Dounreay Particles Advisory Group

Third Report

September 2006

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Publishing Organisation
Scottish Environment Protection Agency,
Erskine Court,
Castle Business Park,
Stirling,
FK9 4TR

Tel: 01786 457700 Fax: 01786 446885
Website: www.sepa.org.uk

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FOREWORD

The Group was faced with the dilemma of producing this Third Report promptly with major gaps in our knowledge, which we had identified, or awaiting provision of the most vital information. We chose the latter option. It was decided that, with a single exception, information received after the end of February could not be considered adequately for inclusion in this Report.

As the exception, the Group considered it essential to confirm in practice our theoretical assessment of the performance of Groundhog Evolution (and its predecessor) in monitoring of beaches for particles. Under the auspices of COMARE, we participated in empirical measurements undertaken at Sandside Bay in April 2006, which was the earliest opportunity circumstances permitted. The Group had also considered it essential to monitor the beach at Dunnet Bay.

A major review of the potential consequences for health of particles was proposed by the Group, commissioned by SEPA and undertaken comprehensively by the Radiation Protection Division of the Health Protection Agency. We have now been able to set our findings in the context of public health, which we regard as the most important factor, and to categorise particles as *Significant*, *Relevant* or *Minor* according to their potential to cause harm.

Information was sought on the relationship between the activity of particles and their mass and density in order to understand better their behaviour in the marine environment. Data relating activity and mass were provided recently but problems remain in establishing reliable measurements of density. Further information was also sought on the distribution of particles in the marine environment and on the Dounreay Foreshore and local beaches.

Unfortunately, for a variety of reasons, delays in producing these data were frustratingly greater than we had anticipated and beyond our control. Post deadline, UKAEA disclosed information on the nature of particles and their classification that was so fundamental it was necessary to make late reference to it and include corrections to data provided previously. Constructively, relevant reports potentially helpful to our understanding have also been provided but too late for their implications to be evaluated by the Group and included in this Report. If the Group is tasked with further consideration of current research conducted by UKAEA, these reports that have now been made available and any others will be addressed in a Fourth Report.

However, although substantial uncertainties remain, we consider that the Report is now as comprehensive as our current knowledge permits, unifying our improved understanding of the diverse aspects of particles in the environment around Dounreay. It is intended to provide a sound basis on which judgements of future action and the need for further research can be made.

As Chairman of DPAG, I wish to record my deep gratitude to the members of the Group for their unstinting dedication and support despite the many competing demands on their professional time. Their collective multidisciplinary expertise was vital in achieving our present overall understanding and production of this Report. We are greatly indebted to our excellent Technical Secretary, Dr. Paul Dale. Despite other major commitments within SEPA, he has served us tirelessly with great enthusiasm and energy as well as providing counsel that is wise beyond his years. Allyson Wilson consistently demonstrated outstanding organisational and administrative skills on our behalf and latterly was ably supported by June Moore. Prior to his appointment as Chief Executive of SEPA, Dr. Campbell Gemmell chaired the

Group with typical commitment, vision and enthusiasm. The Group unanimously accorded him the title of Honorary Member and is grateful for his continued close interest and support. We are grateful for the helpful contributions of our Observers and to UKAEA, Dounreay, for providing information we sought via SEPA.

Professor Keith Boddy CBE, DSc, FRSE.
Chairman of DPAG

Location of Dounreay and local beaches

0 5 10
Kilometres

SEPA Scottish Environment Protection Agency

ACRONYMS AND ABBREVIATIONS

AEA	Atomic Energy Authority
Al	Aluminium
^{241}Am	Americium-241
^{137m}Ba	Metastable Barium-137
bar	1 atmosphere pressure
BPEO	Best Practicable Environmental Option
BMSG	Beach Monitoring Steering Group
BMM	Beach Monitoring Modelling
Bq	Bequerel
CERRIE	Committee Examining Radiation Risks from Internal Emitters
COMARE	Committee on Medical Aspects of Radiation in the Environment
^{60}Co	Cobalt-60
^{137}Cs	Caesium-137
DFR	Dounreay Fast Reactor
DGPS	Differential Global Positioning System
DMTR	Dounreay Materials Test Reactor
DPAG	Dounreay Particles Advisory Group
DSRP	Dounreay Site Restoration Plan
ED_{50}	Dose
EDAX	Energy Dispersive X-ray Analysis
EPS	Electronic Positioning System
et al.	And others
FCA	Fuel Cycle Area
FEPA	Food and Environment Protection Act (1985)
FITS	Fathom Instrument Towed System
g	gramme
g cm^{-3}	grammes per cubic centimetre
GBq	Gigabequerel
GPS	Global Positioning System
Gy	Gray
h	hour(s)
ha	hectare(s)
HAP	High Activity Population
HAT	Human Alimentary Tract
HATM	Human Alimentary Tract Model

HEPA	High Efficiency Particulate in Air
HPA-RPD	Health Protection Agency - Radiation Protection Division
HR	Hydraulics Research
HSE	Health and Safety Executive
ICRP	The International Commission on Radiological Protection
ICRU	International Commission on Radiological Units and Measurements
IAEA	International Atomic Energy Agency
ILW	Intermediate Level Waste
LAD	Low Active Drain
LLI	Lower Large Intestine
LWMOT	Low Water Mean Ordinary Tide
LWN	Low Water Neap tides
MBq	Megabequerel
mGy	milligray
MHWS	Mean High Water Spring tides
MLWS	Mean Low Water Spring tides
$m\ s^{-1}$	Metres per second
mSv	Milli-sievert
MTR	Materials Test Reactor
NaI	Sodium Iodide
^{93}Nb	Niobium-93
^{94}Nb	Niobium-94
NNC	National Nuclear Corporation
NRPB	National Radiological Protection Board
NSPAD	Near Surface Particle Activity Distribution
O	Oxygen
OD	Ordnance Datum
^{238}Pu	Plutonium-238
PFR	Prototype Fast Reactor
PTFE	Polytetrafluoroethylene
^{106}Ru	Ruthenium-106
RWMAC	Radioactive Waste Management Advisory Committee
^{90}Sr	Strontium-90
SE	(The) Scottish Executive
SEM	Scanning Electron Microscope
SEPA	Scottish Environment Protection Agency
SHIP	Shaft Isolation Programme

SS	Stainless Steel
SUERC	Scottish Universities Environmental Research Centre
SURRC	Scottish Universities Research & Reactor Centre
Sv	Sievert
TBq	Terabequerel
Tl	Thallium
TID	Technical Implementation Document
TROL	Tracked Robotic Offshore Logger
U	Uranium
UB	University of Birmingham
UK	United Kingdom
UKAEA	United Kingdom Atomic Energy Authority
UV	ultraviolet
^{90}Y	Yttrium-90

EXECUTIVE SUMMARY

Report Findings

1 The continued presence of fragments of irradiated nuclear fuel 'particles' in the environment has been an understandable cause of concern. In this third report, DPAG provides more definitive information on:

- the sources of particles, their generation and possible routes of release; [Chapter 2]
- their current distribution in the marine environment; [Chapter 4]
- the potential number on intertidal areas on the northern coast of Scotland; [Chapters 5 and 6]
- the possibility that they could be encountered by the public; and, [Chapter 6]
- their potential implications for public health. [Chapter 6]

2 On the basis of potential health effects (see below) the Group has designated particles containing an activity of 10^6 Bq ^{137}Cs or greater as *significant* particles, those with activities between 10^5 Bq and 10^6 Bq ^{137}Cs as *relevant* particles and those with activity less than 10^5 Bq ^{137}Cs as *minor* particles. [Sections 3.2.5-3.2.7]

3 SEPA has recently completed a large amount of research into the hazards of particles and the possibility of exposure to the public. This report necessarily draws upon members' evaluation of the resulting information together with analysis by members of the Group of the potential distribution and migration of particles. [Chapter 3]

4 DPAG has collated numerous reports on the particles and the events that may have led to their release. They demonstrate that potentially up to several hundred thousand particles were discharged from UKAEA Dounreay. [Sections 2.2.7-2.2.14 and Appendix C]

5 A range of particle types has been discharged from the site including MTR, DFR, and particles containing ^{60}Co (SS) and ^{106}Ru (tarry agglomerates). The most important of these, both numerically and in terms of potential risk, are MTR and DFR particles [Section 2.1]

6 MTR particles were generated by milling operations from 1958 until 1973 and by 'crushing and cropping' operations from 1973 until 1996. [Sections 2.2.2 : 2.2.3]

7 DFR particles were generated from 1969 until 1979, primarily by fires in a fuel processing plant and particularly by a fire on 30 May 1972. [Section 2.2.5]

8 Particles have been discharged into the environment by a variety of routes, primarily those involving the Low Activity Drain (LAD), Sea Tanks and Diffusion Chamber. Other routes include the 'Non-active' drains and the Acid Drain. [Sections 2.4.5 - 2.4.7]

9 There is little doubt that operations and events between 1959 and the mid 1980s led to the discharge of the majority of active particles *via* the LAD route. [Sections 2.4.5 – 2.4.8]

10 Consideration of current operations and sources on site, including the Shaft, suggests that a continuing discharge of particles is unlikely, but would, in any case, contribute few particles compared with those already in the environment. Filters have been fitted to the sea discharge line which should prevent any future discharge of particles *via* that route and the shaft is to be isolated. Without remedial action, however, the Old Diffuser remains a potential source of particles. [Sections 1.1.3 : 2.3.8 : 2.3.27]

11 DPAG concludes that a large proportion, especially of the *significant* particles discharged from Dounreay, have been buried in sediment or physically broken up to become smaller or fragmented particles and transported predominantly northeastwards from the site. [Section 4.3]

12 Currently, it is believed that about 1,000 *significant*, 1,000 *relevant* and 3,000 *minor* particles are present within the main particle plume offshore from Dounreay. [Sections 4.3.29 ; 4.3.34 : 4.3.35]

