External Exposure from Contaminated Marine Sediment: Lessons Learnt for Dose Assessment and Site Management – 10529

Dr Adrian Punt
AMEC Earth & Environmental (UK)

ABSTRACT

Engineering works, dredging, even coastal erosion can expose sediments that have been contaminated by historic operations from nuclear sites and may lead to increased radiological exposure of members of the public. Monitoring programmes of levels of radioactivity in coastal sediment and associated external radiation exposure can be complicated by high degrees of both temporal and spatial heterogeneity. This is in part due to the influence of tidal processes on sediment supply and distribution, extent of tidal inundation and shielding of sediment, but also the habits and means of exposure of the public. Understanding the risk this contamination posses can therefore be difficult, particularly if long term monitoring isn't available. Hence, design of appropriate mitigation measures or of monitoring programmes to further evaluate the issues are difficult.

This work involved a detailed programme of external dose rate measurements in a coastal site influenced by both nuclear fuel production and reprocessing operations and has developed a detailed understanding of how tidal processes affect both temporal and spatial heterogeneity of external exposure in a range of different site settings. The implications for management and assessment of contaminated coastal sites and the lessons learnt, particularly with regard to statutory monitoring programmes are discussed.

INTRODUCTION

The Environment Agency of England and Wales (UK) has a statutory responsibility to assess and authorise discharges of radioactivity to the environment under the Radioactive Substances Act (1993). As part of this commitment, the Environment Agency undertakes routine monitoring around nuclear licensed sites in England and Wales. They also contribute to a broader programme of UK wide environmental agencies assessing and subsequently authorising discharges from existing or proposed nuclear licensed sites, or other regulated facilities, to ensure protection of the public and the environment.

The Ribble Estuary in north-west England (Figure 1) receives liquid radioactive effluents, which are discharged under Environment Agency authorisation, from the Springfields Fuels Limited Site, a nuclear licensed site located to the north of the estuary. This site is owned by the Nuclear Decommissioning Authority (NDA) and managed by Westinghouse Electric UK Ltd on their behalf. The facility fabricates a range of uranium fuel products for existing nuclear power stations. The sites operation may also be extended to support the fuel needs for prospective new nuclear build in England and Wales. In 2006, the Springfields 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 from the site, were significantly reduced.

In addition to Springfield's discharges to the Ribble estuary, some of the radioactivity discharged to the Irish Sea from nuclear fuel reprocessing at the Sellafield Ltd Site, formerly operated by BNFL, about 100 km due north, has been transported southward down the coast and has entered the estuary . The radionuclides include caesium-137 (Cs-137), cobalt-60 (Co-60) and americium-241 (Am-241), which have arisen from nuclear fuel reprocessing. Over recent years significant abatement processes have been implemented and discharges are now significantly lower.

Some of the radionuclides discharged from Springfields (primarily isotopes of thorium, uranium and their decay products) or Sellafield sites (particularly, Co-60; Cs-137; and, Am-241) have a tendency to bind with sedimentary particles, particularly in turbid estuarine conditions and 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 saltmarsh 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 UK Food Standards Agency and are reported annually in the 'Radioactivity in Food and the Environment' (RIFE) series.

The RIFE report identifies that houseboat dwellers, wildfowlers and farmers who spend large amounts of time over the saltmarshes of the Ribble, are the most exposed individuals in the area. For these individuals, the 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 is hence influenced to different degrees by discharges from the Springfields and Sellafield Sites.

In 2006, the RIFE 12 report estimated that the annual dose to high-occupancy houseboat dwellers in the Ribble Estuary was 0.075 milli-sieverts (mSv), less than 10% of the Public Dose Limit of 1 mSv. This was higher than in the previous year (estimated as 0.037 mSv) because updated information was available, both on the habits of houseboat owners and from additional measurements on board a houseboat . The extent of these new measurements was however limited.

These assessments 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, the depth of 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 appropriate.

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 the assessment methods from time to time. This study has therefore taken into account habits and usage of the areas, changes in the nuclides present and the beta and gamma dose rates from the mud in the estuary and that associated with historic deposits on adjacent saltmarsh areas. The study has taken into account the need for a consistent and robust approach based on a transparent and soundly based methodology.

