 25 percent (98 hours per year) is assumed to be walking or standing over areas of lower dose rate sediment (approximately 35 nGy hr^{-1}), and 25 percent within the unlined hide pit where doses measured are significantly higher (116 nGy hr^{-1}). In each instance 30 nGy hr^{-1} is assumed to be from natural levels of radionuclides. A ROT Gy to Sv conversion rate is applied to standing positions (over salt marsh and within the pit) and an AP geometry to time spent lying face-down on the sediment. Under this scenario the effective dose due to anthropogenic sources of radioactivity ranges from 4.25 to 73.1 nSv hr^{-1}. The resulting dose over the total exposure period is approximately 13 μSv yr^{-1}, around one percent of the Public Dose Limit:

Dose Rate over Sediment (nGy hr^{-1})	Terrestrial Background (nGy hr^{-1})	R	T	Geo-metry	Sv Gy^{-1} ratio	Dose (nSv hr^{-1})
55	30	N/A	N/A	AP	1.1	27.5
35	30	N/A	N/A	ROT	0.85	4.25
116	30	N/A	N/A	ROT	0.85	73.1

Even if a wildfowler spent 390 hours per year in the hide pit, the total annual exposure would be less than 30 μSv yr^{-1}, which is less than five percent of the Public Dose Limit.

5 Key Conclusions

Three sites in the Ribble estuary were subject to a detailed regime of measurements and sample collection which included: around 320 measurements of gamma dose rate in air; 35 HPGe in-situ gamma spectrometry, 38 NaI in-situ gamma spectrometry and 81 Beta skin dose rate measurements; and 66 soil or sediment samples collected for gamma spectrometry.

Overall, this study confirmed the finding, reported by the Environment Agency in their statutory monitoring programmes, that the use of a Ra-226 calibration for gamma instrumentation is most appropriate for use in the Ribble. It has also been shown that the use of the Sv Gy^{-1} conversion factor of 0.85 is applicable across sites in the estuary for a broad range of habit scenarios. It is recommended that an AP geometry be introduced for calculating effective dose for the time that wildfowlers spend lying down. External exposure, particularly from gamma radiation can vary over time and location, responding to the state of the tide, bank topography and heterogeneity of sediment deposits (both recently deposited sediments and the longer term process of salt marsh accumulation).

Surveys of gamma dose in air on houseboats have demonstrated that the relationship with measurements made over adjacent exposed sediment can be complex, varying with size and structure of the boat, geometry of the channel, state of the tide and inundation of underlying sediment or channel sides. Two key findings are that:

- the ratio between gamma dose rate in air measured over sediment compared to that within a boat at low water ranged from 1 (no attenuation) for a small boat resting at the base of a dry channel to 0.5 (50 percent attenuation) for a medium sized boat adjacent to a channel on a relatively flat area. Although shielding by the boat hull clearly influences the dose rate in the boat, the geometry of exposure is also important. This is particularly the case where at low water; the boat sits at the base of a steep sided channel where the bank sides may rise adjacent to, or higher than the deck area. In this situation, gamma emissions from sediment on the bank sides will contribute to the dose rate measured, and therefore the 'concept' that gamma radiation from a planar source of intertidal sediment below the boat is sequentially attenuated by the hull, internal structures and decking, is not appropriate;

- the ratio of gamma dose rate in air measured in a houseboat at low water, compared with integrated measurements over a range of tidal conditions, can vary depending on where the boat is situated with respect to the limit of tidal inundation. This work has shown that for a boat 'dry docked' towards the limit of tidal inundation, this ratio was around 1, so that for the purpose of dose assessments, there was effectively no shielding by tidal flood waters (apart from during extreme tidal conditions which are very limited). Within the tidal channel where Boats 2 and 3 were located, the ratio varied from 0.5 (a small boat) to 0.3 (a larger boat). This difference was due to the size of the boat and the position of the boat with respect to the bed sediment, and the sides of the surrounding channel. This range is probably applicable to most houseboats types, but only where the surrounding area drains on each ebb tide. For boats moored in deeper water, the underlying sediment is only exposed under more limited tidal conditions and therefore the respective ratios are likely to be lower.

This illustrates the importance that should be placed on consistency in monitoring position and timing with respect to state of tide, and the need to carefully record and clearly report on when measurements were made.

Other findings from this work are summarised below and discussed further in the appendices to this document:

5.1 Instrumentation set up and application

Key points relating to instrumentation set up and application were:

- measurements from standard instrumentation used for gamma dose rate in air in statutory monitoring programmes compared well to measurements derived from in-situ gamma spectrometry;

- in-situ gamma spectrometry showed that a Ra-226 calibration for gamma dose rate in air measurement was suitable for application in the Ribble. All results given in this report are based on this. A calibration based on Cs-137 may potentially over-estimate the dose rate by around 30 percent;

- the cosmic background gamma dose rate in air was assessed as around 45 nGy hr^{-1} over a large body of water. A rate of 60 nGy hr^{-1} was subtracted from all measurements given in this report to account for cosmic radiation (45 nGy hr^{-1}) and also the intrinsic rate of the instrument (15 nGy hr^{-1}). All measurements of gamma dose rate in air quoted in this work are inclusive of terrestrial background;

- the terrestrial background gamma dose rate in air that would be indicative of natural levels of radioactivity (unshielded at one metre over sediment and soil) was predicted to be 30 nGy hr^{-1} based on a sediment core. Where shielding is provided by a boat hull (i.e. the boat is up near the high water mark) a lower value (approximately 15 nGy hr^{-1}) to represent the terrestrial background gamma radiation should be used. This however only applies to measurements made within the boat. The terrestrial background value has only been subtracted as part of the final calculation of the effective dose;

- the typical background value of 70 nGy hr^{-1} used in statutory monitoring programmes to represent cosmic and terrestrial background is therefore reasonable (albeit slightly conservative) for most situations. However, for a houseboat situated up towards the high water mark, reporting within programmes such as RIFE should make it clear that the background value is inclusive of cosmic and terrestrial sources and the potential for variation in both should be acknowledged;

- the Sv Gy^{-1} conversion factor of 0.85 used in statuary monitoring programmes is appropriate for ROT geometries around the Ribble. However, this geometry isn't appropriate for all habits. Where an individual lies face-down on the sediment, an AP geometry is more appropriate and a value of 1.1 Sv Gy^{-1} should be used. Including this conversion factor in future dose assessments will require more data on habits than is currently collected;

- both the RADEYE and SMARTION (Thermo Scientific) beta dose rate meters were trialled and found to be unsuitable for this work. A ruggedised version of the BP19/Electra monitor performed well and had a sufficient limit of detection to measure the low beta dose rates now observed around much of the Ribble estuary;

- in-situ gamma spectrometry using both HPGe and NaI instruments was successfully trialled. The measurements from both instruments were in agreement with gamma dose rate in air measurements made with standard instrumentation used in statutory monitoring programmes;

- monitoring programmes should clearly record the state of the tide and try to coincide with conditions that are most appropriate to critical group exposures.

5.2 Variability in Sediment Activity Concentrations

Assessment of activity concentrations of radionuclides in sediment found that:

- surface sediment concentrations of radionuclides discharged from the Sellafield site were relatively consistent between all three sites, with Cs-137 typically around 300 Bq kg^{-1} (dry weight), Am-241 around 200 Bq kg^{-1} (dry weight) and Co-60 of a few Bq kg^{-1} (dry weight);

- activity concentrations of short-lived radionuclides such as Th-234 and Pa-234m discharged from the Springfields site are now much lower than pre-2006 levels, but can still be quite variable, ranging from tens to thousands of Bq kg^{-1} (dry weight). Key factors influencing this appear to relate to the proximity to the Springfields site discharge point and rate of sediment input to upper bank areas;

- activity concentrations of U-238 and Th-232 decay chain radionuclides are relatively consistent within surface sediments across the estuary.

5.3 Gamma Dose Rates in Air

Key points relating to the measured gamma dose rate in air were that:

- gamma dose rates in air (minus intrinsic and cosmic background) were typically up to 60 nGy hr^{-1} at one metre over sediment and salt marsh (that is up to 30 nGy hr^{-1} from anthropogenic sources);

- it was not possible to detect any consistent reduction in dose rate with distance from intertidal sediment in the channel. All areas assessed in this study were periodically inundated by high tides and bordered by salt marsh where historical deposits of Cs-137 are likely to contribute to most of the dose received. Higher dose rates were found half way up the banks, particularly on terraces that had eroded into the bank face;

- no consistent relationship between dose rate and height of instrument over sediment was observed. This was most likely due to reduction in the instrument field of view and the complex topography of many of the sites assessed;

- dose rates measured in houseboats were highly site-specific depending upon the type of boat, geometry of the surrounding channel or intertidal area and the state of the tide.

5.4 Primary Contributors to Gamma Dose Rate

Use of in-situ gamma spectrometry showed that:

- about half the total dose rate from terrestrial sources was due to K-40 and members of the U-238 decay chain;

- of the radionuclides discharged from the Sellafield site, the gamma dose rate in air was dominated by Cs-137. Virtually no contribution from Am-241 or Co-60 was measured. The RIFE report of statutory monitoring programmes makes the generic statement that both Cs-137 and Am-241 contribute to the measured gamma dose rate in air. This work has shown that the contribution from Am-241 is negligible;

- of the radionuclides discharged from the Springfields site, the contribution from Th-234 and Pa-234m was detectable in Savick Brook, but elsewhere was negligible.

5.5 Effective Dose

Assessment of the effective dose has shown that:

- effective dose rates for a houseboat dweller ranged from 2 to 8.5 nSv hr^{-1} (the smaller the boat the higher the dose rate), for an angler from around 4 to 20 nSv hr^{-1}, and for a wildfowler from around 4 to over 70 nGy hr^{-1} (higher rates were associated with time spent on bank sides or in dug-out hide pits);

- the annual exposure of houseboat dwellers was consistent with that reported in statutory monitoring programmes and less than ten percent of the Public Dose Limit;

- for anglers and wildfowlers, the annual exposure based on estimated habit data (including time spent lying on sediment) was less than one percent of the Public Dose Limit. Although habit surveys do not provide a breakdown of time spent sitting, standing or lying down, even if a wildfowler spent all of the time when wildfowling in a dug-out pit (the highest exposure rate), the total annual exposure would still be very low, less than five percent of the Public Dose limit.

5.6 Areas of Uncertainty

A number of aspects of this study still have some degree of uncertainty associated with them. These include:

- the extent and causes of localised heterogeneity on bank areas remain uncertain. Small changes in monitoring locations or timing with respect to state of tide may lead to a wide range of gamma dose rate in air measurements;

- background dose rates and the contribution of radionuclides discharged from the Springfields site at points along the estuary beyond Savick Brook still have some uncertainty;

- behaviour of wildfowlers and anglers and the time they spend close to the sediment surface or in hide pits have not been fully determined. This bears on the choice of assessment methods that should be applied in statutory monitoring programmes to represent these people.

List of abbreviations

- Am-241 – americium-241
- AP – Anterior-Posterior Geometry (Sv Gy^{-1} conversion factor)
- Bq – Becquerel
- Co-60 – cobalt-60
- Cs-137 – caesium-137
- D_B –– gamma dose in air over sediment due to natural levels of radioactivity in the sediment
- D_S – measured gamma dose rate overin sediment, inclusive of terrestrial background)
- ERL – Environmental Research Laboratory, University of Stirling
- G – Conversion factor between Gy to Sv.
- Gy – Gray
- HPGe – High purity germanium (refering to in-situ gamma spectrometry detector)
- K-40 – potassium-40
- Kg – kilogram
- mSv – milli-seiverts (10^{-3} seiverts)
- NaI – Sodium Iodide (refering to in-situ gamma spectrometry detector)
- NDA – Nuclear Decommissioning Authority
- nGy – nano-gray (10^{-9} grays)
- nSv – nano-seiverts (10^{-9} seiverts)
- Pa-234m – protactinium-234m
- R – ratio between gamma dose in air over sediment and in boat (unit less)
- Ra-226 – radium-226
- RIFE – Radioactivity in the Food and Environment
- ROT – Rotational Geometry (Sv Gy^{-1} conversion factor)
- Sellafield – Sellafield Ltd
- Springfields – Springfields Fuels Ltd
- Sv – Seivert
- T – ratio between gamma dose in air at low water to that integrated over a tidal cycle
- Th-234 – thorium-234
- U-238 – uranium-238
- µSv – micro-seiverts (10^{-6} seiverts)

Appendix A1 – Background Information

In this section the following are discussed: background information on tidal processes and their influence on critical group exposure in the Ribble; processes that lead to the accumulation of environmental radioactivity in the estuary; and previous assessments of external radiological exposure of marine critical groups in the area.

A1.1 Tidal Processes in the Ribble Estuary

The Ribble estuary is a 'macrotidal' estuary; that is it has a large tidal range at its mouth. The tidal range can vary from around three metres on neap tides to up to ten metres on equinox spring tides[6]. During 2008, the average tidal range at the mouth was 6.2 m, and the average high water level was 8.4 m.

Heights of high water relative to Chart Datum predicted for the port at Fleetwood (near to the Ribble) are shown in Figure A1.1. The time of the four monitoring visits undertaken as part of this project is also indicated (A-D). The survey methodology is discussed in more detail in Appendix 2.

It can be seen from Figure A1.1 that the tidal regime in the vicinity of the Ribble consists of the following processes:

- the semi-diurnal (approximately twice daily) ebb and flood of the tide. This dual ebb and flood cycle of the tide is slightly in excess of a 24 hour cycle, and so the times of high and low water change on a day to day basis (increasing by about 50 minutes per day). Consequently, it takes about a fortnight (a spring-neap cycle) for the times of the tide to advance by 12 hours;

- in addition to the semi-diurnal ebb and flood of the tide, there is a longer cycle of tidal processes which ranges from 'spring' to 'neap' tides. Spring tides occur twice during a 28 day lunar cycle (when the gravitational force of the sun and moon are in alignment, i.e. around full moon and new moon times) and are characterised by more extreme tidal ranges (higher high tides and lower low tides). Neap tides (when lunar and solar gravitational forces are in opposition) occur around a week after spring tides and have smaller tidal ranges (lower high tides and higher low tides);

- there are also longer term effects of lunar and solar gravitation forces on the tidal range. Around the March to April and September to October equinox periods, more extreme spring tidal ranges occur. It is during these periods that some of the highest tidal heights are observed. These are extreme conditions and only related to very particular and limited conditions.

Height of high water may also be increased by onshore wind forcing or low atmospheric pressure. In estuarine areas this may also be increased by coincident high river flow. Although the combination of these conditions with equinox high tides can lead to tidal flooding of areas not normally inundated, this is a relatively rare event.

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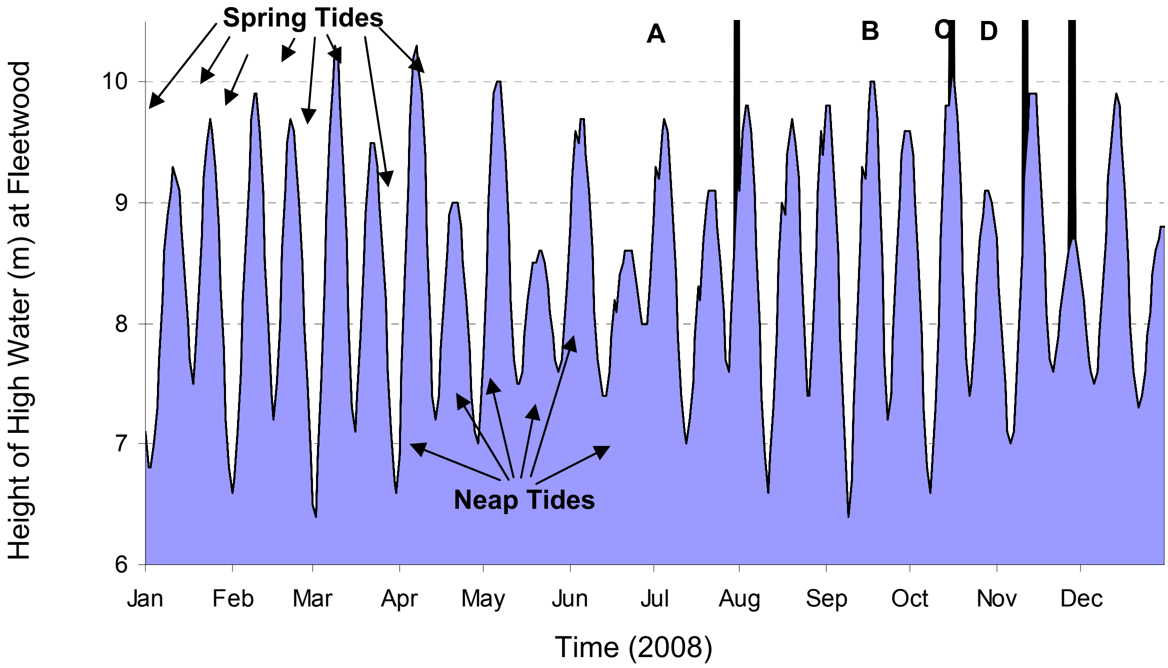
6 Tide Plotter 2008. Belfield Software

Figure A1.1 Daily Heights of High Tide Relative to Chart Datum at the mouth of the Ribble (based on 2008 data for Fleetwood)



Compared to tidal predictions near to the mouth of the estuary, the effect of the tide is clearly reduced in the upstream reaches; the change in water level is smaller. Nonetheless, the relative pattern of changing water levels will be reproduced throughout the estuary.

Within the Ribble estuary, the tidal limit is the City of Preston (around the Lower Penwortham area). In the tributary of the River Douglas (the confluence of which is on the southern side, in the lower half of the estuary) the tidal limit is the village of Becconsall. In the minor tributary of Savick Brook (on the north of the estuary, near Preston) the tidal limit is about 0.5 kilometres (km) north of the A583 road. However, propagation of the tide is at times hindered by a tidal lock gate, situated just downstream of the A583 road bridge (about 0.75 km from the confluence of Savick Brook and the Ribble), that has been installed as part of the Millennium Ribble Link Canal project[7].

The relatively large tidal ranges, and the corresponding high tidal velocities (particularly on the flood tide), tend to 'trap' fine-grained sediments in the upper reaches of the estuary. Another consequence of the relatively large tidal ranges is that along the main channel of the Ribble and its tributaries, wide areas of intertidal sediment can be exposed at low water. During higher spring tides, broad areas of Longton Marsh, Warton Bank Marsh and Banks Marsh are inundated. Although this process is relatively infrequent it does result in the deposition of fresh sediment (and associated radioactivity) onto the salt marsh.

[7] The Lock Gate is operated by the Ribble Link Trust Ltd has part of the Millennium Ribble Link project. This initiative, which was completed in 2002 and provides a route for river/canal boat operators to navigate between the northern Lancaster Canal and that of the southern Leeds and Liverpool Canal via the tidal reaches of the Ribble main channel and subsequently south down the Douglas to Tarleton (south of Becconsall). During the boating season (April till October) the Lock Gate is kept closed during low water periods to maintain water level and hence navigability in the upstream areas of Savick Brook. Navigation of the Link is highly regulated by the operator and boats are only permitted to enter the Link during favourable tidal conditions and only with pre-booking. During 'out of season' (winter) periods when use of the Link is prohibited, the gate is left in the lowered position and hence the tide will influence water level up to the 'natural' (normal) tidal limit.

A1.2 Environmental Radioactivity in the Ribble Estuary and relevance of Tidal State

The association of anthropogenic sources of radionuclides (discharged under authorisation to the marine environment) with fine-grained sediments has been well studied, particularly in the Irish Sea and its coastal environments (e.g. MacKenzie et al., 1999; and, McDonald et al., 2001).

Investigations (e.g. Stanners & Aston, 1982) have long since established that radionuclides discharged from historical operations at the Sellafield site in West Cumbria, are transported south to the Ribble estuary and have subsequently been sequestered (deposited) in intertidal and salt marsh sediments throughout the estuary.

Much work has been done to study the accumulation of anthropogenic radionuclides (particularly isotopes of americium, caesium and plutonium from the Sellafield site, and isotopes of uranium and thorium from the Springfields site), in fine-grained sediments of estuaries such as the Ribble (e.g. Stanners & Aston, 1981; Stanners & Aston, 1982; MacKenzie et al., 1994; Assinder et al., 1997; Mudge et al., 1997; Rainey, 1999; MacKenzie et al., 1999; Brown et al., 1999; Atkin 2000; McDonald et al., 2001; and, Wakefield, 2005). The concentrations of these radionuclides in the environment and the subsequent increased external radiation exposure to members of the public who live and work in the Ribble estuary area are carefully monitored and regularly assessed. Results are reported annually in the Radioactivity in Food and the Environment (RIFE) reports[8].

Calculating external radiation exposure in tidal environments is complicated by how the changing tidal water levels affect the behaviour of the exposed group, and also by the extent that the inundating tide shields gamma emissions from sediment and salt marsh deposits.

For wildfowlers out on the salt marshes, the effect of the tide is likely to be of little importance. Most of the salt marsh area is only inundated during extreme high tide conditions. Wildfowler's exposure is therefore most likely influenced by the longer term processes of sediment deposition and how radioactivity from historical discharges may have been sequestered in salt marsh sediments.

Anglers and other users who spend time along the banks of the estuary may be present over a range of different tidal conditions; however it is uncertain how this may affect their behaviour. They may for example frequent a number of sites, visiting at different times and different states of the tide, or they may prefer higher tidal levels where they do not need to cross areas of thick intertidal sediment.

Houseboat dwellers present a slightly different scenario. It is generally assumed that the boat remains moored in a fixed location. Important factors to consider are the proportion of their time they spend on the houseboat, and how the flood and ebb of the tide affect external exposure from elevated levels of gamma emitting radionuclides that have accumulated in the underlying sediments. With respect to the three aspects of the tidal cycle discussed in Section A1.1 the following points are noted:

- due to the daily shifting of the time of high and low water, a houseboat dweller will experience a wide range of different flood and ebb tide conditions through the course of a year, even if they are only resident on the boat during for example, the evening;

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[8] Covering monitoring and assessments of environmental radioactivity across the UK carried out by the Environment Agency, Food Standards Agency, Northern Ireland Environment Agency and the Scottish Environment Protection Agency

- during spring tides, water levels will drop further than during neap tides, hence more intertidal sediment be exposed. Over the course of the year, a houseboat dweller will experience a wide range of spring and neap tidal ranges;
- the extreme tidal ranges during equinox spring tides only occur on a few days during a year and so are unlikely to have much influence on exposure when integrated across an annual period.

Perhaps of more relevance, particularly with respect to houseboat dwellers, are the location of a mooring site relative to the tidal range, and the typical extent of tidal inundation of that site. A boat may be moored at:

- a site where the area remains flooded and bed sediments are not exposed at any time (for example at a marina or mooring within the centre of a channel which never fully drains);
- a location where the channel or surrounding intertidal area floods and then subsequently drains on a semi-diurnal basis, so that the boat is for a proportion of the time afloat and for a proportion of the time resting on the bed sediment;
- a location towards the upper high tide mark, where the area under the boat is only inundated under the highest tidal ranges (for instance under spring tides around the equinoxes).

The effect of these processes on existing critical groups in the Ribble estuary is discussed below.

A1.3 External Radiological Exposure in the Ribble Estuary

Within the UK, radiation exposure of members of the public arising from historical, current and even anticipated future discharges of radioactive waste is assessed against the Public Dose Limit of 1 millisievert (i.e. 10^{-3} Sv) per year (1 mSv yr^{-1}). Dose may also be quoted in terms of micro-sieverts (i.e. 10^{-6} Sv) per year (µSv yr^{-1}) in which case they should be compared against a value of 1,000 µSv yr^{-1}.

The RIFE annual reports provide an in-depth, yearly compilation of environmental monitoring data and dose assessment studies from across the UK. This monitoring and reporting campaign is undertaken to ensure that any elevation in radiological exposure of the public over background levels remains within authorised levels.

In 2006, a study was undertaken (Chambers & Wainwright, 2006) which questioned the assessment methodology used in the RIFE series for the calculation of dose to houseboat dwellers in the Ribble estuary. This work suggested that potential sources of error in the calculation of external exposure to houseboat dwellers could include:

- the choice of the background gamma dose-rate (inclusive of cosmic radiation and terrestrial sources of naturally occurring radionuclides). This is subtracted from the total (measured) gamma dose-rate, to calculate the anthropogenic component of external exposure. Background values are typically assumed to be 50 nGy h^{-1} for sandy substrates, 70 nGy h^{-1} for mud and salt marsh, and 60 nGy h^{-1} for all other substrates (from McKay et al.,1995). However, there is little information specific to the Ribble area to substantiate this;
- the factor used to convert measurements of gamma dose in air (air kerma, gray) to that of biological exposure (sievert), and how this depends upon

whether an isotropic or rotational geometry is assumed. For example, a factor 0.7 Sv Gy^{-1} is recommended for an 'isotropic' geometry (an irradiation geometry which is independent of direction). However, a value of 0.85 Sv Gy^{-1} is recommended for a rotational geometry (an exposure arising from a dispersed 'flat' (planar) source). This is discussed further in Appendix 5 where recommendations for geometry factors to be used are given;

- instrument efficiencies and statistical variation;

- time and location of measurement, that is spatial and temporal variability of radionuclide concentrations within the tidal reaches of the rivers Douglas and Ribble;

- actual and effective occupancy of houseboat dwellers, where effective occupancy is calculated from the actual occupancy to account for shielding provided by the hull of a houseboat and the effects of the ebb and flood of the tide.

Chambers (2006) then goes on to state that estimates of annual effective dose, as reported by RIFE-10 (Joint Agencies, 2005), were not representative of those likely to be received by the critical group. This was primarily due to overestimating the time the underlying sediment was assumed to be shielded by the inundating tide. Due to the gradual inclusion of this factor through the use of a five year rolling average, a systematic year on year reduction in the estimate of houseboat dweller exposure had been reported.

Chambers (2006) also quoted the radiological habit study published in 2000 (Cefas, 2000) which measured the gamma dose rate in air on a houseboat to be 54 to 76 nGy hr^{-1}. They suggested that the ratio between that measured over unshielded sediment and that within the boat may be nearer to 0.8 (a lower value of 0.73 had been previously assumed). Overall, they concluded that the results significantly underestimated the doses that houseboat dwellers receive. Although not specifically stated, the same conclusions will also apply to RIFE-11 report (Joint Agencies 2006).