13 Of the *significant* particles present in the local marine environment, it is estimated that about 92% of these are within 0.5 km of the Old Diffuser. [Figure 4.20]

14 Of the *relevant* particles present in the local marine environment, it is estimated that about 95% are within 1 km of the Old Diffuser. [Figure 4.21]

15 Particles are not uniformly distributed with depth of sand. The proportion of *significant* particles is greater at depth than in the surface sediments, although the abundance of particles decreases with depth. [Section 4.4.21]

16 Smaller particles, generally having lower activities, are more easily mobilised and transported than physically larger (higher activity) particles. This effect may be reflected in the nature of particles detected on local beaches. [Section 4.4.15]

17 Monitoring of beaches around UKAEA Dounreay, using various methodologies has been undertaken for some time. This has enabled the recovery of particles and the reduction in potential exposure of the public. Early hand-held and wheel barrow monitoring were unsatisfactory, while Groundhog Mk 1 was unable to detect all *relevant* particles under all conditions. Groundhog Evolution is able to detect *relevant* particles to a depth of 100 mm and *significant* particles containing 10^6 Bq ^{137}Cs and greater to a depth of 200 mm on Sandside Beach. [Section 5.4.11]

18 The Group regrets interruptions of monitoring at Sandside Beach, these have made interpretations of findings difficult. [Section 5.1.21]

19 Of the local beaches monitored, up to February 2006, *significant* particles had only been detected on Dounreay Foreshore. *Relevant* particles have been detected only at Sandside Beach and Dounreay Foreshore. *Minor* particles had only been detected at Sandside Beach, Dunnet Beach and Dounreay Foreshore. [Tables 5.1 and 5.2]

20 DPAG considers that the possibility for any member of the public coming into direct contact with a particle with potential to cause harm is extremely small. The chance is 1 in 80 million per year for a particle with activity of 10^5 Bq ^{137}Cs at Sandside Beach. [Section 6.4.7]

21 With respect to the potential for particles to cause harm, DPAG has drawn upon work recently published by SEPA and conducted by the Health Protection Agency – Radiation Protection Division (HPA-RPD) and the University of Birmingham (Harrison *et al*. 2005). This showed that particles with activities of 10^5 Bq ^{137}Cs or less, typical of those currently found at Sandside Beach, would have to remain in stationary contact with precisely the same area of skin for at least 7 hours to cause any discernible effect and that this would be transient. For ingestion, such a particle, held stationary against the gut wall for 6 hours, might cause ulceration which would be repaired by natural regeneration. Committed effective dose following ingestion of particles containing 10^5 Bq ^{137}Cs is estimated as 0.1 mSv for an adult male and 0.5 mSv for a one-year old child. Particles on the Dounreay Foreshore which have contained activity up to 1000 times greater could cause harm, but the Foreshore is effectively inaccessible to the public. [Sections 3.2.14 : 3.2.20: Table 3.3]

22 The Group notes that particles with a composition similar to that of MTR113 would give rise to a slightly greater long-term hazard than other MTR particles due to its solubility in the gut. [Section 3.2.22]

23 The Group concludes that only *significant* particles with activities of 10^6 Bq ^{137}Cs or greater pose a realistic potential hazard to members of the public. However, DPAG considers it prudent that, in addition to significant particles, *relevant* particles with activities of 10^5 to 10^6 Bq ^{137}Cs should also be monitored and removed. [Section 6.2]

24 The Group concludes that there is an extremely small possibility of a member of the public coming into contact with a *relevant* particle on local beaches (with the exception of the Dounreay Foreshore); if they did so, no significant adverse health effects would be expected. [Section 6.4.7]

25 Many of the particles detected on the Dounreay Foreshore could cause significant health effects, if a member of the public came into contact with them, but there is, in practice, no public access to this area. [Sections 7.6.2 : 7.6.3]

26 It is expected that particles will continue to be washed onto local beaches for some decades. [Section 4.6.14]

27 The Group was not required to consider potential effects of the particles on the ecosystem and has not done so. DPAG is aware that the ICRP assessment that "*provided man is sufficiently protected then other organisms are adequately protected*" is under reconsideration; its review is currently incomplete. [Background, para 14]

Recommendations

28 DPAG considers that UKAEA should mitigate the potential future release of particles into the marine environment by isolating the Old Diffuser Chamber. [Section 2.3.47]

29 The Group considers that Low Level Waste Pits should either be emptied or adequately protected from environmental impacts, including potential breaching by exceptionally large waves. [Section 2.3.34]

30 Offshore particles should be characterised further in terms of their extent, numerical density and distribution. [Section 4.3]

31 A larger sample of the particles recovered should be characterised in terms of their mass, density, shape, size, composition, chemical reactivity and radionuclide content, to test assumptions about the behaviour of particles in the sea. [Sections 4.2.9 : 4.2.16 : 4.2.23-25]

32 Further offshore monitoring should be undertaken to provide information on the continuing need for beach monitoring, both in terms of its extent and frequency. [Sections 4.6.7 – 4.6.10]

33 UKAEA should undertake further work to estimate the number of ^{60}Co particles in the environment. [Section 2.1.4]

34 The Group recommends that work should be undertaken to establish an estimate of the proportion of particles of characteristics similar to particle MTR113 that may have been released to the environment. [Section 2.1.18]

35 Beach and Foreshore monitoring systems must be capable of detecting particles having an activity of 10^6 Bq ^{137}Cs and ^{60}Co or greater (*significant*) to a minimum depth of 300 mm. The capabilities of such systems should also allow particles with activities of between 10^5 and 10^6 Bq ^{137}Cs (*relevant*) and ^{60}Co to be detected to a minimum depth of 200 mm. [Section 6.5.1]

36 The Group considers that any new monitoring systems must be empirically validated and compared directly with their predecessor. [Section 5.8.6]

37 The Dounreay Foreshore should be closed to the public until the Regulator decides that this is of no further practical value. Access should be available to local beaches unless future monitoring shows significant deterioration in their condition. [Section 7.8.10]

38 The beaches at Scrabster, Crosskirk, Brims Ness, and Thurso should be appropriately monitored at the intervals current. The beach at Sandside should be monitored comprehensively every two weeks. Melvich, Murkle, Peedie and Dunnet beaches should be monitored annually. [Sections 5.8.1 – 5.8.3]

39 Monitoring of the Dounreay Foreshore and local beaches should continue until the Regulator decides that such procedures are of no further practical value. [Sections 7.6.3 – 7.6.4]

40 In 1998, the then Secretary of State wrote to SEPA asking that "*SEPA ensure that there is sufficient monitoring in place to ensure that any particles finding their way to the beach at Sandside Bay are promptly detected and removed*". This statement was presumably intended to be interpreted in practice, according to the degree of risk entailed. DPAG considers that the removal of literally 'any' particle is impractical and, in the case of *minor* particles, is unnecessary on the grounds of the radiological protection of the public. [Section 7.7.3(iv)]

41 The extent and nature of the contamination of the environment means that it is impractical to aim to return the environment to a pristine condition. Remediation should aim to do more good than harm to the environment. DPAG recommends that serious consideration should be given to the targeted removal of *significant* particles in the marine environment providing that this causes only minimal disturbance to the ecosystem. [Sections 4.6.17 : 6.9.3]

BACKGROUND TO THE ESTABLISHMENT OF DPAG

Formation

1 The Dounreay Particles Advisory Group (DPAG) was set up by UKAEA and SEPA in May 2000 to provide independent scientific advice to UKAEA and SEPA on particles of irradiated nuclear fuel found in the marine environment around the Dounreay nuclear research facility, Caithness.

2 The first documented finding of a particle at Dounreay was in 1979 on the enclosed Dounreay Foreshore, although earlier contamination could have been associated with unidentified particles (RWMAC 1999a). In November 1983, a particle was recovered from the Dounreay Foreshore which was shown by laboratory examination to have been associated with the reprocessing of Materials Test Reactor (MTR) fuel in the early 1960's (Statistical Bulletin 1984). Further particles have been periodically identified on the Dounreay Foreshore.

3 In May 1984, a particle was detected on Sandside Beach at Reay. The beach is located about 3 kilometres to the southwest of the Dounreay site. In 1997, a further 2 particles were found. In 1999, 5 further particles were recovered from Sandside Bay, 6 in 2000, 3 in 2001, 5 in 2002, 24 in 2003, 5 in 2004, 6 in 2005, and 2 particles were recovered up to February 2006.

4 In June 1997, as part of an engineering project in the vicinity of the Diffuser outlet, a diver located a Dounreay Fast Reactor (DFR) particle on the seabed. This find brought forward already planned surveying of the seabed to August and September 1997, and further particles were located and retrieved offshore from the Dounreay site.

5 As a result of these sea-bed finds, on the advice of SEPA, the then Scottish Office imposed a FEPA[1] order. The Order restricted the taking of all seafoods in an area of radius 2 km, centred on the end of the outfall pipe (600 m offshore). The Order covered the removal of any species of demersal or pelagic fish, molluscs and crustaceans. The purpose of the Order is to prevent the use of such species for the supply of food or for the preparation or processing of anything from which food could be derived. The Order came into force on 29 October 1997.

6 In 1998, SEPA published a report (SEPA 1998) that included an assessment of the public health implications of offshore particles. The main recommendations connected with this report were reproduced in the First DPAG Interim Report (2001). The SEPA report and its recommendations were considered by the Scottish Office. The Secretary of State for Scotland subsequently wrote to SEPA asking that:

"SEPA ensure that there is sufficient monitoring in place to ensure that any particles finding their way to the beach at Sandside are promptly detected and removed."

7 To help SEPA to ensure that its statutory duties were fulfilled, and to enable SEPA to provide advice on the technical issues involved in the UKAEA research programme to the (now) Scottish Executive, it was decided to establish DPAG.

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[1] The full title of the Order is the Food Protection (Emergency Prohibitions) (Dounreay Nuclear Establishment) Order 1997 an order made under the Food and Environment Protection Act 1985.

