Radiation Protection Division

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Public Health Implications of Fragments of Irradiated Fuel

Module 4: External dose rates on Sandside beach and other miscellaneous information

KR Smith, P Bedwell, G Etherington and M Youngman

Contract Report

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ABSTRACT

Fragments of irradiated nuclear fuel the size of grains of sand have been found on Sandside Beach, which is adjacent to the Dounreay nuclear research facility in Caithness. Information on fuel fragments found on the beach and the behaviour of individuals on the beach has been used to estimate external doses to individuals using the beach. The probability of a fuel fragment becoming trapped in the eye or ear is also discussed. Additional information supporting the overall assessment of the public health implications of these fuel fragments is also contained in this report. This includes information on the retention time of sand on skin and aspects related to the operation of the beach monitoring system.

This work has been undertaken as part (Module 4) of a study commissioned by SEPA of the public health implications of these fragments of irradiated fuel. **This contract report presents the results of Module 4 of the study.**

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Centre for Radiation, Chemical and Environmental Hazards
Radiation Protection Division
Chilton, Didcot, Oxfordshire OX11 0RQ

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CONTENTS

1 INTRODUCTION

Small fragments of irradiated nuclear fuel have been found on Sandside beach, which is adjacent to the Dounreay nuclear research facility in Caithness. These are generally characterised by their ^{137}Cs content, although if such fragments came into contact with the skin or were ingested, the main contributors to the dose would be ^{90}Sr and its decay product ^{90}Y. UKAEA routinely monitors the beach, and others in the area, to detect fuel fragments using the vehicle mounted Groundhog Evolution monitoring system. The fuel fragments found to date varied in size from approximately 0.02 mm to a few millimetres.

A study, funded by the Scottish Environment Protection Agency (SEPA), to examine the public health implications of these fragments of irradiated fuel is currently underway. This **contract report** relates primarily to work carried out under Module 4 of this study. A detailed description of all aspects of the study can be found in Wilkins et al (2005).

The main purpose of the work carried out under Module 4 was to estimate external (gamma) doses to individuals using the beach from fuel fragments on the beach. This document describes the methodology used to estimate such doses and the results of the calculations undertaken. Estimates have also been made of the probability of a fuel fragment becoming trapped in the eye or ear.

In addition to the results of Module 4 of this study, this report also contains a number of Appendices covering various pieces of work undertaken in support of the overall study that have not been reported previously. These Appendices are self-standing and cover the following:

a the depths at which fuel fragments containing ^{137}Cs in the range 10^5 to 10^8 Bq could be detected by the Groundhog Evolution monitoring system;
b the ability of the Groundhog Evolution monitoring system to detect fuel fragments containing ^{60}Co; and
c residence times of fuel fragments on skin.

2 EXTERNAL DOSE RATES FROM FUEL FRAGMENTS

An individual on Sandside beach in the vicinity of a fuel fragment will receive a dose as a result of the emitted gamma radiation. The primary objective of Module 4 was to estimate such doses.

2.1 Methodology

Smith and Bedwell (2005a) estimated that, for the monitored area of the beach, between 1 and 14 fuel fragments with ^{137}Cs activities above approximately 10^4 Bq are present on Sandside beach at any one time. The estimated average value was about 8. The numbers of fuel fragments on the beach implies that it is entirely appropriate to consider the dose rates from a single fuel fragment. Doses to individuals both standing and lying on the beach were considered.

Fuel fragments were modelled as point sources. Fuel fragments discovered on Sandside beach between November 2002 and April 2004 ranged in ^{137}Cs activity from 8.4 10^3 Bq to 2.8 10^5 Bq. For these calculations a fuel fragment activity towards the upper end of the range, 10^5 Bq of ^{137}Cs (and its decay product, ^{137m}Ba), was used. The dose rates calculated within this study could be scaled accordingly to account for other activities.

