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The measurement of beta dose and gamma air kerma rates in the Ribble Estuary

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Abstract. As a by-product of the fabrication of uranium fuels, BNFL, Springfields are authorised to discharge beta emitting radionuclides, principally ^{234m}Pa into the Ribble Estuary. The accumulation of ^{234m}Pa in the estuarine sediments leads to enhanced beta dose rates not seen elsewhere in the UK. The methods used to determine the beta dose rate and calculate organ and effective doses are presented. The variation in beta dose and gamma air kerma rates in a small area were investigated and recommendations are made as to the number of replicates needed to reduce the error to $\sim 10\%$ of the mean. An example of the dose to a walker on the intertidal areas of the Ribble Estuary is calculated by the detailed methods. The effective dose was $73 \mu\text{Sv a}^{-1}$, of which 86% was derived from gamma irradiation. Doses to hands contaminated by estuarine sediments are also low ($0.004 \mu\text{Sv h}^{-1}$).

1. Introduction

British Nuclear Fuels plc (BNFL) operate a uranium fuel fabrication plant at Springfields, Lancashire. The company are authorised to discharge radionuclides arising from the purification of uranium ore concentrates to the nearby Ribble Estuary. These are principally naturally occurring radionuclides, however, small amounts of artificial radionuclides which are discharged from the utilisation of reprocessed uranium supplied by BNFL, Sellafield can also be present. As part of a radiological assessment of the Ribble Estuary, beta dose and gamma air kerma rates as well as surface sediment samples were taken at a number of sites. Details of the surface distribution of radionuclides can be found elsewhere (Assinder *et al* 1996) as well as the results of dose rate measurements, habit surveys and the calculation of whole body (effective) doses to users of the Ribble Estuary (Mudge *et al* 1996b). A further paper (Mudge *et al* 1996a) covers the dynamics of sediment redistribution. This paper covers the dosimetry used to calculate

the doses. In all cases only the external irradiation pathways are considered.

1.1. Origin of beta dose and total air kerma rates in the Ribble Estuary

The beta dose and total air kerma rates measured at any point in the estuary are derived from several natural and anthropogenic sources. These include:

1.1.1. Cosmic rays. These are derived from particle interactions in the upper atmosphere and the rate at which they impinge on the earth's surface will depend upon the weather, sunspot activity, earth-sun orientation (season) and altitude. Over the area of the estuary, the contribution from cosmic rays to the total air kerma rate is not expected to vary significantly. Small temporal differences may be apparent (likely outdoor cosmic ray dose = 34 nSv h^{-1} , Hughes *et al* 1989).

1.1.2. Naturally occurring non-actinides. Some naturally occurring radionuclides are beta and

gamma emitters, e.g. ^{40}K , and will make a contribution to the measured dose. The magnitude of this component will be dependent upon the mineralogy of the soils and rocks at any one location and the local application of potassium containing fertilisers.

1.1.3. Naturally occurring uranium and thorium series radionuclides. Uranium and thorium present since the origin of the earth occur in rocks and soils of the catchment (for more details see Mudge *et al* 1994a). Within the ^{238}U , ^{235}U and ^{232}Th decay series are a number of gamma emitters, e.g. ^{214}Pb , ^{214}Bi , ^{212}Pb , ^{228}Ac and ^{227}Ac , and these make a contribution to the total gamma dose. The major basement geological units of the Ribble catchment (Carboniferous Limestone), however, are relatively low in these radionuclides. Since the overlying soils are produced from these rocks, it is expected that they will have similar uranium and thorium content. Uranium is often associated with phosphate minerals and fertilisers containing phosphate sometimes have a high uranium content. The application of fertilisers varies widely throughout the estuary (McCaffery 1992). Beta emitters within the uranium and thorium decay series such as ^{214}Pb , $^{234\text{m}}\text{Pa}$ and ^{228}Ac will also make a small contribution to the measured beta dose.

1.1.4. Fallout radionuclides. Nuclear weapons testing during the 1950s and 1960s led to substantial amounts of radionuclides being deposited around the globe, especially in the northern hemisphere. The principal nuclide of interest is ^{137}Cs . The fallout over the estuary itself should be relatively even although a greater input will come from the catchment. Other events such as satellite burn-up and the Chernobyl accident have also led to increased radionuclide deposition (Cambray *et al* 1987).

1.1.5. Sellafield discharges. As part of the nuclear fuel cycle, reactor irradiated U fuel is reprocessed at Sellafield. During this process, some fission and activation products are discharged under licence to the Irish Sea. Oceanographic processes have led to a transportation of these radionuclides to the intertidal areas of the Ribble Estuary. The transfer time to the Ribble Estuary is such that

relatively short-lived radionuclides will have decayed to concentrations below detection limits before reaching the estuary. The principal radionuclides from Sellafield likely to be in the Ribble Estuary are ^{137}Cs , $^{238,239,240}\text{Pu}$ and ^{241}Am . The activity concentrations of these radionuclides in the Ribble Estuary are presented in Assinder *et al* (1996).

1.1.6. Springfields discharges. During fabrication of U fuels at Springfields, some uranium and thorium as well as their daughters are discharged to the Ribble Estuary. These radionuclides can be distinguished from the catchment derived uranium and thorium by use of their isotopic ratios (see Assinder *et al* 1996). The daughters of these radionuclides also make contributions to the total beta and gamma doses. Though principally a beta-emitter, $^{234\text{m}}\text{Pa}$ has a low branching ratio (0.013) to a range of energetic gamma emissions. Since the activity concentrations of $^{234\text{m}}\text{Pa}$ can exceed 1 MBq kg^{-1} , this can also make a substantial contribution to the gamma dose. There will also be a contribution from the gamma decay of ^{237}Np previously discharged. This only occurs when using Sellafield reprocessed uranium.