Purpose of DPAG

8 DPAG provides advice and recommendations to UKAEA and SEPA in respect of ways in which monitoring can be improved and on the various associated research programmes related to radioactive particles.

9 The current remit of DPAG is to:

- provide impartial scientific advice to SEPA and the UKAEA on UKAEA's current research programme in respect of the sea-bed particles;
- comment on the techniques being used and the results being obtained; and,
- provide comprehensive reports on particles in the environment and any associated potential implications for the health of the public.

Membership and Procedures

10 The membership of the Group is drawn from a range of skills and backgrounds. The Group has an independent Chairman. Both SEPA and UKAEA have Observer status on the Group, which permits them to provide information to members during meetings and brief DPAG about current research. The Scottish Executive also has Observer status on the Group. Membership has been reviewed to ensure that the Group has a sufficient diversity of skills to address the issues raised. The membership of DPAG is detailed in Appendix A and biographic details of current members are provided in Appendix B.

11 DPAG holds bi-monthly meetings. In order to facilitate in-depth discussion of issues and presentation of work in progress, DPAG has closed meetings when members of the public are not able to attend. At the end of its meetings, there is an opportunity for members of the public both to listen to an outline of the issues considered by the Group at the meeting and to put questions to DPAG.

12 In order to ensure that DPAG members are able to examine all available pertinent information, some papers are supplied to DPAG on a confidential or restricted basis. Consequently, DPAG papers are not made available to third parties.

13 DPAG's progress has been regularly reported by the Chairman to SEPA and, thence, to SEPA Board meetings. Agendas and minutes of the Group's meetings are available on www.sepa.org.uk/radioactivity/dpag.

Exclusions from this report

14 DPAG does not have a remit to consider:

- the FEPA Order;(see 5, above)
- the Best Practicable Environmental Option being developed by UKAEA Dounreay;
- the effects of particles on the ecosystem.

Chapter 1

INTRODUCTION

1.1 Background

1.1.1 Fragments of irradiated nuclear fuel 'particles', generally similar in size and density to grains of sand, but containing minute fragments of irradiated nuclear fuel, have been generated by practices at UKAEA Dounreay. These fragments commonly contain a range of radionuclides and associated activities. The particles are generally classified according to the amount of ^{137}Cs activity.

1.1.2 UKAEA Dounreay historically released particles into the marine environment primarily *via* the liquid-waste discharge system.

1.1.3 Under the instruction of SEPA, in June 2005, UKAEA Dounreay commissioned a final filter on the radioactive discharge system preventing thereby further release of particles by this route.

1.1.4 Since 1983, particles have been found on the Dounreay Foreshore and, since 1984, on the publicly accessible beach at Sandside Bay. In 2005, a particle was also found on Dunnet Beach.

1.1.5 The Group is not aware of any current procedures at UKAEA that generate particles but they continue to be found in the environment. A large number of particles are present on site and these could potentially enter the marine environment.

1.2 Scope of Work Undertaken by DPAG

1.2.1 In seeking to establish an overall understanding of the particles and their behaviour and the potential consequences of their presence, the Group has considered in depth the following:

a) The nature of the particles.
How, when and where were particles created at UKAEA Dounreay? Can any estimate be made of the number of particles released and the range of radioactivity they contained?

b) Movement of particles.
By which routes were the particles released from the site into the marine environment? Could any estimate be made of the number of particles remaining in the local marine environment, particularly related to their radioactive (^{137}Cs) content? Can an estimate be made on the current distribution of particles? Can their break-up and marine transport be reasonably understood and related to finds on the Foreshore and Sandside Bay? Can predictions be made of their future movement and its implications? Is any information available on any final fate of the particles?

c) Number and Detection.
What types and numbers of particles have been found on the Dounreay Foreshore, at Sandside Bay and other local beaches? What amounts of radioactivity did they each contain? On what dates were they found and to what extent can this information be related to their marine transport? Are the monitoring systems in use adequate for the detection of particles that might have implications for the health of the general public?

d) Potential Hazard
What level of radioactivity in a particle could have significant implications for health, if encountered by a member of the public, through contact with the skin or if ingested or inhaled? What is the probability of such an event on a publicly accessible beach, such as at Sandside Bay?

1.3 Previous Interim Reports

First Interim Report

1.3.1 The first DPAG report was based on the information available to the Group up to December 2000. In this (DPAG 2001), DPAG sought to set out what was known about the historical sources of the particles. The Group gave preliminary consideration as to whether there might be continuing sources for particle release and what are the characteristics of the particles. An initial study of their distribution offshore was presented. It was recognised that much deeper consideration of these aspects was necessary, and topics were identified on which more detailed information was essential.

1.3.2 The Group was provided with data collected from surveys of the seabed, obtained using a towed instrumentation system. Although reservations about the procedure used to collect these data were expressed, a re-analysis of the raw data was undertaken by a member of the Group. Importantly, despite the considerable uncertainties, this analysis cogently suggested a plume-like feature for the distribution of the particles, northeast of the line from the Tunnel to the Diffuser, with few particles extending beyond the sharp limits of the plume.

1.3.3 The report included an initial assessment of the performance of a then recently introduced vehicle-mounted measurement system (Groundhog Mk 1) recently introduced at that time for monitoring local beaches that are accessible to the public.

Second Interim Report

1.3.4 Following the production of the first report, the Group continued to develop its understanding of the various issues relating to the occurrence of particles. Progress made up to December 2002 was summarised in a Second Interim Report (DPAG 2003).

1.3.5 Since the completion of the First Interim Report, a review of the chronology of the generation and potential releases of particles to the environment from UKAEA was undertaken by DPAG. This review drew upon and updated reviews by UKAEA (UKAEA 1999) and by the Radioactive Waste Management Advisory Committee (RWMAC 1999) as well as many other reports. Several issues were identified as requiring more detailed consideration. This historical analysis assisted in the development of the understanding of contemporary aspects of the situation, in terms of the potential numbers of particles discharged, the routes of and a timescale for their release.

1.3.6 Continued recovery of particles in the marine environment and targeted research undertaken by UKAEA Dounreay to investigate the distribution of particles allowed DPAG to present a much improved understanding of the distribution and behaviour of particles in the marine environment. It was estimated at that time that about 2000 particles remained in a plume, parallel to the shore and apparently originating in the area shoreward of the Diffuser. It was reported that a lesser number of smaller particles lie west of the Diffuser and that the Sandside Beach particles have come from this westward transport. It was noted that, while no particles had been found at three sites west of Sandside Bay, in two areas to the east of Dounreay, near Crosskirk and Brims Ness, particles had been found in the seabed in accordance with an oceanographic model. The particles recovered had activities comparable with those found on Sandside Beach. Studies of the re-population of areas of the seabed previously cleared of particles suggested a mobile surface layer containing particles less radioactive than those below 100 mm in the sediment.

1.3.7 The DPAG Second Interim Report (DPAG, 2003) indicated that during recovery of particles, 78 had fragmented suggesting that physically larger particles may break up to produce smaller ones that are more easily transported by seabed currents. The need for further information and analysis was noted.

1.3.8 In this report, a more detailed evaluation of the terrestrial beach monitoring system Groundhog Mk 1 was presented. This showed that the equipment did not meet the required detection criteria, as defined by SEPA, under all conditions. The approximate 'worst-case' detection limit for radioactivity contained by a particle was estimated to be about four times greater than that specified.

1.3.9 The Group also reported its initial consideration of the Groundhog Mk II ('Groundhog Evolution') system, an improved version of its predecessor. It was recommended by DPAG that experiments be established to provide an unequivocal demonstration of the system's capabilities.

1.3.10 The overriding concern arising from the presence of particles in the marine environment was that of their potential adverse affect on health. A preliminary assessment of the health implications for a member of the public encountering a particle was made, based on an earlier report published by SEPA and NRPB (SEPA 1998). This report suggested that "*If a fragment of relatively low activity (less than 10^6 Bequerels (Bq) ^{137}Cs), or if a more active fragment within the bulk of the foodstuff as it passed through the gastrointestinal tract, then deterministic effects might be avoided, while stochastic effects could become more important. In the case of a fragment containing 10^6 Bq ^{137}Cs, the committed effective dose from ingestion could be a few millisievert (mSv)*".

1.3.11 The report indicated that such a dose would correspond to an increased risk of fatal cancer of less than 1 in 1000, compared with an ambient risk of about 1 in 4. It was noted that this result needed to be taken in conjunction with the very small probability of ingesting a fuel particle.

1.3.12 A major suite of research to consider the health implications, specifically related to particles, had been commissioned by SEPA to be carried out under the auspices of NRPB.

1.4 Recommendations from Previous Reports

1.4.1 DPAG made a number of recommendations in its First Interim Report (2001) report. These were superseded by those recommended in the Second Interim Report (2003), which are detailed in Appendix C.