The MicroShield program (Negin, 1986) was used to calculate the external gamma dose rate from a fuel fragment. MicroShield calculates dose rates using the point-kernel method, allowing for attenuation and build-up (accounting for the contribution to dose from multiple scattering of gamma rays) in air and any shielding present between the source and the point where the dose rate is calculated. It is an extensively used code that is simple to operate, but, as noted below, does have some limitations regarding the definition of spatial geometry. Preliminary calculations indicated that the external doses would be low and thus it was considered that the use of more complex and computing intensive calculational methods, such as Monte Carlo codes, was not appropriate in these circumstances.

As indicated above, there exist a number of caveats when using MicroShield. The program calculates dose rate at a point. For an individual at a significant distance from a point source the radiation field incident on the individual will be relatively uniform and it would be appropriate to use the radiation field at any point to estimate the effective dose to the individual. However, at closer distances the radiation field incident on an individual will be significantly non-uniform. For example, assuming an individual of height 2 m is standing 1 m from a point source, the dose received by the head will be lower by a factor of 2.5 than that to the torso. Under such circumstances it is necessary to choose a point at which the dose is determined and assume that this dose is representative of that to the whole body. For a standing individual, the dose to the torso, which is assumed to be 1 m above the ground, was chosen to represent the dose to the whole body. This is an assumption that has been used in other studies and is consistent with the relative radiosensitivity of organs within the torso compared with the extremities. For an individual lying on the beach it was assumed that their torso was directly above the fuel fragment and the doses at 0.1 m (ie to the centre of the torso), with an additional distance accounting for a suitable air gap, were representative of exposure of the whole body.

A further limitation of MicroShield is the assumption that all radiation is incident normal to the surface of the human body. This is a good approximation when there exists a significant (in the order of metres) distance between the source and the point at which the dose is received. As this distance diminishes the approximation breaks down. This is because photons are attenuated within the body before irradiating the organs and tissues of concern, and the attenuation depends on the amount of body tissue through which the photons have to pass. Radiation from point sources close to a body typically arrives at an angle to that body and therefore incurs a greater amount of attenuation. Hence, with regard to ‘short’ (ie of the order of centimetres) distances between the source and the exposed individual, the doses generated by MicroShield should be considered very approximate.

Dose rates to individuals standing on the beach, directly above the fuel fragment, and at a series of horizontal distances (0.1, 0.2, 0.5, 1, 2, 5, 10, 20, 50 and 100 m) away from that point were determined. Dose rates to individuals lying on the beach were calculated assuming 10 mm and 50 mm air gaps between fuel fragment and skin, thus implying total distances of 110 mm and 150 mm (to the centre of the torso), respectively.

The largest dose rates received will occur when there is no shielding, ie when a fuel fragment resides on the surface of the beach. However, for comparative purposes fuel fragments buried at depths of 50, 100 and 200 mm were also considered for an individual standing on Sandside beach. A bulk density of sand on Sandside beach of 1.7 10^6 g m^{-3} (RWE Nukem, 2002), as used by Smith and Bedwell (2005b), was used in this study to characterise the shielding.

2.2 Results and conclusions

Estimated external gamma dose rates are presented in Table 1 for a 10^5 Bq ^{137}Cs fuel fragment on the surface of the sand, ie no shielding other than air exists between the source and the point at which the dose is delivered. The dose rates observed are relatively small.

Table 1 External gamma dose rate from a 10^5 Bq fuel fragment of ^{137}Cs

Horizontal Distance (m)	Vertical Distance (m)	Effective Dose Rate (Sv h^{-1})
Individual lying on the beach		
0	0.11	6.1 10^{-7}
0	0.15	3.3 10^{-7}
Individual standing on the beach		
0	1	7.4 10^{-9}
0.1	1	7.3 10^{-9}
0.2	1	7.1 10^{-9}
0.5	1	5.9 10^{-9}
1	1	3.7 10^{-9}
2	1	1.5 10^{-9}
5	1	2.8 10^{-10}
10	1	7.2 10^{-11}
20	1	1.8 10^{-11}
50	1	2.8 10^{-12}
100	1	6.3 10^{-13}

For comparative purposes Figure 1 displays the variation of gamma dose rate as a function of the depth of burial in the sand. For any degree of shielding the dose rate drops away rapidly for horizontal distances greater than 1 m from the source. Figure 1 also includes the background dose rate from sandy substrates (measured at 1 m above the sand) detailed in CEFAS (2004), illustrating that doses from a fuel fragment to an individual standing on Sandside beach would be lower than general background radiation levels.