2. Dose rate measurements

The majority of the sites were identified on Ordnance Survey maps initially and were located using a Garmin GPS-100 Satellite Navigation System. Some sites were chosen while in the field. The location of these sites is shown elsewhere (Assinder *et al* 1996).

2.1. Beta and gamma measurement techniques

Gamma air kerma rates at a height of 1 m above the sediment were determined using a Mini Instruments 6-80 environmental monitor fitted with a vertically held gamma compensated G-M tube (MC71) calibrated against ^{226}Ra . The MC71 detector used with the Mini Instruments 6-80 is designed to measure the quantity of photon fluence and is calibrated in air kerma. This value can be converted to effective dose equivalent rate using the factor 0.86 Sv Gy^{-1} (air kerma)

which is appropriate for a person standing on a contaminated area (Clark *et al* 1993).

Beta dose rates were assessed using a Berthold LB1210B contamination monitor. This has an 11 cm square thin titanium windowed proportional counter. It was mounted on an open frame supported by thin aluminium legs at a height of 30 cm above the surface. The instrument responds to both beta and to a lesser extent gamma radiation. The count rate due to the beta radiation was determined by making two measurements, one with the detector unshielded and the other with the detector covered by 10 mm of perspex and 10 mm of aluminium. Subtracting the two average count rates generated a reasonable approximation to the beta only count rate as it was inevitable that some small proportion of the gamma radiation was attenuated in the cover. The long time constant available on the instrument was used to reduce statistical fluctuation. The characteristics of the instrument are discussed fully in Burgess and Iles (1981).

The instrument is scaled in counts per second and in order to determine the dose rate at a specific height above the sediment, a suitable calibration factor was determined using a set of NPL beta dose rate reference sources. Measurements were performed for the nuclide $^{90}\text{Sr}/^{90}\text{Y}$ for both normal incident radiation and for radiation incident at angles of 30° and 60° . The value of the calibration factor at normal incidence was taken as representative for radiation incident between 0° and 15° , at 30° for radiation incident between 15° and 45° , and at 60° for radiation incident between 45° and 75° . These values were weighted for the proportion of the solid angle from 0° to 75° . The net result was $32 \text{ counts s}^{-1}/(\mu\text{Sv h}^{-1})$ for the measurement of $H'(0.07)$, i.e. the skin dose equivalent rate.

The instrument was also used to determine the variation in dose rate with height.

There are inevitably uncertainties associated with this process as the instrument window is rather too thick leading to an under response for lower energies. It was chosen, however, because of its ease of use and robustness essential for work such as this. Use of a more radiologically accurate instrument such as one of the large thin windowed refillable proportional counters would, it was judged, have led to more failures.

2.2. Vertical surface corrections and variation with height

Radionuclide beta emissions in sediments are attenuated by the intervening air between the detector or organ and the source. The variation in dose rate with height for the instrument used is shown in figure 1. These readings were taken above an apparently uniform flat mud surface at least $5 \times 5 \text{ m}$.

The line shown in figure 1 is fitted from the following equation

$$I_x = I_0 e^{-\mu x}$$

where I_x is the calculated dose rate at x (cm) above the surface; I_0 is the calculated dose rate at the reference height (30 cm); μ is a factor describing the reduction in rate with height; and x is the height above the reference height (cm).

The value for μ for normal incidence $^{90}\text{Sr}/^{90}\text{Y}$ beta radiation is $3 \times 10^{-3} \text{ cm}^{-1}$ for air, based on the measured transmission of 1 cm of tissue of 0.04 (i.e. $H'(10)/H'(0.07)$) and allowing for the difference in density of 900 between air and tissue. The observed value was $9.4 \times 10^{-3} \text{ cm}^{-1}$ which agrees, given that the source is a large flat plane which means that the mean path length, weighted for the solid angle, will be two or three times the instrument height.

For vertical surfaces such as skin, a factor needs to be introduced since any particular area of the skin is only irradiated by half of the source. This can be accounted for by multiplying the dose rate by 0.5. For those people who tend to lie on the sediments (e.g. wildfowlers) only the lower surface of the body is irradiated. Hence, in the calculation of effective dose, the calculated skin dose rate is also to be multiplied by 0.5

2.3. Transmission factors

The shielding induced by different types of clothing expected to be worn while engaging in various outdoor activities were determined by *in situ* measurements. Sections of clothing including part of a wellington boot, at least $30 \text{ cm} \times 30 \text{ cm}$, were placed directly on contaminated sediments. The LB1210B was placed 0.5 cm above the fabric and the dose rate recorded. The

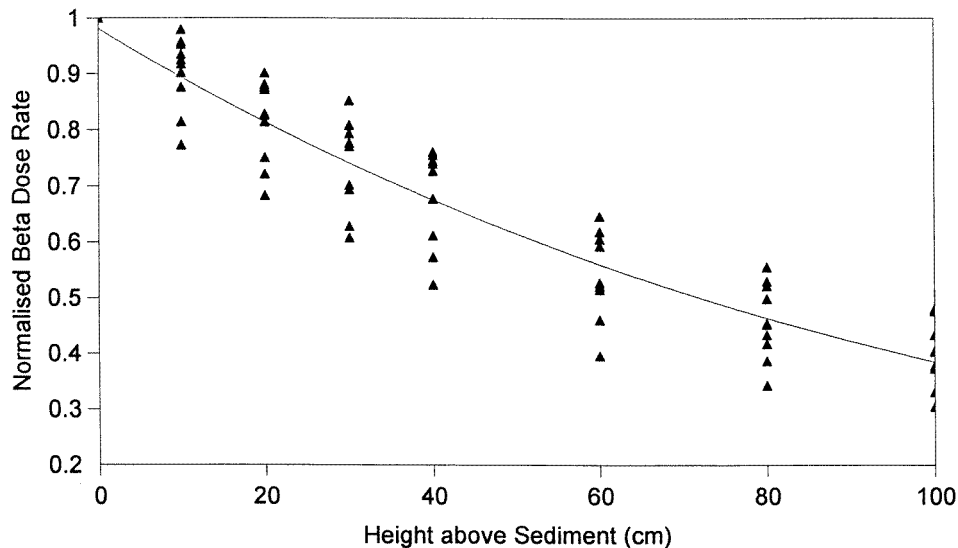


Figure 1. Variation in beta dose rate with height above the sediment.