1.5 The Present Report

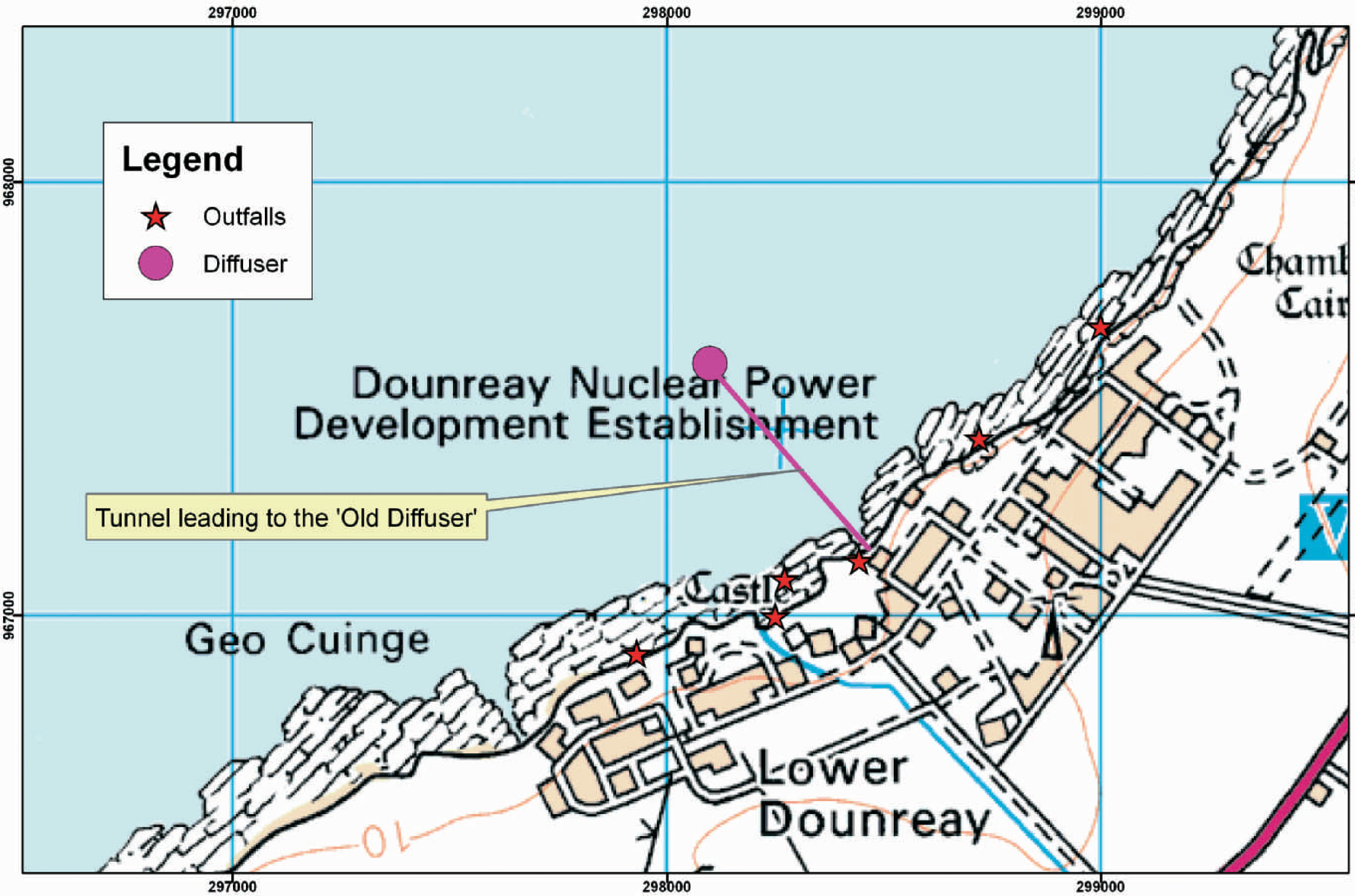
1.5.1 Like its predecessors, the present report sets out progress in our understanding of the nature and behaviour of particles in the environment.

1.5.2 A major new development has been the recent completion of the comprehensive study of the potential health implications of particles to which reference has already been made. As a consequence, a timely opportunity was created to bring together our various findings in an assessment of the current situation, particularly in relation to public health.

1.5.3 In so doing the Group took a common-sense view of the limited information available.

1.5.4 The report seeks to be realistically definitive to the extent that these limitations allow. It also identifies areas in which further work could be undertaken and its potential value.

1.5.5 In order to be as comprehensive and self-contained as reasonably practicable, where appropriate, essential details or summaries of previous work have been reproduced, mainly as appendices.



N

0 0.25 0.5 Kilometres

Figure 1.1 Location of 'Old' Diffuser, Shaft tunnel and Dounreay 'Non-active' outfalls.

SEPA
Scottish Environment Protection Agency

Chapter 2

NATURE, ORIGINS AND ROUTES OF RELEASE OF PARTICLES TO THE ENVIRONMENT FROM UKAEA DOUNREAY

2.1 Nature

Types of radioactive particulate matter

2.1.1 Three types of radioactive particulate matter have been so far identified in the environment around UKAEA Dounreay. These are:

- Particles of spent nuclear fuel;
- Particles containing ^{60}Co;
- Particulate matter containing ^{106}Ru.

Particles of spent nuclear fuel

2.1.2 These are principally of two types containing fragments of either Materials Test Reactor (MTR) or Dounreay Fast Reactor (DFR) spent fuel together with associated fission products and actinides. Both types are so predominant numerically and in terms of potential health effects that they are given detailed consideration.

2.1.3 A few particles have been identified as containing fragments of Prototype Fast Reactor (PFR) spent fuel. This fuel was treated in the PFR Reprocessing Plant. The procedures were quite different from those used with MTR and DFR fuel with greatly reduced potential for their discharge to the environment.

Particles containing ^{60}Co

2.1.4 Four particles containing ^{60}Co have been found on the Foreshore at Dounreay and eight offshore (UKAEA, personal communication, 2006). Similar particles have also been found on-site. UKAEA categorise these particles as Stainless Steel (SS) particles. The radioactive component is predominantly ^{60}Co, generated by neutron activation of cobalt in the stainless steel structure of reactor components or in components of some fuel elements. Their route to the environment has not been established.

Particulate matter containing ^{106}Ru

2.1.5 This material comprises black tarry agglomerations of large numbers of minute particles bound in an organic matrix incorporating granules of sand, hair, seaweed and man-made fibres. These agglomerates, found in 1983, followed a clean out of the upstand pipes of the Old Diffuser which had been designed to disperse low level radioactive liquid effluent discharged into the sea. Their source was identified as the Scrubber Plant of the Dounreay incinerator. Following modifications (including improved filtration), in 1984, these have not been found. They are not considered further.

MTR particles

Uranium-aluminium alloy elements (Higginson 2000)

2.1.6 The total number of MTR fuel elements reprocessed to the end of 1973, when the milling process ceased (see below), was approximately 7850. Of these, it is estimated that about 7800 elements comprised uranium-aluminium alloy as the fuel component.

2.1.7 These MTR particles are similar both in size (about 0.4 to 3 mm diameter) and density (3.1 +/- 0.7 grams per cubic centimetre (g/cm^3)) to sand grains on the Dounreay Foreshore and at Sandside Beach. On average, particles found on the Foreshore and Beach are physically larger and contain greater levels of radioactivity than those found on the site.

2.1.8 Significant variations of the ^{137}Cs activity in particles of the same mass are to be expected for several reasons. First, a particle may be of pure aluminium (Al), containing no fission products and, therefore, would be undetectable, whereas others may contain varying amounts of uranium (U) and associated fission products. Second, the ^{137}Cs content for particles containing a mass of uranium depends upon the radiation history of the fuel from which it originated. The amount of ^{137}Cs increases with neutron fluence (or ‘burn-up’), which is proportional to the power and duration at which the reactor operated and also depends on the position of the fuel element in the reactor core (generally being greater for an element in the centre than for one on the periphery of the core). It is also dependent on where in the fuel element the particles originated.

2.1.9 There is a degree of correlation between mass and activity as illustrated in Figure 2.1. This is given detailed consideration in Chapter 4.

2.1.10 At the request of the Group, via SEPA, UKAEA has undertaken measurements of the density of some MTR particles. Examination of the composition of MTR fuel (Toole, J. UKAEA, Personal Communication, October 2005) showed that it comprised a uranium-aluminium alloy of Al + UAl_4. For the range of uranium content, the theoretical density range is from about 3.1 to 3.6 g/cm^3. The empirical findings for MTR particles are inconclusive and the methodology needs to be developed further.

2.1.11 The particles primarily comprise aluminium with very small inclusions of uranium and associated products, of which ^{137}Cs, ^{90}Sr and its daughter ^{90}Y, and actinides are of greatest radiological significance. Radiochemical analysis of three particles from the Foreshore found that the fission products were within a structure of aluminium and uranium, the latter being typically 10% to 28% by weight. Both the structure and composition are characteristic of irradiated MTR fuel.

2.1.12 The radioactive isotopes ^{137}Cs and ^{134}Cs decay at different rates. Using this relationship, estimates of the dates that the particles were irradiated can be made. For 15 particles found in early 1984, their ages were in the range of 17 to 22 years with a corresponding irradiation date of 1965 +/- 3 years. The age of a further particle, found in March 1993, was determined as 27 years, which would correspond with an irradiation date similar to that estimated for the particles found 9 years previously.

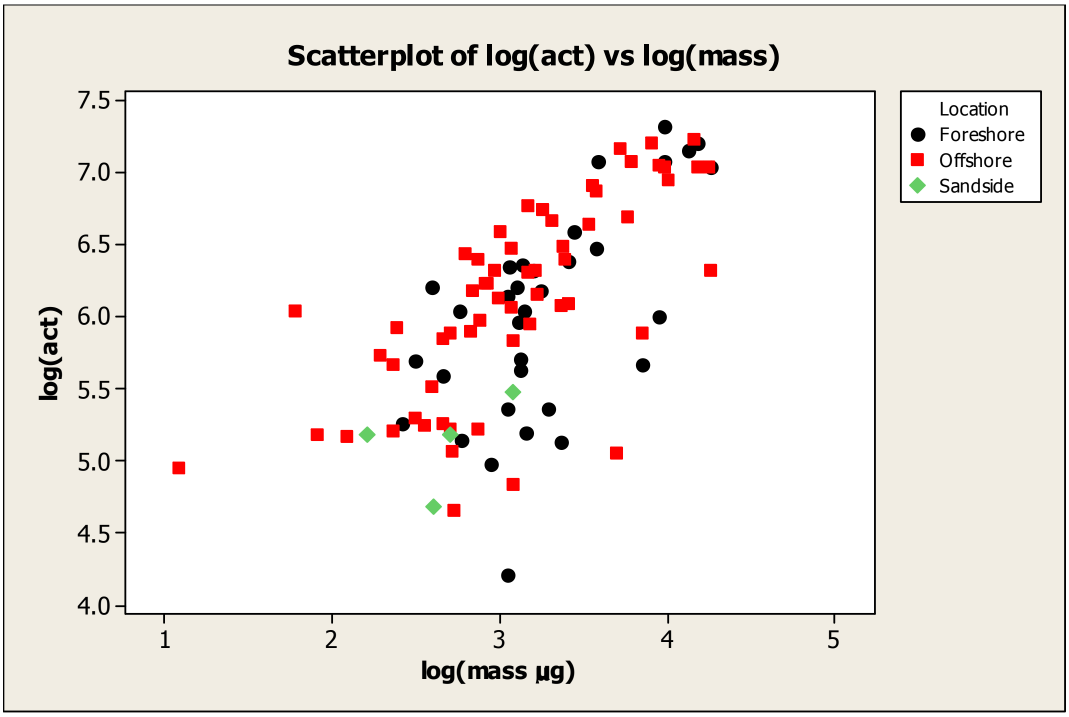


Figure 2.1 **A mass-activity plot for a selection of particles recovered from Dounreay Foreshore, offshore and Sandside Beach**

2.1.13 Although radiation doses are dominated by emissions of beta rays associated with ^{90}Sr and ^{90}Y, the particles are usually detected and, for convenience, quantified by the gamma rays emitted during the decay of ^{137}Cs and its daughter ^{137m}Ba. The level of radioactivity per particle ranges from $<10^4$ up to about 10^8 Bq ^{137}Cs.