Following the work of Chambers & Wainwright (2006) and Chambers (2006) an updated radiological survey of houseboat exposure was undertaken (Cefas, 2007). This work concluded that:

- the mean occupancy for houseboat residents that were assumed to be the critical group in the Ribble was 8,300 hours per year (about 95 percent of the time resident on the boat). As the area under the boat was only flooded under very rare high tides, this value did not need adjusting to account for shielding by water. This assessment corrects the error identified by Chambers (2006);

- the dose to occupants would be 127 μSv per year, based on a measurement of 88 nGy hr^{-1} made in the boat, an assumed background of 70 nGy hr^{-1}, a Sv Gy^{-1} conversion factor of 0.85 and an occupancy of 8,300 hours. This is equivalent to spending 3,800 hours over unshielded sediment.

However, they note that the dose calculated was based on just one measurement (which was three and a half times that measured in 2000) and could therefore be subject to a large degree of uncertainty.

Results of the Cefas radiological surveys and their re-evaluation of historical annual dose to houseboat dweller are given in Table A1.1. The ratio between gamma dose rate in air over sediment and in the boat has also been calculated – the average ratio is

0.79 which is in good agreement with the recommendations given by Chambers (2006). It is important to note that if the ratio is based on measurements where an assumed background has been deducted, the resulting values are significantly lower (on average about half).

Table A1.1 Cefas Air Kerma Measurements and Dose Rate Estimation

Year	Air Kerma (nGy hr^{-1})						Dose (µSv per year)
	On-board	On-board with background subtracted	Mud	Mud with background subtracted	On-Board: Sediment Above		
					Including Background	Background subtracted	
1991	NM	NA	130	60	NA	NA	NM
1992	120	50	140	70	0.86	0.71	353
1993	100	30	130	60	0.77	0.50	212
1994	90	20	110	40	0.82	0.50	141
1995	88	18	120	50	0.73	0.36	127
1996	83	13	120	50	0.69	0.26	92
1997	91	21	110	40	0.83	0.53	148
1998	NM	NA	NM	NA	NA	NA	NM
1999	NM	NA	NM	NA	NA	NA	NM
2000	75	5	90	20	0.83	0.25	35
2001	NM	NA	NM	NA	NA	NA	NM
2002	NM	NA	120	50	NA	NA	NM
2003	NM	NA	95	25	NA	NA	NM
2004	NM	NA	93	23	NA	NA	NM
2005	NM	NA	NM	NA	NA	NA	NM
2006	88	18	109	39	0.81	0.46	127

NM = Not Measured, NA = Not Applicable

The RIFE-12 report for monitoring undertaken in 2006 (Joint Agencies, 2007) included the updated information derived from Cefas (2007) and as a consequence the annual exposure to houseboat dwellers was reported as approximately double that presented in the previous years report.

The most recent survey reported for 2007 (Joint Agencies, 2008), RIFE-13[9], states that in terms of radiation exposure from waste discharges to the marine environment, after those living near to the Sellafield site, the group of people most affected in the UK were those living on houseboats in the Ribble estuary. In 2007, their dose was estimated to be 73 µSv (similar to the dose in 2006, of 75 µSv), however, updated monitoring results were not available and the dose was calculated based on the 2006 monitoring campaign. It is important to note that this is still less than eight percent of the annual 1 mSv (1,000 µSv) dose limit for members of the public. Most of this exposure was stated to be due to external dose from radionuclides discharged from the Sellafield site that had accumulated in intertidal sediments, particularly Cs-137 and Am-241.

A1.4 Summary and Key Points

A brief literature review has been presented in this appendix. It provides a concise summary of environmental processes in the Ribble, how this has facilitated the accumulation of radioactivity in sediments and the resulting dose to members of the public. Key points include:

- the Ribble estuary is macrotidal with a relatively high tidal range and large areas of intertidal sediment and salt marsh which are periodically inundated by the tide. The historical accumulation of a range of radionuclides discharged under authorisation by the nuclear industry is very well studied;

[9] RIFE 14, the annual report for monitoring undertaken during 2008 will be published later in 2009.

- members of the public in the area who receive elevated levels of external gamma radiation include: houseboat dwellers who spend most of their time resident in the boat, wildfowlers who spend large amounts of time on the salt marshes and other (potential) groups such as anglers. This exposure is carefully monitored and reported annually. Levels of exposure are a small fraction (less than percent) of the Public Dose Limit;

- questions have been raised as to the accuracy of some monitoring results, particularly with regard to: the choice of appropriate background subtractions, the need to determine levels of exposure from anthropogenic sources of radiation, conversion of gamma dose rate in air values to that of biological damage, uncertainty associated with instrument measurements, time and location of monitoring results, and rates of occupancy used in assessments.

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Appendix A2 – Methods and Instrumentation

Details of the survey rationale and methodology, instrumentation, and laboratory analytical procedures used during this project, are discussed in this section. Assessments of doses to houseboat dwellers, anglers and wildfowlers are provided in Appendices 3 and 4 respectively.

Sampling, gamma spectrometry analysis of samples in the laboratory, and in-situ monitoring with standard Geiger Műller detectors coupled to Mini/Thermo 6-80 ratemeters were all conducted to Stirling's UKAS accredited standards.

A2.1 Field Strategy Rational and Methodology

The sample sites and monitoring strategy were identified initially in consultation with the Environment Agency, and finalised with input from both the Environment Agency and the environmental manager at Springfields Fuels Ltd.

The survey strategy focused on three sites (see Figure 1, Chapter 2):

- Becconsall Boatyard which is located towards the tidal limit of the River Douglas. Specifically this is located on a tidal creek which is inundated on a semi-diurnal basis. Boats were moored at this location, and houseboats could be present. In this area three different boat geometries were assessed;

    - **Boat 1** – a medium sized boat with a small internal living area and fibreglass hull, 'dry docked' on a relatively level terrace which cuts into the upper bank of a tidal channel where the area under the boat is only inundated on extreme (equinox) high tides;

    - **Boat 2** – a large, keeled, sailing vessel with a fibreglass hull and wooden decking that was moored within a small, relatively steep sided tidal channel which floods and drains on each cycle of the tide. At low water the keel of the boat rests on the bed sediment and the below deck areas are flanked to either side by intertidal sediments on the channel banks[10]. At high water the boat is elevated up by the rising tide, not just off the sediment in the channel base, but up above that on the flanking channel sides so that the deck area is around three metres above the level of the adjacent salt marsh; and,

    - **Boat 3** – a small, flat bottomed, fibre glass vessel, which was moored in the same tidal channel as Boat 2. As with Boat 2, it was elevated up above the sediment on bed and channel sides with the inundating tide. At high water the area within the boat is approximately level with that of the adjacent salt marsh. At low water the flat bottomed hull sat on the intertidal sediment.

- Longton Marsh, located between the confluence of the rivers Ribble and Douglas. This is a broad area of salt marsh frequented by wildfowlers and included two wildfowler 'hide' pits approximately one cubic metre in size;

[10] The boat is maintained in an upright position by supporting struts which have been fixed into the base of the channel

- Savick Brook, which is a small tidal tributary to the north of the Ribble estuary, situated just upstream of the Springfields site effluent discharge point. It forms part of the Millennium Ribble Link canal route. This area may be used by anglers or frequented by other members of the public. When the Link is operational during the summer, a boat may moor for a few hours upstream of the tidal lock gate waiting for appropriate tide and weather conditions to navigate the Link. However, water level is maintained in this upstream location by the Sea Lock and no intertidal sediments are exposed. There are no mooring points for boats downstream of the tidal lock gate. Nonetheless, it is possible that a boat could be stranded in this area over a tidal cycle under exceptional circumstances (although the Link is carefully managed to ensure that it is only navigated under appropriate tide and weather conditions).

These three sites where chosen to include a range of critical group behaviours (existing and prospective), different tidal influence and variable distance from local effluent discharges to the estuary.

A summary of the sampling/measurement strategy is outlined in Table A2.1. In all, around 320 gamma dose rate in air, 35 HPGe in-situ gamma spectrometry, 38 NaI in-situ gamma spectrometry and 81 beta skin dose rate measurements were taken, and 66 soil or sediment samples for gamma spectrometry collected.

Table A2.1 Field strategies.

Visit	Date (2008)	Location	High Water (m)*	Measurement & Monitoring
A	31st Jul	Becconsall Boat Yard (Boat 1)	9.2	• 19 air kerma measurements on-board Boat 1, 12 underneath the boat, 6 along the bank edge and 9 at other locations around the boat yard • 2 in-situ gamma spectrometry (HPGe) • 6 soil/sediment samples from underneath Boat 1, 3 samples from edge of path, 1 sediment core, and 1 dust sweep within the boat collected and processed by gamma spectrometry
	1st Aug	Savick Brook	9.1	• 24 air kerma readings taken at various heights and distances along bank and 12 readings taken over intertidal sediment • 10 beta dose attenuation with height readings (taken with a Rad-Eye) • 3 intertidal sediment, 6 bank sediment downstream of the Lock Gate and 1 upstream of the Lock Gate collected and processed by gamma spectrometry
B	16th Oct	Becconsall Boat Yard (Boat 1)	10.1m	• 32 air kerma measurements taken on-board Boat 1, 12 underneath the boat, 3 along the bank edge and 3 at other locations in the Boatyard • 11 in-situ gamma spectrometry (HPGe) spectra collected within Boat 1 and 4 spectra collected above the sediment around Boat 1 • 8 in-situ gamma spectrometry (NaI) spectra taken within Boat 1 and 2 spectra collected above sediment around Boat 1 • 5 beta dose measurements taken above the carpet in Boat 1

Visit	Date (2008)	Location	High Water (m)*	Measurement & Monitoring
				• 6 soil/sediment samples under Boat 1, 3 collected along the path edge and 1 galley dust sweep were collected and processed by gamma spectrometry • 27 air kerma measurements taken on Boat 2
	17th Oct	Becconsall Boat Yard (Boat 2)	10m	• 76 air kerma measurements taken on board Boat 2, 7 readings along the bank, 3 above intertidal sediment beside boat, and 3 at other locations in the boat yard • 12 in-situ gamma spectrometry measurements (NaI) were taken on the deck at the bow end of Boat 2 and 1 was taken within the main quarters of Boat 2 at low tide. 3 spectra were collected along the bank adjacent to Boat 2, and 1 over the intertidal mud under the boat • 6 in-situ gamma spectra (HPGe) were collected within the main quarters of Boat 2 over the time of the ebb tide, 2 on the deck at high tide (bow and stern). 3 spectra were also collected on the bank adjacent to Boat 2. • 9 beta dose readings taken onboard Boat 2 and 3 measurements were made over bank sediment • 6 intertidal sediment samples were taken from around Boat 2, 3 sediment samples collected from along the south bank, together with 1 dust sweep sample. Samples were processed by gamma spectrometry
C	10th Nov	Longton Marsh	8.6m	• 5 air kerma measurements were taken in wildfowler 'hide' pits, 13 from around the pits and 3 from along a intertidal gulley • 3 in-situ gamma spectrometry measurements (HPGe) taken at different heights above the salt marsh • 14 beta dose measurements taken in pits, 5 measurements above salt marsh, and 5 measurements above intertidal sediment • 4 pit sediment samples and 1 intertidal sediment sample collected and processed by gamma spectrometry
	11th Nov	Savick Brook	9.2m	• 36 air kerma measurements taken downstream of Lock Gate (9 of which were above intertidal sediment), and 1 measurement taken upstream of the gate • 23 beta dose measurements taken above intertidal sediment and 14 garment attenuation measurements made • 3 in-situ gamma spectrometry measurements taken over salt marsh and 1 over intertidal sediment at low tide (HPGe) • 3 bank sediments, 2 lower terrace, and 1 intertidal sediment samples were collected downstream of Lock Gate, 1 bank sediment collected upstream of Lock Gate. All samples were processed by gamma spectrometry. One 30 cm core sample was also collected from the bank edge, subdivided into 5 cm slices and analysed using gamma spectrometry
D	28th Nov	Becconsall Boat Yard (Boat 3)	8.7m	• 18 air kerma measurements were taken on Boat 3, 34 on the eastern and western banks of the channel, and 7 on the edge of the western bank • 3 beta dose measurements taken above sediment

Visit	Date (2008)	Location	High Water (m)*	Measurement & Monitoring
				• 6 intertidal sediment around Boat 3 and 3 bank sediment samples collected and processed using gamma spectrometry • 7 in-situ gamma spectrometry measurements (NaI) collected on board Boat 3, 2 above intertidal sediment and 1 on bank edge

* Height of high water at Fleetwood. Annually averaged (2008) height of high water at Fleetwood was 8.4m

Sediment sampling was undertaken within ERL's accreditation. Sediment samples were collected by taking surface scrapes (0.01 m) at each site. Additionally cores were taken under Boat 1 (0.04 m depth) to assess potential heterogeneity in the top layer of sediment, and on the upper surface salt marsh surface of Savick Brook (0.3 m depth) to establish the Cs-137 depth distribution at 5 cm intervals. This helped validate the calibration used for the in-situ gamma spectrometry measurements.

A2.2 Field Instrumentation

Field instrumentation was used to take measurements for gamma dose rate in air, beta skin dose and in-situ gamma spectrometry.

A2.2.1 Gamma Dose in Air

Due to the potential environmental heterogeneity in complex radiation fields, a UKAS accredited Thermo 6-80 detector, with an MC71 gamma probe (Geiger Műller, GM Tube) was used. This was supplemented by two further instruments (Mini Instruments) which were also calibrated by a UKAS accredited calibration laboratory. Consistency in instrument performance was checked before and after the field campaigns and was demonstrated not to have changed.

All measurements given are based on a 600 second count time and unless otherwise stated related to an instrument set up where the centre of the probe was positioned 1 metre above the ground. To determine the effect of height over sediment on gamma dose rate in air, further measurements were made with the centre of the probe positioned at 0.5 m and 0.15 m above the ground. These are discussed in Appendix A4.

The instruments were calibrated against both Cs-137 and Ra-226 sources[11]. Through concurrent use of the in-situ gamma spectrometer, the dominance of Cs-137 to the dose rate could be estimated. The Cs-137 gamma photon flux contributed less than (or much less than) 50 percent in all measurement sites. The Ra-226 calibration was therefore identified as the most appropriate for estuary wide comparison[12]. All results presented are based on the Ra-226 calibration. This is consistent with the approach of Mudge *et al*. (1997). Further discussion is provided in Appendix 5.

[11] Cs-137 and Ra-226 are the two primary sources used when calibrating gamma dose rate instrumentation. The former is typically used when the dose rate is anticipated to arise predominantly from higher energy emitting radionuclides, for instance Cs-137 itself. The later is more typically used where the radionuclides likely to be found are of lower energy or represent a mix of energies.
[12] It was determined that the Cs-137 calibration would over predict gamma dose in air by 30 percent.

The units in which dose should be reported depend on the objectives of the survey. Following the recommendations of the British Committee on Radiation Units (1989) all gamma dose monitoring results are reported as gamma dose rate in air (air kerma). The units of nano-Grays (10^{-9} Grays) per hour (nGy h^{-1}) are used throughout this report.

All gamma dose rate in air measurements presented have had the intrinsic background[13] and the contribution from cosmic radiation background[14] subtracted (a total of approximately 60 nGy hr^{-1}). The contribution to gamma dose rate in air from intrinsic and cosmic background was determined from instrument testing (see Section A5.1.2 for details) and can be defined with a reasonable amount of certainty. However, the contribution from naturally occurring levels of radioactivity present in soils and sediment can be more variable, depending upon the substrate type and the local geology (as discussed in Appendix 1). To avoid any bias which may arise from this uncertainty, gamma dose rate in air measurements are reported inclusive of terrestrial background.

The conversion of gamma dose rate in air to units of biological damage (sieverts), either in terms of the effective dose (H_E) or the ambient dose equivalent (H*(10)) are discussed in Appendix A5.

A2.2.2 Beta Skin Dose

In addition to assessing gamma dose rate in air, this project also measured beta skin dose (H'(0.07)) arising from beta emitting radionuclides. The basic traceable quantity for measuring external photon radiation is absorbed dose (Gy). This is then converted to effective dose or ambient dose equivalent (Sv) by using weighting factors (Appendix 5). Beta skin dose (H'(0.07)) is the estimated dose at 0.07 mm depth in the skin (Sv).

Two instruments were initially trialled, but were found to be unsatisfactory:

- RADEYE (Thermo Scientific) is an instrument primarily designed for mono-energetic beta radiation sources and not complex radiation fields found in the natural environment. The instrument was found to be too sensitive for low energy beta emissions (Th-234) and may also be influenced by alpha emitting radionuclides close to the sediment surface[15].

- SMARTION is an instrument manufactured by Thermo Scientific and was recommended for use by several instrument suppliers and identified as a potentially suitable instrument through discussion with the Environment Agency. However, it was found to be incapable of measuring the beta dose rates at environmental levels currently found in the Ribble estuary, primarily because typical realistic detection limits for this instrument (2,000 to 3,000 nSv h^{-1} per cm^2) are around an order of magnitude greater than the levels found in the environment. In addition, the instrument was affected by intrinsic instability at low dose measurements (requiring long counting times), and the measurements

[13] The intrinsic background is a small, but unavoidable, count rate given by any gamma monitoring instrument (even without any external source of gamma radiation) that arises due to naturally occurring radionuclides within the material of the instrument. This is assessed through calibration and testing and then the value subtracted from meter readings.
[14] Cosmic background due to solar radiation was determined within a boat in the centre of Esthwaite Water (Cumbria) using UKAS accredited procedures. The mean of six readings per detector was used to establish the background whilst the boat was maintained at the centre of the lake with no shore line closer than 100 m to the instrument (62.3 ± 7, 62.4 ± 4.6 and 57.8 ± 8 nGy hr^{-1} (2 sigma uncertainties) for the three detectors). These are similar to other measurements made by ERL over the Lake of Mentieth in Scotland and those determined by Mudge et al (1997) of about 49 ± 6 nGy hr^{-1}.
[15] Alpha particle cannot penetrate the skin, hence their measurement could overestimate the beta skin dose.

were strongly influenced by temperature, humidity and wind fluctuations, therefore the realistic detection limits are likely to be even greater.

Following discussion with a leading UK expert in beta dosimetry[16] it was agreed that a large area probe was required and the ruggedised version of the Thermo BP19RD, (which has a wide monitoring area 100 cm^2, coupled to a digital ratemeter - Thermo Electra) should be used. A 12 millimetre Perspex shield was constructed to shield out any beta emissions and so enable the gamma contribution to the instrument to be established. In addition, the instrument without the Perspex shield was placed in a plastic file pocket for protection and to reduce the influence from low energy betas which have a negligible influence on skin dose rate. The instrument was calibrated under UKAS accreditation by Nuvia against: strontium-90 (Sr-90) and yttrium-90 (Y-90); chlorine-36 (Cl-36) and carbon-14 (C-14), with and without the protective file pocket in place. Conveniently, with the file pocket in place, the conversion from counts per second to H'(0.07) was the same for low energy beta (e.g. C-14) as high energy beta (Sr-90 + Y-90). Thus the use of a single conversion factor provided a robust estimate of the skin dose rate (8.0 s^{-1} nSv^{-1} h).

The use of a wide-area monitor was also similar to previous measurements undertaken in the Ribble (Hunt *et al.,* 1992; Mudge *et al.,* 1996; Mudge *et al.,* 1997) providing temporal comparability and realistic detection limits down to 200-300 nSv hr^{-1} per cm^2. For each measurement location, dual 20 second measurements were made with the BP19RD covered by the file pocket to measure total beta and gamma contributions and with the 12 mm Perspex shield attached to measure the gamma-only contribution. If required, better sensitivity could be achieved by counting for longer.

The gamma-only measurement was subtracted from the total beta-gamma measurement and the UKAS accredited calibration coefficient applied to determine beta skin dose (H'(0.07)). All results presented have been corrected in this way and are given as nSv hr^{-1} per cm^2.

A2.2.3 In-situ Gamma Spectrometry

Two instruments were used to identify the contributions to the gamma dose rate from individual radionuclides in the underlying substrate.

- a 35 percent relative efficiency n-type high purity germanium (HPGe) detector was used. The instrument was cooled to -190°C by liquid nitrogen and typically deployed at a 1 metre height above the study surface from a tripod. The detector height was adjusted to examine the contributions to air kerma at 0.5 m and 0.15 m (in addition to 1 m). High spectral resolution gamma emission spectra were acquired for around 1,000 second instrument count times (e.g. Full Width at Half Maximum at 662 keV = 1.4 keV). Gamma Vision (32) software was used to process the spectra. The calibration used was ERL's empirical calibration derived from a number of calibration sites across the UK and from a number of projects (e.g. Tyler & Copplestone, 2007). The calibration has been demonstrated to be robust in comparison with conventional soil sample analysis. The natural series radionuclides were reported as Bq kg^{-1} (dry weight) assuming a relatively uniform vertical activity distribution. Estimates of Cs-137 depth distributions were also estimated from forward scattering procedures (e.g. Tyler, 1999; and, Tyler, 2007). This was used to improve the accuracy of the Cs-137 inventory assessment (Bq m^{-2}). International Committee for Radiological Units 1994 (ICRU 1994) conversion factors were used to convert measured radionuclide concentrations to air kerma

[16] Personal communication (2008) with Pete Burgess (Nuvia)

contributions and found to compare well with the conventional Thermo and Mini Instrument 6-80 estimates of air kerma (see Figure A2.1);

- a 2 inch by 2 inch Sodium Iodide (NaI) detector coupled to digital electronics (Digibase) monitor was also used. This was a substantially more portable instrument and was used to supplement the measurements made by the HPGe detector. It was used on Boat 3 which was less stable and unable to accommodate the large HPGe detector. The NaI detector has a spectral resolution of about 6 percent at 662 keV and this required careful spectral processing to deconvolute (separate out) spectral interferences. Stripping coefficients were used to estimate the interference from primary and secondary gamma photons derived from U, Th or K on each other and on full energy peaks of lower gamma photon energy (e.g. Cs-137). These stripping coefficients were determined from concrete calibration pads at the Scottish Universities Environmental Research Centre, East Kilbride. Gamma emission spectra were acquired over 1,500 seconds. The background was subtracted and the spectra were stripped to provide net Tl-208 (equivalent Th-232), net Bi-214 (equivalent U-238), net K-40 and net Cs-137. These counts were converted to natural series radionuclide concentrations and Cs-137 inventories by empirical comparison with the calibrated HPGe detector. The same ICRU (1994) air kerma conversion factors were used to calculate and reconstruct the air kerma contributions. Again a good agreement was identified with the conventional Thermo and Mini Instrument-6-80 estimates of air kerma.

Figure A.2.1 shows the inter-comparison between estimates of gamma dose rate in air derived from HPGe in-situ spectrometry and estimates derived using the Thermo 6-80 instruments.

Although there is scatter within the comparison, the 2 sigma error bars generally demonstrate a good statistical comparison in the data. Nevertheless, the HPGe detector tended to overestimate the dose rate slightly, particularly in the more complex radiation fields around and within the boat compared to the Thermo instrument. This may be function of the stratification of natural radioactivity within the thin sediments or apparent stratification induced by the boat structure. This could have led to a small overestimation of the scattered secondary gamma photon contribution to the dose rate at lower energy (a photon flux which is in reality more strongly attenuated by the boat structure). In simpler radiation fields, such as Longton, the comparison is better.

For ease of presentation, the in-situ measurements, where emissions from radionuclides have been detected are presented as:

- potassium-40 (K-40);

- uranium-238 (U-238) series inclusive of thorium-234 (Th-234); protactinium-234m (Pa-234m); radium-226 (Ra-226); lead-214 (Pb-214); bismouth-214 (Bi-214); and, lead-210 (Pb-210);

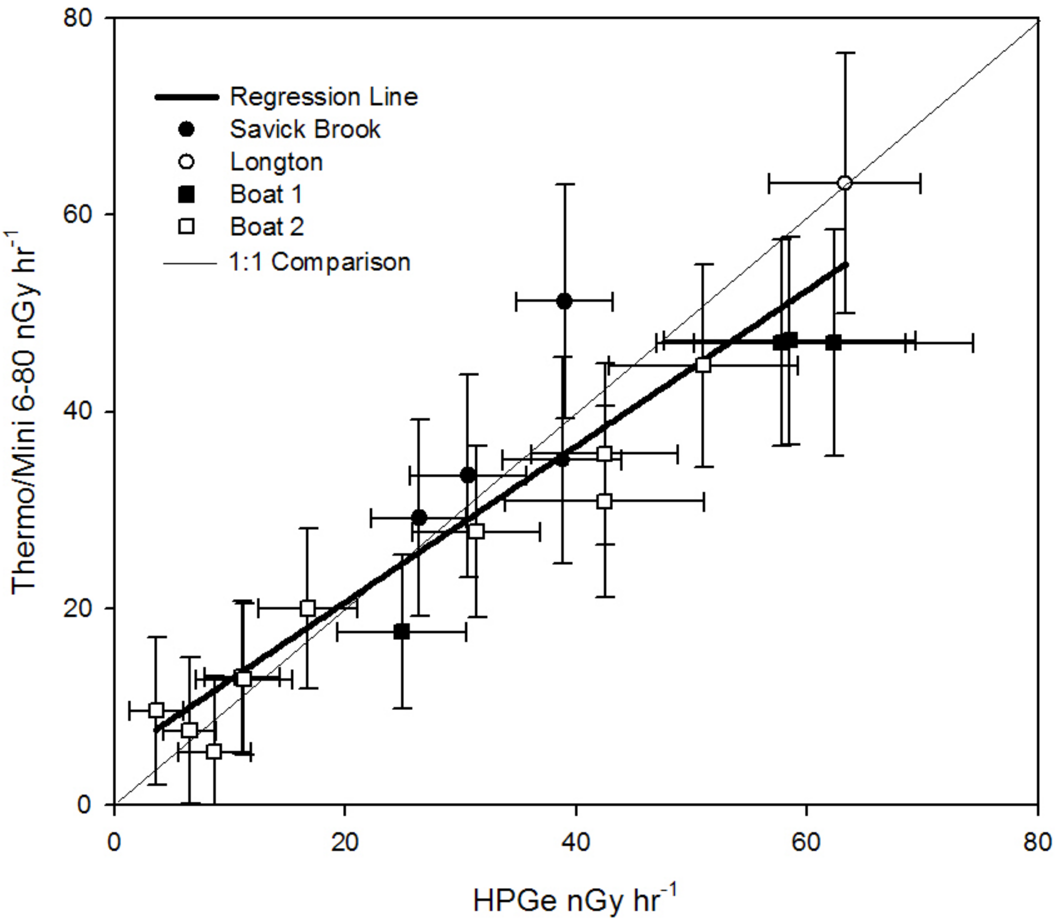
- thorium-232 (Th-232) series inclusive of actinium-228 (Ac-228); radium-224 (Ra-224); lead-212 (Pb-212); bismouth-212 (Bi-212); and, thalium-208 (Tl-208);

- caesium-137 (Cs-137);

- excess thorium-234 (Th-234) and protactinium-234m (Pa-234m) (excess estimated as the disequilibrium between Th-234, Pa-234m and the daughters Bi-214, Pb-214);

- americium-241 (Am-241).