OBJECTIVE

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

- Elucidating how estuary bank geometry combined with tidal water level, affect the observed radionuclide dependent gamma dose rate in air (Air Kerma) measurement observed in boats, and how the combination of occupancy and tidal cycles affect the absorbed (effective) dose rates;

- Identifying the key radionuclides affecting the beta/gamma external doses over sediment and how these dose rates vary with activity concentration within sediment and 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 whether someone is standing, sitting, crouching or lying prostrate, affect their 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; and,

- Providing recommendations for the approaches to calculation of external exposure at other coastal sites.

METHODS

A monitoring and sampling campaign was implemented to measure external beta and gamma dose rates at a number of points around the estuary (including on and around houseboats) to assess how these varied with tidal inundation, height over sediment and distance to the bank.

Standard instruments used in routine monitoring programmes 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 also 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 m).

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 (on the north of the estuary). The field sites visited are shown in Figure 1.

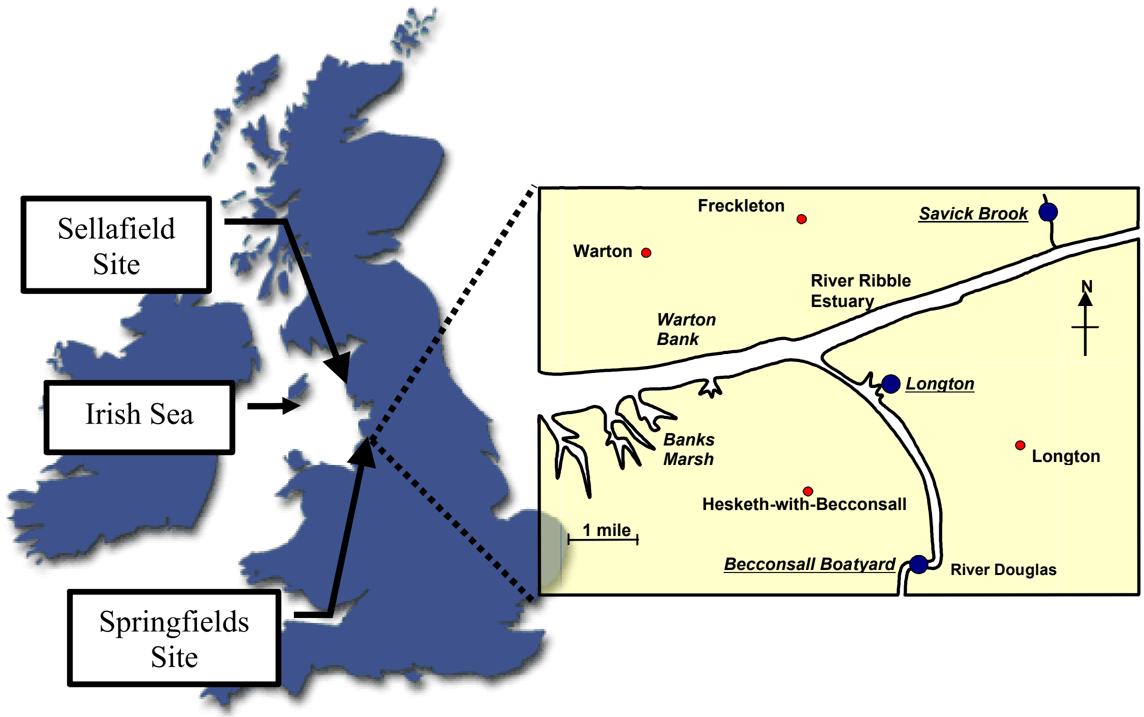

Fig. 1. Monitoring site locations and overall position relative to Sellafield and Springfields sites

At each location the following measurements were taken:

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

- Gamma dose rate in air (nGy per hr) was measured at 0.25 m, 0.5 m and 1 m over the sediment surface and in houseboats 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 both over intertidal sediment and at various distances from intertidal sediment up the bank edge and onto adjacent saltmarsh. 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 also undertaken using both 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 trails of standard beta dose rate instruments (the RADEYE and SMARTION instruments provided by Thermo Scientific) showed that they lacked sufficient sensitivity for this work. 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 (100 cm^2), coupled to a digital ratemeter. A 12 mm Perspex shield was constructed to shield out any beta emissions and hence enable the gamma contribution to the instrument to be established. The instrument was calibrated by Nuvia Ltd. Measurements were made at various distances (0.01 m; 0.05 m; 0.15 m; 0.5 m; and, 1 m) from the sediment surface and the shielding effects of a range of clothing materials were also assessed.