Experimental MTR fuels (Cartwright, P., UKAEA, Personal Communication, May 2006)

2.1.14 In May 2006, UKAEA disclosed that about 900 experimental MTR fuel elements, some of which did not contain uranium-aluminium alloy, had been reprocessed to the end of 1973.

2.1.15 Three Canadian NRX elements containing a plutonium-aluminium alloy were reprocessed. These elements were dismantled manually. As they were not subject to the milling process, no particles would have been generated and they are, therefore, not considered further.

2.1.16 Between 1962 and 1973, 862 elements from the Danish reactor at Riso were reprocessed. Most of these contained uranium-aluminium alloy but up to 10 elements are believed to have contained uranium oxide (U_3O_8) –aluminium alloy plates and were subjected to milling. The density of these particles has been estimated to be about 2.7 g/cm^3.

2.1.17 In 1971, 39 Greek elements containing an alloy of uranium and silicon were reprocessed with particles likely to have been created during milling. The density of the particles has been estimated to be 4.5 - 4.8 g/cm^3.

2.1.18 This information suggests that the number of elements reprocessed that did not contain uranium-alloy was less than 1% of the number that did and that the number of particles generated and subsequently discharged is assumed to be proportionately smaller. Their potential significance relates to differences in their behaviour if ingested in the human body, as discussed in Chapters 3 and 6.

DFR particles (Higginson 1999)

2.1.19 These particles comprise material from spent fuel elements of DFR. However, they differ from MTR particles in being apparently non-metallic, lacking structural strength and usually containing niobium (which was the cladding material for DFR fuel). The form of the material is unlike that of the fuel elements and, as discussed below, metallurgical change had occurred during reprocessing. DPAG has been advised by UKAEA that a method is not available for the measurement of single DFR particles because of their friable and porous nature.

2.1.20 Their fragile nature and small size restricted measurement of the specific mass to two particles, requiring estimates to be made of the upper mass limit for a further four particles. Values reportedly ranged from 0.08 mg to an estimate of < 2 mg. Evidently, no accurate measurements of density have yet been made, but the DFR particles found on the sea-bed appear to fall within a range 1.5 –7.0 g/cm^3.

2.1.21 Energy Dispersive X-ray Analysis (EDAX) of particles suggested that their major constituents were approximately 40% niobium, 20% uranium and 15% iron with the remainder comprising a variety of minor constituents in the range of 0.5% to 3%.

2.2 Generation of particles

MTR particles

2.2.1 The first stage of reprocessing activities at Dounreay was to dismantle fuel elements under water, initially in the D1204 Pond from 1958 and then in the DMTR Pond from 1964 to 1969 and subsequently in D1204. Both facilities had connections to the Low Activity Drain (LAD). The DMTR Pond had been designed for cutting pure aluminium components.

2.2.2 A milling process was used to remove the aluminium casing of Mark II fuel elements in preparation for reprocessing. This process generated swarf, not only from the casing, but also inadvertently from time to time from some of the underlying uranium fuel plate and associated fission products. Consequently, a fraction of the aluminium swarf (estimated crudely as between 0.1 and 1.0%) contained active fuel particles embedded in the substrate.

2.2.3 From 1973 to 1996, "crushing and cropping operations" replaced milling but this practice also created particles, though not necessarily identical in structure to those produced through the milling process. These operations produced slivers rather than the more rounded particles, generated by milling.

2.2.4 All of the swarf and particles produced were originally to be disposed of in the Shaft, which is described in Section 2.3 and is known to contain several tonnes of swarf. Later, disposals of swarf were also made to the Silo However, as discussed in Section 2.3, it is certain that many particles were also discharged to the sea *via* the LAD system to which the processing ponds were connected.

DFR particles

2.2.5 Between 1969 and 1979, DFR fuel was treated using a leach dissolver. During the process, spontaneous combustion periodically occurred that created particles of irradiated fuel 'fused' with niobium cladding. Some of the particles were discharged to sea *via* the LAD system.

2.2.6 A more detailed chronological account of the practices in reprocessing these fuels and associated events that could also have resulted in discharges of particles to the environment was published in the Second Interim Report of DPAG (DPAG 2003). For ease of reference in the following discussion, the relevant sections of that account (with some updating) are reproduced in Appendix D.

Estimates of the number of particles discharged

2.2.7 Estimation of the number of particles discharged to the environment would improve understanding of the past and present situations, but is fraught with great uncertainty.

2.2.8 As summarised in Appendix D, events have been recorded in which swarf had accumulated in, or leaked from, the LAD following its inappropriate discharge from the MTR Treatment Ponds. Further consideration of two of these events and early practices can provide some indication of the numbers of particles that may have been released to the sea and also illustrate the inevitable uncertainties.

2.2.9 A UKAEA report (Simson 1998) on the event that occurred in 1963 estimates that the activity of swarf washed down the LAD was up to 0.6 TBq ($6x10^5$ MBq). If its radioactive composition was similar to that of current particles, about half of this activity would be attributable to ^{137}Cs. Some of this material is likely to have been retained in sludge that remained in the Effluent Tanks at the time of discharge. From 1961, sludge was removed manually and disposed of in the Shaft. For the purposes of illustration, a nominal activity per particle of $1x10^6$ Bq ^{137}Cs has been used, and retention by sludge has been taken as 90% (*viz.* 10% of particles present would be discharged to sea). Therefore, in this illustration, the activity within the LAD would correspond to about 300,000 particles of which some 30,000 would have been discharged to the environment. However, we do not know the size or activity distribution of particles at the time of their release into the environment. The current size range and number of particles in the marine environment does not necessarily reflect these parameters at the time of discharge. Some particles will have fragmented while they have been in the marine environment, and smaller particles may have cleared the area. Clearly, if each of the released particles contained a ^{137}Cs activity 100 times greater than in the example above (*i.e.* 10^8 Bq corresponding to roughly the largest activity yet found in the environment) then our estimate of the number released would be 100 times lower, *i.e.* only 300 particles. If a much lower activity of 10^5 Bq were assumed, corresponding to the commonest particles among those now in the environment, the number released would be estimated as 300,000. Similar uncertainty exists over the number of incidents in which particles were released and the total activity involved in each, as described below. In reality, it is likely that different incidents released different numbers of particles and having a range of activities as well as innumerable particles of pure aluminium.

2.2.10 Measurements of swarf that had leaked through a hole in the LAD, in 1964, suggested that the leaked material contained about 1,000 particles similar to those subsequently found on the Foreshore. As the report indicates, this level in leakage through a hole in the pipe "*implies that an even greater quantity of swarf had been discharged from the Pond into the LAD*" (Higginson 2000). If the leakage amounted to as much as 1%, about 100,000 particles would have been discharged into the LAD, similar to the 1963 event. However, anecdotal evidence suggests that hosing caused overflow of at least some of the material into the ('Non-Active') Acid Drain. This material would not have been retained in the Effluent Tanks.

2.2.11 In the early years of Pond operations, high dose rates on the duct carrying the LAD were also reported, implying that discharge of substantial quantities of active swarf was not uncommon.

2.2.12 No evidence is currently available to support or refute the assumed percentage of particles retained in sludge within the Effluent Tanks. However, if this were an underestimate, it would be offset by the fact that, from the beginning of operations until July 1960, sludge containing particles in the Tanks was agitated and then discharged directly to the environment with the liquid waste.

2.2.13 As a consequence of the great uncertainties intrinsic to these estimates, the number and activity of particles released into the environment will never be known with any degree of confidence.

2.2.14 As will be recognised in the remainder of the report, DPAG has concerned itself only with those particles that remain in the immediate vicinity of Dounreay.

2.3 Routes of Release of Particles to the Environment

Sources on land excluding drainage systems

2.3.1 Investigations have been undertaken by UKAEA of sources on land that could potentially have been routes of release for particles at least to the Foreshore. Reports of these studies (Simson 1997) were carefully considered by the Radioactive Waste Management Advisory Committee and its findings were set out in its report published in 1999 (RWMAC 1999a). The principal conclusions, except for those relating to drainage systems, are summarised here with updating where appropriate.

Transport of swarf to the Shaft

2.3.2 Swarf was transported in flasks across the site from the processing areas for disposal in the Shaft by the authorised procedure. The use of the flasks did not preclude spillage or loss of particles in transit.

2.3.3 Comprehensive surveys of roadways, verges, loading bays and soil areas resulted in the finding of 79 particles up to 1999. The small number found suggested that they were unlikely to represent an on-going reservoir yielding the consistent numbers then being found annually on the Foreshore (about 11 per year). In particular, the levels of radioactivity and surface characteristics of the particles found on site are significantly different from those on the Foreshore, being physically smaller and less well rounded.