Table 1. Transmission factors appropriate to the Ribble Estuary.

| Shielding type | Transmission factor |
|-------------------------------|---------------------|
| Waterproofs (PU nylon) | 0.94 |
| Cotton (T-shirt or underwear) | 0.99 |
| Heavy cotton jeans | 0.83 |
| Wellington boots | 0.23 |
| Fisherman's tackle boxes | 0.24 |

ratio between shielded and unshielded beta counts was used as a transmission factor (see table 1). This methodology is potentially better than that employed by Hunt (1992) who measured the density of the material; this does not account for the porosity of the fabric. The transmission factor for fishing tackle boxes was measured at the top of the box with and without it in position over the sediments.

2.4. Energy deposition into perspex—dose to testes and eyes

The energy deposition into various organs was accounted for by measuring the attenuation of the beta dose rate through known thicknesses of perspex sheeting. Layers of perspex, 1–2 mm

thick, were placed between the sediment and the detector. This was repeated at four sites of different surface activity concentrations and the decrease in normalised dose rate is presented in figure 2.

The fitted line to the data in figure 2 is derived from the following equation:

$$\text{Normalised beta count rate} = \frac{1}{1 + \gamma(\text{shield}^\delta)}$$

where: *shield* is the mass per unit area of the shielding in g cm^{-2} ; and γ and δ are constants which describe the rate of attenuation. γ is a scaling factor which accounts for the thickness and δ is a measure of the attenuating properties of the material.

The constants were fitted using a non-linear regression based on the Marquardt algorithm (Nash 1979). The values for each of the parameters is shown in table 2 together with the correlation coefficient.

The 11 data sets ($n = 213$) measured at a range of unshielded count rates ($53\text{--}1210 \text{ counts s}^{-1}$) all describe a similar curve and the combined results are shown above. This independence of the attenuation on the initial count rate indicates that the differences measured in the dose rate are due to differences in activity concentration per unit

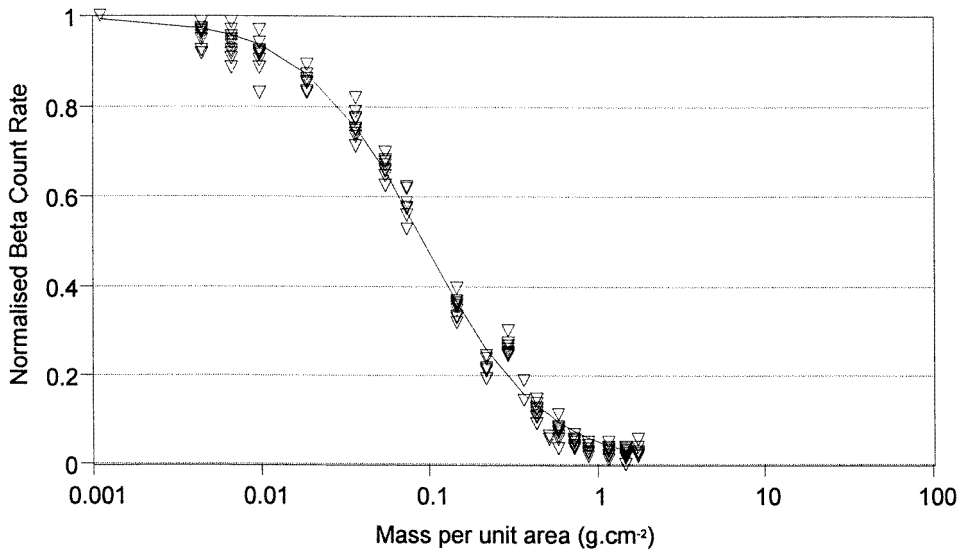


Figure 2. Reduction in normalised beta count rate with increased mass per unit area of perspex between the source mud and the detector. Eleven data sets were taken at different sites in the Ribble Estuary ($n = 213$).

Table 2. Parameters describing the equations of the lines in figure 2.

| Parameter | |
|------------------|-------|
| γ | 17.51 |
| δ | 1.21 |
| number of points | 213 |
| R^2 | 0.98 |

area rather than variation in activity with depth in the sediment.

Hunt (1992) uses a dose reduction factor for the testes of 0.02. This incorporates energy deposition into approximately 100 mg cm^{-2} of clothing and an average tissue layer of $2.2 \pm 0.6 \text{ mm}$. The factor for unshielded testes would be 0.03 (from table 2 in Hunt 1992) equivalent to approximately 250 mg cm^{-2} . This factor is low because the dose is averaged throughout the testes, some parts of which would not be irradiated. This effect is much greater than the dose rate reduction produced by the clothing. In subsequent calculations we have used the 0.03 factor and modified the dose rate according to the clothing worn by people using the estuary.

For doses to the eye, the dose rate, corrected for height (1.5 m above the sediment) and vertical orientation, is multiplied by a factor of 0.4. This

allows for attenuation by the outer layers (Hunt 1992).