It is unlikely that an individual would spend a significant time in close proximity to a fuel fragment, but even if this did occur the doses would be small. For example, assuming an individual lies on the beach directly above a 10^5 Bq ^{137}Cs fuel fragment for 4 hours (97.5th percentile of the duration of a single beach visit to Sandside (Smith and Bedwell, 2005b)) they would receive a dose of only 2.4 µSv. Similarly, if an individual stood directly on top of a 10^5 Bq ^{137}Cs fuel fragment for 330 hours, corresponding to the annual high rate occupancy for a member of the adult bait digger exposed group (Smith and Bedwell, 2005b), the resultant dose would be only a few microSieverts. In this context it is worthy of note that the International Atomic Energy Agency (IAEA) has concluded that an individual radiation dose, regardless of its origin, is likely to be regarded as trivial if it is of the order of some tens of microsieverts per year (IAEA, 1988).

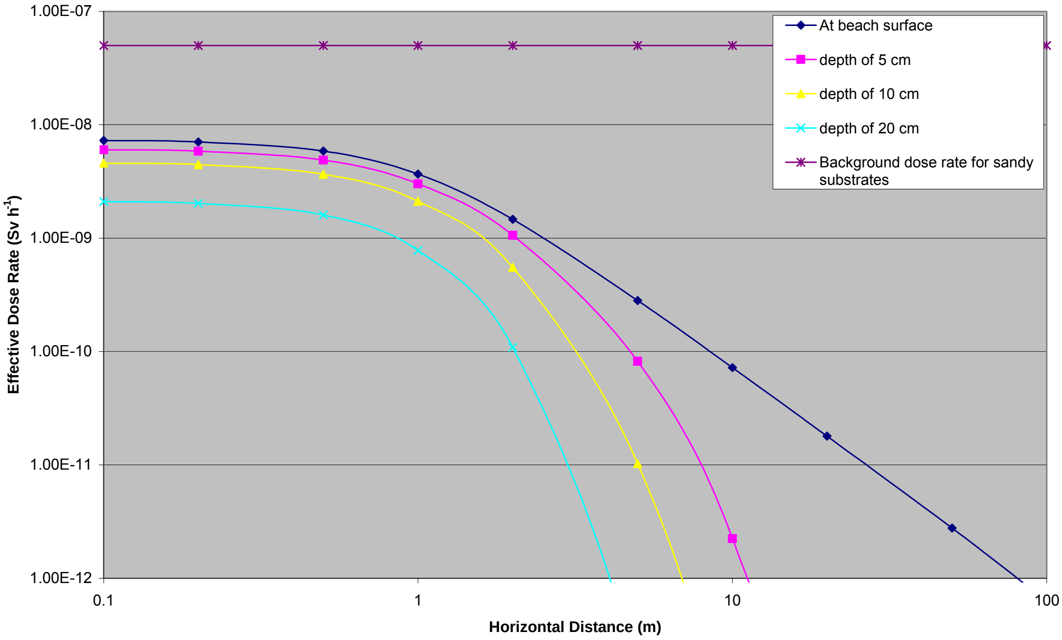

Figure 1 External gamma dose rate to a person standing on Sandside beach as a function of distance from a 10^5 Bq fuel fragment at various depths in the sand

3 THE PROBABILITY OF A FUEL FRAGMENT BEING TRAPPED IN EYE OR EAR

Several potential pathways by which an individual could come into contact with a fuel fragment were identified in Module 3 (Smith and Bedwell, 2005b). These included: inhalation, ingestion (inadvertent or in seafood) and skin contact. Estimates of the probability of individuals coming into contact with a fuel fragment by these pathways were made (Smith and Bedwell, 2005b). Following the publication of this Module 3 report a further two potential pathways have been identified: trapping of a fuel fragment in either the eye or ear. It was therefore considered important to estimate the likelihood of contact with a fuel fragment via either of these two pathways.