Roofs, gutters and gulleys

2.3.4 No particles were found in gutters, gulleys or among roof chippings, which could have harboured wind-borne particles (UKAEA 1999).

Cliff overburden and cliff faces

2.3.5 Material excavated on site has been deposited in cliff overburdens and in the East Landfill. If the material contained particles, erosion could result in their direct deposition on the Foreshore. The cliff has been and continues to be subject to erosion and coastal retreat.

2.3.6 A detailed survey of the cliffs in 1996 found one particle of the DFR type containing 4.8 x 10^4 Bq ^{137}Cs and no particles were detected in the re-survey of 1998.

2.3.7 No particles were found in surveys of the exposed rock face, the eroding landfill slope, or the areas where stabilisation matting had been removed at the East Landfill.

2.3.8 The findings effectively excluded these areas as an on-going source, being incompatible with the consistent annual finding of particles on the Foreshore at that time.

The Dounreay Foreshore

2.3.9 In seeking an explanation for the fairly consistent number of particles found annually on the Foreshore, it was recognised that the sand and pebble beach of the west Foreshore might harbour a 'store' of particles, some being brought to the surface periodically.

2.3.10 In August 1996, the beach was methodically stripped by removing successive layers each of 100 mm thickness down to bedrock at about one metre depth. The surface of each layer was monitored before its removal.

2.3.11 In total, four particles were found at depths between 400 to 700 mm. Their characteristics are similar to those found previously and are of the MTR type.

2.3.12 Following completion of this investigation, a further three particles were found between September and December 1996. The annual total of 16 was only five more than the long-term average at that time, despite this comprehensive search.

2.3.13 It seems clear that the Foreshore was not harbouring a substantial store of particles, and *significant* particles continued to be found after this effective clearance of the Foreshore.

The Shaft

2.3.14 In 1956, a shaft 65.4 metres deep and 4.6 metres nominal diameter was excavated (see Figures E.6 and E.7). Its purpose was to allow removal of earth and rubble to the surface from a 600 metre-long tunnel being constructed to house the site's pipeline for the discharge of liquid waste to the sea.

2.3.15 The Shaft is unlined apart from the top eight metres where the rock is covered with a wire mesh and shotcrete. About 12 metres of the Shaft are above sea level with the main Shaft (and hence any contents) in contact with the Dounreay Shore Formation bedrock and groundwater system.

2.3.16 By August 1957, UKAEA had decided to seek authority to use the Shaft for waste disposal of Intermediate Level Waste (ILW). A reinforced concrete plug was emplaced in the connecting tunnel (see Figures E.6 and E.7) and pressure grouted to isolate the Shaft from both the pipeline tunnel and the sea. In 1959, the Scottish Office licensed the Shaft as a disposal facility for ILW. Authorised disposals took place between 1959 and 1977.

2.3.17 Swarf, amounting to about six tonnes (of which very approximately between 0.1 and 1.0% was estimated to be active (UKAEA 1999) was disposed of in the Shaft. This would represent a very substantial store of possibly millions of particles.

2.3.18 A UKAEA review (Walford 1995) of contemporary Health Physics Survey reports confirmed that operation of the Shaft as an open-air facility and the crude tipping of swarf into the Shaft was a potential source for airborne dispersal of particles outside of the area around the Shaft, especially in windy conditions. Some of the "hot spots" recorded in the 1964-65 surveys were consistent with the presence of fuel particles of the "beach particles" type. Indeed, several reports were quoted as containing recommendations for "immediate decontamination" using full protective clothing.

2.3.19 It seems reasonably certain that cliff-top areas outside the Shaft compound were routinely contaminated by active particles. However, for this contamination to account for the fairly constant and continuing rate of annual finds on the Foreshore, a substantial store of particles being released by erosion would have been necessary. The surveys of cliffs in November 1996 and March 1998 indicated unequivocally that there was not such a store.

2.3.20 On 10 May 1977, a well-documented violent explosion occurred in the gas space at the top of the Shaft, resulting in the dispersal of some radioactive material from within. The UKAEA review (Walford 1995) stated (paragraph 7.8): "*There is some evidence, though it is not conclusive, that irradiated MTR fuel particles (typical of the "beach particles" found on the Dounreay Foreshore from November 1983 onwards …) were present –though not identified –both within and outside the compound in the days following the explosion*" It was suggested that any 'particles' could have been ejected by the explosion from crevices (*viz.* surface irregularities) in the superstructure rather than from the volume of waste deposited in the Shaft. However, routine surveys showed only a slight increase in activity on the Foreshore at a point on the rocks just below the Shaft about four months after the explosion. For the remainder of 1977, the findings were within the normal range of activity. This evidence suggests that the explosion was not an enduring source of particles.

2.3.21 Water has been pumped from the Shaft since its inception and discharged to the LAD. It was unfiltered until 1985 and could, therefore, have contributed particles *via* this route, especially when swarf disposals were concurrent with operation of pumping.

2.3.22 Hypothetically, particles could escape from the Shaft *via* the concrete plug in the stub tunnel at the base. The plug was inspected from the seaward side using a remotely operated vehicle in May 1992. It was apparently in good condition and there was no evidence of significant radioactivity. However, even if this were a route of release, particles would enter the adit and the effluent tunnel. The water velocities in the adit and effluent tunnel are too small to move particles into the environment, so that any that entered the Tunnel would remain there.

2.3.23 Self-evidently, the Shaft was not a purpose-built disposal facility. It would not satisfy current standards for such use, especially when, at the surface, it is only about five metres from the cliff face. As indicated earlier, it has a lining only on the upper eight metres and deposited particles are almost certainly at greater depths. The potential exists, therefore, for hydrogeological leakage of particles. This possibility has been the subject of much examination (see Appendix E).

2.3.24 A report produced by RWMAC (RWMAC 1999b) concluded that "*it is extremely unlikely that particles can migrate via any natural fracture flow system through the mass of the Caithness Flagstone Group to the near-shore environment*".

2.3.25 Subsequently, an intensive programme of drilling and hydrogeological investigation has been conducted around the Shaft and proximal parts of the

Tunnel as part of UKAEA's Shaft Hydrogeological Isolation Programme (SHIP). This has revealed more detail of the rock structure than was previously known and is as summarised in Appendix E. The Shaft has been shown to intersect two bedding-parallel permeable zones which dip at ~100 northwest, *i.e*. seawards. DPAG concludes that particles entrained by flow in the higher of these, the Upper Permeable Zone, would be carried to the Tunnel where they would be trapped by the very low water velocities within the Tunnel itself. However, water flow passing out from the Shaft into the Lower Permeable Zone may bypass the tunnel and continue in a northwestward direction at a level lower than that of the Tunnel floor. It is possible that some fresh groundwater from this zone flows upwards to the sea bed *via* fault/fracture systems, driven by the high hydraulic heads that have been detected during the SHIP investigations. The viability of this largely hypothetical route for the transport of particles to the sea is conceivable, but highly improbable. It would require dense particles to be transported for hundreds of metres along tortuous, irregular and narrow pathways (as is explained more fully in Appendix E).

2.3.26 Overall, our assessment coincides with that of RWMAC (1999a). We can conceive that such transport is theoretically possible but, given that it requires such a coincidence of favourable factors, we regard it as highly improbable.

2.3.27 After 1971, the Shaft was only used for the disposal of items that were too large for a Wet Silo in building D9833, which became operational at that time. All disposals to the Shaft ceased in 1977 following the explosion in the headspace. Progress is now being made to isolate the Shaft from its surroundings, thereby containing any continuing release of particles.

The Wet Silo

2.3.28 The Wet Silo is a purpose built facility, replacing the Shaft, for storage of ILW and sludges. The structure is that of a box, having a volume of 761 m^3, below ground level. It was not designed to facilitate waste retrieval. Around the Silo's concrete walls is a breeze block wall that is coated internally with three layers of waterproof bituminous felt and outside is back-filled with coarse aggregate. A surface manhole is available to sample water entering the aggregate no significant activity has been detected. A separate manhole would collect any water passing through the silo's concrete walls but again no significant activity has been found. Borehole sampling in the vicinity has shown no traces of contamination of the groundwater.

2.3.29 The waste, some being pumped from the Liquid Effluent Discharge Tanks, is covered by water fed from an engineered pipe. The level of water is monitored and excess water is pumped to the LAD system. Discharged water, with any suspended contaminants and particulates, was unfiltered until 1984.

2.3.30 Transfers to the facility ceased in 1998.

The Low Level Waste Disposal Pits

2.3.31 Low Level radioactive waste has been disposed of for many years in seven pits. The pits are several metres deep, penetrating into the bedrock, some 32 metres from the cliff edge towards the northern boundary of the site.

2.3.32 Disposals primarily comprise drummed, compacted, uncompacted and bulk wastes but the inclusion of particles cannot be excluded.

2.3.33 The pits are drained to allow water movement to be controlled. Although sampling and analysis of leachate is undertaken, the pits are not fully engineered and contained, possibly permitting leakage to the groundwater system.

2.3.34 Clearly, the total number of any particles in the pits must be extremely small compared with the number in the Shaft. The pits are vulnerable to longer term coastal erosion and possible inundation during storms (RWMAC 1999a). Unless remediation is carried out, this may result in the release of particles to the environment in the future. DPAG therefore recommends that remediation work to mitigate this possibility be carried out.

Drainage Systems

2.3.35 The drainage infrastructure of the Dounreay Site contains several systems for the discharge of liquid effluent, including low level radioactive effluents. The routes of potential discharge of MTR and DFR particles are shown diagrammatically in Figure 2.2 and, in further detail for DFR particles, in Figure 2.3.