2.5. Gamma response of the Berthold in a high beta field

The response of the Berthold LB1210B to gamma and beta radiation is not the same as the Mini Instruments 6-80. Figure 3 clearly indicates this difference, especially when the beta count rate is high. The contaminants present emit both penetrating gamma radiation and low energy (17–100 keV) x-radiation. The Berthold instrument has a non-dosimetric response in that the count rate per unit air kerma rate increases rapidly as the radiation energy reduces. In contrast the MC71 probe has a response which is effectively independent of energy down to approximately 60 keV. The lower energy x-radiation is significantly attenuated with 1 cm of mud absorbing approximately 99% of the 20 keV radiation i.e. it is not much more penetrating than the beta emissions from $^{234\text{m}}\text{Pa}$. Situations where there is a high activity concentration of $^{234\text{m}}\text{Pa}$ on surface sediment will also generate a relatively high x- and γ -count rate from the Berthold instrument compared with that of the MC71.

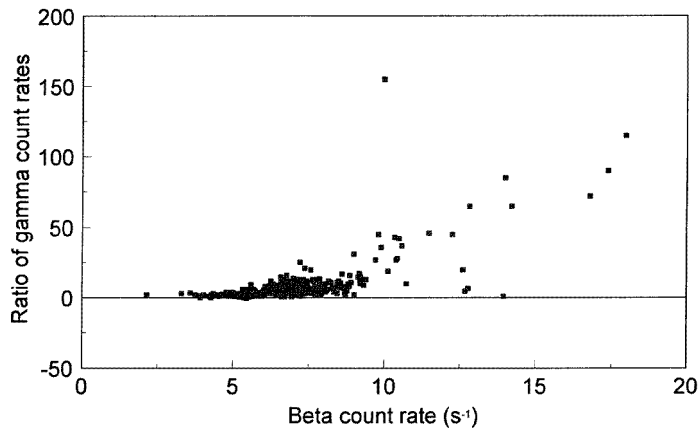


Figure 3. The ratio of the gamma count rates (Berthold/MC71—background rate) plotted with the recorded beta count rate from the Berthold.

2.6. Dose to hands from mud contamination

Some of the activities undertaken on or near the Ribble Estuary can lead to the contamination of the skin, especially the hands, with mud. Such activities include fishing and children playing in the intertidal zone. The presence of the radionuclides in the mud can produce a dose to the body. An example of the likely maximum dose for children playing at Penwortham in the intertidal sediments is produced below using the maximum measured activity concentrations.

The dose to skin (D_{skin}) from mud contaminating their surface is calculated by the following equation:

$$D_{\text{skin}} = tC\rho l(d_{\beta} + d_{\gamma})$$

where t is the time the hands are contaminated (h); C is the activity concentration of the mud (Bq g^{-1}); ρ is the density of the mud (1.3 g cm^{-3}); l is the thickness of the layer of mud on the hands (assumed to be 10^{-2} cm); d_{β} is the skin dose equivalent rate to the basal layer of epidermis for beta irradiation e.g. $2.40 \times 10^{-6} \text{ Sv h}^{-1}$ per Bq cm^{-2} for $^{234\text{m}}\text{Pa}$ assuming a skin depth of 7 mg cm^{-2} (Kocher and Eckermann 1987); and d_{γ} is the skin dose equivalent rate to the basal layer of epidermis for gamma irradiation e.g. $7.0 \times 10^{-10} \text{ Sv h}^{-1}$ per Bq cm^{-2} for $^{234\text{m}}\text{Pa}$ assuming skin depth of 7 mg cm^{-2} (Chaptinel *et al* 1988 and NRPB calculations (Mayall, personal communication)).

It is assumed that the area of the hands is 600 cm^2 and the surface area of the whole body is $17\,000 \text{ cm}^2$. This proportion together with the tissue weighting factor of 0.01 for the skin is used to calculate the dose from such contamination in accordance with the recommendations in ICRP publication 60.

2.7. Intensive survey at one site

The homogeneity of the beta dose and gamma air kerma rates measured at 30 cm and 1 m above the sediments was assessed at one location in the main channel opposite the Springfield discharge pipe. The area chosen was 12 m wide and extended for 100 m along the side of the River Ribble main channel. The area closest to the river channel was mud and the area furthest away was an emergent salt marsh. The variation of the beta dose and gamma air kerma rates measured at 40 and 20 points respectively within the area are shown in figures 4 and 5.

Comparison of these two plots with the grain size distribution shows no obvious correlation. This is also true to a lesser extent throughout the whole estuary. In order to use the information from this small scale survey as a predictor for the likely confidence that can be placed on individual results, certain pre-conditions need to be met.

In general, statistical tests on field results require the data to be normally distributed. If this condition is not met, only non-parametric tests can