At the boatyard in-situ gamma spectrometry and gamma dose rate in air, on and around three boats, was also measured repeatedly 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 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 was around 3 m above the level of the adjacent saltmarsh at low water. This boat was birthed for the winter months and represents a potential for seasonal (e.g. six month) occupancy; and,

- **Boat 3** – a small, flat bottomed, fibre glass 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 on bed and channel sides with the inundating tide. At high water the area within the boat was approximately level with that of the adjacent saltmarsh. This was a small boat, unsuitable for living 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 compared to in-situ gamma spectrometry measurements, was found to over predict the gamma dose rate in air by 30%. Reported values have all been corrected for the contribution from intrinsic and cosmic radiation (a total of ca. 60 nGy hr^{-1}). Gamma dose rate in air values quoted are however inclusive of naturally occurring radionuclides in the sediment and those which may be derived or enhanced by anthropogenic activities.

In-situ gamma spectrometry has then been used to determine the respective contribution from naturally occurring, Springfields enhanced and Sellafield derived radionuclides in the sediment and site specific back-ground rates derived for naturally occurring levels of radionuclides (ca. 30 nGy hr^{-1}). This terrestrial background rate has been subtracted as part of the Dose Equivalent calculation.

RESULTS – POTENTIAL EXPOSURE RATES

The results of the study are described in this Chapter. 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.

HOUSEBOAT DWELLERS

As stated previously, three boats were surveyed in or next to a tidal channel adjacent to the Becconsall Boatyard. This aimed to assess the likely levels of external exposure under different potential houseboat use scenarios and summary results are set out below.

Sediment Activity Concentrations

In sediments around the boats at Becconsall Boatyard, 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 (maximum concentrations in the channel bed sediment were up to around 1,000 Bg kg^{-1} dry weight). Those on higher areas of the bank were of the order of a 100 Bq kg^{-1} dry weight[1]. 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.

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) on the bank edge, over intertidal sediment and within the boats are given in Table 1. The within boat measurements 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.

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

Gamma dose rate in air, underneath the hulls of the vessels studied, ranged from 40 to 50 nGy hr^{-1}. In all instances, the gamma dose rate in air in the 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 between above and below deck measurements.

Within a houseboat, particularly that moored in a tidal channel, the concept of a planar source of gamma radiation from the bed sediment, that is in some way 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 emitters not just in the sediment under the boat, but also on the channel sides or adjacent saltmarsh which may flank the boat on either side.

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

Boat	Average Gamma dose rate in Air (nGy hr^{-1})				Gamma dose rate Ratios		
	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 h^{r-1}) subtracted, but include terrestrial background. To calculate the gamma dose rate in air due to anthropogenic activities subtraction of a dose rate of 30 nGy h^{-1} is recommended.

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 appear applicable across a broad range of tidal conditions. Low water dose rates in the boat were 40 to 60% 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, and derived from multiple points within the boat, was 11 nGy hr^{-1} (i.e. around 30% of the low water value). Low water dose rates in the boat were about 75% of those over sediment; and,

- 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, (i.e. about 50% of the low water value). Low water dose rates in the boat were comparable to those measured over sediment.

Primary Contributors to the Gamma Dose Rate

In-situ gamma spectrometry within boats or over surrounding soils and sediments determined 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 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 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 (less than 1% 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 position relative to any bank areas (lower gamma dose rate in air measurements were found on the larger boat particularly when elevated both up of the sediment and above and away from the adjacent channel sides).

Beta Skin Dose

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

ANGLERS & WILDFOWLERS

Sediment samples and beta and gamma dose rate measurements on saltmarshes and bank edges were taken at Longton Marsh near to the east side of the River Douglas and in the tidal reaches of Savick Brook to assess variation of exposure with distance from channel edge, height over sediment and shielding by different clothing materials[2].

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, ranging by up to two orders of magnitude in this instance. 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. The ranges measured also differed significantly between the two sites, with those in Savick Brook (just up stream of the Springfields Fuels Ltd site) being the 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 each. 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 historic levels which pre-date UK nuclear industry activities.

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

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 was potentially due to reduction in the instrument field of view when lowered down, but 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 saltmarsh upon which sediment and radioactivity has also been sequestered.