Figure A2.1 Example comparison between HPGe and Thermo 6-80 Air Kerma Estimates



A2.2.4 Location and Positioning

Air kerma and in-situ gamma spectrometry measurements were undertaken at the standard height of 1 metre. The instruments were also lowered to 0.5 m and 0.15 m to examine the height dependency of the measurements.

Beta skin dose rate measurements were typically undertaken at 0.01 m height, but height dependency was also examined at 0.05 m, 0.15 m, 0.5 m and 1 m.

Positions were assessed using a Garmin GPS 72, with 6 to 12 metre vertical and 3 to 6 metre horizontal spatial resolution. A real time kinematic differential GPS (Leica System 300 GPS) was used to reconstruct topographic profiles across stream channels and provide relative boat position with a 0.05 to 0.06 m vertical uncertainty and a 0.04 cm horizontal resolution.

A2.3 Sediment Sampling

Surface sediment scrapes to a depth of 0.01 m were taken at each of the survey sites. In addition, two cores were collected at Savick Brook and Becconsall Boatyard with an adapted 0.1 m diameter golf hole corer, capable of sampling to 0.4 m depth. Typical, surface scrapes of between 0.5 to 1 kilogram of wet weight sample was collected. In addition, a new, battery operated, car vacuum cleaner was used to collect dust samples from Boats 1 and 2. Dust samples were typically of the order of 0.004 to 0.01 kilograms.

A2.4 Laboratory Analysis

On return to the laboratory the samples were logged into ERL's UKAS accredited Quality system. Samples were dried, ground, containerised, sealed and stored for a minimum of two weeks to enable U-series equilibration (i.e. to allow the Radon-222, (Rn-222) and its progeny to build up within the sample to ensure equilibration between Ra-226 and Bi-214 and Pb-214). Samples were counted for typically 80,000 seconds and processed to provide specific activity concentrations. All ERL calibrations are traceable to International Atomic Energy Agency (IAEA) and National Physical Laboratory (NPL) standard reference materials, as part of the laboratory's regular participation in international inter-laboratory trials.

A small number of samples from the intertidal surfaces of Savick Brook were analysed wet immediately on return to the ERL to establish the presence of short-lived radioisotopes. These samples were then processed in the same way as the rest of the samples (i.e. dried, ground, containerised etc) and recounted.

The small dust samples were compressed to form a pellet of a defined geometry under a 10 tonne press and then processed within a sealed petri-dish.

All activity concentration data in sediment, soil and dust sample are reported as Bq kg^{-1} (dry weight).

A2.5 Summary and Key Points

A detailed monitoring programme was designed and implemented. It included collecting sediment and soil samples which were analysed in a laboratory using gamma spectrometry, and also taking field measurements of gamma dose rate in air, in-situ gamma spectrometry and beta skin dose. Key points to note are:

- all gamma dose rate in air measurements are presented with intrinsic and cosmic background radiation (around. 60 nGy hr^{-1}) subtracted, but are inclusive of contribution from naturally occurring radionuclides in the substrate.

- a calibration coefficient based on Ra-226 was found to give the best agreement between gamma dose rate in air and in-situ gamma spectrometry. Based on this inter-comparison a calibration coefficient using Cs-137 would over-predict the dose rate by 30 percent.

- the RADEYE and SMARTION (Thermo Scientific) beta skin dose instruments were both tested in the field and found to be inappropriate for environmental work. A ruggedised version of the Thermo BP19RD probe with a purposed built removable Perspex shield was found to perform well and give adequate levels of detection.

- good agreement was found between estimates of gamma dose rate in air derived using GM Tubes and Thermo 6-80 rate meters, and derived from in-situ gamma spectrometry.

A2.6 References

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Appendix A3 – External Exposure of Houseboat Dwellers

The results of the survey for prospective houseboat dwellers moored at the Becconsall Boatyard are described in this Appendix. All gamma dose rate in air measurements have had the intrinsic count rate of the instrument and cosmic background subtracted, but include the contribution from naturally occurring radionuclides in the environment. Of the three boats surveyed:

- Boat 1 had a geometry most appropriate to a relatively small houseboat with a flat bottomed hull (or other configuration), such that it is relatively low lying and remains stable when intertidal areas are exposed. It represents a boat that could be situated on level ground towards the high water mark, for instance in a small bay or harbour, or adjacent to a tidal channel. It may be occupied throughout a full annual period;

- Boat 2 had a geometry most appropriate to that of a large, keeled, sailing vessel, that spends the winter months in a relatively small tidal creek where the boat is maintained in a stable upright position by struts;

- Boat 3 was a small relatively flat bottomed fibreglass vessel that would not be suitable as a houseboat. The geometry is appropriate to a small pleasure craft that could be used daily for angling or other water based recreation, and could become stranded and laid up on intertidal sediments over a tidal cycle.

All the boats surveyed were situated within or adjacent to a tidal creek. The creek was about 700 metres long running south to north from the River Douglas. The boatyard was situated to the west of the creek (on higher ground) with lower lying salt marsh to the east. The creek was about ten metres wide at its top, about five metres deep and about four metres wide at its base. The creek bed and lower channel sides were covered by deep fine-grained and mobile intertidal sediment[17].

The boatyard site was visited during Survey A, Survey B and Survey D (Survey C was focused on the Longton and Savick sites) as follows:

- Boat 1: 31st July 2008 (Survey A);

- Boat 1: 16th October 2008 (Survey B);

- Boat 2: 17th October 2008 (Survey B);

- Boat 3: 28th November (Survey D).

Each visit was made on a spring tide, although the maximum tidal heights during these periods varied significantly (see Figure A1.1 and Table A2.1). Initially it was planned to visit the site on both spring and neap tides. However, under direction from the Environment Agency the neap tide visit was cancelled and replaced by one to assess the effect of an equinox spring tide (in October).

During the visits the flood tide started to fill the creek around two hours before high water (at Fleetwood). During these visits, inundation of the creek was rapid (taking

[17] A Health and Safety assessment concluded that access by foot along the base of the creek was not acceptable due to the depth and mobility of sediment. Consequently all samples and measurements were either made from the safely accessible bank sides or from over the edge of a boat.

about two hours), particularly during the October visit, when a small tidal bore was observed in the main channel of the River Douglas. The channel then drained completely two to three hours after high water.

As stated, the site was not visited during neap tides. Due to the relatively large tidal ranges that can occur in the Ribble, it is probable that during some neap tides that the creek will not fully drain and that the changes in water level will be less rapid[18].

A3.1 Permanent Annual Occupancy (Boat 1)

Boat 1 was surveyed on two occasions covering different tidal conditions (31st July, a high spring tide of 9.2 metres and 16th October an extreme equinox spring tide of 10 metres). Data was collected, where possible, to cover periods of high and low water. During the first visit only the area under the stern of the boat was inundated (to a depth of 10 to 20 centimetres). In the second, the full area under the boat was inundated (the water depth was highest at the stern, at around 1 metre; towards the bow it was about 0.3 metres).

Summarised below are: activity concentrations from sediment under the boat, at the very top of the bank; and in dust collected from within the boat; gamma dose rate in air below, within the boat and at the top of the bank; beta skin dose within the boat; and gamma dose contribution from different radionuclides within the boat at different states of the tide (assessed via in-situ gamma spectrometry).

A3.1.1 Environmental Setting

Boat 1 was effectively 'dry docked'. It was situated with its axis perpendicular to the creek on a small area of relatively level ground that forms a terrace cut into the upper west bank of the creek (the bow faces into the bank and the stern towards the creek). A schematic diagram of this is given in Figure A3.1; here water levels at different states of the tide relative to the position of the boat are approximate and given for illustration only. Areas of soil/sediment accumulation on bank areas that could contribute to the gamma radiation on the boat are indicated with arrows[19]. The lengths of the arrows aim to indicate the respective contribution to the gamma radiation arising from different areas of exposed soil and sediment. This is however only illustrative and it was not possible to measure this directly during this study.

Boat 1 was supported by struts on either side of the main hull so that the centre of the boat is elevated by around 0.8 to 1 metre above the sediment surface. The boat was approximately 14 metres long with an internal 'living quarter' area of about 2.5 by 5 metres. The internal galley floor was approximately 1.3 metres above the sediment surface.

The main hull of the boat was constructed from 12 millimetres marine ply with an additional 1 millimetre epoxy coating-fibreglass weave. The remaining cladding was 4 millimetre ply including veneered internal surfaces. The internal floor was made from 12 millimetre exterior grade marine ply. There were three 30 gallon water tanks between the galley floor and the keel of the boat, each about 0.4 metres in height and constructed from polyester fibreglass. These tanks contained drinking water and are typically re-filled over a three week cycle. The galley was situated in the aft section of

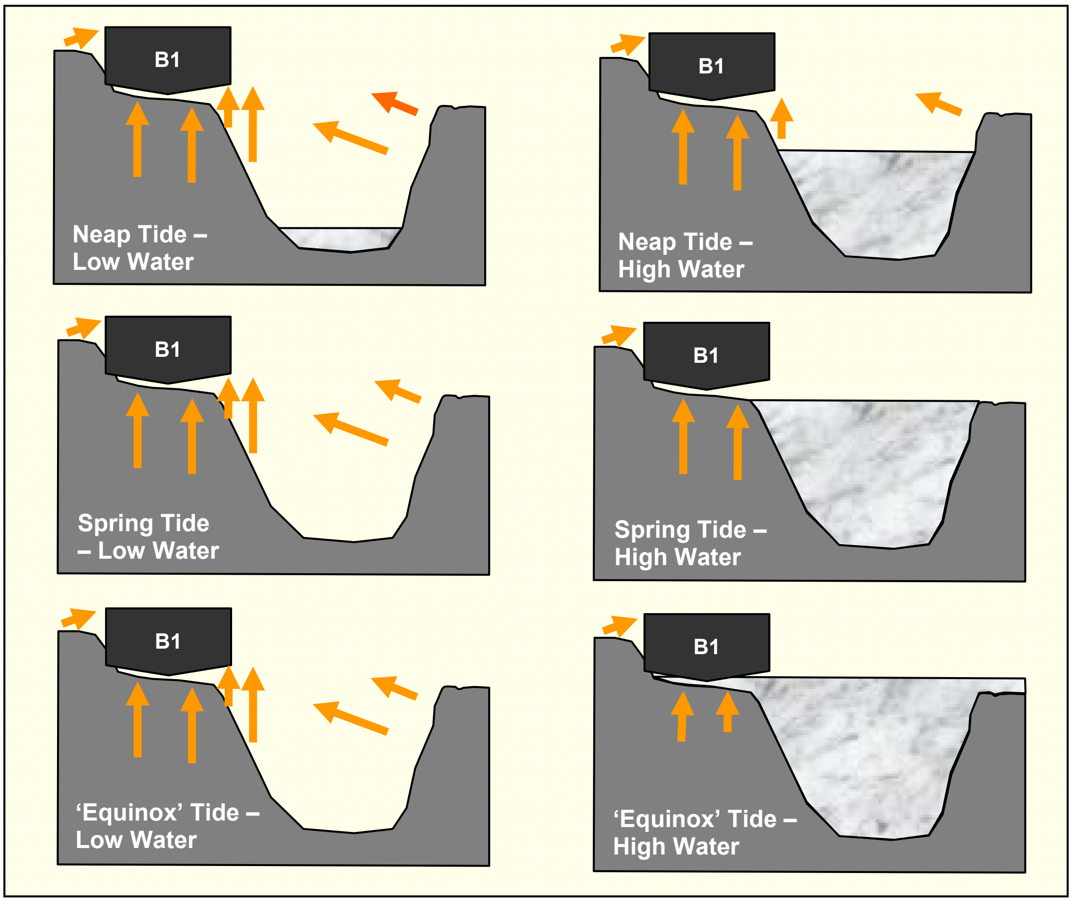
[18] As noted in Section A1.1, the duration of the semi-diurnal ebb and flood of the tide remains relatively constant, irrespective of tidal range. Consequently, spring tides are characterised by higher tidal current velocities and a more rapidly flooding (or ebbing) tide. During neap tides, current velocities and the rate of flooding or ebbing of the tide are lower.

[19] The conditions under neap tidal states have been estimated.

the boat (towards the bank). The wheelhouse at the stern of the boat faced out above the channel of the creek.

It is important to note that the full area under Boat 1 was only inundated at the most extreme high tide situations ('equinox' tides)[20]. Under more typical spring tides only a small area under the stern of the boat is inundated at high water (during neap tides it is unlikely that any ground under the boat will be inundated).

Figure A3.1: Conceptual Environmental Setting for Boat 1 (B1)



Based on tidal data discussed in Section A1.1, tidal ranges of 10 metres or more at the mouth of the estuary were only predicted to occur about 14 times during 2008 (i.e. about 2 percent of tides would lead to inundation of the ground under the boat). During the approximate 6 hour ebb and flood of each of these tides, the area under the boat was only inundated for an hour or so at high water, so this is clearly a rare event.

A3.1.1 Soil and Sediment Activity Concentrations

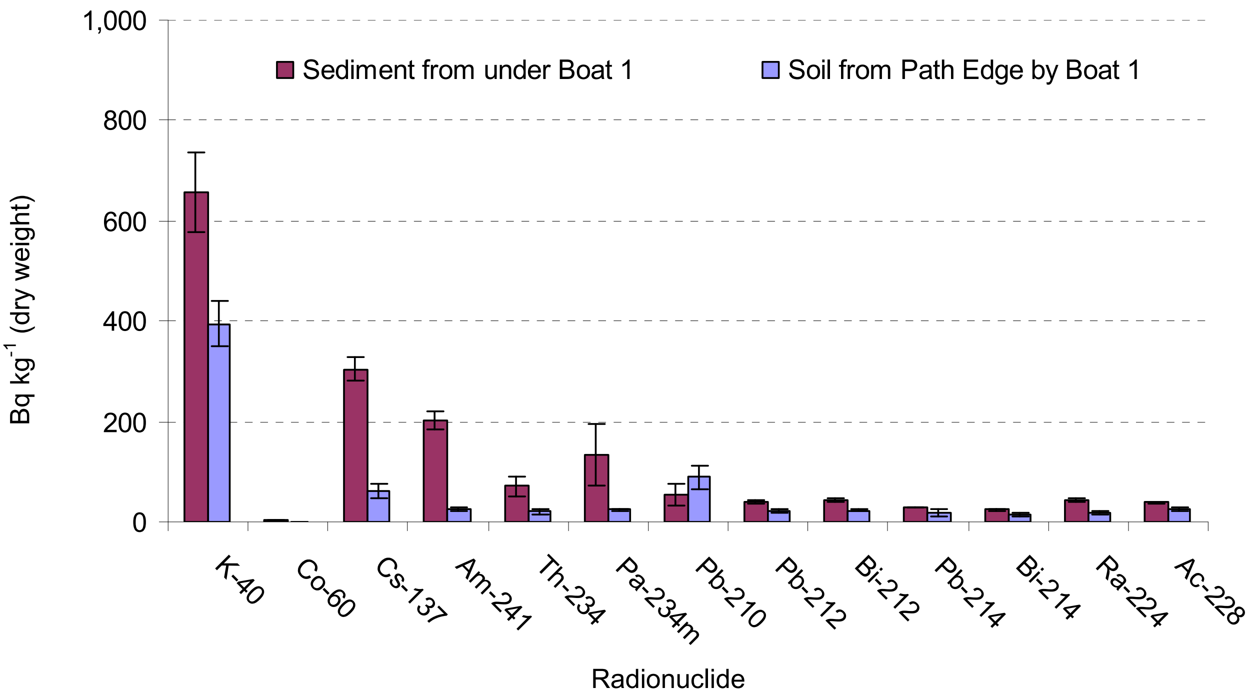
Activity concentrations of radionuclides within surface sediment samples from under the boat were collected at low water and subject to high resolution gamma spectrometry. Further soil samples at the top of the bank (adjacent to a path running around the boatyard) were also taken[21]. The results (averaged over the two visits) are

[20] Even under extreme high tides it is our understanding that the boat is not normally lifted up off the ground by the rising water.

[21] This location is one of the routine monitoring points used by the Environment Agency when collating data for the RIFE report. It is possible that this area may flood under a combination of extreme tidal and extreme weather conditions. Anecdotal evidence suggests that this has occurred at times in the past; however, this is likely to have been infrequent.

given in Figure A3.2. The standard deviation associated with the mean results are illustrated by error bars.

Figure A3.2: Soil and Sediment Activity Concentrations around Boat 1 – July 31st



Activity concentrations of radionuclides in sediment under the boat were consistent between the two surveys. Of the radionuclides discharged from the Sellafield site, the highest activity concentrations were of Cs-137, with a mean of around 300 Bq kg^{-1} (dry weight). The activity concentration of Am-241 was around 200 Bq kg^{-1} (dry weight). Only very low activity concentrations of Co-60 (of a few Bq kg^{-1} dry weight) were detected.

Activity concentrations of Th-234 and Pa-234m were more variable, ranging from around 20 to 200 Bq kg^{-1} (dry weight). Other uranium and thorium decay chain products were much more consistent, typically between 25 to 30 Bq kg^{-1} (dry weight), while Pb-210 was about 60 Bq kg^{-1}.

Samples from the top of the bank adjacent to the path edge had lower activity concentrations for almost all the radionuclides assessed, with the exception of Pb-210 which was about 1.3 to 2 times that found in the sediment under the boat. Activity concentrations of Cs-137 and Am-241 were particularly low (less than 20 percent of those under the boat) while the rest of the radionuclides were between 30 and 60 percent of those measured under the boat. The reason behind the lower value of K-40 activity concentration associated with soil from the path edge is unclear, but is likely to include a contribution from marine sediments that may have been deposited on this area under extreme storm surge conditions.

The activity concentrations of dust samples collected from within the boat were comparable to those of the sediment under the boat or the soil on the path. The small sample size collected and the respective uncertainties in the count statistics means that a more detailed inter-comparison was not practicable.

In addition a shallow (4 centimetre depth) core was also taken underneath the boat. The activity concentrations of almost all radionuclides at this depth were comparable (within a factor of two) with those from a surface scrape (1 centimetre depth). Shorter lived Th-234 and Pa-234m were exceptions, their sub-surface activities were factors of three and ten (respectively) lower than at the surface.

A3.1.2 Gamma Dose Rate in Air

Gamma dose rate in air was measured under the bow, mid section and stern of the boat during both surveys. This was repeated along the sides of the boat. A total of 12 measurements at 1 metre above the soil surface were made. Measurements at 0.15 and 0.5 metres above the sediment surface were also taken to identify any changes in dose rate with height over the surface.

Within the boat, gamma dose rate in air was measured in the galley (the main living area), in the stern and on top of the wheelhouse roof. A number of other measurements were also taken in the locality and these are discussed below.

Gamma dose rate in air measurements are illustrated in Figure A3.3. For measurements taken onboard the boat, the error bars give the 2 sigma uncertainty associated with a single measurement. For measurements taken underneath the boat, the error bars represent the standard deviation of the six measurements made at low water (which for ease of illustration, are presented across the tidal cycle). All measurements are given respective to the time of high water at Fleetwood.

Gamma dose rate in air measured under the hull of the boat (1 metre above the sediment surface), at low water, ranged from 47 nGy hr^{-1} during the July visit to 57 nGy hr^{-1} for the October visit. The mean value over both surveys was 49 +/- 4.2 nGy hr^{-1}.

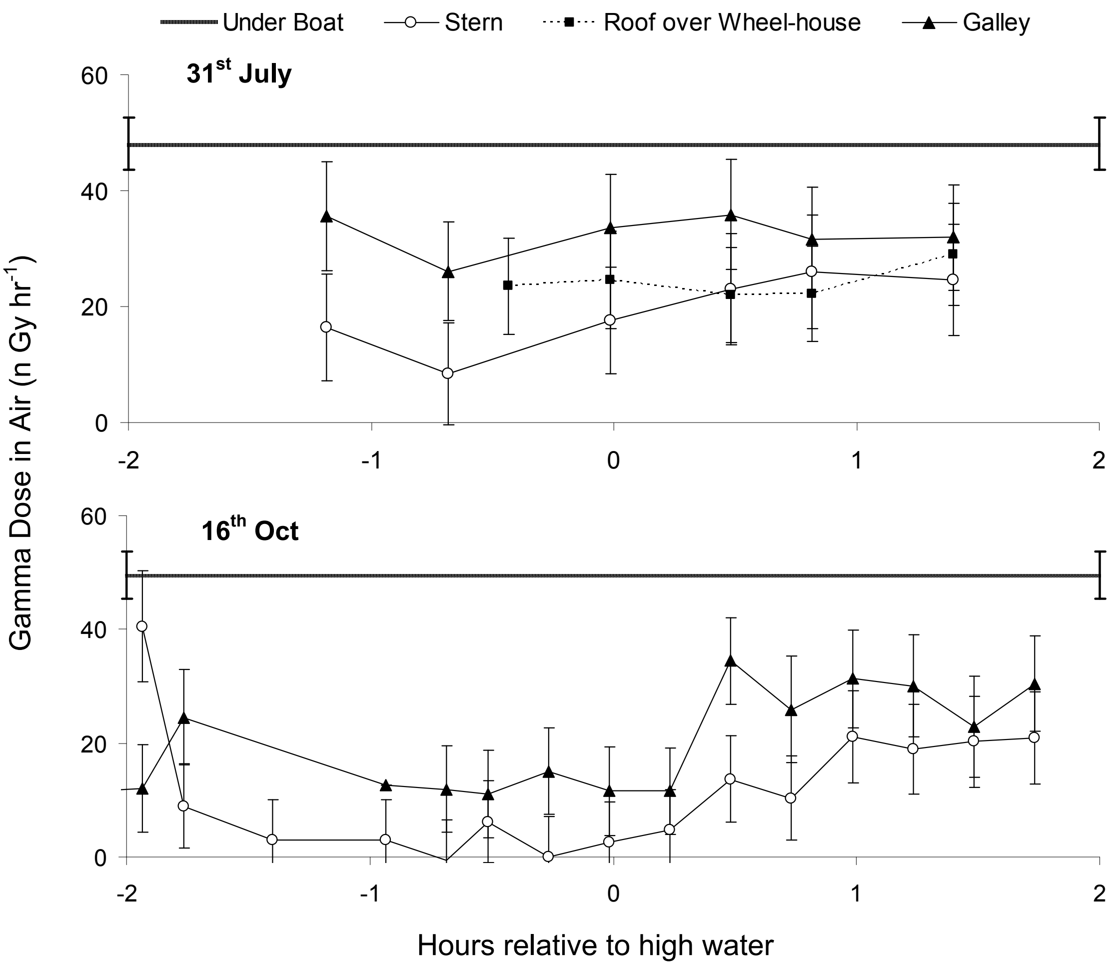
The measured activity concentrations within the boat appeared to decrease with inundation of the channel at high water, for example. during a typical higher spring tide (31^{st} July). A more significant reduction was observed during an extreme high tide (31^{st} October) when the channel and the area under the boat were inundated. Although gamma dose rates in air were near zero around high water in October, this survey was undertaken during extreme tidal conditions that are not representative of the annually averaged tidal range in the Ribble.

When the channel was not fully inundated, the gamma dose rate in air within the stern of the boat was relatively constant, between 19 and 26 nGy hr^{-1} (average of 20 +/- 1.0 nGy hr^{-1}) while in the galley was between 23 and 36 nGy hr^{-1} (average of 30 +/- 4.2 nGy hr^{-1}).

Based on the available data, it is not possible to predict a detailed profile of gamma dose rate in air across a wide range of tidal ranges. However, both surveys were undertaken during tidal ranges that were larger than the annual average (that is excluding the spring high water), and so cover a range of water levels in the channel likely to be typical throughout much of the tidal cycle, and across the vast bulk of spring-neap tidal conditions experienced through an annual period.

The ratio of gamma dose in air in the stern compared to that over the sediment was 0.41 while that for the galley was 0.61. These values have had intrinsic and cosmic, but not terrestrial background, deducted (see Section A2.2.1 for details). They are not therefore directly comparable to those presented in Table A1.1.

Figure A3.3: Gamma Dose Rate in Air (nGy hr^{-1}) in and around Boat 1



Further gamma dose rate in air measurements were also taken in the area:

- seven measurements were made on the jetty within the main channel of the River Douglas over two separate occasions. At low water when the underlying sediment was exposed the dose rate was 11 +/- 7.6 nGy hr^{-1} while at high water it was 1.8 +/- 8.6 nGy hr^{-1}.

- nine measurements at the top of the bank, along the edge of the path (in the vicinity of the Environment Agency routine monitoring point. The mean of these measurements was 27 +/- 3.5 nGy hr^{-1}.

- six measurements on the other side of the path adjacent to the main boatyard building, the mean of which was 18 +/- 3.2 nGy hr^{-1}.

On higher ground away from the creek, levels of radioactivity in the sediment decreased and the corresponding gamma dose rate in air also decreased. This area was clearly subject to different processes compared to sediment under the boat.