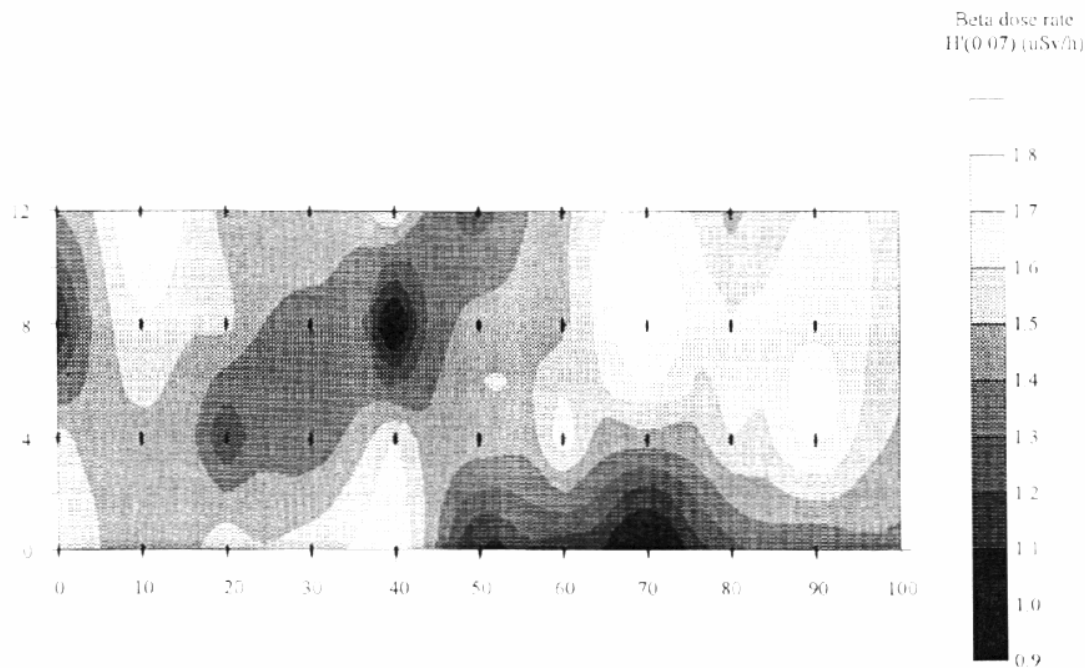


Figure 4. Spatial variation of the beta dose rate assessed at 30 cm above the sediment surface within the small scale survey area. The spatial coordinates are in metres with the river running parallel to the top edge. The upstream direction is with increasing x values.

be conducted. Statistical testing indicates that the small scale gamma data are normally distributed and the beta dose rate data are not (see figure 6A and 7A). The non-normal distribution of the beta dose rate may be attributed to the accumulation of high activity muds from recent Springfields' discharges in micro-topographic structures, e.g. hollows on the sediment surface (McKay *et al* 1992). The summary statistics for this survey is presented in table 3.

The same treatments can be applied to the data for all sites throughout the estuary although there is no reason why these data should be normally distributed. Plots of the gamma air kerma rate do indicate an approximation to a normal distribution (figure 6B), however, the beta dose rate data is strongly skewed towards high values (figure 7B). This reflects the accumulations of high activity sediments especially in Savick Brook and Penwortham. The summary statistics for all the estuarine sites is also shown in table 3.

The variances of both the beta dose and gamma air kerma rates between the small scale and full

survey are significantly different ($P < 0.001$). This implies that the variation in these rates throughout the estuary is greater than the variation at a single sampling site and that measurements taken at different sites could have come from statistically different populations.

Neither the beta nor gamma data show a significant variation with grain size ($\% < 63 \mu\text{m}$) due to the wide range of sites sampled within the estuary. Some areas, e.g. Savick Brook have fine grained sediment contaminated with both Springfields and Sellafield discharged radionuclides. Other areas of fine grained sediment accumulation, e.g. Beconsall have fine grained sediments that are relatively less contaminated. All high rates occur in areas of fine grained sediment accumulation although not all areas of fine grained sediments have high rates.

Using the summary statistics for the dose rates both on the small scale and throughout the estuary, it is possible to calculate the coefficient of variation for each data set (table 4). As expected, the greatest variation is within the beta dose rate

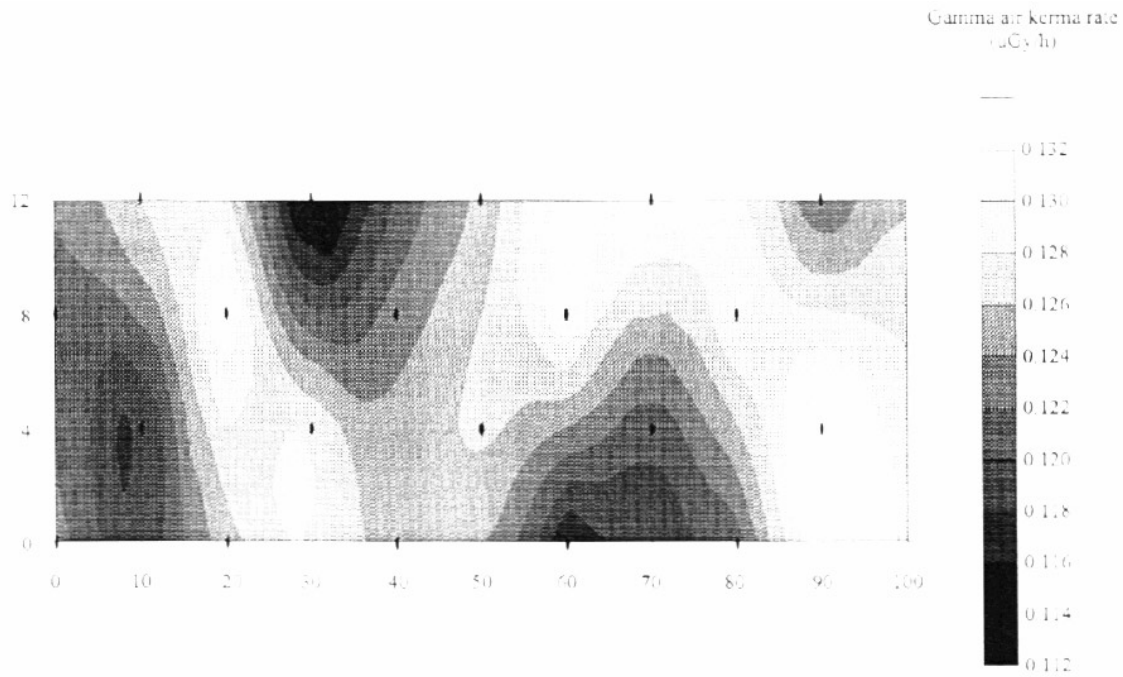


Figure 5. Spatial variation of the gamma air kerma rate assessed at 1 m above the sediment surface within the small scale survey area. The spatial coordinates are in metres with the river running parallel to the top edge. The upstream direction is with increasing x values.