It has been estimated that, on average over the year, approximately 8 fuel fragments with ^{137}Cs activities above approximately 10^4 Bq are present on the monitored area of the beach (to a depth of 200 mm) at any one time (Smith and Bedwell, 2005a). The number of sand grains in the monitored area of the beach down to a depth of 200 mm has been estimated using the following equations:

$ms = ma \times d \times \rho_{bulk}$

$mg = (4/3) \times \pi \times (rg)^3 \times \rho_{grain}$

$nsg = ms / mg$

where,

ms = mass of sand present on monitored are of the beach down to a depth of 200 mm, kg

ma = monitored area of the beach, 230,000 m^2 (Smith and Bedwell, 2005a)

d = depth of sand, 0.2 m

ρ_{bulk} = bulk density of sand, $1.7\ 10^3$ kgm^{-3} (Smith and Bedwell, 2005b)

mg = mass of a sand grain, kg

rg = radius of sand grain, $0.15\ 10^{-3}$ m, see below

ρ_{grain} = density of sand grain, $2.0\ 10^3$ kgm^{-3} (Smith and Bedwell, 2005b)

nsg = number of sand grains in the monitored area of the beach down to a depth of 200 mm

Sand grains on the beach range in diameter from around 0.1 mm to 1.5 mm, with the majority in the region of 0.2 mm to 0.3 mm (UKAEA, 2001). For this estimate a diameter of 0.3 mm was assumed. On the basis of the above assumptions it is estimated that the number of sand grains in the monitored area of the beach down to a depth of 200 mm is $2.8\ 10^{15}$. Comparing the number of sand grains with the estimated number of fuel fragments present, namely 8, it is clearly very unlikely that a particle from the beach that gets trapped in an individuals eye or ear would be a fuel fragment rather than a sand grain. The probability can be estimated as follows - probability that a particle trapped in the eye is a fuel fragment = $8 / 2.8\ 10^{15} = 2.9\ 10^{-15}$ (ie around 1 in 10^{14}).

It is difficult to estimate the annual probability of an individual getting a fuel fragment trapped in their eye as there is little information available on the frequencies with which sand grains become trapped in people's eyes. However, anecdotal evidence would suggest that the probability of getting a sand grain trapped in the eye is significantly less than one for any particular beach visit. To scope the annual probability it has been very conservatively assumed that an individual visits the beach every day for a year and on each occasion gets a particle trapped in their eye. The annual probability of getting a fuel fragment trapped in the eye under these extreme circumstances can be estimated using the following formula,

$P_{eye,a} = N_v \times P_{trap} \times P_{ff}$

where

$P_{eye,a}$ = the annual probability of a fuel fragment being trapped in the eye, y^{-1}

N_v = number of visits to the beach each year, 365 y^{-1}

P_{trap} = probability that a particle becomes trapped in the eye per beach visit, conservatively assumed to be 1

P_{ff} = probability that a particle trapped in the eye is a fuel fragment, 2.9 10^{-15}, see above

The above gives an annual probability of getting a fuel fragment trapped in the eye of 1 10^{-12}, ie around 1 in a million million per year. For the reasons described above, it is clear that the actual probability would be even lower.

It is more difficult to make a reasonable estimate of the probability of a fuel fragment becoming trapped in the ear as there is even less information available on the frequency with which sand grains get trapped in the ear. It is reasonable to assume, however, that the annual probability would be of the same order or less than the probability of particles becoming trapped in the eye.