2.3.36 The LAD System carried contaminated liquid effluent from reprocessing areas, the Shaft and the Silo (not shown in Figure 2.2) to the Low Active Liquid Effluent Tanks (or “Sea Tanks”) located in Building D1211. Over time, the cast iron pipe of the original LAD (“old LAD”) corroded, resulting in leakages which sometimes reached the Acid (Non-active) drain. A “new LAD” was installed in the late 1970’s, following the same route as the original.

2.3.37 UKAEA has estimated that at least several hundreds of thousands of particles entered the LAD. However, not all of them would have reached the marine environment as some would have settled in the Effluent Tanks. Their subsequent release would have depended upon the degree of mixing, with agitation of the contents of the Effluent Tanks, shortly before discharge.

Low Active Liquid Effluent Tanks (“Sea Tanks”)

2.3.38 Two tanks, one of 300 m^3 capacity and the other of 315 m^3, held effluent from the LAD for sampling (after agitation) and subsequent discharge to sea via discharge pipelines and a Diffuser. The tanks were operated in sequence, a full tank being discharged at the optimum tide window while the other received effluent. Once or twice per year, a tank was taken out of use for desludging, cleaning, re-pointing, etc.

2.3.39 There is evidence, (cited in Higginson 2000), that, up to 1960, high pressure water jetting was used deliberately to mobilise settled sludge for discharge to the sea. It seems reasonable to assume that practically all of the particles, including large ones, would have been discharged in this procedure. Thereafter, mixing and agitation continued, but the settled sludge was “removed manually from the Effluent tanks”. An unquantifiable fraction of the particles remaining would presumably have continued to be discharged with the effluent and as residues. However, the fact that the sludge, containing fission products and other contaminants, was removed manually could imply that most particles had been discharged leaving relatively few particles remaining in the sludge. There is no information as to whether hosing was used to remove residues following the manual removal of sludge. This would have been another potential mechanism by which large numbers of particles could have been released to the marine environment.

2.3.40 Particles were found in the tanks during an investigation in the 1960’s and presumably thereafter. Evidently, particles could have been released to the seabed from the effluent tanks without either being detected or their significance understood in sampling, sludge removal or other activities over many years.

2.3.41 From 1971 to 1973 and from 1980 to 1984, sludge from D1211 was placed in drums and disposed of to the Silo. The material is still drummed, but the drums no longer go to the Silo. During the intervening periods, the D1211 pits were washed down and the resultant slurry was pumped directly to the Silo (*i.e.* 1974-1980 and 1984-1998). The Silo was fitted with “candle filters” until 1991 when ultrafiltration was introduced.