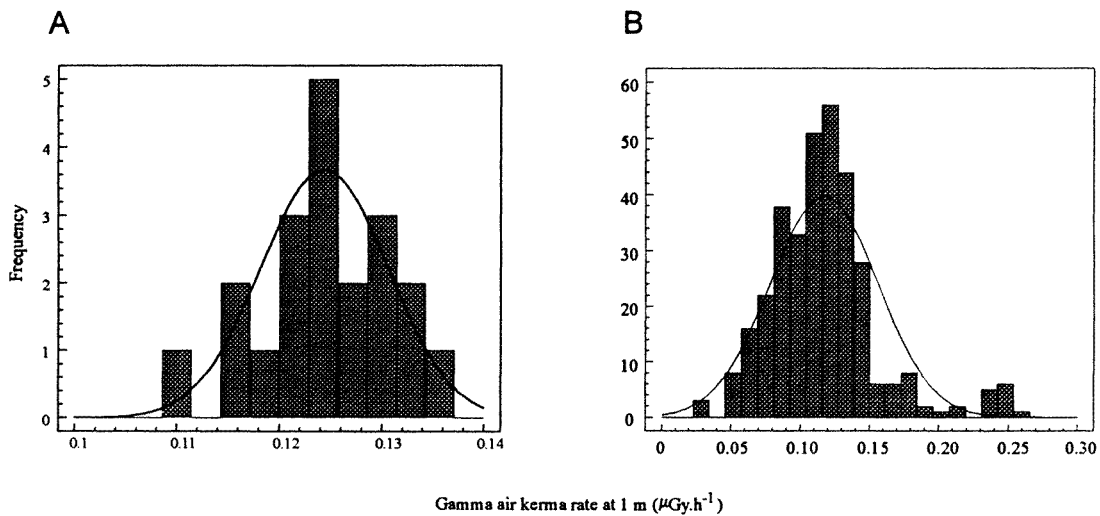


Figure 6. Frequency histograms for the total air kerma rate including the background rate. Figure A is from the small scale survey alone and figure B is for the whole estuary. The normal curves are appropriate for the mean and standard deviation of the data.

at all sites within the estuary. These data have a wide range of values, skewed towards the high

end. The variation in the small scale survey is significantly smaller although the data still have

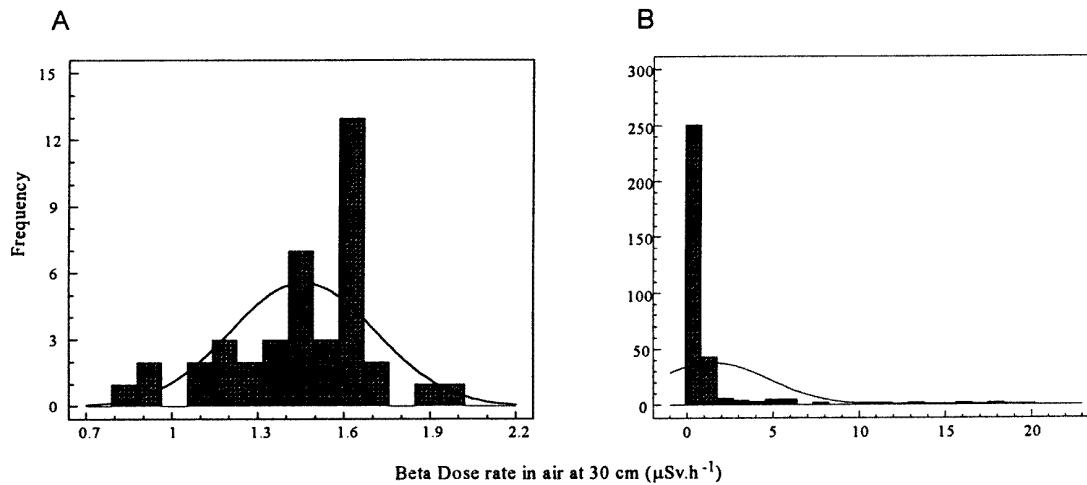


Figure 7. Frequency histograms for the beta dose rate including the background rate. Figure A is from from the small scale survey alone and figure B is for the whole estuary. The normal curves are appropriate for the mean and standard deviation of the data.

Table 3. Summary statistics for the beta dose and gamma air kerma rates.

| | Small scale survey | | Full survey | |
|------------------------------|---|--|---|--|
| | Beta dose rate ($\mu\text{Sv h}^{-1}$) | Gamma air kerma rate ($\mu\text{Gy h}^{-1}$) | Beta dose rate ($\mu\text{Sv h}^{-1}$) | Gamma air kerma rate ($\mu\text{Gy h}^{-1}$) |
| Sample size | 40 | 20 | 313 | 318 |
| Sample mean | 1.46 | 0.12 | 1.1 | 0.11 |
| Sample standard deviation | 0.25 | 0.01 | 1.95 | 0.03 |
| Variance | 0.06 | 1×10^{-4} | 3.8 | 9.1×10^{-4} |
| Minimum | 0.8 | 0.11 | < 0.06 | 0.02 |
| Maximum | 2 | 0.14 | 19.38 | 0.26 |

a range of $0.8\text{--}2.0 \mu\text{Sv h}^{-1}$, hence the larger coefficient of variation compared with the gamma data. Since the path length for emissions to the gamma detector is greater than that of the beta detector, the gamma air kerma rate inherently smooths out many of the small scale variations which the beta methodology will identify. This is due to the much wider field of view of the detectors.