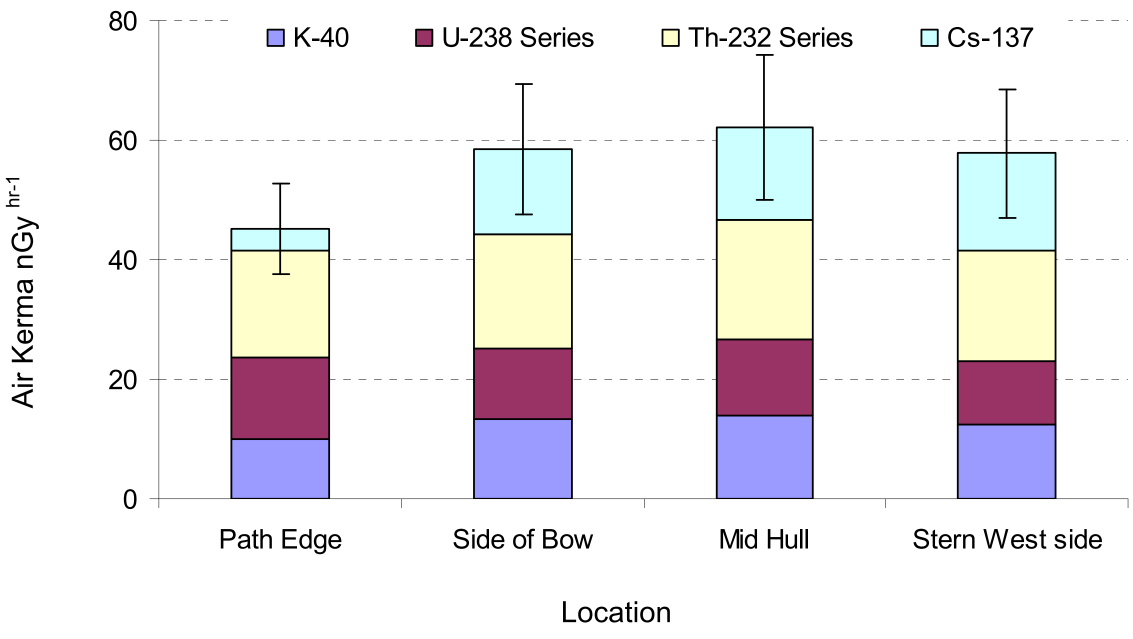
In addition to measurements at 1 metre over sediment under Boat 1 (49 +/- 4.2 nGy hr^{-1}), the dose rate was also assessed at 0.5 metres (51 +/- 6.5 nGy hr^{-1}) and 0.015 metres (54 +/- 5.6 nGy hr^{-1}). Mean values show a small increase with proximity to the soil surface (maximum 5 nGy hr^{-1}). However, there was a lot of variability and the increase was not statistically significant. The area under the boat had a complex environmental geometry with a sloping surface, channel behind the boat, and banks to south and west of the boat. It is unclear what shielding the boat itself offers in this situation. There was no easily determinable relationship between dose rate and height and position under the boat.

A3.1.3 Primary Gamma Dose Contributors

In-situ gamma spectrometry was undertaken concurrently with the gamma dose rate in air measurements, both within and around the boat. HPGe and NaI detectors were both used during the October survey[22]. Based on the spectrum derived from these, the contribution to gamma dose rate in air from individual radionuclides has been assessed. The results from this are given in Figures A3.4 to A3.6.

The majority of the dose over the path edge and under the boat (Figure A3.2) in October appears to have a relatively constant contribution from K-40 (10 to 14 nGy hr^{-1}); the U-238 series (18 to 20 nGy hr^{-1}); and, the Th-232 series (10 to 13 nGy hr^{-1}). Of the radionuclides discharged from the Sellafield site, the contribution from Cs-137 at the top of the bank was 4 nGy hr^{-1}, while under the boat was 14 to 16 nGy hr^{-1} (12 to 34 percent of the dose). The contributions from Am-241 and excess Th-234 and Pa-234m were very low (less than 0.01 nGy hr^{-1}) and are not presented.

Figure A3.4: Air Kerma derived from In-situ (HPGe) Gamma Spectrometry over Soil



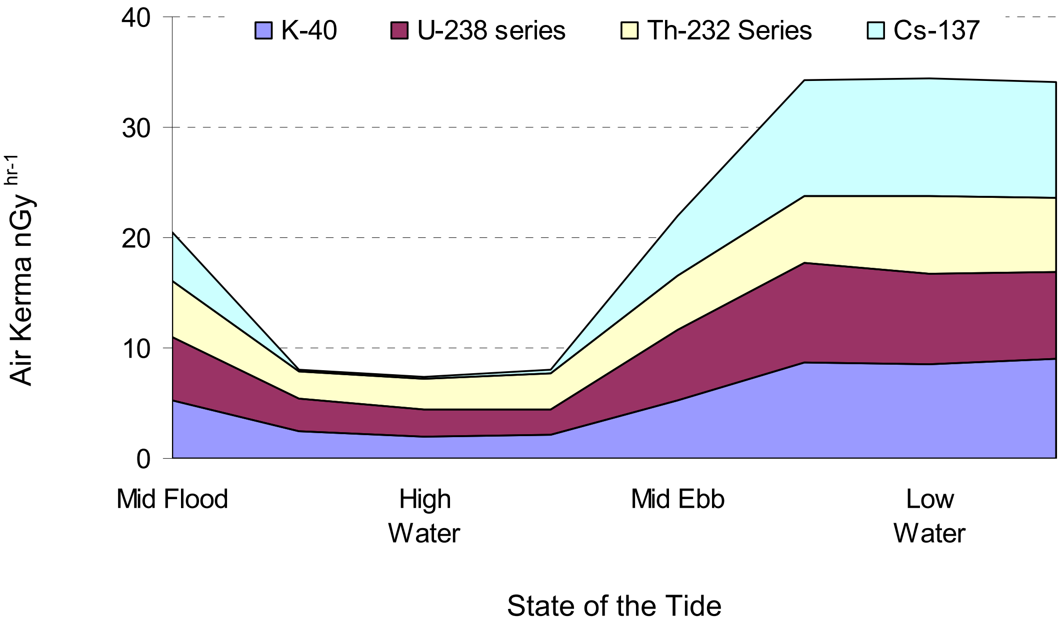
The gamma dose in air was measured by in-situ spectrometry in the galley of Boat 1 using a NaI Detector (Figure A3.5), and in the wheelhouse of Boat 1 using a HPGe Detector (Figure A3.6). Measurements were made at around half hour intervals, from between about 1.5 hours prior to high water to about 3 hours after (a total of 8 and 10 measurements respectively).

Around high water there was virtually no contribution from Cs-137 (less than five percent) in either the galley or the wheelhouse. The U-238 and Th-232 series made a

[22] In-situ measurements were taken in the boat during the initial July visit. However, high levels of humidity within the boat adversely affected the instruments and results are not presented.

roughly equal contribution to 70 percent of the measured dose. K-40 contributed about 25 percent.

Figure A3.5: Radionuclide Specific Contribution to Gamma Dose Rate in Air (nGy hr^{-1}) Boat 1 Galley (16 Oct) - NaI Detector



At low water, the primary dose contributor in the galley was Cs-137 (approximately 30 percent). K-40 and the U-238 series contribute slightly less (25 percent each), and the Th-232 series about 20percent. In the wheelhouse the Th-232 series dominated the dose (46 percent), K-40 and the U-238 series contributed equally (about 20 percent each) and Cs-137 accounted for only about 15 percent of the dose.

A3.1.4 Beta Dose

The calibrated beta dose rate BP19/Electra monitor was also used to take measurements above a carpet in Boat 1 during the October visit. Four measurements were taken, each at or very close to the detection limits. The mean of the four beta skin dose measurements was 97 +/- 41 nSv hr^{-1} per cm^2.

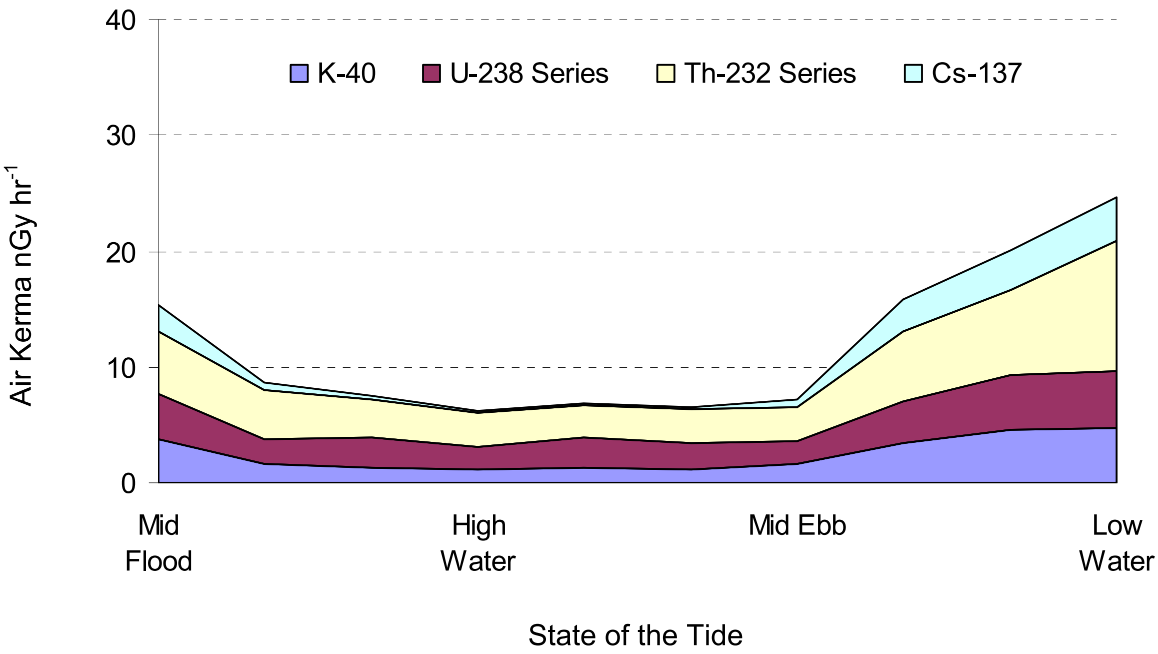
A3.2 Seasonal Occupancy (Boat 2)

Boat 2 was not moored up during the July visit, so it was only surveyed during the October visit. Although some limited measurements were made on the 16th October (concurrently with the study on Boat 1) the discussion below focuses on the more detailed suite of measurements undertaken on the 17th October.

Data was collected through a full tidal cycle from low water through the high tide and back to low water (a survey period of about 6.5 hours).

Summarised below are: activity concentrations from intertidal sediment under the boat, on the bank of the adjacent salt marsh; gamma dose rate in air (below the boat, within the boat and at the top of the bank); beta skin dose within the boat; and gamma dose contribution from different radionuclides within the boat at different states of the tide (assessed via in-situ gamma spectrometry).

Figure A3.6: Radionuclide Specific Contribution to Gamma Dose Rate in Air (nGy hr^{-1}) Boat 1 Wheelhouse (16 Oct) - HPGe Detector



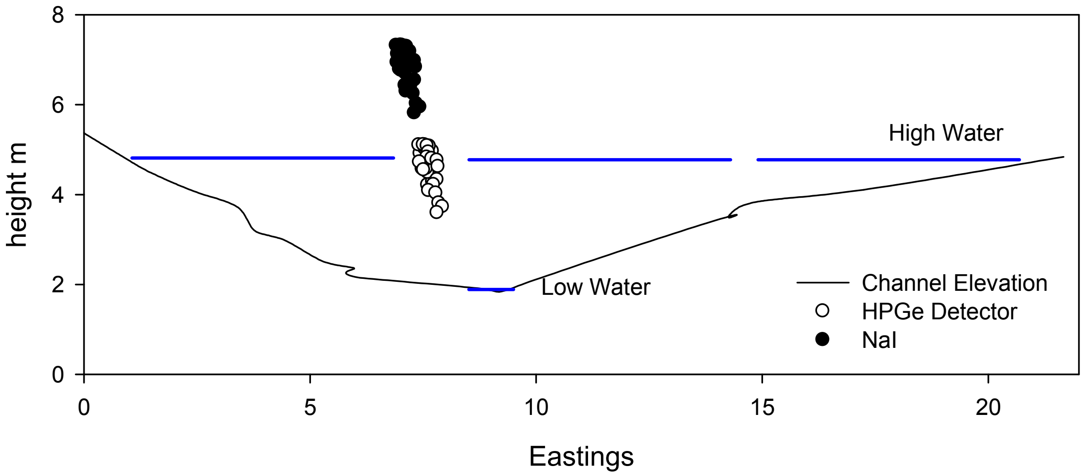
A3.2.1 Environmental Setting

Boat 2 was moored within the centre of the creek parallel to the bank. It was a large sailing vessel (in excess of 15 metres in length) with a fibreglass hull and teak wooden decking. At low water the boat rested in the centre of the channel where the base of the hull was elevated up from the bed sediment by about 1 metre by the boat's large keel (it remained upright due to supporting struts driven into the bank on either side of the boat). At low water the upper deck was about three metres above the underlying channel bed (roughly level with the surface of the adjacent salt marsh). Figure A3.7 illustrates the detector positions within the context of the creek cross section, along with the high and low water tides.

The channel was fully inundated during the survey, and the intertidal sediment on the channel bed and sides was covered by water as the tide rose. As the boat floated on the rising tide, the upper deck was approximately in line with the adjacent salt marsh.

Figure A3.8 indicates the prospective sources of gamma radiation, illustrated by arrows, for different tidal ranges outside of those surveyed.

Figure A3.7 Channel Cross Section, Relative Detector Position on Boat 2 through the Tidal Cycle and Approximate Water Level at High and Low Tide relative to Chart Datum



A3.2.1 Sediment Activity Concentrations

Three bed sediment samples were collected from each side of Boat 2 at low water (six in total). The samples were taken from the bank using a trowel firmly attached to a boat hook to provide a safe sampling procedure. In addition three further surface samples were collected from the western bank parallel with the jetty, starting from the bank and extending towards the exposed sediment, in order to assess the range of activity concentrations. Activity concentrations of radionuclides within these sediments were subject to high resolution gamma spectrometry and results are given in Figure A3.9. The standard deviation associated with the mean results are illustrated by error bars to provide an estimate of the variability.

Activity concentrations of all radionuclides in the channel bed sediment during the October survey were, with the exception of Th-234 and Pa-234m, similar to those measured in the surface sediment under Boat 1. Those of Th-234 were an order of magnitude higher and those of Pa-234m a factor of seven higher.

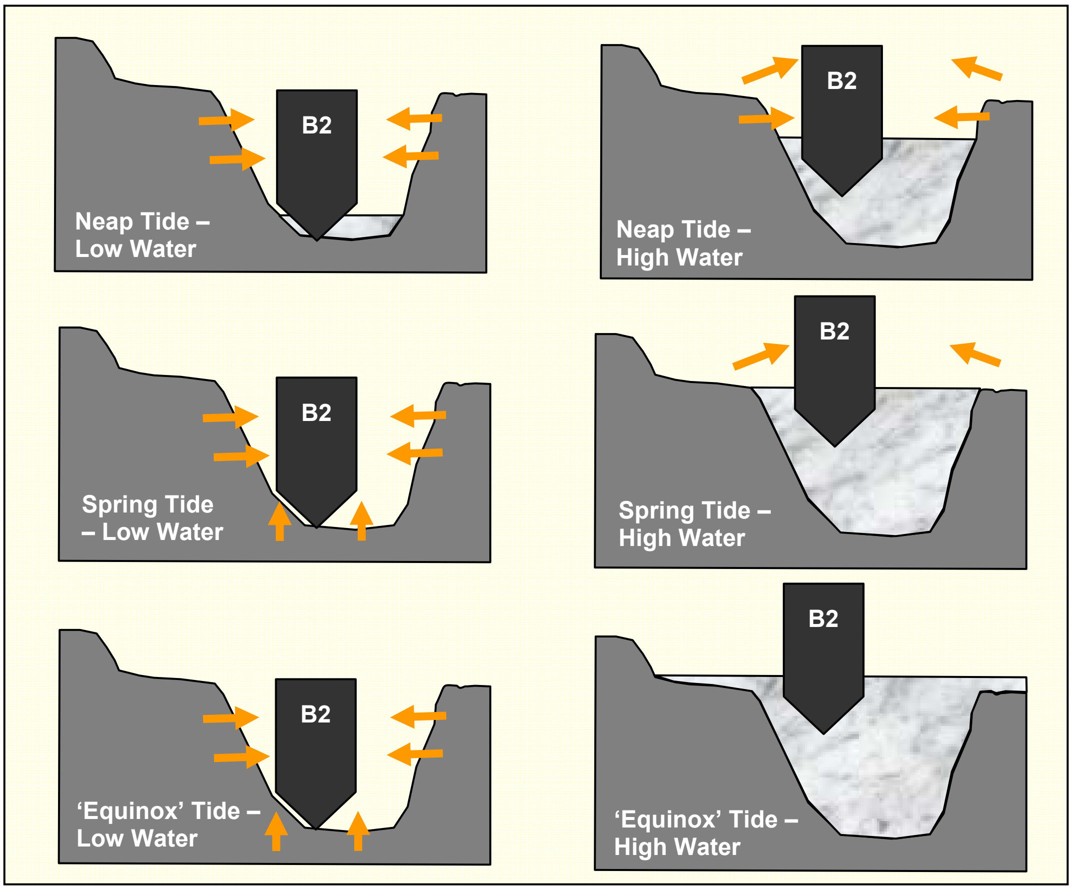
A significant difference was found between activity concentrations in the bed sediment and that on the bank leading down into the creek. The variability of these bank sediments was considerable, especially for the shorter lived Th-234 and Pa-234m radionuclides – concentrations varied from 11 Bq kg^{-1} to around 350 Bq kg^{-1} further down the bank towards the exposed intertidal sediments (no vegetation cover).

A3.2.2 Gamma Dose Rate in Air

Gamma dose rate in air was measured periodically throughout the majority of two consecutive tidal cycles on deck at the stern and bow, and within the main quarters of the boat. In addition, gamma dose rate in air measurements were made at one metre above the bed sediment by lowering the GM instruments down the outside of the hull at low water (three measurements were made, two on the west side of the keel and one on the east side)[23].

[23] Due to the depth and mobile nature of the intertidal sediment exposed at low water it was not possible to gain access to the centre of the channel by foot.

Figure A3.8: Conceptual Environmental Setting for Boat 2 (B2)

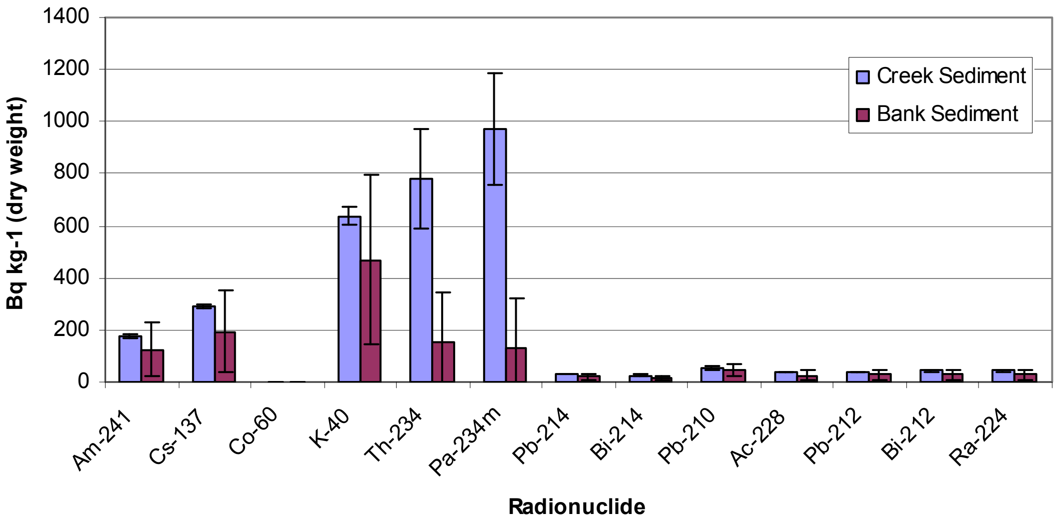


Gamma dose rate measurements are illustrated in Figure A3.10. Error bars for the measurements in the boat give the 2 sigma uncertainty associated with a single measurement. The error bars for those measurements taken over bed sediment represent the standard deviation of three measurements.

The gamma dose rate in air measured over sediment on the east (salt marsh) side of Boat 2 was 32 nGy hr^{-1} while the two measurements made on the west (boat yard) side were 42 and 45 nGy hr^{-1} (average of the three measurements is around 40 nGy hr^{-1}).

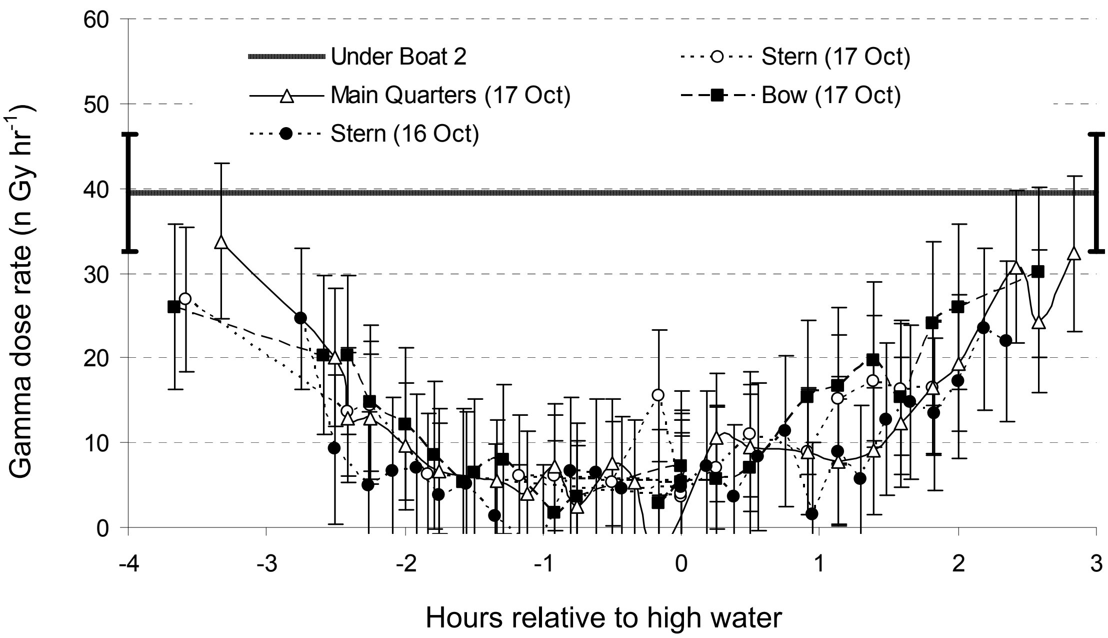
These values are lower than those measured under Boat 1, despite similar activity concentrations of gamma emitting radionuclides in each environment. However, they may not be representative of exposure from a planar source, because the keel of the boat may have provided some shielding. The measurements made may reflect the gamma dose rate in air arising from bed sediment directly below the probe and the adjacent bank (but not the whole channel). Also some surface water was still present on the eastern side of the boat as water drained out of the creek and this may have shielded some sediment areas.

Figure A3.9: Sediment Activity Concentrations around Boat 2 – October 17th



On the boat, gamma dose rate in air was measured on deck at the bow and the stern and below deck in and around the main living quarters. At low water gamma dose rate in air on the boat ranged from 26 to 34 nGy hr^{-1}. However there appeared to be no consistent bias for higher dose rates above or below deck.

Figure A3.10: Gamma Dose Rate in Air (nGy hr^{-1}) on Boat 2 (16 & 17th Oct)



Unlike Boat 1, there was a very clear reduction in gamma dose rate in air as the channel became inundated and the boat was lifted up off the bed sediment and above the profile of the channel sides. Over a period of one to two hours around high water, the dose rate onboard was much lower; mean rates typically at, or below, 5 nGy hr^{-1}. As the water level in the channel dropped and Boat 2 descended back down to the base of the channel, gamma dose rate in air increased back up to levels consistent with the start of the survey.

The gamma dose rate in air averaged through the full tidal cycle was 13 nGy hr^{-1} in the main quarters and bow, and 10 nGy hr^{-1} in the stern. Averaged across all time series data gives a mean dose rate of 11 nGy hr^{-1}. Figure A3.11 provides a regression plot of the influence of approximate water depth with gamma dose rate in air[24].

Figure A 3.11. Comparison of Gamma Dose Rate in Air with Water Depth.

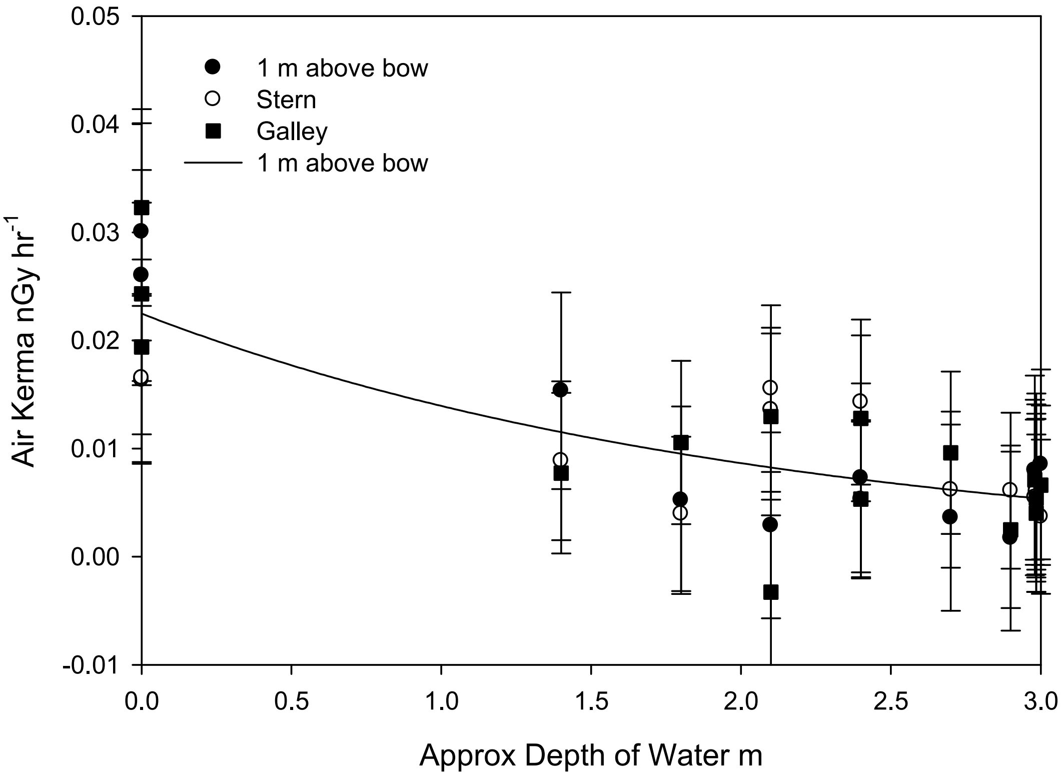


Figure A3.11 illustrates some scatter in the data, partly as a result of the uncertainty with estimating water depth. A number of comparative gamma dose rate in air measurements were taken at low water at different points in the boat, five above deck and four below deck. There was no discernable difference between the measurements made above deck (32 +/- 4.6 nGy hr^{-1}) and below (31+/- 2.5 nGy hr^{-1}) deck. Above deck measurements varied by about 10 nGy hr^{-1} and below deck measurements by about 5 nGy hr^{-1}. However, no consistent relationship with position in the boat was observed. The data from the stern of the boat may reflect more shielding around the cabin area and above the boat's engine area.