4 REFERENCES

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APPENDIX A Depths at which fuel fragments containing ^{137}Cs in the range 10^5 to 10^8 Bq could be detected using the current detection system

A1 BACKGROUND

The current system used to detect fragments of irradiated nuclear fuel on Sandside beach is the Groundhog Evolution system. Reliable values of minimum detectable activity (MDA) and detection probability for the Groundhog Evolution system can only be computed for the depth range for which calibration factors have been derived (ie 0 m – 0.2 m). The MDA for a scan speed of 1.2 ms^{-1} and a depth of 0.2 m is 230 kBq ^{137}Cs (Etherington and Youngman, 2005). Under these conditions, a fuel fragment containing 10^5 Bq ^{137}Cs is detected with a probability of 43% (Etherington and Youngman, 2005). Fuel fragments with activities of 10^6 Bq ^{137}Cs or greater are detected with probabilities very close to 100%.

A2 METHOD

Approximate estimates of MDA at depths greater than 0.2 m can be made by extrapolating the calculated values. MDA is expected to depend very approximately on *exp*(d), where d is the depth of the fuel fragment. This involves the implicit assumptions that :

a the dependence on depth of the measured count rate is dominated by the attenuation of gamma radiation by the sand in which the fuel fragment is buried
b in comparison, the effect of the inverse square law can be neglected
c only the vertical depth of the fuel fragment need be considered, rather than path lengths through the sand when the fuel fragment is not vertically below the detector array
d deviations from the exp(d) dependence arising from inelastic scattering of photons are negligible.

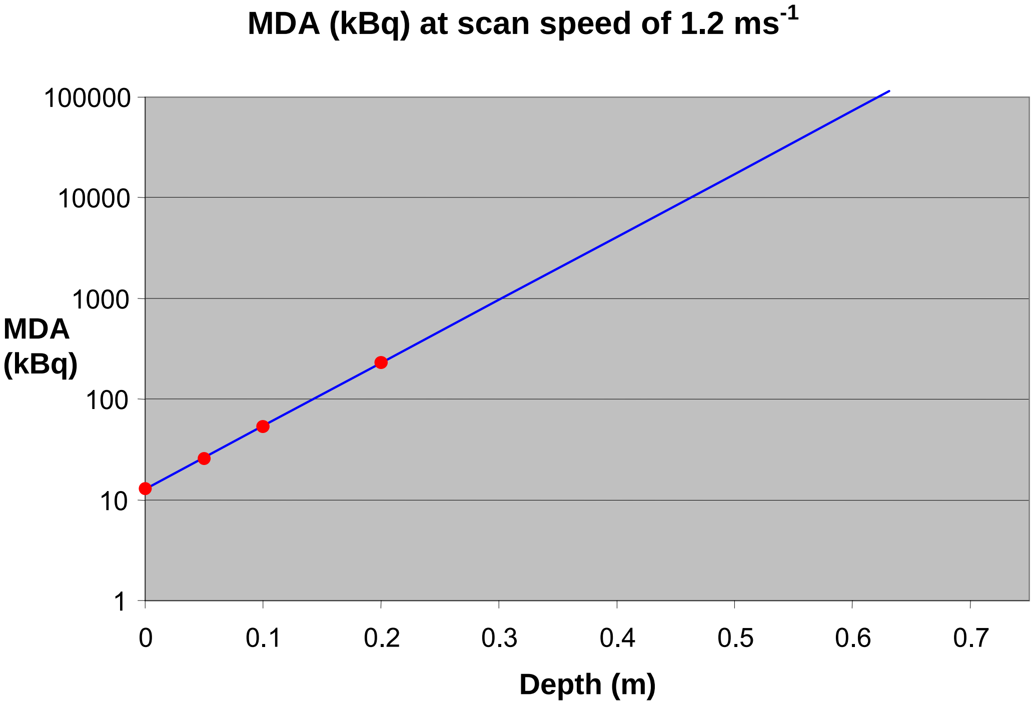
For a rough approximation, these assumptions seem reasonable, but would need to be checked by simulation or measurement for different depths before confidence could be placed in the results of the extrapolation.

A3 RESULTS

As depth increases above 0.2 m, decreasing confidence should be placed in the extrapolated values. The figure shows that 10^5, 10^6, 10^7 and 10^8 Bq particles might be reliably detected (ie at better than the 95% confidence level) at depths of, respectively, 0.15, 0.3, 0.45 and 0.6 m.