It is possible using the above data and the t -statistic, to calculate the 95% confidence interval for sites throughout the estuary assuming the relative variation at each point will be the same as that determined in the small scale survey. Using a typical gamma air kerma rate for Longton Marsh

Table 4. Coefficients of variation for the surveys.

| Survey | Coefficient of variation(%) |
|---------------------|-----------------------------|
| Gamma (all sites) | 32 |
| Gamma (small scale) | 5 |
| Beta (all sites) | 223 |
| Beta (small scale) | 17 |

($0.192 \mu\text{Gy h}^{-1}$) and assuming this value was the mean of a number of readings (n), we can calculate how many observations are needed to reduce the error, expressed as a percentage of the mean, to less than 10%. These data indicate that four

Table 5. Occupancy data and dose rates for Lytham Marsh. Excess rates are calculated by removing the appropriate background dose rate ($0.06 \mu\text{Gy h}^{-1}$ for gamma and $0.16 \mu\text{Sv h}^{-1}$ for beta).

| Sediment | Occupancy (h a ⁻¹) | γ air kerma rate ($\mu\text{Gy h}^{-1}$) | Excess γ air kerma rate ($\mu\text{Gy h}^{-1}$) | β dose rate $H'(0.07)$ ($\mu\text{Sv h}^{-1}$) | Excess β dose rate $H'(0.07)$ ($\mu\text{Sv h}^{-1}$) | Transmission factor |
|----------|-----------------------------------|---|--|--|--|------------------------|
| Mud | 1820 | 0.09 | 0.03 | 0.75 | 0.59 | 0.82 |
| Marsh | 260 | 0.15 | 0.08 | 1.06 | 0.9 | 0.82 |

or more gamma dose rate readings are required assuming the same coefficient of variation at all sites as determined in the small scale survey.

With only a single estimate of the air kerma rate at any one site is only possible to quote the counting errors based on the number of counts recorded by the Mini-Instruments 6-80. For routine monitoring work, four gamma air kerma rate readings in close proximity at a single site would improve the confidence in the dose at that point, as would longer counting times. The same exercise can be completed with the beta dose rate which has a higher coefficient of variation (17.3%). As a result, 10 observations are required to reduce the error to 12% of the mean.

Further surveys (unpublished data) have shown that within a 1m^2 area, the beta dose rate can vary by a factor of two. This was strongly linked to micro-scale topological differences in the sediment surface. Therefore, when measuring the beta dose rate, several readings should be taken within a small area. Longer counting times will not remove these inherent differences in activity concentrations.

2.8. Dose to critical group

The critical group identified by MAFF (Camplin 1993) are a small group of houseboat dwellers who moor in the muddy creeks and tributaries of the Ribble Estuary. The annual dose to this group has been estimated by MAFF as $150 \mu\text{Sv}$ for 1991 (Camplin 1993) and $125 \mu\text{Sv}$ by BNFL (BNFL 1992). These doses are well within the 1mSv annual dose limit for members of the public in the UK and are principally derived from gamma irradiation.

A full treatment of the occupancy and dose to the most exposed groups in this survey is

presented in Mudge *et al* (1996b). An example of the exposure a walker using Lytham Marshes receives is presented below. The calculated dose is the maximum for our survey of leisure users of the estuary. Table 5 indicates the beta dose and gamma air kerma rates and clothing transmission factors appropriate to this habit. This leads to organ and external exposure to the whole body as shown in table 6.

The effective dose was approximately half of the value for the critical group identified by MAFF and is mainly (86%) due to gamma irradiation. The breakdown of the dose by β and γ irradiation presented in Mudge *et al* (1994b) shows that the radionuclides responsible for this dose are principally derived from Sellafield marine discharges.

The hourly dose to hands contaminated by maximum activity mud from Penwortham is presented in table 7. Of this total hourly effective dose, 89% is derived from $^{234\text{m}}\text{Pa}$. The activity concentration of this radionuclide can vary dramatically between sites and even tidal cycles in the Ribble Estuary (Assinder *et al* 1996; Mudge *et al* 1996b) and so this may be considered to be a worse case. No direct observation was made of people with hands contaminated from intertidal mud during our survey. However, discussions with users of the Estuary suggest that 15h a^{-1} is a reasonable likely exposure rate and the annual dose contribution this pathway makes is only $0.06 \mu\text{Sv}$.

3. Conclusions

1. Beta dose rates can be assessed by use of a Berthold LB1210B with the appropriate calibration factors. Account needs to be taken of the variation in dose rate with height above the sediment and the shielding afforded by different clothes.

Table 6. Organ and effective dose (all units $\mu\text{Sv a}^{-1}$). The mean ratio between clothed and unclothed skin is taken to be 0.75:0.25.

| Sediment | β to skin unclothed | β to skin clothed | Total β to skin | Eyes | β to testes | Effective β | Effective γ | Total |
|----------|------------------------------|----------------------------|--------------------------|------|----------------------|----------------------|-----------------------|-------|
| Mud | 537 | 440 | 464 | 146 | 18 | 8.2 | 44.3 | 52.5 |
| Marsh | 117 | 96 | 102 | 31 | 4 | 1.8 | 18.6 | 20.4 |
| Total | | | | | | | | 72.9 |

Table 7. Hourly dose rate to hands.