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 historic sediments with higher activity concentrations). Equally exposure immediately adjacent to a fully inundated area may be 30% lower than measurements made at low water. This affect is however relatively localised (within about 5 m of the waters edge).

Further gamma dose rate measurements were made in dug-out hide pits on Longton Marsh. These pits are approximately 1 m by 1 m by 1 m. 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 surface 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.

Primary Contributors to Gamma Dose Rate

In-situ gamma spectrometry over sediment and saltmarsh 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 presented for Becconsall Boatyard. The contribution from excess Th-234 and Pa-234m (from discharges from the Springfields site) varied depending upon the site. At a maximum (at Savick Brook) this contributed around 10 to 15% of the observed gamma dose rate.

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

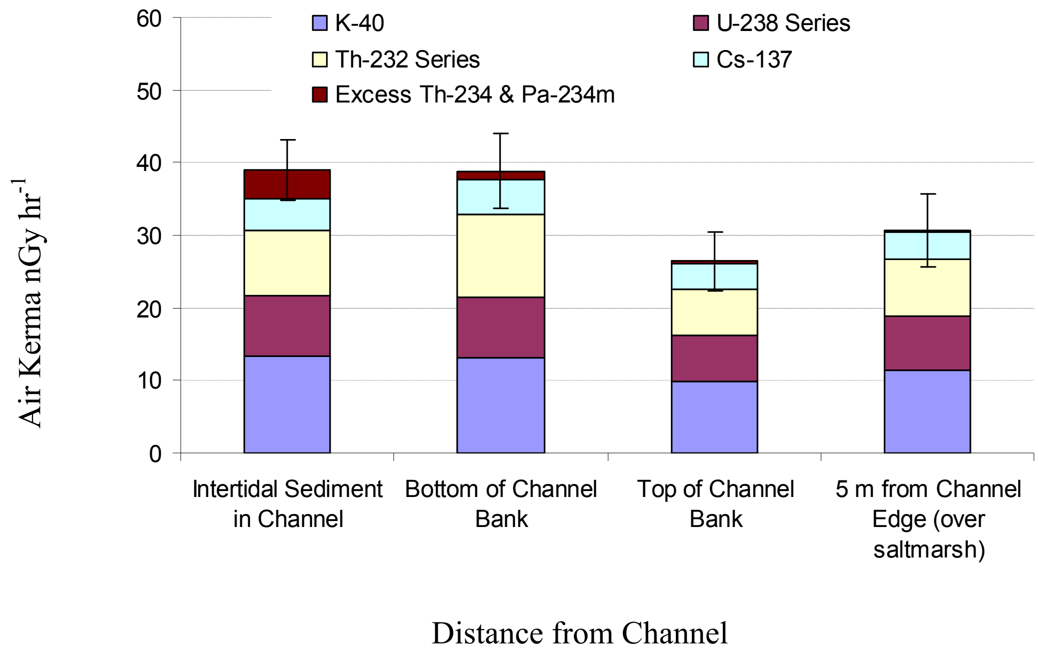

Figure 2: Air Kerma at Savick Brook (HPGe Detector)

Beta Skin Dose

Dose rates at a height of 0.01 cm above the intertidal sediment surface at Savick Brook were ca. 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 m above the sediment surface, and then decreased in a relatively linear fashion after that. At 1 m, beta skin dose was between 50% and 75% of that measured at 0.01 m.

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

Table 2 Beta Skin Dose Attenuation by Clothing

	Beta Skin Dose Rate Attenuation Factor	
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, but also 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% reduction in the measured beta skin dose, while that of thicker rubber boots resulted in an approximate 80 to 90% reduction.

BACKGROUND RATE SUBTRACTION

Cosmic background, determined over a large body of water was found to be between 42 and 48 nGy hr^{-1} a mean of 45 nGy hr^{-1}. A value of 60 nGy hr^{-1}, inclusive of intrinsic and cosmic background has been subtracted from all gamma dose rate in air measurements reported.

The terrestrial background from naturally occurring levels of radioactivity can be both site and substrate specific. Based on a single saltmarsh core collected from the area adjacent to Savick Brook, the contribution from natural levels of radioactivity in sediment has been calculated as ca. 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 and intrinsic background, e.g. 60 nGy hr^{-1}, appears to be appropriate (albeit slightly conservative).

Use of the 70 nGy hr^{-1} value may not however be appropriate in all situations. For measurements made in a boat, particularly one 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% 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 to wildfolwers, anglers etc, i.e. in any instance where there isn't a structure present that shields them from terrestrial sources of radiation.