A3.2.3 Primary Dose Contributors

In-situ gamma spectrometry was undertaken within and around the boat (using both the HPGe and NaI detectors) at the same time as the gamma dose rate in air measurements during the October survey. The contribution to gamma dose rate in air from individual radionuclides has been assessed based on the spectrum derived from this. The results from this are given in Figures A3.12 to A3.13.

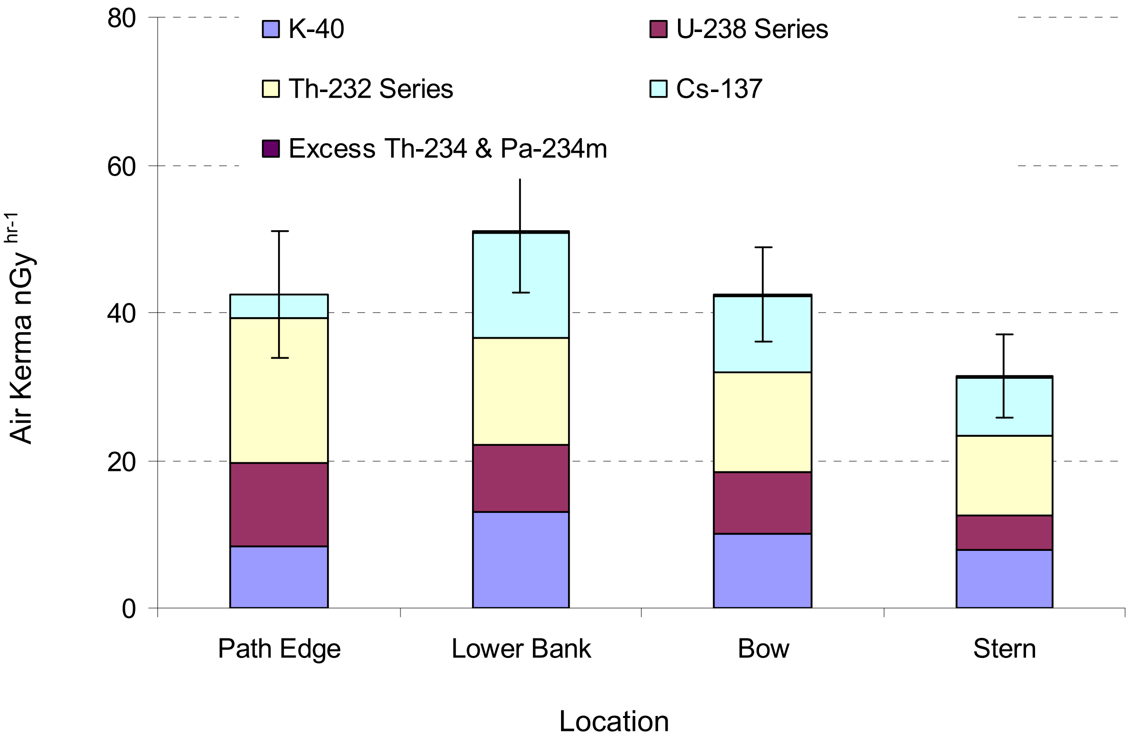
Figure A3.12 shows a series of in-situ measurements made at low water where gamma dose rate in air ranged from around 30 to 50 nGy hr^{-1}. The majority of the dose over the path edge and over the lower bank appears to have a relatively constant contribution from K-40 (8-13 nGy hr^{-1}); the U-238 series (9 to 11 nGy hr^{-1}); and, the Th-

[24] Estimating water depth below about 1.5 m was difficult as the boat sat on its keel whilst the remaining water drained from the channel.

232 series (14-17 nGy hr^{-1}). Of the radionuclides discharged from the Sellafield site, the contribution from Cs-137 at the top of the bank was 3 nGy hr^{-1} while that on the lower bank was 14 nGy hr^{-1} (about 27 percent of the observed dose rate). The contribution from Am-241 was low (less than 0.01 nGy hr^{-1}) and is not presented.

Some limited contribution from excess Th-234 and Pa-234m was detected over the lower bank (although this was small, approximately 0.2 nGy hr^{-1}).

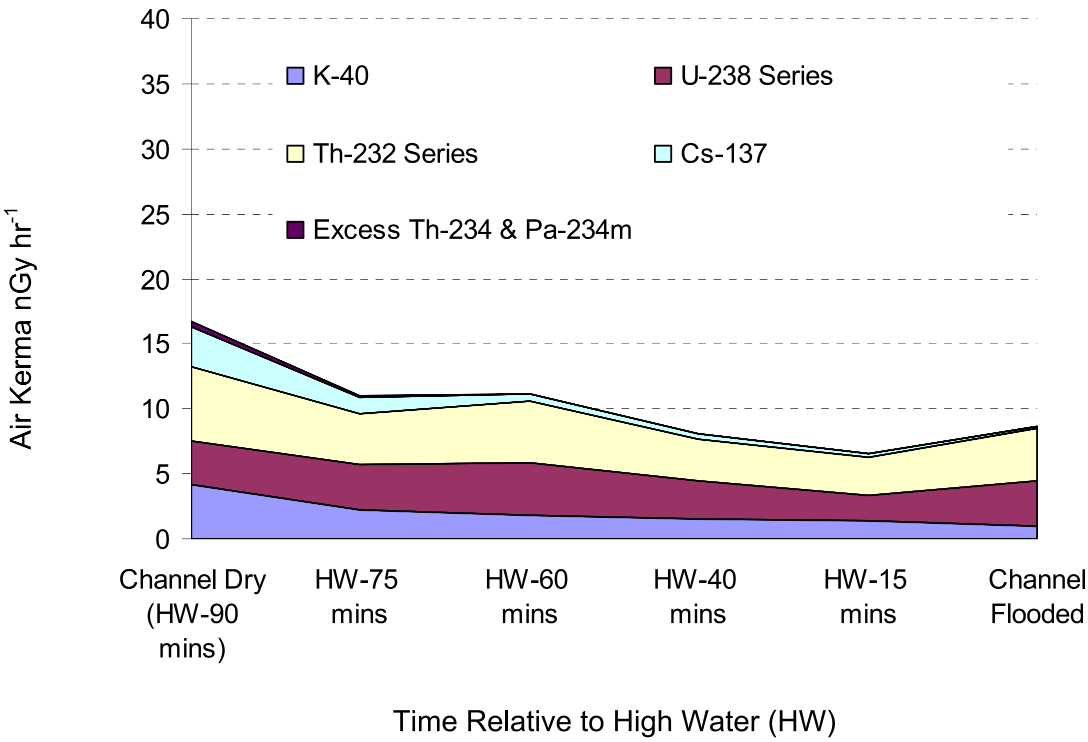
Figure A3.12: Air Kerma derived from In-situ (HPGe) Gamma Spectrometry in Boat 2 (Bow and Stern) and over Soil (Path Edge and Bank)



Measurements taken 1 m above the deck in both the bow and stern of Boat 2 are lower than the measurements above sediment, particularly at the bow. The contribution from K-40 ranged from 8 to 10 nGy hr^{-1}; U-238 series from 5 to 8 nGy hr^{-1}; Th-232 series from 11 to 14 nGy hr^{-1}; and, Cs-137 from 8 to 10 nGy hr^{-1}. Excess Th-234 and Pa-234m contribution was negligible, about 0.3 nGy hr^{-1}.

Figure A3.13 shows a clear reduction in dose rate with increasing depth of water.

Figure A3.13: Radionuclide Specific Contribution to Gamma Dose Rate in Air (nGy hr-1) Boat 2 Galley (17 Oct) - HPGe Detector



A3.2.4 Beta Dose

The calibrated beta dose rate BP19/Electra monitor was used to take measurements at a number of locations on the upper deck of Boat 2 during the October visit. Six measurements were below detection limits. The mean of positive measurements was 78 +/- 48 nSv hr^{-1} per cm^2.

A3.3 Occasional Occupancy (Boat 3)

Boat 3 was hired by the project team specifically to assess prospective doses that may be received within a very small boat stranded on intertidal sediment over the course of a single tidal cycle. Data therefore relate to the 28th November visit only. The survey period was restricted by the small size of the boat, logistics of access and limited daylight, but it did cover a period from just after high water, through to low water.

Six sediment surface scrape samples were collected from around the boat at low tide; three to the east and three to the west of the hull. An additional three samples were collected (parallel with the jetty) on a transect down the bank from the path toward the exposed sediments. Gamma dose rate in air was measured over sediment around the boat at low tide, within the boat and along a transect leading up the bank parallel with the jetty and coincident with the sampling points mentioned above. Similar measurements were made with the NaI detector to assess the gamma dose contributions[25]. Beta skin dose measurements were also made on the bank.

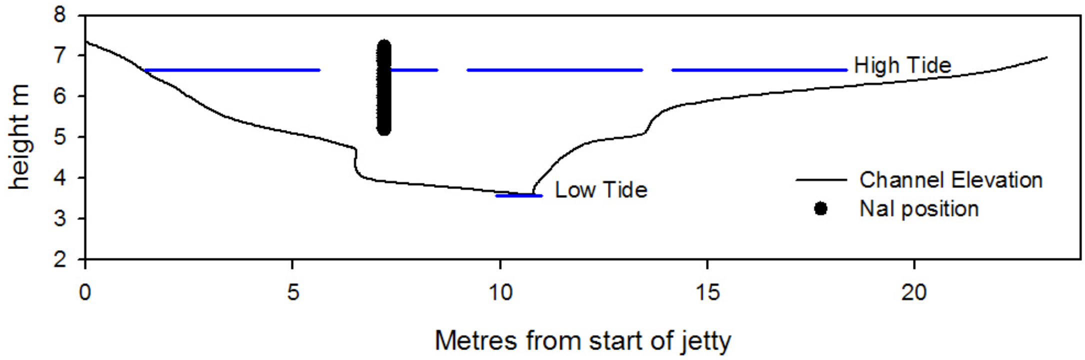
[25] Due to the small size of the boat only the smaller NaI detector was deployed on the boat itself.

A3.3.1 Environmental Setting

Boat 3 was moored for the purpose of this study on the western (Boatyard side) of the creek, just downstream of Boat 2, and was aligned parallel to the bank. It was a small fibreglass (four metres in length) vessel with only a partially covered cabin area and single deck area able to sit four people; the type of boat that might be used by anglers on limited duration excursions (i.e. day trips).

At low water the boat rested in the centre of the channel with the full area of the hull lying on the bed sediment (see Figure A3.14). At this time the deck area was about 0.4 metres above the bed sediment, and the boat was flanked by the channel sides.

Figure A3.14 Channel Cross Section, Relative Detector Position on Boat 3 through the Tidal Cycle and Approximate Water Level at High and Low Tide relative to Chart Datum



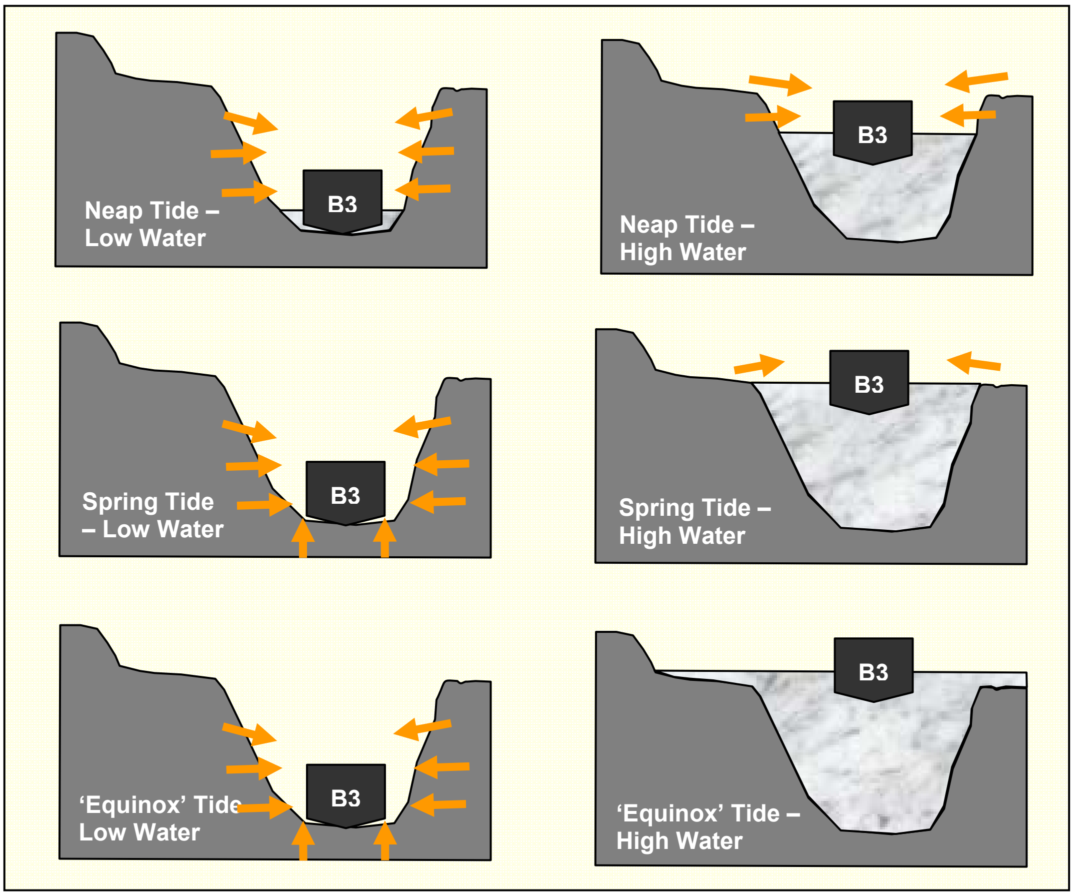
At high water, the boat was raised by about two metres off the bed sediment by the flood tide and the deck area of the boat was level with the upper sections of the bank and the salt marsh to the eastern side. This is illustrated in Figure A3.15. Prospective sources of gamma radiation are indicated by arrows for tidal ranges outside of those surveyed.

A3.3.2 Sediment Activity Concentrations

Three surface sediment samples were collected from the channel bed around Boat 3 at low water. In addition three intertidal sediment samples were collected from the upper, middle and lower areas of the west (Boatyard) side of the bank. Activity concentrations of radionuclides within these sediments were subject to high resolution gamma spectrometry and results are given in Figure A3.16. Error bars illustrate the standard deviation associated with the mean results.

Activity concentrations of all radionuclides in the channel bed sediment during the November survey were (with the exception of Th-234 and Pa-234m) similar to those measured in the surface bank sediment under Boat 1 and intertidal sediment under Boat 2. Compared to Boat 1 (July), activity concentrations of Th-234 were a factor of ten higher and of Pa-234m a factor of seven higher, and compared to Boat 2 (October) about one and a half times higher.

Figure A3.15: Conceptual Environmental Setting for Boat 3 (B3)

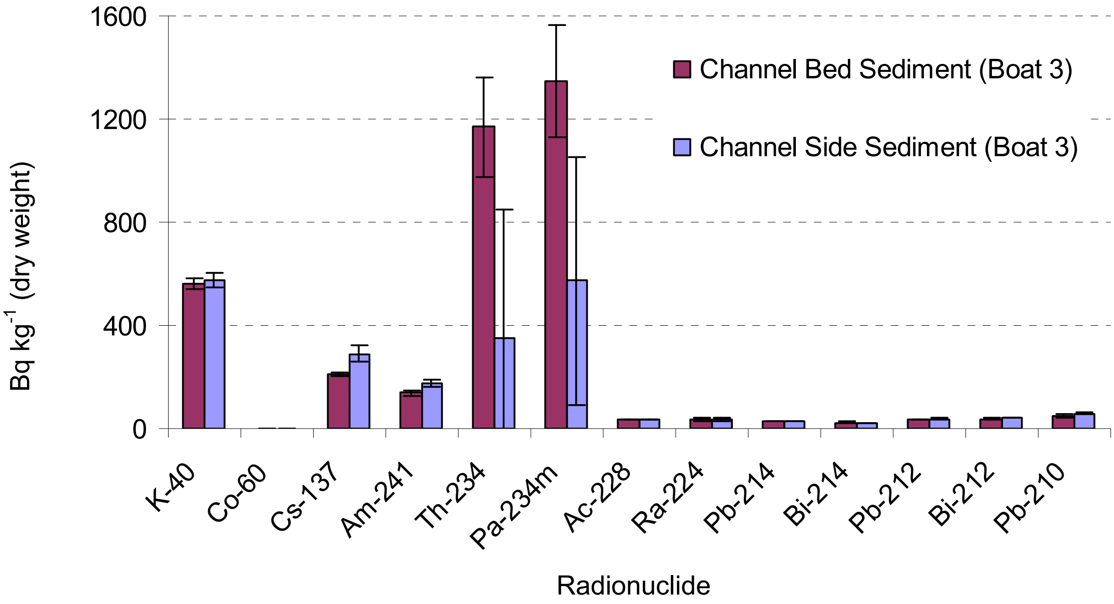


It is uncertain why activities in channel bed sediments may vary with time, particularly as the mobile bed sediment can be assumed to be relatively homogeneous. It may be related to different rates of sediment transport through the estuary depending upon tidal and / or river flow conditions, or variations in the discharge regime from the Springfields site. A reduction in activity concentrations in sediment on the channel side, when activity concentrations decrease further up the bank, probably relates to the time since that level of the bank was last flooded and sediment deposited.

A3.3.3 Gamma Dose Rate in Air

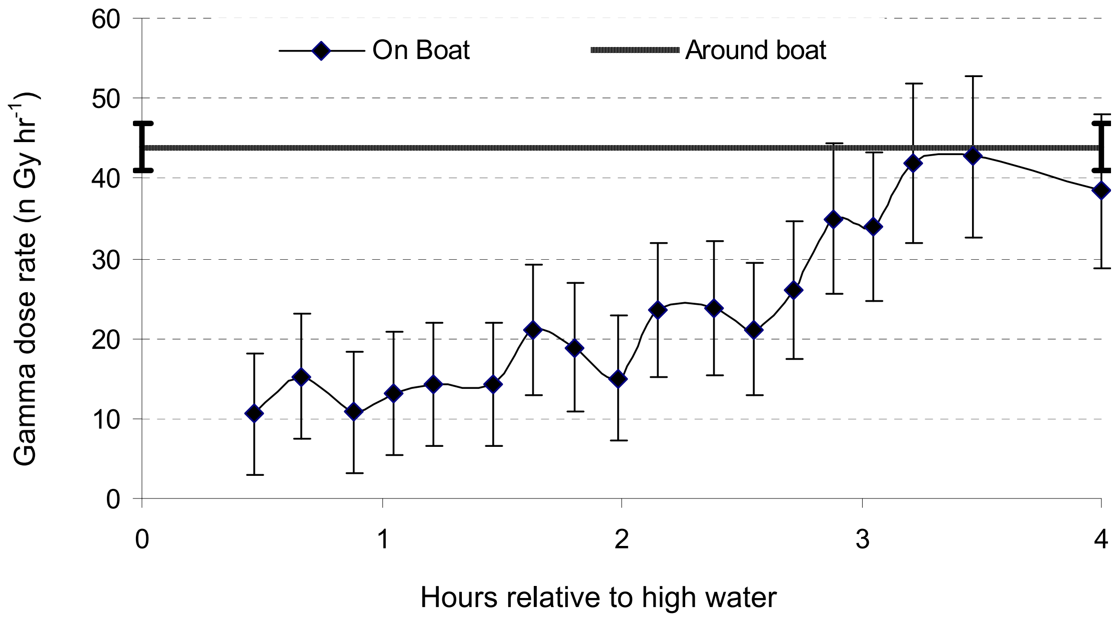
Gamma dose rate in air was measured on the deck area of Boat 3 periodically from high water over a four hour period until the channel was fully drained. In addition gamma dose rate in air measurements were made (from the boat) at one metre above the intertidal surface. Measurements were made to the east, west and south of the boat.

Figure A3.15: Sediment Activity Concentrations around Boat 3 – November 28th



Gamma dose rate measurements are illustrated in Figure A3.16. Error bars for the measurements made within the boat give the 2 sigma uncertainty associated with a single measurement. Those for the measurements taken over the bed sediment represent the standard deviation of three measurements.

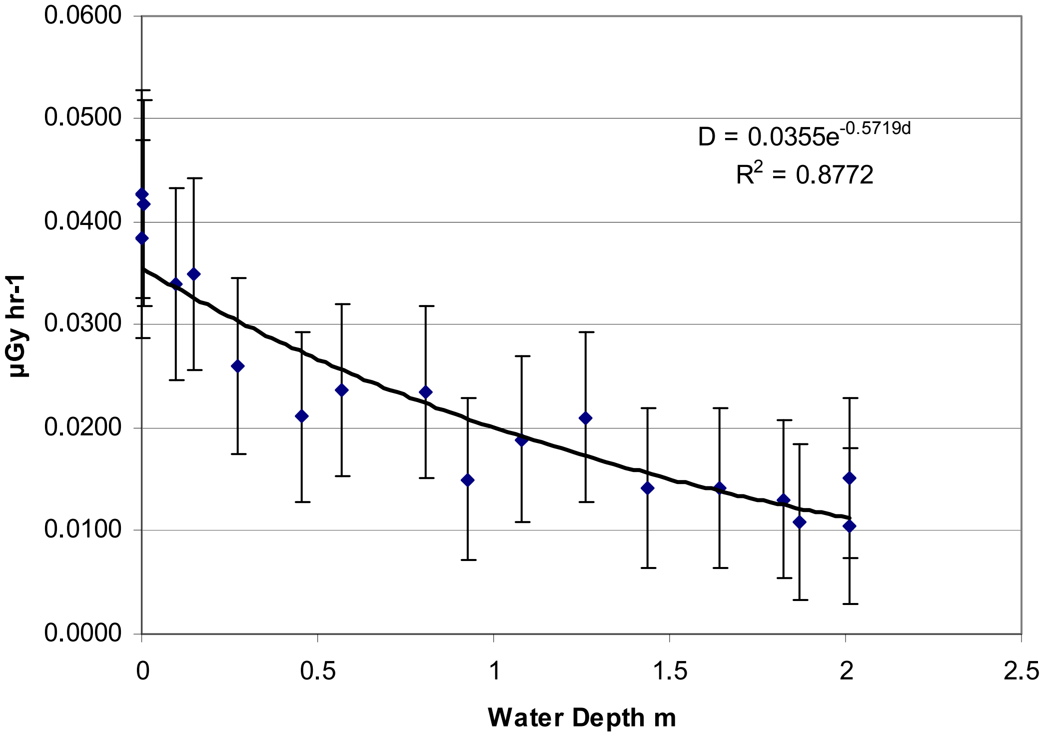
Figure A3.16. Gamma Dose Rate in Air (nGy hr^{-1}) on Boat 3 (28th Nov)



The gamma dose rate measured over exposed intertidal sediment around Boat 3 was 44 +/- 3 nGy hr^{-1}. This was within the range measured for Boat 2.

On the boat gamma dose rate in air was measured one metre over the centre of the deck repeatedly as the tide ebbed. At high water (when the boat was shielded from the bed by the tide, but not adjacent channel sides) the gamma dose rate in air was around 10 nGy hr^{-1}. The dose rate then increased exponentially as the water level dropped (see Figure A3.17). At low water the gamma dose rate measured in the boat was in excess of 40 nGy hr^{-1} and indistinguishable from that over sediment. It is reasonable to assume that the hull of the boat provided some shielding from gamma emissions directly under it, however, it appears that this had little effect on gamma dose rate onboard the boat, due to the contribution from the bed sediment surrounding the boat, and sediment on the channel sides.

Figure A3.17. Variation in Gamma Dose Rate in Air (nGy hr^{-1}) with Water Depth on Boat 3 (28^{th} Nov)



A3.3.4 Primary Dose Contributors

In-situ gamma spectrometry was undertaken using the NaI detector within and around the boat at the same time as the gamma dose rate in air measurements during the November survey. Based on the spectrum derived from these, the contribution to gamma dose rate in air from individual radionuclides has been assessed. The results from this are given in Figures A3.18 to A3.19.

Figure A3.18 shows a series of in-situ measurements made at low water. The total gamma dose rate in air measured via NaI in-situ gamma spectrometry was 34 nGy hr^{-1} at the bank edge of the adjacent salt marsh, and around 48 nGy hr^{-1} over intertidal sediment to either side of Boat 3 at low water. These were very much in agreement with the GM tube instruments, and illustrate that Th-234 and Pa-234m contributed little to the observed dose rate. At the top of the bank Cs-137 contributed about 3 nGy hr^{-1}, and K-40, Th-232 series and U-238 series approximately 10, 13 and 9 nGy hr^{-1} respectively (the Cs-137 contribution accounted for about 9 percent of the dose). Over intertidal sediment exposed at low water the distribution was different, with Cs-137 contributing over 17 to 19 nGy hr^{-1}; K-40 13 to 14 nGy hr^{-1}; the U-238 series 6 to 11 nGy hr^{-1}; and the U-238 series around 8 nGy hr^{-1} (the Cs-137 contribution accounted for about 37 percent of the dose).