| Radionuclide | Dose factor (β) ($\mu\text{Sv h}^{-1}$ per Bq cm^{-2}) | Dose factor (γ) ($\mu\text{Sv h}^{-1}$ per Bq cm^{-2}) | Activity (max) (Bq kg^{-1}) | Total ($\mu\text{Sv h}^{-1}$) |
|------------------------------|---|--|--|------------------------------------|
| ^{137}Cs | 1.6 | 3.30×10^{-2} | 973 | 2.1×10^{-2} |
| ^{241}Am | 2.51×10^{-3} | 1.70×10^{-2} | 522 | 1.3×10^{-4} |
| ^{228}Th | 4.57×10^{-2} | 1.00×10^{-1} | 58 | 1.1×10^{-4} |
| $^{230}\text{Th}^{\text{a}}$ | 0 ^b | 3.80×10^{-3} | 254 | 1.3×10^{-5} |
| ^{232}Th | 2.05×10^{-3} | 1.70×10^{-1} | 32 | 7.1×10^{-5} |
| $^{238}\text{U}^{\text{a}}$ | 1.83×10^{-3} | 9.70×10^{-3} | 29 | 4.3×10^{-6} |
| ^{234}U | 2.40×10^{-3} | 2.70×10^{-3} | 28 | 1.8×10^{-6} |
| $^{239,240}\text{Pu}$ | 0 ^b | 2.60×10^{-3} | 199 | 6.7×10^{-6} |
| ^{238}Pu | 0 ^b | 2.70×10^{-3} | 38 | 1.4×10^{-6} |
| $^{234}\text{Th}^{\text{a}}$ | 3.54×10^{-1} | 1.18×10^{-3} | 263 454 | 1.2 |
| $^{234\text{m}}\text{Pa}$ | 2.40×10^0 | 7.00×10^{-4} | 319 547 | 9.9 |
| | | | Total $\beta + \gamma$ | 11.2 |
| | | | Whole body ^c ($\mu\text{Sv h}^{-1}$) | 0.004 |

^a These dose factors include contributions for all or some of the daughter radionuclides. However, since the total dose is dominated by that of $^{234\text{m}}\text{Pa}$ and the beta emissions from ^{234}Th , this is not considered to be a significant over-estimate.

^b The plutonium isotopes and ^{230}Th have no beta emissions although they do have alpha and gamma dose factors.

^c It is assumed that the area of the hands is 600 cm^2 and the surface area of the whole body is $1.7 \times 10^4 \text{ cm}^2$. Conversion to whole body dose uses the tissue weighting factor of 0.01 from ICRP 60.

2. Investigation of one small area of intertidal mud has indicated that the spatial variations in dose rates require 4 replicate measurements of the gamma air kerma rate to reduce the error to $< 10\%$ of the mean. For beta dose rate measurements, 10 replicates are needed to reduce the error to $< 12\%$ of the mean. This is in part due to the inherent smoothing associated with use of a Mini Instruments 6-80.

3. The effective dose rate to a walker using the Ribble Estuary has been calculated to be $73 \mu\text{Sv}$ from external pathways. This is less than half of the dose received by the critical group of

house boat dwellers identified and monitored by MAFF.

4. The exposure received from contamination of the hands by mud is small ($0.004 \mu\text{Sv h}^{-1}$).

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Résumé

Le BNFL, Springfields, est autorisé à rejeter, dans l'estuaire de la Ribble, des radionucléides émetteurs bêta—surtout ^{234m}Pa —qui sont des sous-produits de la fabrication des combustibles à base d'uranium. L'accumulation de ^{234m}Pa dans les sédiments de l'estuaire conduit à une augmentation des débits de dose bêta, que l'on ne rencontre pas ailleurs en Grande-Bretagne. On présente les méthodes employées pour déterminer le débit de dose bêta, et pour calculer les doses aux organes, comme la dose efficace. On a déterminé la variation de la dose bêta et des débits de kerma gamma dans l'air, dans une petite région; on présente des recommandations en ce qui concerne le nombre de répliques nécessaires pour réduire l'erreur de 10% en moyenne. Mettant en oeuvre des méthodes détaillées, on donne, à titre d'exemple, le calcul de la dose reçue par un promeneur dans les régions intertidales de l'estuaire de la Ribble. La dose efficace étant de $73 \mu\text{Sv a}^{-1}$, 86% provenant de l'irradiation gamma. Les doses au niveau des mains contaminées par les sédiments de l'estuaire sont également faibles ($0.004 \mu\text{Sv h}^{-1}$).

Zusammenfassung

Als Nebenprodukt der Herstellung von Uran-Kernbrennstoffen, wurde BNFL in Springfields ermächtigt, Beta-strahlende Radionuklide, hauptsächlich ^{234m}Pa in die Ribble-Flußmündung abzugeben. Die Akkumulation von ^{234m}Pa im Sediment der Flußmündung führt zu erhöhten Beta-Dosisleistungen, die nirgendwo sonst in UK beobachtet werden. Die Methoden, die zur Bestimmung der Beta-Dosis und zur Berechnung der Organ- und effektiven Dosis benutzt werden, werden vorgestellt. Die Schwankung in der Beta-Dosis und den Gamma-Luft-Kerma-Raten in einem kleinen Gebiet wurden untersucht und Empfehlungen ausgesprochen bezüglich der Anzahl der Replikate, die benötigt werden, um den Fehler auf $\sim 10\%$ des Mittelwertes zu reduzieren. Ein Beispiel für die Dosis, die eines Spaziergänger im Küstengebiet der Ribble-Flußmündung erhält wird durch detaillierte Methoden berechnet. Die effektive Dosis betrug $73 \mu\text{Sv a}^{-1}$, wobei 86% von der Gamma-Strahlung stammen. Die Dosen für Hände, die durch das Sediment der Flußmündung kontaminiert wurden ist ebenfalls gering ($0.004 \mu\text{Sv h}^{-1}$).

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