GRAY TO SIEVERT CONVERSION

Calculation of the Dose Equivalent in terms of sieverts (Sv) from gamma dose rate in air measurements depends upon the geometry of exposure and the energy of emissions of radionuclides in the sediment.

Two exposure geometries have been considered, the Anterior-Posterior (AP) geometry applicable to when a person is lying face down on the sediment and the Rotational (ROT) geometry when 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 the one typically applied to gamma dose rate in air measurements made at 1 m 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 1 m) 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 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 of 1.1 is more appropriate and again should be applied to measurements made at 1 m 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. Hence the dose rate measured may have been more influenced by adjacent sediment deposits, not just those directly below the instrument.

ASSESSMENT OF DOSE EQUIVALENT

As discussed in this report there are a number of variables that may influence the dose (in terms of Dose Equivalent) that a member of the public may receive around the Ribble Estuary. It is also important to note insufficient data on site specific habits of these people exist to fully assess the ranges of actual exposure. Therefore five main hypothetical exposure situations have been derived in an attempt to illustrate the variability that exists. These relate to the three boats studied, an angler and a wildfowler. This is described below.

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

$$H_E = D_S - D_B * R * T * G \qquad \text{(Eq. 1)}$$

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 (unit less);
- T — Ratio between gamma dose in air at low water to that integrated over a tidal cycle (unit less); and,
- G — Conversion factor between Gy to Sv (Sv Gy^{-1}).

Annual exposure, A_E (µSv yr^{-1}) has been calculated by multiplying the predicted hourly Dose Equivalent by the anticipated annual exposure period, E_P (hr yr^{-1}). A factor of 1,000 is used to convert nSv to µSv. See Equation 2:

$$A_E = A_E * E_P / 1,000 \qquad \text{(Eq. 2)}$$

The results for the scenarios considered discussed below and summarised in Table 3 and discussed below.

Table 3 Dose Assessment Results for Scenarios Considered

Exposure Scenario	Posture	D_S (nGy hr^{-1})	D_B (nGy hr^{-1})	R	T	Geo-metry	G (Sv Gy^{-1})	H_E (nGy hr^{-1})	E_P (hr yr^{-1})	H_E (µSv yr^{-1})
1. Houseboat 1	N/A	50	30	0.5	1	ROT	0.85	8.5	8,300	70
2. Houseboat 2	N/A	40	30	0.75	0.3	ROT	0.85	1.9	4,150	8.0
3. Boat 3	Sat in boat	40	30	1	0.5	ROT	0.85	4.3	12	0.1
4. Angler	Sat (exposed channel)	55	30	N/A	N/A	ROT	0.85	21	125	3.2
	Sat (inundated channel)	35	30	N/A	N/A	ROT	0.85	4.3	125	
5. Wildfowler	Lying face down	55	30	N/A	N/A	AP	1.1	28	185	13
	Standing	35	30	N/A	N/A	ROT	0.85	4.3	98	
	Standing in pit	116	30	N/A	N/A	ROT	0.85	73	98	

Scenario 1 represents a houseboat situated up near the very extreme of the tidal limit where the residents are occupant virtually all of the time throughout a full year. Gamma dose rate in air under the boat is around 50 nGy hr^{-1} (30 nGy hr^{-1} assumed to be from natural levels of radionuclides) and that, averaged across different areas within the boat at low water, is about half of this. The effect of typical tidal variations are negligible and a ROT geometry applied. Under this scenario the Dose Equivalent due to anthropogenic sources of radioactivity is 8.5 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 ca. 70 µSv yr^{-1}, less than 10% of the UK Public Dose Limit.

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

Scenario 3 represents a small boat (potentially out on a fishing trip), that remains at one locality within a channel area over a full tidal cycle (ca. 12 hours) such that the boat is for a proportion of the time afloat and for a proportion of the time resting on sediment. Gamma dose rate in air under the boat is around 40 nGy hr^{-1} (30 nGy hr^{-1} assumed to be from natural levels of radionuclides) and that 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% of that at low water and a ROT geometry applied. Under this scenario the Dose Equivalent due to anthropogenic sources of radioactivity is 4.3 nSv hr^{-1}. The resulting dose over the 12 hour period is ca. 0.1 µSv yr^{-1}, around 0.01% of the Public Dose Limit.