Figure A3.18: Air Kerma in Boat 3 (NaI Detector)

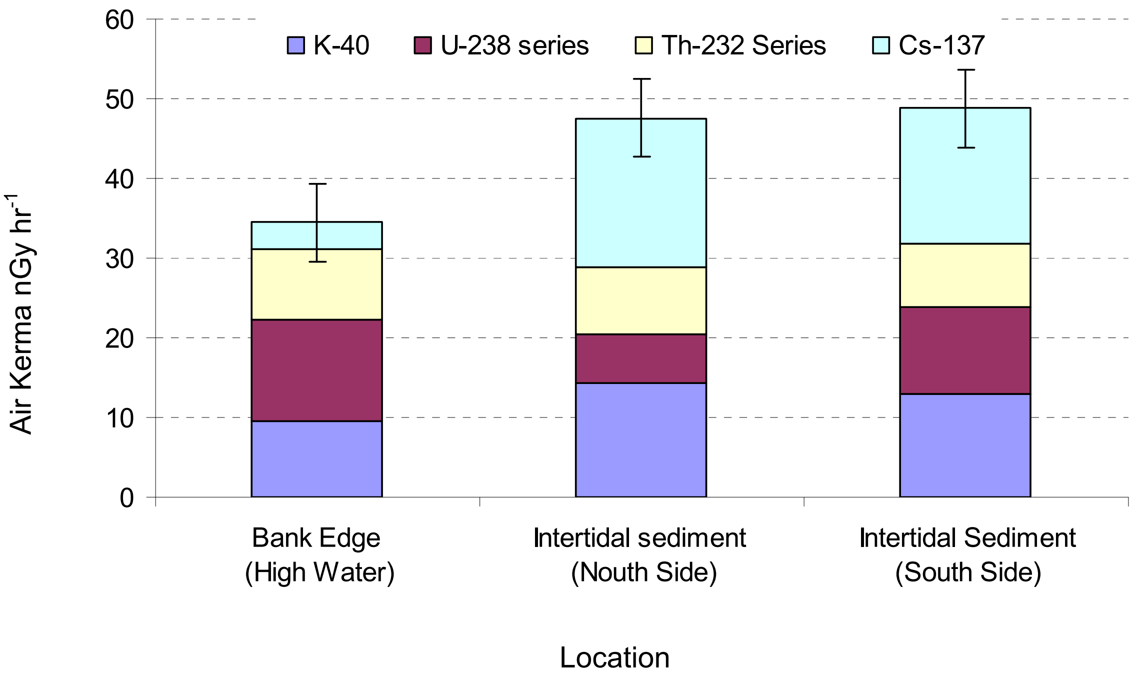
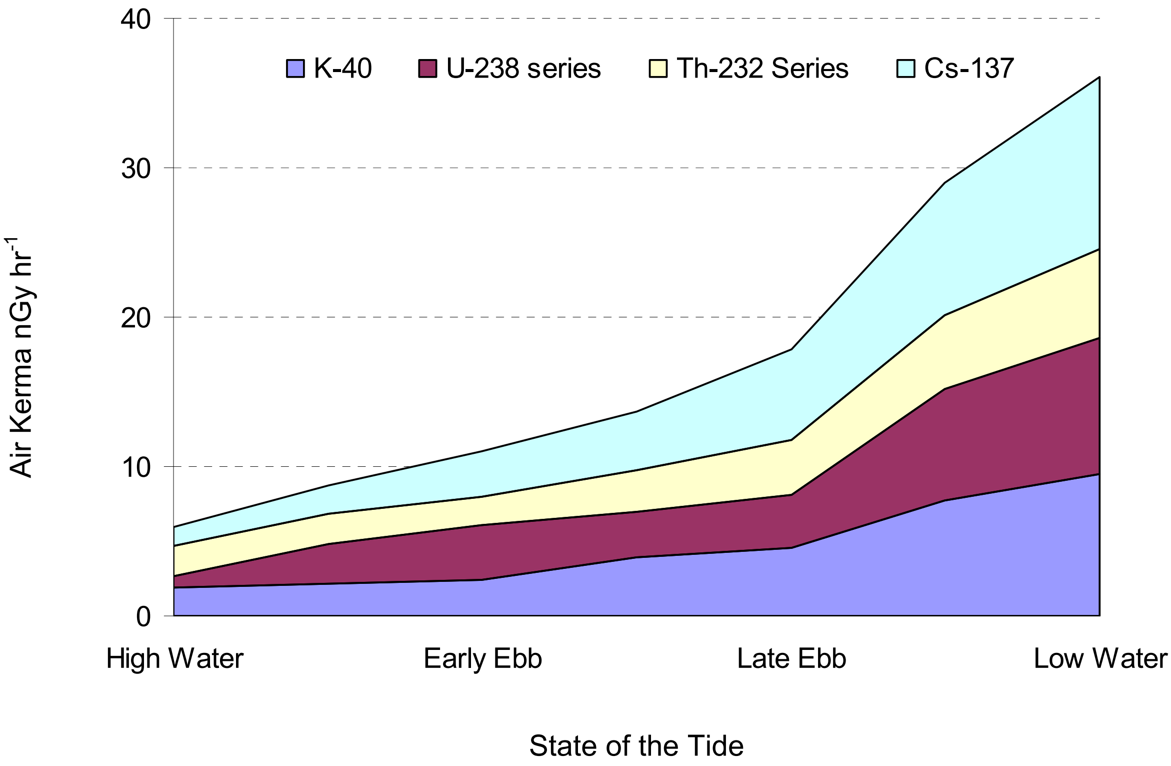


Figure A3.19 gives a clear indication of how the contribution from different radionuclides varies with changes in water depth.

Figure A3.19: Air Kerma in Boat 3 (NaI Detector)



A3.3.5 Beta Dose

No addition beta dose rate measurements were made during the survey of Boat 3.

A3.4 Summary and Key Points

A detailed assessment of activity concentrations in soil and sediment, external gamma dose and beta skin dose has been made for three different environmental settings pertinent to use of boats as either living accommodation or daily pleasure craft. Key points from this include:

- activity concentrations of Cs-137 were typically around 300 Bq kg^{-1} (dry weight) while that of Am-241 was around 200 Bq kg^{-1} (dry weight). Only very low activity concentrations of Co-60 (of a few Bq kg^{-1} dry weight) were detected. Activities were consistent between surveys. Activity concentrations of Th-234 and Pa-234m were more variable, ranging by over an order of magnitude, typically influenced by position in the bank. Those of the other uranium and thorium decay chain products were much more consistent, typically between 25 to 30 Bq kg^{-1} (dry weight);

- where gamma dose rate in air monitoring is undertaken in a dynamic tidal environment, consideration has to be made with respect to the state of the tide. This can have a large influence on the dose rates measured in a boat in a tidal channel or on a jetty overlying intertidal sediments, and is heavily dependent upon the environmental setting of the boat and the tidal range. At a minimum, the state of the tide should be clearly recorded with the dose measurements, so that subsequent review of results can be made. Ideally monitoring should be scheduled to coincide with conditions that are representative of an annual mean and are not biased to extreme conditions;

- clearly it is not always practicable, within the context of statutory monitoring programmes, to measure gamma dose rate in air aboard an occupied houseboat. Nonetheless, the use of 'surrogate' monitoring points should be considered carefully, whether these be over intertidal sediment under the boat, or on an adjacent bank. If exposures are to be calculated from data collected from surrogate monitoring point, care should be taken when selecting a predetermined ratio between the dose rate under and within the boat, given that different ratios will be calculated depending upon whether background has or has not been subtracted;

- care should be taken when converting between actual and effective occupancy, specifically when accounting for the amount of time that gamma emissions from underlying bed sediment are shielded by the inundating tide. Any such adjustment needs to be based on site-specific knowledge and a generic 50:50 split may not be appropriate;

- within a houseboat, particularly that moored in a tidal channel, the concept of a planar source of gamma radiation issuing from the bed sediment that is in some way sequentially attenuated by the hull, and then by the upper decking, is not appropriate. At low water a boat occupant may be exposed from gamma emitters not just in the sediment under the boat, but also in the channel sides which may flank the boat on either side;

- gamma dose rates measured at different heights under Boat 1 showed no statistically significant variation with proximity to sediment;

- in the limited survey area, activity concentrations of the shorter-lived beta emitters, Th-234 and Pa-234, were highly variable over both space and time. It is uncertain why activities in channel bed sediments may vary with time, particularly as the mobile bed sediment could be assumed to be relatively homogeneous. This may be related to different rates of sediment transport through the estuary depending upon tidal and/or river flow conditions, or variations in the discharge regime from the Springfields site. Reduction in activity concentrations in sediment on the channel side, where decreasing activity concentrations occur further up the bank, probably relates to the time since that level of the bank was last flooded and sediment deposited;

- in-situ gamma spectrometry within boats and over surrounding soils and sediments determined that Cs-137 was the primary dose contributor arising from discharges from the Sellafield site. At low water there was virtually no contribution to the gamma dose rate in air from Am-241 and only very low levels from excess Th-234 and Pa-234m (from discharges from the Springfields site). There was no measurable contribution from Co-60. At high water the gamma dose rate in air (minus intrinsic and cosmic radiation) approached zero, but this depends upon the size of the boat and position relative to any bank areas;

- Beta skin doses were low, typically around 100 nSv hr^{-1} per cm^2.

A4 – External Exposure of Anglers and Wildfowlers

Details of the survey results to assess prospective external exposure of anglers and wildfowlers are described in this Appendix. In particular the following factors were considered:

- gamma dose rate in air, radionuclide specific contributions (determined by in-situ gamma spectrometry) and activity concentrations of radionuclides in soils and sediment associated with salt marsh and bank areas;

- gamma dose rate in air along transects perpendicular to tidal channels (at low and high water) to assess any changes with increasing distance away from intertidal sediments;

- gamma dose rate in air in and around wildfowler 'hide' pits;

- variation in gamma dose rate in air with height of measurement over sediment;

- beta skin dose, how this varied with height over sediment and also the influence of clothing material on shielding.

Data was collected at the following locations and dates (Surveys B and D focused on the boatyard as discussed in the previous appendix):

- Savick Brook - 1st August 2008 (Survey A);

- Longton Marsh 10th November 2008 (Survey C);

- Savick Brook 11th November 2008 (Survey C).

The visits covered a range of different tidal conditions. All gamma dose rate in air measurements have had the intrinsic count rate of the instrument and cosmic background subtracted, but include the contribution from naturally occurring radionuclides in the environment.

A4.1 Savick Brook

Savick Brook was surveyed on two occasions (1st August and 11th November), both during relatively high spring tides of around 9.2 metres. Data was collected, where possible, to cover periods of both high and low water.

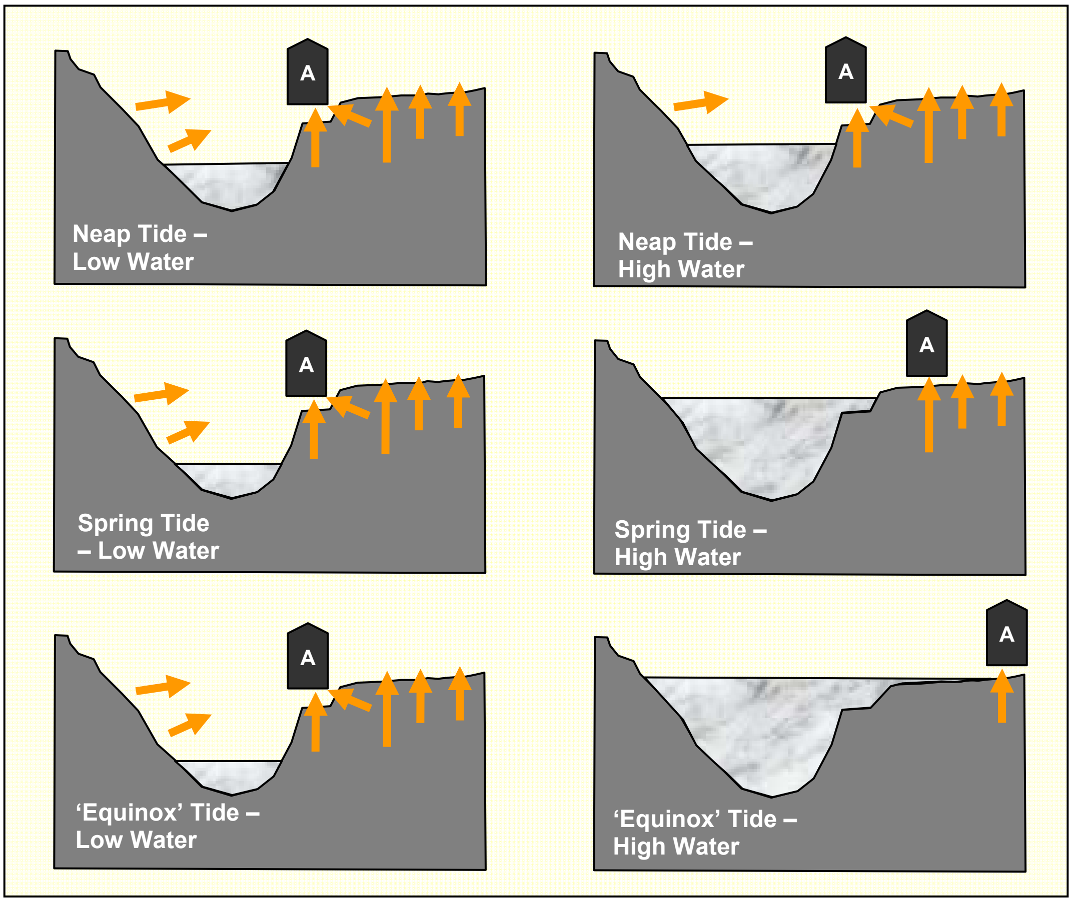
Summarised in the following sections are: activity concentrations from sediment; gamma dose rate in air (both over intertidal sediment and adjacent pasture land); beta skin dose; and gamma dose contribution from different radionuclides at different locations along the brook (assessed via in-situ gamma spectrometry).

A4.1.1 Environmental Setting

Savick Brook is a small tidal tributary situated in the upper reaches of the Ribble. It is about 20 to 30 metres wide at the top of the bank and about 3 to 5 metres deep in the centre. It runs northward from the confluence with the Ribble up until the A583 road bridge, after which it progresses in a more easterly direction. South of the road bridge there is flood protection banking to the west and salt marsh to the east.

At low water, the lower sections of the brook drain, exposing thick and mobile intertidal sediment on the banks. Due to freshwater input, the base of the channel remains covered by about 0.5 metres of water, depending upon freshwater flow rates and the state of the tide. At high water the channel fills and during spring tides, adjacent areas of salt marsh are also inundated. A larger area is flooded during equinox spring tides. This is illustrated in Figure A4.1. Prospective sources of gamma radiation are indicated by arrows.

Figure A4.1: Conceptual Environmental Setting of an Angler (A) in Savick Brook



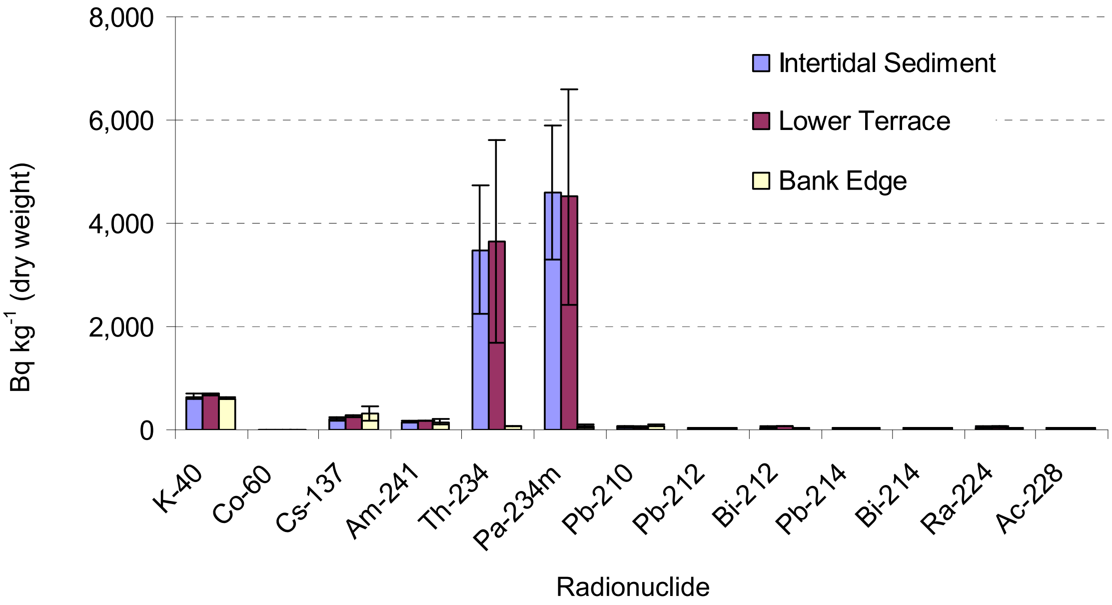
Savick Brook forms part of the Millennium Ribble Link. During construction of the link, the upper (non-tidal) reaches of the brook were canalised and a number of lock gates were added. Just south of the road bridge, the channel was widened to provide a waiting area for boats about to navigate the Link. A rotary sea lock gate was installed just south of this widened area. During both surveys the Lock Gate was in the lowered (open) position.

A4.1.2 Sediment Activity Concentrations

During the initial August visit, sediment samples were collected from each of the following locations downstream of the Lock Gate: three intertidal sediment samples towards the bottom of the creek; three from a terrace mid way up the channel bank; and three at the top of the channel. One bank surface sediment sample was collected from upstream of the Lock Gate. In November, three additional bank top samples, two lower terrace samples and one sample upstream of the Lock Gate were collected.

Activity concentrations of radionuclides within these sediments were determined by high resolution gamma spectrometry. Results for the August survey are given in Figure A4.2. The standard deviation associated with the mean results are illustrated by error bars.

Figure A4.2: Sediment Activity Concentrations along Savick Brook – August 1st



Downstream of the Lock Gate, activity concentrations of radionuclides discharged from the Sellafield site were around 200 to 300 Bq kg^{-1} (dry weight) for Cs-137; 100 to 200 Bq kg^{-1} (dry weight) for Am-241 and 1 to 3 Bq kg^{-1} (dry weight) for Co-60. These results were broadly comparable between the two surveys, and are also consistent with data collected around all three boats at Becconsall Boatyard.

Results for K-40 (600 to 700 Bq kg^{-1} dry weight) and for the U-238 and Th-232 series (20 to 50 Bq kg^{-1} dry weight) were again broadly consistent between surveys and with data from intertidal sediment at Becconsall. Activity concentrations of Pb-210 were higher at the bank top (approximately 90 Bq kg^{-1} dry weight), but were consistent with the path edge soil values determined at the boatyard.

Activity concentrations of Th-234 and Pa-234m (in bed and channel side) sediments were at least a factor of two higher than the maximum values measured at Becconsall. Activity concentrations of Th-234 were 3,000 to 4,000 Bq kg^{-1} (wet weight) and of Pa-234m were 4,000 to 5,000 Bq kg^{-1} (dry weight). As at Becconsall, the activity concentrations of these short lived radionuclides were lower at the top of the bank by about a factor of ten. Again, this is probably due to the lower rates of fine-grained sediment input to areas that are only inundated under higher tidal ranges.

The activity concentrations of all radionuclides measured in sediment were similar both upstream and downstream of the Lock Gate. As with other sites, activity concentrations of Th-234 and Pa-234m in sediment were variable, appearing to depend upon height on the bank and therefore frequency of deposition.

It should be noted that for most of the radionuclides assessed, activity concentrations were higher in August compared to the November study. Although this was typically less than a factor of two, the effect was consistent across radionuclides discharged from the Sellafield site and those that may arise locally (either from the underlying geology of the catchment of the Ribble or discharged from the Springfields site). This suggests that the difference was not a result of changes in discharges regime from either the Sellafield site or the Springfields site; instead it could arise through the accumulation of finer-grained sediments in the upper estuary during periods of lower summer river flow.

In addition to the surface scrape sediment samples, a 0.3 metre depth core was taken on the salt marsh bank adjacent to the brook. The core was sectioned into 5 cm depth samples and each sample analysed via gamma spectrometry. The results show a clear decrease in activity concentration with depth for the radionuclides discharged from the Sellafield site (Co-60, Cs-137 and Am-241) such that values were negligible and consistent below a depth of 0.15 metres.

Activity concentrations of K-40 were consistent with depth and with surface sediment samples collected at Becconsall. The activity concentrations of the U-238 and Th-232 series were more variable, gradually increasing nearer to the surface but with a significant decrease towards the top of the core. The activities in the surface sample were similar to those measured at depths deposited before any influence of discharges from the Sellafield site. The exception was Pb-210 which showed a clear reduction in activity with depth.

A4.1.3 Gamma Dose Rate in Air

Gamma dose rate in air measurements at Savick Brook focused on assessing changes with distance from the channel edge and with height over sediment. The results are discussed below.

A4.1.3.1 Variation with Distance from the Channel Edge

Gamma dose rate in air along three transects set out perpendicular to the brook, were undertaken at low and high water during both visits. Each transect consisted of four measurements at roughly 0, 2.5, 5 and 10 metres from the start point. At low water the transect extended from the low water mark, up the bank side and onto the adjacent salt marsh at the top of the bank. At high water (when the channel was flooded) the transect extended 10 metres further out over the salt marsh.

Gamma dose rate in air ranged from around 30 to 60 nGy hr^{-1} varying with position on the bank, state of the tide and between surveys:

- at low water, gamma dose rate in air measured on a transect up the bank side was highly variable, at points fluctuating by over 15 nGy hr^{-1}. There was no consistent variation with distance from the low water mark, although higher dose rates were often measured part way up the bank, particularly on terraces adjacent to more rapidly rising sections of the bank. The variation may be due to the increased contribution from the adjacent bank face (representing an additional source), and/or from exposed older sediments with higher levels of sequestered activity;

- there was a clear difference in gamma dose rate in air measured at comparable positions at the edge of the salt marsh between high and low water. At high water, when the top of the bank area was flooded and the detector was at the high water mark, the dose rate was reduced by 13 to 14 nGy hr^{-1} (which is a reduction of slightly less than 30 percent). However, within a distance of five metres, measurements increased to a point where they were consistent with initial readings, at around 50 nGy hr^{-1};

- gamma dose rate in air, particularly in the transect up the bank side, varied between the two surveys. For instance in August the mean dose rate, along the low water transect, was 49 +/- 6.0 nGy hr^{-1} while in November it was 37 +/- 6.0 nGy hr^{-1}. This is consistent with the changes in activity concentrations measured throughout the brook.

A4.1.3.2 Variation with Height over Sediment

Gamma dose rate in air was measured at heights of 1 m, 0.5 m and 0.15 m at three locations along Savick Brook during the August and November visits.

The results were variable and showed no consistent relationship with height above sediment. Where there was a positive increase in dose rate with proximity to sediment this mainly occurred between 0.5 m and 0.15 m. Occasionally the increase was around 10 nGy hr^{-1} (ian increase of 20 to 25 percent). However, this relationship was not consistent and at times the dose rate decreased with reduced height.

The mean results (over the six measurements) were 46.1 +/- 5.4 nGy hr^{-1} at 1 m; 46.6 +/- 4.4 nGy hr^{-1} at 0.5 m; and, 51.2 +/- 3.9 nGy hr^{-1} at 0.15 m. Overall they imply a small increase in dose rate when the probe is nearer to the sediment surface; however, the trend is not statistically significant.

This variability may arise due to differences in topography at the locations where the measurements were taken. On a slope, dose rates increased with proximity to the soil surface, which may be due to the increased contribution from the adjacent bank face or older sediments that have been exposed by bank erosion. Over level areas, the opposite appeared to be true, so the measured gamma dose rate in air decreased with increasing proximity to sediment. This effect is believed to be due to the relative reduction in the instrument field of view at lower heights.

Therefore, the site layout needs to be considered carefully when assessing the effect of differing posture heights over sediment on the exposure of people on bank sides.

A4.1.4 Primary Dose Contributors

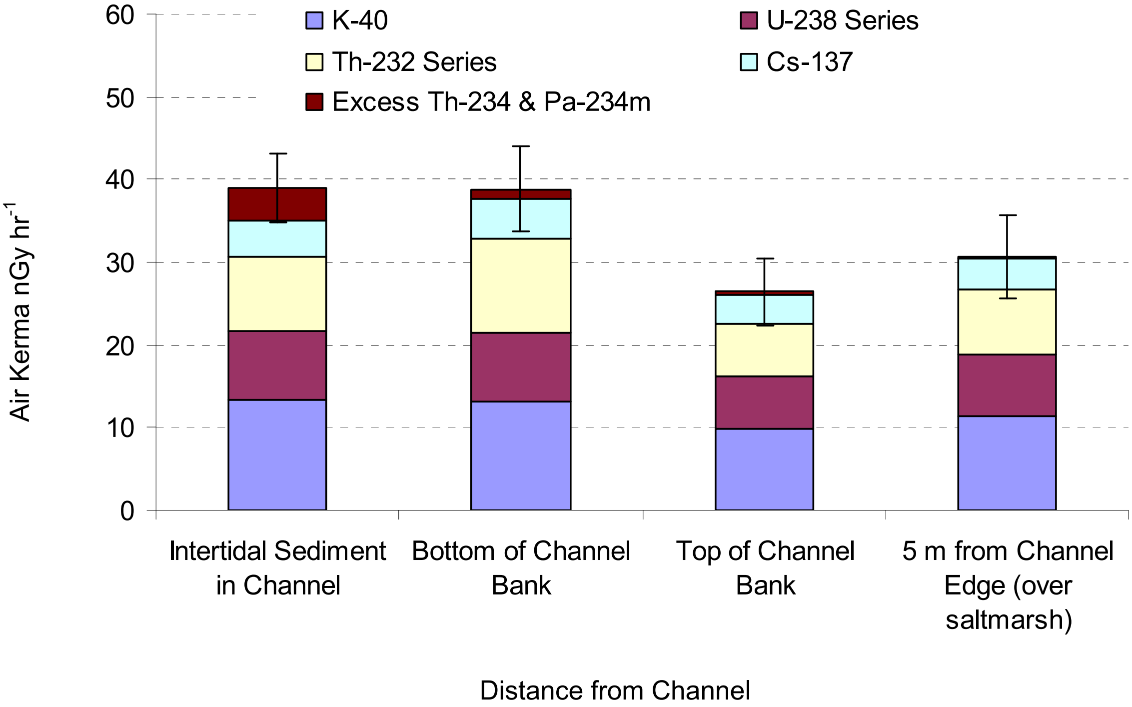
In-situ gamma spectrometry was undertaken at a number of points along the brook at one metre above the sediment surface in addition to the gamma dose rate in air measurements during the November survey. Based on the spectrum derived from these, the contribution to gamma dose rate in air from individual radionuclides has been assessed. The results from this are given in Figure A4.3.

Figure A4.3 shows a series of in-situ measurements made at both low and high water. The total gamma dose rate in air measured via HPGe in-situ gamma spectrometry was around 30 to 40 nGy hr^{-1}.

In each measurement the gamma dose rate in air contribution from K-40 was relatively constant (9 to13 nGy hr^{-1}), as was that of the U-232 series (6 to 8 nGy hr^{-1}). The Th-232 series was more variable (6 to 11 nGy hr^{-1}) with higher values over intertidal sediment. The contribution from Cs-137 was between 3 to 4 nGy hr^{-1} (which is 11 to 14 percent of the total dose). In contrast to the other sites, a noticeable contribution from excess Th-234 and Pa-234m was measured over intertidal sediment (4 nGy hr^{-1}; about 10 percent of the gamma dose rate in air)[26]; however, over salt marsh the contribution was negligible. As with other sites, there was virtually no contribution from Am-241 to the measured dose rate at any of the points assessed.

[26] The contribution may be higher as ICRU conversion factors do not exist for surface Th-234 and Pa-234m contaminated intertidal sediment and hence they may contribute as much as 15 percent of the observed dose rate.

Figure A4.3: Air Kerma at Savick Brook (HPGe Detector)



A4.1.5 Beta Skin Dose

Variation of beta skin dose with height over sediment and the effects of shielding of different clothing materials were assessed and are discussed below.