The fit of an exponential function to the MDAs computed for the depth range 0 m – 0.2 m is shown in Figure 1. The finding that the fit lies close to the computed values provides some confidence in the assumptions made.

Figure A1 Estimated minimum detectable ^{137}Cs activity (MDA) as a function of depth, at a scan speed of 1.2 ms^{-1}



A4 REFERENCES

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APPENDIX B Ability of Groundhog Evolution to detect fuel fragments containing ^{60}Co

The current beach monitoring system, Groundhog Evolution, as described in the Module 5b report (Etherington and Youngman, 2005), measures the counts-per-second (cps) in three spectral regions known as regions of interest (ROI). These are:

> 500-750 keV, the region that contains the ^{137}Cs(^{137m}Ba) emission, known as ‘in window’ ROI
>
> > 750 keV, known as the ‘above-window’ ROI
>
> < 500 keV, known as the ‘below-window’ ROI

For a detection alarm to occur, two criteria must be met simultaneously. First, the sum of all counts in all of the ROIs must exceed a threshold (gross gamma criterion). Second, the ‘in window’ ROI count must exceed a threshold based on a prediction of the background count in this ROI. The predicted background value is calculated from a mean of previous ‘in window’ to ‘above-window’ ratios multiplied by the current ‘above-window’ measurement.

The radionuclide ^{60}Co has two gamma-ray emissions at 1173 and 1332 keV, and the presence of a fuel fragment containing ^{60}Co would result in elevated counts in all three ROIs (for ^{137}Cs only the counts in the ‘in window’ and ‘below-window’ ROIs are elevated). If the system encounters a ^{60}Co containing fuel fragment of sufficient activity the gross gamma criterion would be satisfied. However as the emissions of ^{60}Co appear in the ‘above-window’ ROI the second criteria would not necessarily be met as the predicted background ‘in-window’ count would increase with the ‘above-window’ count. Therefore the system would not be sensitive to fuel fragments containing mainly ^{60}Co. The presence of a ^{60}Co containing fuel fragment would also have the effect of increasing the detection limit for ^{137}Cs.

If a particle alarm criterion was introduced when the counts in the ‘above-window’ ROI exceeded a threshold, then the system would be able to detect fuel fragments containing ^{60}Co. The limits of detection for detection of ^{60}Co could be determined if calibration factors for a range of depths and detector to source distances were determined. To optimise the system for detection of ^{60}Co the lower bound of the current ‘above-window’ ROI would need to be increased from 750 keV.

B1 REFERENCES

Etherington G and Youngman MJ (2005). *An evaluation of the sensitivity of the Groundhog Evolution™ beach monitoring system*. Chilton, RPD-DA-01-2005.

APPENDIX C Residence time of fuel fragments on skin

C1 INTRODUCTION

The health implications of direct skin contact with a fuel fragment have been discussed extensively in the Module 1 report (Harrison et al, 2005). Clearly, as discussed in that report, the time during which a fuel fragment remains in contact with skin impacts upon the level of skin exposure and thus the potential health impact. To support the discussion in Module 1 a brief literature review of retention times of particles, such as fuel fragments, on skin was undertaken.

C2 LITERATURE REVIEWED

Brief notes for each of the reports and papers considered in the review are given below:

DEFRA and EA (2002). The Contaminated Land Exposure Assessment Model (CLEA): Technical basis and algorithms. R & D Publication CLR10. The CLEA model assumes a skin contact duration of 12 hours as default. This is the amount of time, from first contact, that the soil or indoor dust remains adhered to the skin before it falls away naturally or is removed by washing. The report notes that there is little published information assessing contact duration and quotes the US Environment Protection Agency's suggestion of a contact duration related to the period between washings in the range of 8 to 24 hours.