Scenario 4 is applicable to an angler who spends time immediately adjacent to a channel sitting or standing over intertidal or saltmarsh sediment. Their total annual occupancy is assumed to be 250 hours per year based on local habit observations. However, this data dose not provide a breakdown of activities within this overall period. It has therefore been assumed that 50% of the time (125 hours per year) is located on a mid bank terrace, over a range of tidal conditions other than high water, such that higher dose rates (ca. 55 nGy hr^{-1}) are received. The other 50% of the time (125 hours per year) is assumed to be at the top of the bank adjacent to a fully inundated channel (when the dose rates are lower, ca. 35 nGy hr^{-1}). In each instance 30 nGy hr^{-1} is assumed to be from natural levels of radionuclides and a ROT geometry applied. Under this scenario the Dose Equivalent 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 over the total exposure period is ca. 3 μSv yr-1, less than 1% of the Public Dose Limit.

Scenario 5 is applicable to a wildfowler who spends time over saltmarsh sediment. Their total annual occupancy is assumed to be 390 hours per year based on local habit data. As noted in Scenario 4, habit data dose not provide a breakdown of activities within this overall period. It has therefore been assumed that of this period 50% of the time (185 hours per year) is assumed to be lying down on the saltmarsh surface (particularly on bank sides) where dose rates may be higher e.g. ca. 55 nGy hr^{-1}. Of the remaining time, 25% (98 hours per year) is assumed to be walking or standing over areas of lower dose rate sediment (ca. 35 nGy hr^{-1}) and the remaining 25% within the unlined hide pit where doses measured where significantly higher (116 nGy hr^{-1}). In each instance 30 nGy hr^{-1} is assumed to be from natural levels of radionuclides. A ROT geometry is applied to standing positions (over saltmarsh and within the pit) and an AP geometry to time spent lying, face down, on the sediment. Under this scenario the Dose Equivalent 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 ca. 13 μSv yr^{-1}, around 1% of the Public Dose Limit.

CONCLUSIONS AND LESSONS LEARNT

In summary, three sites in the Ribble Estuary were subject to a detailed regime of measurements and sample collection which included 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 and 66 soil or sediment samples for gamma spectrometry.

This study confirmed the findings reported by the Environment Agency in their statutory monitoring programmes and that the use of a Ra-226 calibration for gamma instrumentation is most appropriate for use in the Ribble. It has also 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. However, the introduction of an AP geometry for calculation of the Dose Equivalent for the time that wildfowlers spend lying down is recommended. The work has shown that external exposure, particularly from gamma radiation, can be both temporarily and spatially variable, responding to state of the tide, bank topography and heterogeneity of sediment deposits (both recently deposited sediments and the longer term process of saltmarsh accumulation).

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

The ratio between gamma dose rate in air measured over sediment and 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% attenuation) for a medium sized vessel adjacent to a channel on a relatively flat area. Shielding by the boat hull clearly influences the dose rate in the boat, but the geometry of exposure is also important, particularly where the boat, at low water, sits at the base of a steep sided channel. In this instance gamma emissions from sediment on the bank sides may contribute to the dose rate measured. In this instance 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 a gamma dose rate in air measured at low water in a houseboat compared to that integrated across a range of tidal conditions, can vary depending upon where the boat is situated with respect to the tidal limit. This work has shown that for one boat assessed, a boat ‘dry docked’ towards the limit of tidal inundation, this ratio was around 1, i.e. for the purpose of dose assessments there was affectively no shielding by tidal flood waters apart from extreme tidal conditions which are very limited. Within the tidal channel where Boats 2 and 3 were survived, the ratio varied from 0.5 (a small boat) to 0.3 (a larger boat). In this instance the difference arose due to the size of the boat and the position respective to not just the bed sediment, but also 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 berths, where the underlying sediment is only exposed under more limited tidal conditions, the respective ratios are likely to be lower.

The discussion above hopefully illustrates the importance that should be placed on not just consistency in monitoring position, but also timing with respect to state of tide and the need to carefully record and clearly report on when measurements were made. A number of areas of uncertainty also exist:

- The extent and causes of localised heterogeneity in the gamma exposure field on bank areas remains uncertain and 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 from Springfields discharges 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 is uncertain, as are the appropriate assessment methods that should be applied in statutory monitoring programmes to represent this.

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