A4.1.5.1 Variation with Height over Sediment

Attenuation of beta skin dose with increasing height over sediment was assessed at three points along the brook, over intertidal sediments on the channel bed or lower sides. Dose rates were measured at 0.01, 0.05, 0.15, 0.5 and 1 metre above sediment.

Dose rates closest to the sediment surface were approximately 2,000 nSv hr^{-1} per cm^2, significantly higher than those measured at Becconsall. Dose rates appeared relatively constant up to a height of 0.2 metres above the sediment surface, and then decreased in a relatively linear manner with increasing height. At 1 metre, beta skin dose was between 50 and 75 percent of that measured at 0.01 metres. Again, there is evidence of localised heterogeneity between the three locations monitored (potentially due to influence from bank sides), and this may contribute to the trends observed.

A4.1.5.2 Beta Skin Dose Attenuation by Clothing

Attenuation of beta skin dose by clothing materials was assessed by placing different materials over the detector surface. The assessment was made during the November visit to the brook. In each instance, measurements were made at the same location as the point that gave the highest dose rate from the height attenuation study. All measurements were repeated at 0.05 and 0.5 metres above the same sediment surface. The results are given in Table A4.1 (presented as a faction relative to an unshielded measurement).

Table A4.1 Beta Skin Dose Attenuation by Clothing

Garment	Height over Sediment (m)	
	0.05	0.5
Rubber Boot	0.79	0.91
Waterproof (breathable) Jacket	No measurable attenuation	0.05
Woollen Jumper	0.04	No measurable attenuation
Plastic sheeting	0.05	0.06
Wax Jacket	0.30	0.22
Rubber Wader	0.32	0.39

The results show that for thin materials, such as plastic sheeting and light weight waterproofs, and thicker low-density materials such as a woollen jumper, there was effectively no attenuation of the beta emissions. A wax jacket and rubber waders resulted in an approximate 20 to 40 percent reduction in the measured beta skin dose, while thicker rubber boots resulted in an approximate 80 to 90 percent reduction.

A4.2 Longton Marsh

Longton Marsh was surveyed on one occasion (10th November) during a low water period.

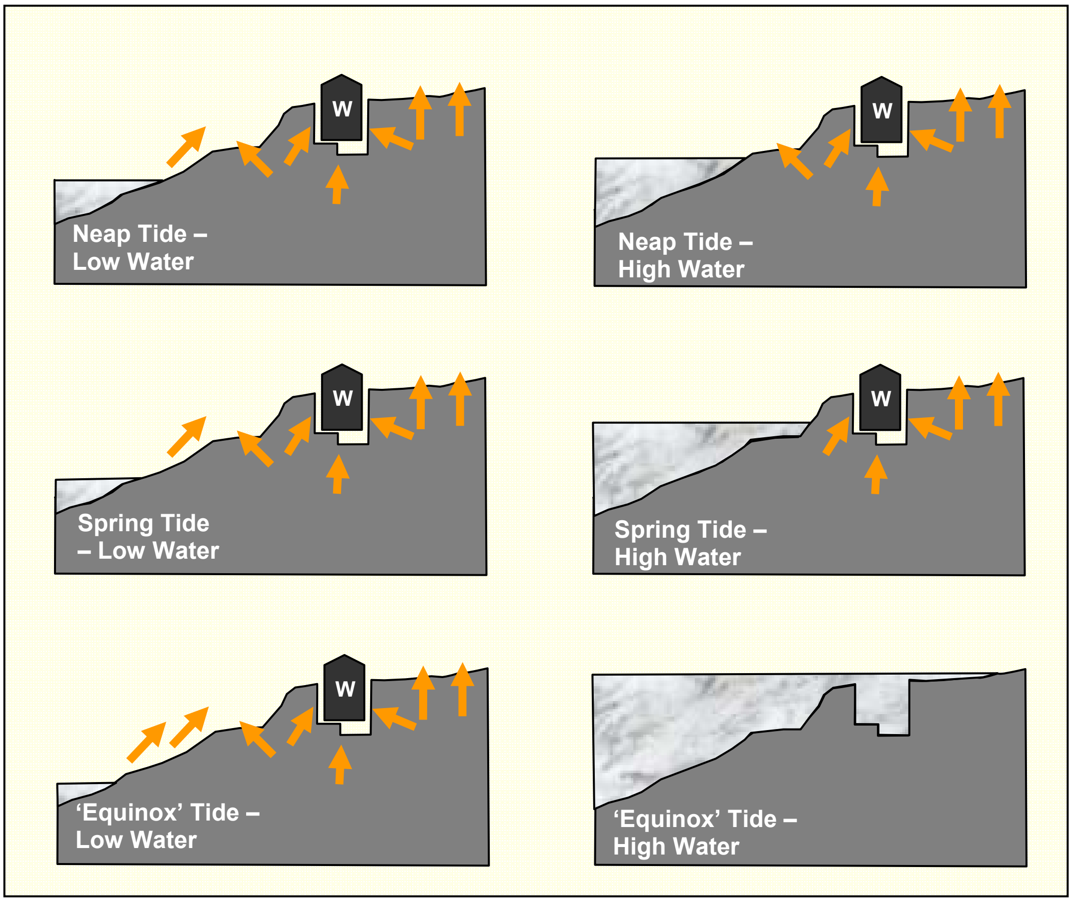
Summarised below are: activity concentrations from sediment; gamma dose rate in air (both over intertidal sediment and salt marsh); beta skin dose; and gamma dose contribution from different radionuclides at different locations and heights over sediment (assessed via in-situ gamma spectrometry).

A4.2.1 Environmental Setting

Longton Marsh is a broad area of salt marsh, used as grazing land. It is bordered to the north by the tidal reaches of the Ribble and to the west by the River Douglas. A number of small tidal creeks cut across the salt marsh (typically one to ten metres wide) which tend to be inundated during higher tidal ranges. The salt marsh is only fully inundated during extreme high tide conditions. There are a large number of pools and other areas of standing water which makes the area attractive to wildfowl bird species and associated wildfowlers.

The survey focused on an area to the west of the marsh. This was an open and level area of salt marsh adjacent to the main channel of the Douglas. The location was chosen because of the presence of two wildfowler ‘hide’ pits, illustrated in Figure A4.4. Prospective sources of gamma radiation are indicated by arrows for different tidal ranges outside of those surveyed.

Figure A4.4: Conceptual Environmental Setting for a Wildfowler (W) at Longton Marsh



These 'hide' pits were situated two to three metres apart. Each pit was roughly square in shape, 0.7 to 0.8 metres wide at the opening and up to about 1 metre deep. The pits had been dug so that there was a sitting ledge at about 0.6 metres from the top. One pit had bare earth sides (Pit 1) while a second (Pit 2) had been lined by wooden planking and was covered by a wooden trap door.

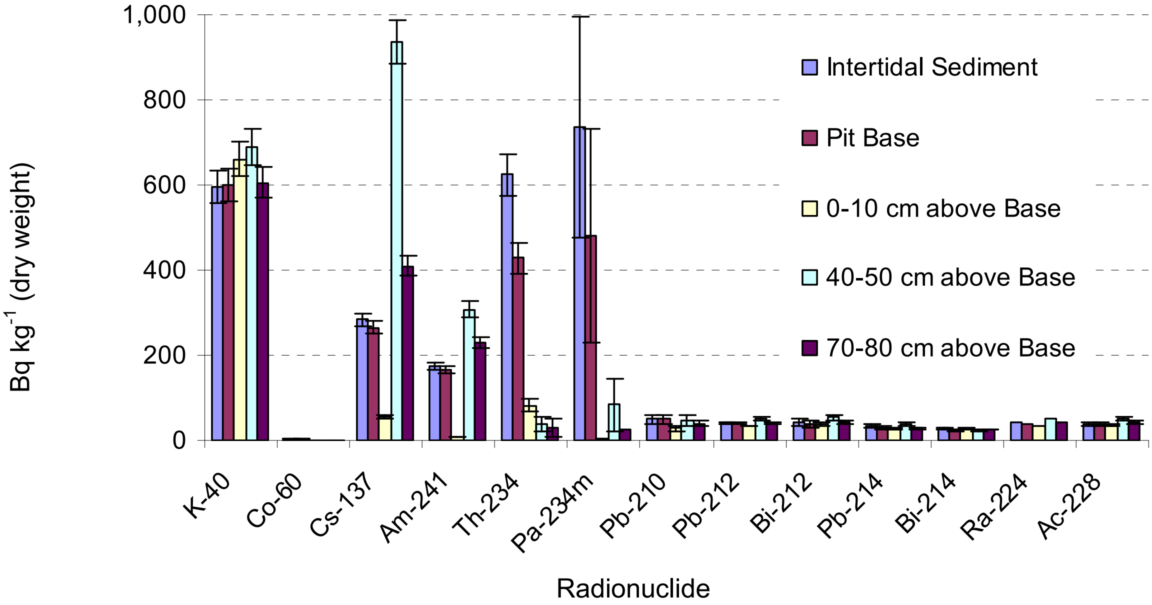
A4.2.2 Sediment Activity Concentrations

During the November visit, sediment samples were collected from an adjacent intertidal area and from the sides and base of Pit 1. Activity concentrations of radionuclides within these sediments were determined by high resolution gamma spectrometry and results are given in Figure A4.5. The two sigma uncertainty associated with each result is illustrated by error bars.

In the intertidal sediment, activity concentrations radionuclides discharged from the Sellafield site were consistent with those at both Savick Brook and Becconsall Boatyard. Activity concentrations of Cs-137 were 284 +/- 16 Bq kg^{-1} (dry weight); Am-241 were 174 +/- 10 Bq kg^{-1} (dry weight); and Co-60 were 1.7 +/- 0.8 Bq kg^{-1} (dry weight).

Results for K-40 (around 600 Bq kg^{-1} dry weight) and for the U-238 and Th-232 series (20 to 50 Bq kg^{-1} dry weight) were also consistent with data from intertidal sediment at Savick Brook and Becconsall.

Figure A4.5: Sediment Activity Concentrations at Longton Marsh – Nov 10th



Activity concentrations of Th-234 and Pa-234m were significantly lower than those measured in Savick Brook, and slightly lower that those measured in bed sediment at Becconsall. This probably relates to high level of the channel side from where they were taken.

Sediment taken from the base of Pit 1 had activity concentrations comparable to those taken from intertidal areas, with the exceptions of Th-234 and Pa-234m which had slightly lower activity concentrations. This sediment was probably deposited when the whole area was inundated under the last extreme high tide conditions and so represents a homogenous source.

Sediment samples cut from the side of Pit 1 are clearly indicative of historical salt marsh deposits. For instance, at about a mid-depth in the pit (40 to 50 centimetres), activity concentrations of Cs-137 were over 900 Bq kg^{-1} (dry weight), which is over three times that measured in surface intertidal sediments. This is also consistent with the depth of the subsurface maximum estimated from the in-situ HPGe detector.

A4.2.3 Gamma Dose Rate in Air

Gamma dose rate in air measurements at Longton Marsh focused on assessing changes with distance from the channel edge, with height over sediment and in and around the hide pits. The results are discussed below.

A4.2.3.1 Variation with Distance from the Channel Edge

Gamma dose rate in air was assessed along a single transect. This was set perpendicular to a large gully on the edge of the Douglas and was undertaken at low water. The transect started over intertidal sediment, with subsequent readings from this at five metres (at the top of the bank) and ten metres (on a level area of salt marsh).

In the transect, the gamma dose rate in air ranged from 47 to 58 nGy hr^{-1}. However, there was no consistent change with increasing distance away from the channel.

As with discussions relating to Savick Brook, it is probable that the dose over salt marsh is dominated by Cs-137 sequestered into the underlying soil, and not by emissions from the channel.

A4.2.3.2 Variation with Height over Sediment

Gamma dose rate in air was measured at heights of 1, 0.5 and 0.15 metres above the ground surface at three locations at the salt marsh sampling site.

The mean results (over the three measurements) were 62 +/- 5.1 nGy hr^{-1} at 1 m; 61 +/- 1.3 nGy hr^{-1} at 0.5 m; and, 57 +/- 4.3 nGy hr^{-1} at 0.15 m. Overall, they imply a small decrease in dose rate when the probe is nearer to the sediment surface. However, the trend was not statistically significant.

As with Savick Brook, there was no consistent relationship with height above sediment, although there was a tendency for the measured dose rate to decrease with proximity to the sediment. Where this occurred it was between 0.5 m and 0.15 m and was up to 9 nGy hr^{-1} (a 20 to 25 percent decrease). This reduction in dose rate with proximity to sediment probably relates to the reduction in the exposure field of the instrument at lower heights (when on a flat surface).

A4.2.3.3 Dose in and around the 'Hide' Pits

A series of six gamma dose rate in air measurements were taken at one metre around and above the 'hide' pits. Results were 61 +/- 3.7 nGy hr^{-1} and were comparable to measurements discussed in the previous two sections.

The dose rate was also measured within the centre of each pit. In Pit 1 (unlined) the dose rate was 116 nGy hr^{-1}, nearly double the dose rate measured over the sediment surface. In Pit 2 (wood plank lined) the dose rate was 88 nGy hr^{-1}. A further measurement made towards the top of Pit 1 gave a result of 86 nGy hr^{-1}.

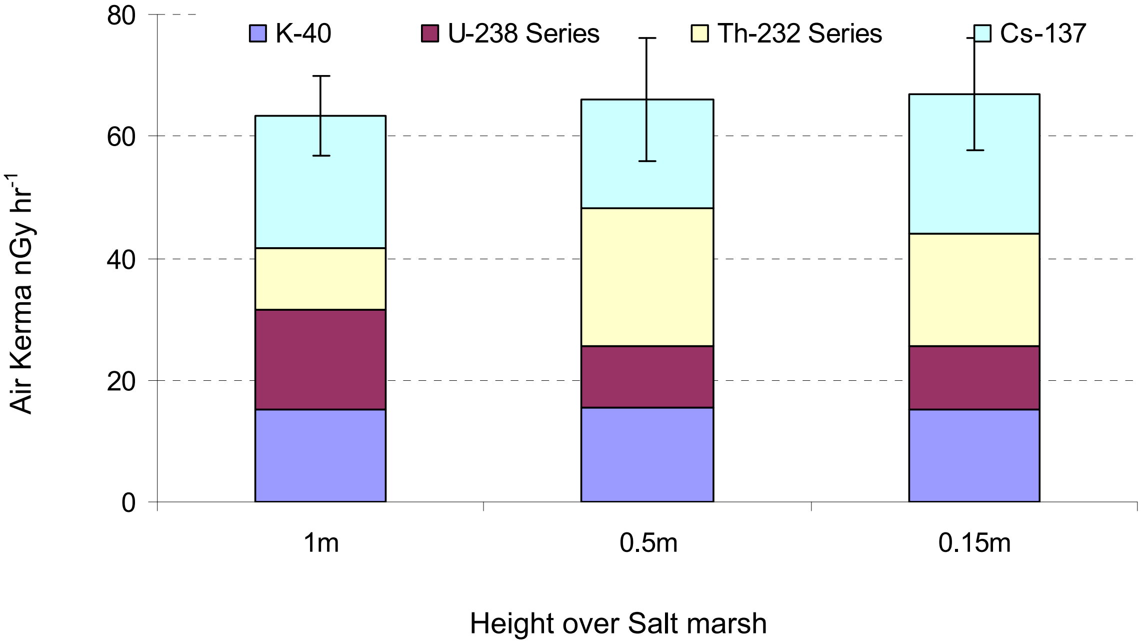
Although a limited range of measurements were taken, they clearly showed elevated levels of gamma exposure in the pits. This is probably due to exposure of the Cs-137 subsurface maxima and also the 'encompassing' geometry.

A4.2.4 Primary Dose Contributors

In-situ gamma spectrometry was undertaken at 1, 0.5 and 0.15 metres above the sediment surface, in addition to the gamma dose rate in air measurements during the November survey. Based on the spectrum derived from these the contribution to gamma dose rate in air from individual radionuclides has been assessed. The results from this are given in Figure A4.6.

Overall the total dose rate varied from 63 +/- 6.5 nGy hr^{-1} (at 1 m) to 66 +/- 10 nGy hr^{-1} (at 0.5 m) to 67 +/- 9 (at 0.15m). Considering the measurement uncertainty involved, the overall different between the three measurements was not statistically significant. This confirms the results derived from the Thermo instrument used to measure gamma dose rate in air.

Figure A4.6: Air Kerma over Longton Salt marsh (HPGe Detector)



Over the three heights the contribution from K-40 was relatively constant (15 to 16 nGy hr^{-1}). However, between 1 m and 0.5 m, there appears to be a decrease in the U-238 series contribution (but is in part balanced by the contribution from the Th-232 series). These variations are however likely to reflect statistical noise in the data.

A4.2.5 Beta Skin Dose

Variation of beta skin dose with height over sediment and within the wildfowler pits are discussed below.

A4.2.5.1 Variation in Height over Sediment and Salt marsh

Beta skin dose was measured at 0.01, 0.05, 0.015, 0.5 and 1 metre above intertidal sediment and over salt marsh.

Dose rates closest to the sediment surface were approximately 500 nSv hr^{-1} per cm^2, and are more comparable to those measured at Becconsall than those at Savick Brook. Dose rates decreased rapidly, particularly within the first 0.2 metres. Between 0.5 to 1 metre above the sediment surface the beta skin dose was about 50 percent of that measured at 0.01 metres.

Beta dose rate was assessed over short salt marsh grass around the perimeter of the wildfowler pits. No detectable skin dose was measurable at any height over sediment.

A4.2.5.2 Variation within the Pits

Beta skin dose was measured with the detector held horizontally at 0.01, 0.05, 0.015, 0.5 and 1 metre from the base of each pit. In Pit 1 (unlined) the highest dose was about mid way down the pit and gave a dose rate slightly in excess of 300 nSv hr^{-1} per cm^2. Dose rates at the bottom and at the top were about half of this value. Aligning the detector to the pit side demonstrated that the beta dose contribution was coming from the pit sides and not the base.

Measurements at different heights above the base were repeated in Pit 2 (lined). In this instance dose rates were lower; the highest value was around 200 nSv hr^{-1} per cm^2. They were only detectable up to about 0.2 metres above the base, so were due to recently deposited sediments that have settled at the base of the pit when the area was last inundated, rather than from higher levels of radionuclides discharged from the Sellafield site.

A4.2.6 Summary and Key Points

A detailed assessment of activity concentrations in soil and sediment, external gamma dose and beta skin dose has been made for two different environmental settings pertinent to use of areas around the estuary for recreational activities such as angling or wildfowling. Key points from this aspect of this appendix include:

- activity concentrations of Cs-137 in surface sediment were typically around 300 Bq kg^{-1} (dry weight) while that of Am-241 was around 200 Bq kg^{-1} (dry weight). Only very low activity concentrations of Co-60 (of a few Bq kg^{-1} dry weight) were detected. These results are consistent with those discussed in Appendix 3;

- activity concentrations of Th-234 and Pa-234m were again variable, by up to two orders of magnitude. The sampling position at any one site, relative to the extent of tidal inundation (and hence frequency of sediment supply) appears to be the dominant factor in this variation. The ranges measured also differed significantly between the two sites, with those in Savick Brook (which is located just upstream of the Springfields site) being higher;

- activity concentrations of other uranium and thorium decay chain products were much more consistent, typically between 25 to 30 Bq kg^{-1} (dry weight). Comparison of surface measurements with those derived from the base of a core sample indicated that activity concentrations in surface sediment are only marginally elevated over historical levels which pre-date UK nuclear industry activities;

- all gamma dose rate in air measurements are quoted minus intrinsic instrument background and cosmic radiation (approximately 60 nGy hr^{-1}) and are based on a Ra-226 instrument calibration;

- where gamma dose rate in air monitoring is undertaken in a tidally dynamic environment, the state of the tide has to be considered, because it can have a large influence on the dose rates measured, particularly when monitoring at the edge of an inundated area. However, this effect appears to be limited to about five metres from the edge of the water. Consistency and clarity in recording when and where measurements are derived is important;

- no universally-consistent relationship between gamma dose rate in air and height above sediment was observed. Nonetheless, on a broad level area, dose rates appear to show a small decrease with proximity to the ground surface (assumed to be due to the restriction in the gamma dose field measured by the instrument). On channel sides, particularly those with a terraced or stepped profile, the situation is more complex. This effect is presumed to arise from a combination of gamma emissions from both the underlying ground surface and also the adjacent face of the rising bank profile (and its proximity). The situation may be further complicated if the side of the channel face has eroded into older salt marsh deposits, where higher activity concentrations of gamma emitting radionuclides exist, derived from historical discharges. A similar effect was observed in wildfowler pits excavated into the salt marsh surface, within which gamma dose rates in air were around double those measured over the surface;

- following the points above, the variation in gamma dose rate in air with proximity to the channel can be highly influenced by the extent of recent sediment deposition and the topography of the bank. In both areas assessed, extreme high tides flood the salt marsh land adjacent to channel and are likely to have caused deposition of activity over an extended period. Over much of this area, the gamma dose rate in air is heavily influenced by radioactivity historically deposited on these areas, and not from gamma emissions arising from contemporary levels in intertidal sediments (the exception being the elevated activity concentrations of Th-234 and Pa-234m at Savick Brook);

- in-situ gamma spectrometry over sediment and salt marsh determined that Cs-137 was the primary dose contributor arising from discharges from the Sellafield site. At both sites, there was virtually no contribution to the gamma dose rate in air from Am-241 and there was no measurable contribution from Co-60. This is consistent with the findings from the survey at Becconsall. The contribution from excess Th-234 and Pa-234m (from discharges from the Springfields site) varied depending upon the site, and at its highest (at Savick Brook) this contributed around 10 to 15 percent of the observed gamma dose rate;

- beta skin dose varied between the sites and was significantly higher over intertidal sediment in Savick Brook compared to any other site surveyed (of the order of a few 1,000 nSv hr^{-1} per cm^2). At Longton Marsh, the highest beta skin dose rates (of the order of a few 100 nSv hr^{-1} per cm^2) were measured in an unlined wildfowler pit, at a level consistent with higher levels of activity historically deposited onto the salt marsh;

- the results for beta skin dose attenuation from clothing show that for thin materials, such as plastic sheeting and light weight waterproofs, and thicker, but low density materials, such as a woollen jumper, there was effectively no attenuation of the beta emissions. A wax jacket and rubber waders resulted in an approximate 20 to 40 percent reduction in the measured beta skin dose, while thicker rubber boots resulted in an approximate 80 to 90 percent reduction.

A5 – Estimation of Dose and Potential Sources of Variability

As introduced in Section A1.3, measurements of gamma dose rate in air need to be converted to units of equivalent dose (sievert (Sv)), to compare external gamma exposures with regulatory limits. To do this a number of factors need to be considered, specifically:

- the instrument calibration factor used and whether this is based on Cs-137 or Ra-226;
- the intrinsic count rate of the instrument (typically determined during calibration);
- the value subtracted to account for natural cosmic radiation;
- the value subtracted to account for natural levels of radioactivity in soil and sediment;
- the gray to sievert conversion factor;
- the duration of exposure (typically in terms of annual exposure when comparing to the Public Dose Limit).

To assess the contribution from anthropogenic sources against the Public Dose Limit (see Appendix 1), intrinsic and cosmic radiation, and natural levels of radioactivity present in the environment need to be accounted for and subtracted from environmental measurements. Also, in some environments (such as the Ribble estuary) where radioactivity may be derived from authorised discharges from different sites, establishing the relative contributions may help regulators to define appropriate discharge limits for each of the respective sites.

Where exposure is presented relative to annual exposure limits, the degree of occupancy (typical expressed in terms of hours per year) at a particular site, and the means of exposure, also need to be taken into account.

These factors are discussed in this appendix.

A5.1 Calibration and Background Rate Subtraction

Calibration and intrinsic and background subtractions are discussed in this section.

A5.1.1 Gamma Dose Rate in Air Calibration

As discussed in Appendix 2, when reporting data using Geiger counter instrumentation, the fundamental quantity of external photon radiation, gamma dose rate in air (or air kerma) (Gy), is initially reliant on which calibration coefficient is used. The choice is usually between Cs-137 and Ra-226.

The Geiger counter used in this work is energy compensated (as are those typically used throughout UK baseline environmental surveys), but nevertheless does not have a flat energy response. Thus, calibrations based on Cs-137 and Ra-226 will result in different readings being reported.

In complex radiation fields that arise from a range of radionuclides that may exist in the environment, it is unlikely, in most cases, that Cs-137 will dominate the dose rate. However, without spectral information, it is difficult to substantiate this. In this work we have demonstrated good comparison between gamma dose rate in air derived from the Ra-226 calibration through using in-situ gamma spectrometry. This has shown that Cs-137 does not dominate the observed gamma dose rate in air in the Ribble, and that the Ra-226 calibration is more suitable for complex gamma photon emission environments. It is important that calibration details are reported clearly as the difference may account for 30 percent of the reported value (a Cs-137 calibration leads to an overestimate).

All gamma dose rate in air results presented in this report are based on a Ra-226 calibration.

A5.1.2 Intrinsic and Cosmic Background Subtraction

Any gamma dose rate in air measurement will be influenced by the intrinsic count rate of the instrument. This is a positive, but small value that will always be recorded even in the absence of any external radiation field to the instrument. The instruments used in this study had a typical intrinsic count rate of 0.2 to 0.3 counts per second (cps).

In addition to the intrinsic count rate, all measurements will be influenced by cosmic radiation, the amount of which varies with latitude and altitude. A typical value of 0.8 to 0.9 cps is estimated for this type of instrument (manufacturer's and calibration specification).

The combined effect of intrinsic and cosmic background on instrument readings has been determined over a large body of water (see Appendix 2) and found to be around 60 nGy hr^{-1}, that is 12 to 18 nGy hr^{-1} from intrinsic and 42 to 48 nGy hr^{-1} from cosmic sources. However, it is typically assumed that the cosmic contribution is approximately 32 nGy hr^{-1} (UNSCEAR, 1993).

As described in Appendix 2, our background estimates (intrinsic and cosmic) were made from multiple measurements over open water. Whilst our measured background rates may contain a contribution from personnel on the boat and the boat materials themselves, these are likely to be minor. It is therefore possible that use of a generic value, such as that given by UNSCEAR (1993), may underestimate the contribution from cosmic radiation and therefore lead to an overestimation of the gamma dose rate in air from terrestrial sources, whether these be from anthropogenic or naturally occurring radionuclides.

All gamma dose rate in air results presented in this report have had 60 nGy hr^{-1} deducted to account for intrinsic and cosmic background. The results presented are however inclusive of gamma radiation from all radionuclides (natural and anthropogenic) within underlying soils and sediment.