Wong EY, Shirai JH, Garlock TJ and Kissel JC (2000). Adult proxy responses to a survey of children's dermal soil contact activities. J Expo Anal Environ Epidemiol 10 (6 pt1) , 509-517. This report covers the results of a telephone survey conducted to obtain information on the pattern of children's exposure to soil. Such information may be required to estimate dermal exposures for inputs to contaminated site clean-up decisions. Telephone surveys were used to question a randomly selected sample of US households. A randomly chosen child, under the age of 18 years, was targeted in each responding household having children. Play activities as well as bathing patterns were investigated to quantify total exposure time, defined as activity time plus delay until washing. Of 680 total survey respondents, 500 (73.5%) reported that their child played outdoors on bare soil or mixed grass and soil surfaces. Among these "players," the median reported play frequency was 7 days per week in warm weather and 3 days per week in cold weather. Median play duration was 3 hours per day in warm weather and 1 hour per day in cold weather. Hand washes were reported to occur a median of 4 times per day in both warm and cold weather months. Bath or shower median frequency was seven times per week in both warm and cold weather. Finally, based on clothing choice data, a median of about 37% of total skin surface is estimated to be exposed during young children's warm weather outdoor play.

Sedman RM (1989). The development of applied action levels for soil contact: A scenario for the exposure of humans to soil in a residential setting. Environmental Health Perspectives 79, 291-313. The model presented in this paper essentially assumed that the soil remained on the skin for the whole day but was removed, presumably by washing, at the end of the day.

Goosens LHJ, Cooke RM, Kraan BCP, Ehrhardt J, Fischer F, Hasemann I, Jones JA, Brown J, Khursheed A and Phipps A (2001). Probabilistic accident consequence uncertainty assessment using Cosyma – Uncertainty from the dose module. Brussels, EUR 18825en. This report gives the following uncertainty distribution on the residence time on skin of aerosols produced by nuclear accidents.

TABLE C1 Distribution on skin residence time (Goosens et al, 2001)

Percentile of the distribution	Residence time (days)
Minimum	0.50
5th	2.00
20th	2.17
35th	2.33
50th	2.50
65th	2.67
80th	2.84
95th	3.00
Maximum	15.0

The uncertainty on the residence time of material on skin was specified by project staff. The estimation of retention time was based on considerations of the time for which stains (such as paint) remain on the skin.

Jones A, Mansfield P and Bell K (1998). Implications of deposition on skin for accident consequence assessments. Radiol Prot Bull 207, 9-14. A series of measurements were undertaken related to the deposition and retention period of material on skin and clothing, simulating deposition indoors and outdoors. The following particle sizes and deposition surfaces were used:

a Deposition to skin - 2.6, 6.2 and 9.2 µm particles
b Deposition to clothing - 1.4 and 6.2 µm particles
c Deposition to wigs and swimming caps - 1.4 and 6.2 µm particles

The retention time on skin was measured in a test chamber using a video fluorescent system. Images of the deposited aerosol were recorded at a series of times after initial contamination, and the deposit remaining was quantified by analysis of the intensity of the fluorescent signal. The results corresponded to retention half-lives between about 1 and 3 hours. The clearance from clothing was determined by washing the clothing in a domestic washing machine and measuring the amounts of material remaining on the fabric after the clothes had dried. Retention on the wigs was measured by placing parts of the wigs in polythene bags and washing them gently with a soap solution. The measurements showed that between 30% and 90% of the original deposition was removed by the washing process, for both clothing and wigs.

Fogh CL, Byrne MA, Andersson KG, Bell KF, Roed J, Goddard AJH, Vollmair DV and Hotchkiss SAM (1999). Quantitative measurement of aerosol deposition on skin, hair and clothing for dosimetric assessment – final report. Riso-r-1075en. Experiments showed that cold water washing removed a substantial proportion of deposited 4.5 µm particles. Human activity experiments, whereby exposed individuals engaged in normal indoor and outdoor walking, yielded a clearance half life for 2.5 µm and 4.5 µm particles of the order of, respectively, a few days and a few hours. It was postulated that the clearance half-life for sub-micron particles would be longer than that recorded for 2.5 µm particles.