The component of the gamma dose rate in air results that arises from naturally occurring levels of radioactivity in soil and sediment in the Ribble is discussed below.

A5.1.3 Terrestrial Background Subtraction

All soils and sediments will contain some level of radioactivity derived from natural sources, for instance radioisotopes of the Th-232 and U-238 decay chains and K-40. These can arise from the weathering of rock formations in the river catchment, input from the coastal environment and deposition from naturally occurring atmospheric sources.

The Ribble estuary receives authorised discharges of radionuclides from the Springfields site which processes uranic materials to produce uranium based fuels. Therefore levels of these radionuclides may be enhanced; however levels of K-40 are unlikely to be influenced[27].

Some radionuclides, such as Cs-137 and Am-241, do not occur naturally and are the result of human activities. Low levels of Cs-137 and Am-241 may be attributable to existing nuclear power stations (for instance at Heysham in Lancashire and at Wylfa on Anglesey). However, within coastal environments of the western side of the Irish Sea, levels of these radionuclides are dominated by historical discharges from the Sellafield site, primarily due to spent nuclear fuel reprocessing. Caesium-137 and Am-241 are not discharged from the Springfields site. Therefore, any dose contribution from these radionuclides can be primarily attributed to former operations of the Sellafield site[28].

The results of this study demonstrate that the anthropogenic contribution to sediment activity concentrations varies both spatially, (between sites and locations at any one site, including with depth) and with time (longer term trends may result from changes in discharge regimes from nuclear sites, but short term fluctuations can result from differences in tidal process and rates of sediment supply). This variability is particularly important for discharges of the short lived radionuclides Th-234 and Pa-234m from the Springfields site. In contrast, concentrations of the natural series radionuclides remain relatively consistent across the sampling sites examined around the estuary, and between salt marsh soils and surface intertidal sediments.

As discussed in Appendix 4, a 0.3 metre depth core (Ordnance Survey Grid Reference SD47917-29578) was sampled on the upper terrace of Savick Brook, just upstream of the Springfields site effluent discharge point. This is therefore arguably one of the most impacted parts of the estuary with regard to radionuclides discharged from the Springfields site. The core was sectioned into five centimetre intervals. Figure A5.1 summarises the depth distribution of the anthropogenic and natural series radionuclide distributions. The activities of Am-241 and Cs-137 rapidly decline with depth, suggesting that the sedimentation rate at this upper terrace site was very low.

Thorium-234 activity concentrations were elevated towards the surface of the sediment. A slight excess of U-238 and the U-238 series daughters (Bi-214 and Pb-214) is observed in the sediment[29].

Excess Pb-210 was also very apparent, derived from atmospheric deposition from the decay of naturally occurring airborne radon-222 (Rn-222) gas. Equilibrium was observed between Pb-210 and Bi-214/Pb214 at around 12.5 ± 2.5 cm depth. When the uncertainties are taken into account, equilibrium between Th-234 and daughters (Pb-214, Bi-214 and Pb-210) may occur from 12.5 centimetres, although actual activity concentrations converge at around 22.5 ± 2.5 centimetres depth. A similar decline was observed in the Th-232 daughters (Ac-228, Pb-212 and Bi-212). The radionuclide K-40

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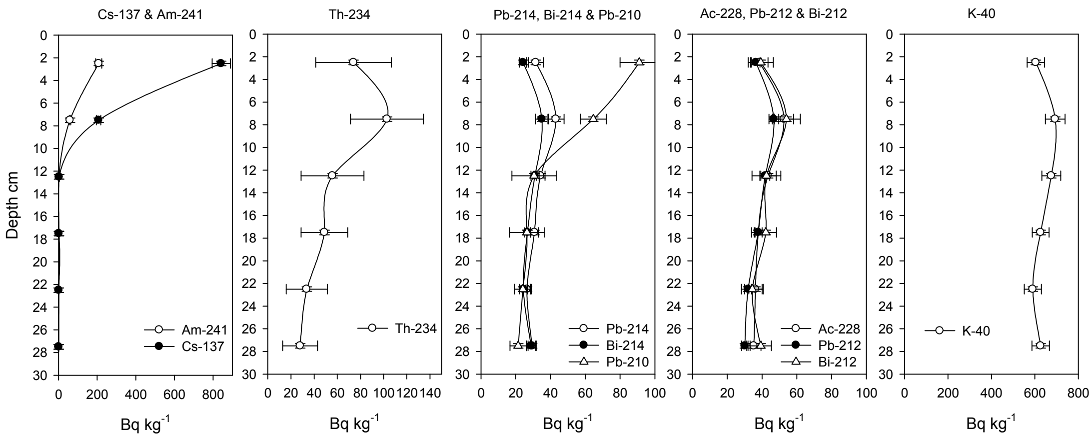
[27] Former coal mining operations in the Ribble catchment may have led to increased releases of naturally occurring radionuclides until the industries declined in the 1950s. Also some anthropogenic processes, e.g. processing of phosphate rich cores for fertiliser production, may lead to enhanced levels of K-40 in the environment. However, assessment of these was outside the scope of the project. 'Natural', in terms of levels of radioactivity in the environment, in this report means not influenced by the nuclear industry.

[28] Although discharges of these radionuclides from the Sellafield site continue, levels are significantly lower than those associated with former operations and will continue to decline in the future.

[29] Excess refers to elevated concentrations of natural radioactivity above those expected. This may be expected from processes of technological enhancement of natural radioactivity prior to discharge, either through the coal industry or more recently discharges from fuel fabrication at the Springfields site.

exhibited a relatively uniform activity with depth, indicating that there was no local source of K-40 that may enhance its concentration, other than perhaps natural variation reflected in the mineralogy and tidal conditions with time.

Figure A5.1: Radionuclide Depth Distributions at Savick Brook



Without greater depth resolution, it is difficult to identify exactly where, within the surface five centimetres, the maximum Cs-137 activity occurs (relating to the peak of historical discharges from the Sellafield site that occurred in the mid 1970s). The presence of this near surface maximum suggests that the sedimentation rate on tidal washed areas along Savick Brook was of the order of 1 ± 0.5 millimetres per year. From the excess Pb-210 it was also possible to crudely estimate the age where no excess Pb-210 was detectable (typically four to five half lives). This suggests that the sediment at 12.5 centimetres depth in the core, was likely to have been deposited at least 100 years ago[30].

The International Committee for Radiological Units, ICRU report 53 (ICRU, 1994) give factors to predict gamma dose rate in air (at one metre) based on activity concentrations of radionuclides in sediment and the associated moisture content. These have been used to calculate gamma dose rate in air values, which then have to be validated against field measurements.

Within the Savick Brook salt marsh core, the moisture content varied from 60 percent at the surface to 20 percent at depth (giving a depth integrated moisture content of 50 percent). Based on this and a depth integrated activity concentration determined from all the gamma emitting radionuclides measured, predictions of gamma dose rate in air based on ICRU (1994) have been calculated and compared to the in-situ gamma spectrometry measurements made (see Table A5.1).

Within the analytical uncertainties, that are unavoidable in complex environmental conditions, there was a good agreement between measured and predicted dose rates, so the ICRU factors and a mean moisture content of 50 percent were considered appropriate for use in this study.

[30] The half life of Pb-210 is 22.5 years. The excess contribution, observed in the surface sediments, is unsupported (i.e. there are no parent atoms decaying into Pb-210) and thus it decays away at the rate of it's half life, (i.e. half the Pb-210 will decay away in 22.5 years). This is in contrast to the supported Pb-210; this is typically in equilibrium with the U-238 decay series. With new sediment deposition and atmospheric input, the Pb-210 activity at the surface of the sediment profile will remain relatively constant, whilst the buried sediment declines through radioactive decay. Thus, where no excess Pb-210 is measurable in the sediment profile, the sediment may be assumed to be 4 to 5 half lives in age (that is 90-113 years old).

Table A5.1 Comparison between in-situ HPGe Measurement and ICRU Predictions

Approach	Gamma Dose in Air (nGy hr^{-1})									
	Cs-137	2 σ	U-238 series	2 σ	Th-232 series	2 σ	K-40	2 σ	Total	2 σ
ICRU Predicted	4.18	0.8	8.7	3.3	15	5	15.6	3.7	43.5	7.2
Measured In-Situ	4.89	0.6	8.3	3.9	11.4	2.9	13.2	1.7	38.8	5.2

Based on the activity concentrations measured towards the bottom of the core, which are not influenced by anthropogenic activities (see Table A5.2), the ICRU (1994) method has been applied to predict the anticipated gamma dose rate in air over sediment that would arise if there had been no input from anthropogenic sources (see Table A5.3). Results are presented based on the measured average moisture content (of 50 percent) and also for a 'dry soil' scenario. The contributions from Am-241 or Co-60 are not listed as these have been determined as insignificant by in-situ spectrometry.

Table A5.2 Activity Concentrations Assessed as Typical of Background

Activity Concentration	Activity Concentration (Bq kg^{-1} dry weight)							
	Cs-137	2 σ	U-238 series	2 σ	Th-232 series	2 σ	K-40	2 σ
> 20 cm depth	0	0	29	3.5	35	7.6	627	40

The 'natural' gamma dose rate in air background over salt marsh, with a typical moisture content (i.e. 50 percent), that is indicative of pre-anthropogenic influence, is likely to be around 30 nGy hr^{-1}. This consists of a contribution of around 7 nGy hr^{-1} from the U-238 series, 11 nGy hr^{-1} from the Th-232 series and 13 nGy hr^{-1} from K-40.

Table A5.3 Predicted Gamma Dose in Air assuming no Nuclear Industry Discharges

Approach	Air kerma (nGy hr^{-1})							
	U-238 series	2 σ	Th-232 series	2 σ	K-40	2 σ	Total	2 σ
Air Kerma nGy hr^{-1} (50 percent moisture)	6.7	0.8	10.6	2.3	13.1	0.8	**30.3**	**2.6**
Air Kerma nGy hr^{-1} (Dry Soil)	13.4	1.6	21.1	4.6	26.3		**60.7**	**5.1**

Considering comments given in Section 5.1.2, an appropriate 'background' value, inclusive of both cosmic and terrestrial influences, applicable to dose rate measurements over salt marsh in the Ribble estuary, is likely to be of the order of 70 to 80 nGy hr^{-1}.

It is important to note, as illustrated in Table A5.3, that these results are highly dependent upon the moisture content of the substrate. In instances where the soil is very dry, the gamma dose rate in air may be twice that discussed above. On salt marsh areas such as those in the Ribble, soil moisture content will almost certainly vary seasonally through both precipitation and episodic flooding. However, assessment of this, and determination of what is a typical annual average is out of the scope of this project. Therefore, further conclusions are based on the assumption that a depth integrated soil moisture content of 50 percent is a reasonable annual average.

It is also worth noting that surface intertidal sediments exhibited a 60 percent moisture content and may well have a similar decline in moisture with depth and thus are likely to provide a similar gamma dose rate in air (however this was not assessed).

Based on the results from one sediment core it would appear that the most appropriate value for background dose rates around the Ribble estuary (either over sediment or salt marsh with a 50 percent moisture content) are around 30 nGy hr^{-1} for natural levels of radioactivity in soil and sediment and 40 to 50 nGy hr^{-1} for cosmic contribution, i.e. a total of 70 to 80 nGy hr^{-1}.

The value of 70 nGy hr^{-1}, used to account for terrestrial and cosmic background in statutory monitoring programmes (see Appendix 1) may slightly overestimate the contribution from anthropogenic sources, but is nonetheless considered to be reasonable (if slightly conservative) for exposure directly over sediment. However, to avoid confusion it should be clearly stated that the use of the 70 nGy hr^{-1} value is inclusive of both terrestrial and cosmic contributions and it should be acknowledged that the respective contribution from each may vary upon location.

Application of the background value described above to determine exposure received in a boat may not however be appropriate, particularly when values are integrated across a tidal cycle. As described in Appendix 2, the terrestrial contribution to the gamma dose rate in air may drop to around zero at high water on a relatively large boat where the channel is fully inundated (or on a pontoon over an inundated channel).

A5.2. Contributions from Sellafield and Springfields

The contribution to gamma dose rate in air from discharges from the Sellafield site is apparent from the in-situ gamma spectrometry measurements of Cs-137. The results presented in Appendices 3 and 4, show that the gamma dose rate in air contribution from Cs-137 ranged from 3 to 5 nGy hr^{-1} (on bank tops and other areas with a low sediment input rate) to between 15 to 20 nGy hr^{-1} over sediments and more frequently inundated salt marsh. There was a negligible contribution from Am-241 at all sites assessed.

Excess Th-234 and Pa-234m can be directly attributed to discharges from the Springfields site. A trace contribution to the gamma dose rate in air from these radionuclides was detected over intertidal sediment at Becconsall; no contribution was measured at Longton Marsh. Over intertidal sediment within Savick Brook, the contribution was between 1 nGy hr^{-1} (bank top) to 4 nGy hr^{-1} (over intertidal sediment). It is reasonable to assume that, apart from areas near to the Springfields site effluent discharge point, the contribution of these radionuclides to external exposure is now very low.

At Savick Brook, both over sediment and salt marsh, the contribution from the U-238 series was relatively constant around 6 to 8 nGy hr^{-1} and that of Th-232 of around 11 nGy hr^{-1}. This implies very little (around 1 nGy hr^{-1}) elevation over background for these radionuclides. Elevation in dose rate was primarily due to Cs-137, Th-234 and Pa-234m.

Results from Becconsall and Longton Marsh are more difficult to assess. The contributions (over soil and sediment) from the U-238 series ranged from 9 to 13 nGy hr^{-1} (implying an elevation over background) while those of Th-232 were typically between 6 and 14 nGy hr^{-1} (values of 18 to 20 nGy hr^{-1} were measured along the path edge running around the boatyard). It is unclear why this variation occurred. Potential sources of uncertainty may be: varying moisture content of the substrate; differing geologies and anthropogenic activities between the catchments of the Ribble and Douglas; complexities in the gamma field due to varying topographies; and, particularly at the boatyard, the potential that hardcore and other material with a different mineralogical composition may have been imported for ground levelling or path construction. There is therefore some uncertainty, but it may be reasonable to conclude that at Becconsall and Longton Marsh the majority of external gamma dose rate in air from nuclear site operations relates to the Sellafield site.

Although there is some uncertainty, it is clear that the contributions to gamma exposure around the estuary from discharges from the Sellafield site and the Springfields site can be quite variable, differing between sites and also depending upon where measurements are made at any one site.

A5.3 Calculation of Effective Dose

In the UK, doses are presented as effective dose - although this approach is not universal across European Union Member states. The coefficients used can vary, depending upon the gamma emitting radionuclides present and the posture of the individual, relative to the source of gamma emissions.

Key points relevant to statutory monitoring programmes are discussed below.

A5.3.1 Effective Dose

The effective dose (H_E), expressed in terms of sieverts, is the International Commission on Radiation Protect (ICRP) document 26 (ICRP, 1977) recommended quantity for presentation of dose results and is used by many countries, including the UK, for dose reporting (Clark et al., 1993).

Clark et al. (1993) provide a review of the historical development of the conversion factors between gamma dose rate in air and effective dose. The ICRP documents 51 (ICRP, 1987) and 57 (ICRP, 1990) categorise and define these conversion factors, giving different rates depending upon the posture of the individual exposed (that is their geometry with respect to the source of the gamma radiation). The geometries most appropriate for this work are the:

- anterior-posterior (AP) geometry: is used in the situation where the source of ionising radiation (the sediment) is incident on the front of the body. This best describes the geometry of a wildfowler lying, face-down, on top of sediment;

- rotationally isotropic (ROT) geometry: is the geometry most suitable for a person standing above sediment which contains deposited radionuclides.

Other geometries also exist, such as the Isotropic (ISO) geometry. This geometry is typically applied when an individual is 'immersed' in an all-encompassing gamma radiation field, so that the contribution is equal from all directions. Although this work has shown that an individual may be exposed from gamma emissions resulting from multiple directions, particularly when within a channel, this exposure does not represent a uniform radiation field as it is likely to be biased by emissions from the channel bed, or, one or other, adjacent sides of the channel. It is therefore not easy to apply the ISO geometry to a terrestrial/environmental setting and detailed consideration of this has not been possible within the context of this project. Further discussions focus on the AP and ROT geometries.

The typical Sv Gy^{-1} conversion factor (based on a gamma dose rate in air measurement at one metre) for a ROT geometry is accepted to be around 0.86 Sv Gy^{-1} (after ICRP, 1987; Clark et al., 1993). A value of 0.85 Sv Gy^{-1} is used when reporting the results from statutory monitoring programmes. However, this conversion can vary between 0.82 to 0.96 Sv Gy^{-1} as a result of the complexity and nature of the gamma radiation field.

Figure A5.2 (after ICRU, 1998) demonstrates the variation in the conversion factors (Sv Gy^{-1}) for different gamma photo energies depending upon whether an AP or ROT geometry is considered. Conversion factors for Ambient Dose Equivalent[31] are also given for comparison.

These factors have been used to estimate the influence on the mean conversion factor from sites across the Ribble, where the calculation has included the surface gamma photon flux estimated from the gamma emission data (40-3,000 keV) to weight the mean conversion factor between the gamma dose rate in air to effective dose.

Here the energy dependent gamma photon flux is estimated by converting the measured radionuclide concentration to the gamma emissions for each full energy peak and weighting the conversion factors appropriately to provide an approximate conversion factor for a number of sites across the estuary (for Th-234, Pa-234m, Ra-226, Bi-214, Pb-214, Pb-210, Ac-228, Ra-224, Pb-212, Bi-212, Tl-208, K-40, Be-7, Co-60, Cs-137 and Am-241). The results (based on Clark et al. 1993) are summarised in Table A5.4[32].

Table A5.4 shows some variability in the dose rate conversions, perhaps more so for the AP geometry as this conversion factor exhibits greater variation with the energy of emission of the radionuclides present. Nonetheless, the results for the ROT geometry were highly consistent across the different sites in the Ribble that were assessed, and the value of 0.85 Sv Gy^{-1}, typically used in statutory monitoring programmes, is concluded to be acceptable for a wide range of exposure scenarios (although it will lead to a very small overestimate of the dose).

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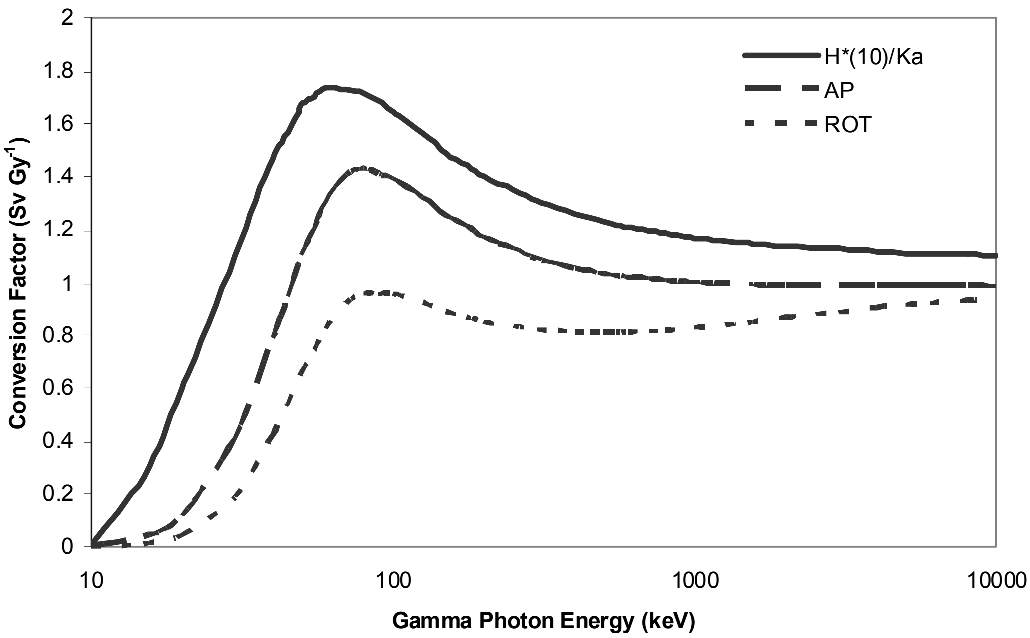
[31] The Ambient Dose Equivalent (H*(10)), introduced by ICRU in 1985 is the tissue equivalent dose at 10 millimetres depth and is again highly energy dependent (Figure A5.2). This unit has become increasingly used as the calibration unit for monitoring instruments and personnel dosimeters across Europe. It has been preliminary assessed that typical Sv Gy^{-1} values for sites around the Ribble would be of the order of 1.21 to 1.32 Sv Gy^{-1} in instances where the Ambient Dose Equivalent is reported. This reporting method is not however used in the UK and all doses in this report are given in terms of the effective dose.

[32] This approach does not take account of the secondary scattered gamma photon contributions – which are especially important over water. Further clarification would require extensive modelling to derive the results required; however this is not relevant considering the doses received.

Figure A5.2 Conversion from Air Kerma to Effective Dose (AP and ROT geometries) and Ambient Dose Equivalent (H*(10) (Sv Gy^{-1})



However, it is important to note that the ROT geometry factor may not be applicable for all activities. This is particularly true where an individual is lying flat, face-down, on the sediment surface. In this instance, use of a ROT conversion factor may not be appropriate (and would underestimate the Effect Dose Equivalent) from a gamma dose rate in air at one metre measurement. For time spent lying on the sediment, an AP geometry value of between 1.0 and 1.1 Sv Gy^{-1} would provide a more reasonable dose rate conversion[33].

Table A5.4 Gy to Sv Conversion Factors

Location	Conversion Factor (Sv Gy^{-1}) based on Air Kerma at 1 m		
	AP Geometry	ROT Geometry	Comment
Estimated Mean		0.86	Estimated from Clark et al., 1993
Longton Marsh	1.03	0.83	High ^{137}Cs activity
Savick Brook 1	1.06	0.83	Bank Edge Tide In
Savick Brook 2	1.04	0.83	Bank Edge Tide Out
Savick Brook 3	1.1	0.84	^{234}Th & ^{234m}Pa contribution
Boat 2 - 1	1.03	0.84	Path by Boat 2

Use of the AP geometry is not currently considered in statutory monitoring programmes. Its application would require realistic estimates of time spent lying on sediment - information that is not currently available. Using the AP geometry in statutory monitoring programmes should be assessed further.

Comparable conversion factors (based on gamma dose rate in air measurements at one metre) do not exist for seated postures such as an angler sat on a channel side. In addition, the relationship of gamma dose rate in air with height over soil / sediment can be highly variable, potentially due to local differences in topography. Therefore it is not possible to provide any posture-specific conversion rates. A wildfowler sat in a pit that has been dug down through salt marsh sediments, also represents a complex

[33] Use of an AP geometry may also be appropriate for a wildfowler in a hide pit who is stood up, leaning face forward, against the pit wall. However, it is not appropriate to apply this factor to a gamma dose in air measurement made in the pit as the detector is surrounded on four sides by the pit walls.

geometry that is not fully addressed by established dose conversion factors available - the determination of which is not within the scope of this project.

A5.3.2 Occupancy Rates

This study did not aim to assess habits or occupancy rates for members of the public around the Ribble estuary. Points from the most recent habits survey commissioned by the Environment Agency, relative to the sites assessed, are given below (from Cefas 2007):

- during earlier Cefas studies up to four houseboats at the Becconsall boatyard had been used for full time occupancy. In 2006, only one boat was occupied on a near full time basis. Cefas assess the mean occupancy rate for people on this boat as 8,300 hours per year;

- wildfowling around the Ribble (including the Longton Marsh area) is restricted to autumn and winter months (September to late February). The Cefas study states that much of the wildfowlers time is spent lying, sitting and kneeling on the salt marsh and in the muddy gullies (channels) that cut across the salt mash. Cefas quote a mean occupancy rate for this group of 390 hours per year. No mention of use of the hide pits at Longton is made or a breakdown of time spent lying down, kneeling or sitting given;

- freshwater angling in the lower stretch of the Ribble Link around the road bridge area have been observed on the bank adjacent to tidal areas (but not over intertidal sediments). In addition, angling from an area of concrete hardstanding adjacent to the Ribble Link sea lock gate in Savick Brook has been observed, but is believed to be limited. Angling is popular in the upper reaches of the Ribble estuary, particularly from the walls of Preston Marina and over intertidal areas (typically sat on a fishing tackle box). Angling adjacent to the Becconsall boatyard has also been observed. Cefas estimate the mean occupancy rate for anglers over intertidal sediment to be 250 hour per year.

A5.4 Summary and Key Points

Background rates that should be subtracted from environmental monitoring studies, the relative contribution of operations at the Springfields site and the Sellafield site to doses, dose conversion factors and occupancy rates for use of areas around the estuary for angling, wildfowling or other recreational activities have been reviewed. Key points from this appendix include:

- use of a Ra-226 calibration coefficient is most appropriate for gamma dose rate in air monitoring in the Ribble;

- the background contribution from cosmic radiation was determined over a large body of water as 42 to 48 nGy hr^{-1}, higher than usually assumed. Based on activity concentrations from the base of a sediment core collected from the Savick Brook area, the terrestrial background rate indicative of pre-nuclear operations is around 30 nGy hr^{-1}. This value is dependent upon soil moisture content and may not be fully applicable across all sites around the Ribble. Nonetheless, the use of the value of 70 nGy hr^{-1} to represent total background over soil and sediment in statutory monitoring programmes is considered acceptable, and it should be clearly stated that this relates to terrestrial and cosmic background. Using this value to represent background within a houseboat situated up near the high water mark is not considered appropriate because the boat hull shields a proportion of the terrestrial contribution to the dose rate. In this instance a value of between 50 to 60 nGy hr^{-1} may be appropriate. Where a boat sits in a channel that is inundated during each tide, the background rate will be much lower and at high water may just be restricted to cosmic contributions;

- the respective contribution to the external dose rate arising from discharges from the Sellafield site and the Springfields site varies significantly depending upon location. Over intertidal sediment in Savick Brook the contribution from each is roughly equal, at other locations it appears to be dominated by Cs-137 discharged from the Sellafield site;

- the dose conversion value of 0.85 Sv Gy^{-1} is considered appropriate for ROT geometry types of exposure. However, it is not considered appropriate when an individual is lying face-down on the sediment, in this case use of an AP geometry and a Sv Gy^{-1} value around 1 is more suitable. Calculation of geometries for seated positions has not been possible;

- typical mean occupancy rates in the estuary are 8,300 hours per year for houseboat dwellers, 390 hours per year for wildfowlers and 250 hours per year for anglers. For wildfowlers and anglers much of this time is spent sitting close to, or lying over sediment, but no data currently exists of the proportion of time spent in each position.

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