A series of clothing washing experiments indicated a dependence of particle removal efficiency on particle size. Also, the data suggested that the micro-physical fibre structure (smooth in the case of synthetic fibres and rougher in the case of natural fibres) of clothing was a more important determinant of particle removal efficiency than the macro-physical weave of the garment itself. An experiment was carried out to determine clearance half-lives of particles from hair under normal human activity. Here, a test person had a shower every morning, prior to each new exposure, and the clearance effect was found to be great, even though the particles applied were as small as 0.5 µm.

Sheppard SC and Evenden WG (1994).Contaminant Enrichment and Properties of Soil Adhering to Skin. J Environ Qua, 23, 604-613. Sheppard and Evenden examined the impact on adhesion of soil on skin of particle size. They studied the dermal adhesion properties of 11 different soils including a number of sandy soils. They found that adhering skin surfaces preferentially selected particles with diameters smaller than 0.1 mm. For soils that originally had few particles smaller than 0.1 mm, the particle size distribution of the adhering soil was markedly different from that of the original soil. They found that dry particles above 50 µm did not adhere to dry skin. However, this effect was less marked when the soil moisture was higher. Microscopic images of soil adhering to skin undertaken for their study showed that clay-sized particles (<2 µm diameter) are of the same scale as the surface roughness features of the skin. Thus, clay particles can be incorporated into the skin surface and may be quite resistant to cleaning.

C3 SUMMARY

Only a small number of studies on the residence of particles on skin were found. The papers addressed the adhesion of soil and very fine aerosols. These adhere more strongly to the skin than sand (Sheppard and Evenden, 1994) and thus are expected to stay on the skin longer than the sand-grain-sized fuel fragments found at Sandside beach.

In general, the assumption in the majority of reported assessments of skin contamination by soil or other materials was that the contaminated individual would have a thorough wash/shower in the evening and that this would remove any remaining soil that had not already fallen off or been removed by other processes. It therefore seems reasonable to assume that all sand (and any associated fuel fragment) remaining at the end of the day will be removed from the skin by washing in the evening on the day in which time was spent on the beach. This is consistent with general information on washing patterns.

If washing were the prime removal mechanism a reasonable maximum fuel fragment residence time would be in the region of 12 hours and a minimum duration in the region of 4 hours. These estimates were based on the period between time spent on the beach and the time at which washing occurred. However, the majority of sand (and any associated fuel fragment), especially dry sand, will not be removed by washing but will fall off or be removed by other processes beforehand. Thus the potential range of skin contact times with a fuel fragment will be in the region of fractions of seconds to around 12 hours. Particles still remaining on the skin at the time of washing will predominantly be those trapped against the skin by clothing. For example, sand on the feet trapped by socks. It should be recognised, however, that it is unlikely that an individual fuel fragment or sand grain will remain in exactly the same position for all this time. As the foot dries, for example, the sand does not adhere tightly and is therefore likely to move. On the basis of the above arguments it is clear that 12 hours would be an extreme estimate of the residence time of a fuel fragment on a particular spot on the skin.

It is expected that residence times of a fuel fragment in dry sand will be significantly lower than that of such fragments in wet sand. It is also expected that residence times of fuel fragments on skin that is covered tightly by clothing following exposure will be higher than that for skin that remains exposed when leaving the beach.

Dry sand is likely to remain in contact with skin for only a brief period. In the majority of cases such sand would be swept off or fall off within minutes. It is possible that if sitting relatively still a sand grain may stay on for up to a few hours if temporarily trapped by a hair, but this is unlikely and at the extreme end of the distribution. Wet sand will generally adhere more strongly to skin. On a hot day the sand will dry out very quickly and its adherence will then be similar to that for dry sand. On a less hot day this drying may take some time. For exposed skin (or skin loosely covered following time on the beach) it is still expected that the vast majority of sand would have fallen off or been removed by other processes before washing. For wet sand on exposed skin therefore a best estimate residence time of 3 hours is recommended.

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