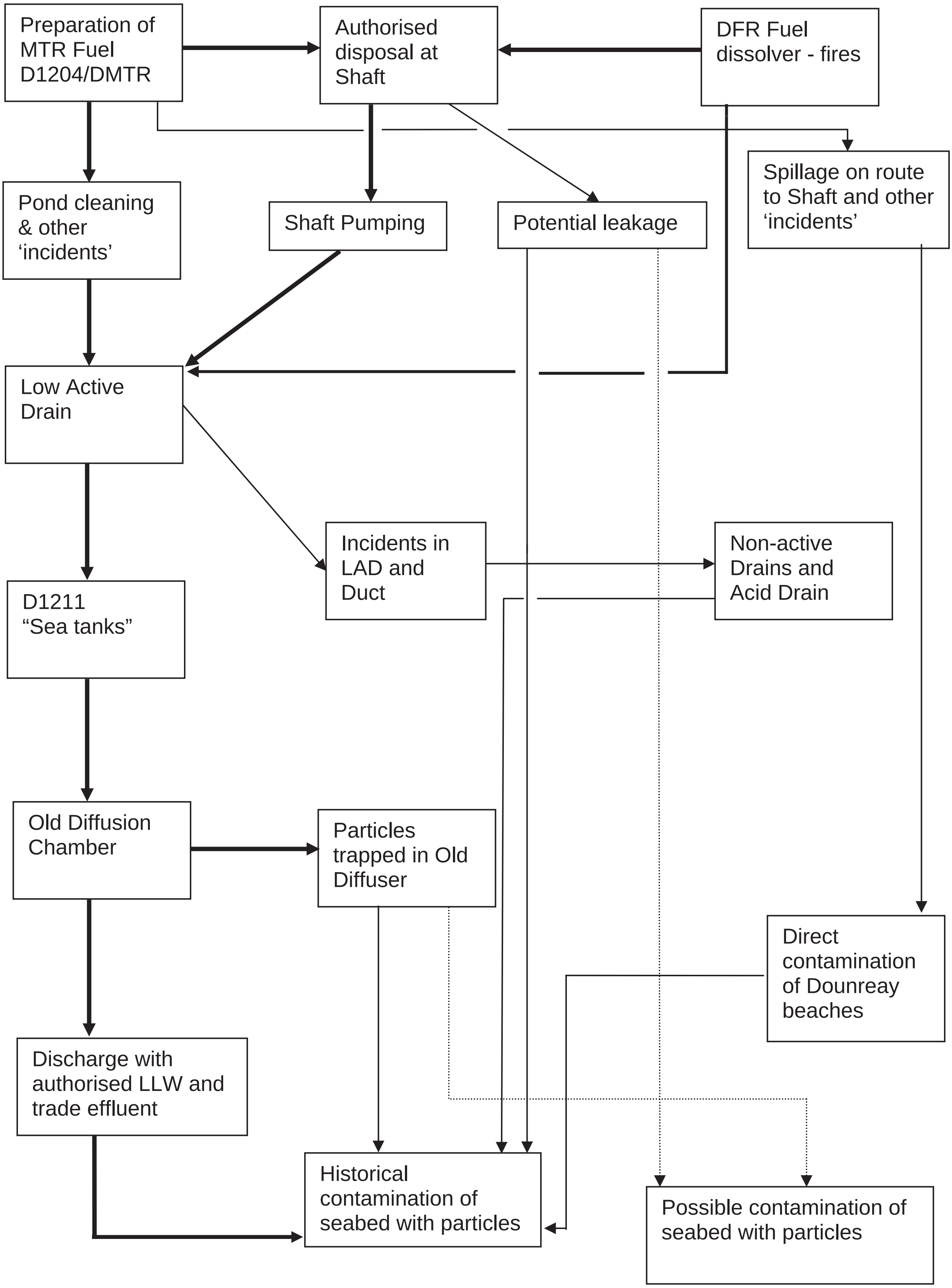


Figure 2.2 Liquid discharge routes for particles

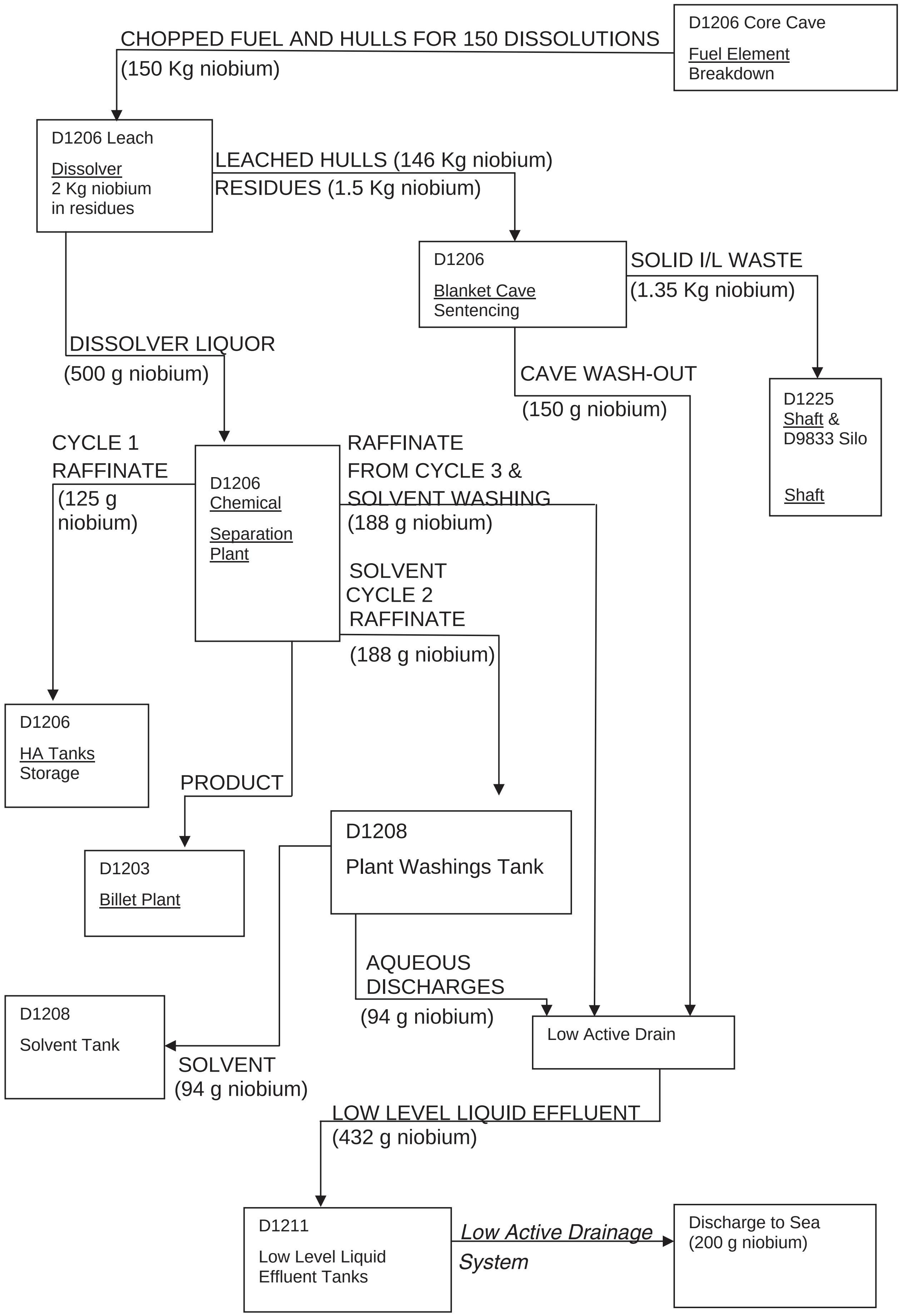


Figure 2.3 Liquid Discharge Routes for DFR Particles

The Liquid Effluent Sea Discharge Pipelines and Diffuser

The Original ('Old') System

2.3.42 The original discharge system consisted of four cast-iron pipes, each of about 230 mm diameter, housed in the Tunnel. The Tunnel terminated about 600 m offshore and 25 m under the seabed at the Old Diffuser. This Diffuser comprises a concrete chamber some 3.5 m in diameter and 7.5 m long. Within it, each pipe branches, *via* valves and reducers, into four risers. The sixteen risers emerged at a rocky area of the seabed initially identified as being clear of sand waves. Corrosion of the pipework in the Diffuser has probably occurred since it was flooded and commissioned in 1956. It is understood that the valves and some pipework are of mild steel having a poor resistance to corrosion. The system was taken out of routine operational use in 1992 when it was replaced by a 'new' system, described below. As described in Appendix D, reductions in flow and blockages of the upstands occurred from time to time. Perhaps of greatest significance, in 1979, the discharge rate from the Effluent Tanks decreased considerably. Diving confirmed that the seabed area had been covered by a sand wave. Substantial pumping pressures, reportedly of 3.4 to 10 bar, were applied to the discharge pipeline and Diffusion Chamber system from the landward side. As later evidence seems to confirm, this action probably led to failure of already corroded pipework within the Diffuser. Divers reported "*four areas where the outlet chamber had been breached*" and *"it is probable that the pipes in the outfall chamber are broken and corroded*". It is believed that these comments relate to small cracks in the chamber through which water could penetrate. Investigations using dye showed that there was no longer a unique connection between the discharge line used and the vertical riser through which dye was discharged, implying interconnection between the risers. In 1983, divers used a high-pressure water-jetting gun to clear blocked discharge lines, releasing black material ('agglomerate').

2.3.43 While the pipework from the Effluent Tanks to the upstands discharging effluent to the sea was intact, the Diffusion Chamber itself should have been effectively free of particles. The dye test carried out in 1981 confirmed that the pipework had failed significantly, but the deterioration presumably began earlier when increased resistance to flow through the discharge pipework was noted from 1979 onwards (Higginson 2000). Failure of the pipework would have resulted in particles entering the Chamber itself and being likely to settle there with a substantially reduced potential for discharge to the marine environment.

2.3.44 Consequently, a cache of particles could have accumulated in the Diffusion Chamber up to 1980 and prior to the summer of 1983; on both occasions, high pressure water jetting was used to clear blockages in the upstands. Assessment of the effect of these operations in displacing particles within the Chamber would be speculative, ranging from little change to major clearance. The first finding of a particle on the Foreshore occurred in November 1983, about three months after this operation. It may have been a consequence of the jetting or simply a coincidence.

2.3.45 Whether or not all of the particles were cleared from the Diffuser in 1983, it should be recalled that, of necessity and despite the failed pipework, the Diffuser continued to be used until 1992 when a replacement became operational. Once a month, until 1998, one of the old discharge lines was used "to keep it open" in case it was needed. Steps such as the introduction of filters for water from the Ponds, in 1984, should have eliminated or, at least, reduced the number of particles being discharged during that decade. Depending on the nature and degree of failure of the pipework, some particles would have continued to be discharged directly and, during the release of effluent, might also have entrained some particles settled within the Chamber. At least a fraction of the particles nominally being discharged is likely to have accumulated in the old Diffusion Chamber. Together with any particles remaining after the jetting operations, they are likely to be still present. It is unlikely that their number can be reliably estimated.

2.3.46 It seems reasonable to assume that for about a decade until 1992, and possibly until 1998, particles could have been both discharged from and settled in the Diffuser.

2.3.47 A recent report (Hoch & Jefferies 2001) suggests reassuringly that hydrodynamic conditions within the now isolated Old Diffuser would presently support only relatively small and declining losses of particles if any remained in the upstands, but not from settled material. In addition, capping of the upstands has been undertaken which should prevent or minimise regular losses to the environment. Nevertheless, it is a matter of concern that the potential for a significant 'Event' remains when the structure of the Chamber eventually collapses. DPAG recommends that this chamber should be isolated from the environment to minimise the possibility of the risk of any future release of particles.

The Replacement ('New') System

2.3.48 The 'new' pipeline system comprises a multi-bore polythene pipe. For a large part, it is within the existing tunnel. It is brought to the surface of the seabed at an angle of 45 degrees to the remaining section of the tunnel, terminating at a new Diffuser near the Old Diffuser upstands.

The non-active and 'acid' drainage systems

2.3.49 The site drainage infrastructure includes non-active and 'acid' drainage systems, separated from the active drainage systems, and, in principle, should not have represented a pathway for contaminated effluent.

2.3.50 In practice, particulate matter contaminating the surface of the site could be washed into non-active drains by rain or hosing associated with leakages from active drains. Appendix D identifies events in which such contamination undoubtedly occurred and has been confirmed by recent findings of residual contamination, including particles, in the non-active system.

2.3.51 Such particles would have been released into a part of the marine environment different from that of those passing through the Diffuser.

2.4 Summary

2.4.1 Many MTR, but fewer DFR, particles were generated as a result of procedures at the plant from 1959 to 1997. PFR and ^{60}Co particles are also likely to be few in number.

2.4.2 It seems reasonable to conclude that most particles, at least those associated with MTR fuel, comprised only aluminium. The remainder contained wide-ranging quantities of radioactive material; this is significant in considering any implications for health (Chapter 3). There are significant differences between particles found on Site and on the Foreshore. The range of physical size, mass and density of the particles is similar to that of sand grains, implying that their transport in the marine environment and deposition on the Foreshore and beaches will also be similar. In general, the activity of particles increases with their mass, but wide variations (up to three orders of magnitude in some cases) have been found. These observations are relevant to assessing the significance of transported particles.

2.4.3 Estimation of the numbers of particles generated and subsequently released to the environment is extremely difficult. Any numerical estimates would be therefore subject to great uncertainties. This inability to be more precise about the numbers does not, however, preclude, on the basis of almost 30 years of environmental study, being able to provide a realistic description of both the movement of particles and their longevity in the environment both of these aspects are discussed in Chapter 4.

2.4.4 Investigations of the routes for release of particles from the Site strongly suggest that sources on land could have made no more than a minor and transient contribution to the sustained finding of particles on the Foreshore and virtually no contribution to the marine environment or Sandside Beach. The routes include the surface of the site, cliff tops, roofs and gulleys as well as dumping operations at the Shaft. A similar conclusion can be drawn for the explosion in the Shaft.

2.4.5 In contrast, there is strong evidence that many MTR particles were discharged to the marine environment *via* the LAD, the Effluent Tanks, Discharge Pipeline and ultimately the Diffuser. As Appendix D makes clear, operations primarily in the 1960's and 1970's led unequivocally to release of many particles from the reprocessing ponds and the tanks due to persistent failures to remove all particles, overflow of water and lack of effective filtration. Various events have been identified that involved the release of perhaps 100,000 or more particles on more than one occasion.

2.4.6 Similarly, DFR particles were almost certainly released *via* the LAD. The principal release probably occurred in 1972 as a result of the most substantial inadvertent fire. Reprocessing of this fuel ceased in 1979 and release of any particles thereafter would be attributable to residues held in the discharge system.

2.4.7 There is less clear evidence that PFR particles (Owen, RG., UKAEA, Personal communication, June 2004) and those containing ^{60}Co were discharged *via* the LAD though a route for the former (and MTR and DFR particles) could have been as a result of pumping water and any entrained material from the Wet Silo.

2.4.8 The Shaft contains millions of particles, as, to a lesser extent, does the Wet Silo. Particles were probably discharged *via* the LAD as a consequence of pumping water from these facilities, at least, until about 1984 when filters were put in place. Significant hydrogeological leakage of larger particles from the Shaft to the marine environment is considered highly unlikely and will be precluded when the Shaft has been isolated from its surroundings. The Wet Silo has an engineered design preventing such leakage.

2.4.9 As noted in Appendix D, in 1979 the application of substantial pressures from landward to the Discharge Pipeline (intended to improve flow rates) almost certainly led to rupture of its corroding structure within the Diffuser. Evidently, as a consequence, the sixteen risers no longer functioned independently and probably were effectively interconnected to the Diffuser, which was then acting essentially as a 'mixing chamber' and as a receptacle for particles.

2.4.10 In 1980, divers cleared the area of the outfall and nearby rocks using sand jetting. This procedure would probably have disturbed particles in the seabed within the area. In 1983, high-pressure water jetting using a flexible lance was applied down the bore of blocked risers in an attempt to clear them. It was reported that "black particulate" sludge and sand (tarry agglomerate) were ejected. The first finding of a positively identified particle on the Foreshore occurred three months after this procedure and at Sandside Beach in 1984. It may have been a consequence or a coincidence.

2.4.11 The foregoing suggests that the vast majority of particles had been discharged to the marine environment *via* the Diffuser during several decades and that events involving the discharge system between 1979 and 1983 exposed a 'cache' of particles remaining in the seabed around the Diffuser. MTR and DFR particles greatly predominate numerically. Despite its state of disrepair, the Old Diffuser remained in use until 1992 when the 'New Diffuser' became operational, but one old discharge line was used monthly until 1998. During that period, particles remaining in the Old Diffuser could have continued to be discharged, together with particles generated in the Ponds until effective filtration was provided there. A final filter was placed on the discharge line in 2005 to ensure no further discharge of particulate matter.

2.4.12 As discussed in subsequent chapters, this 'cache' of particles in the offshore environment represents a source for particles found not only on the Foreshore, but also farther afield, such as at Sandside Beach. It seems certain that particles were also discharged *via* the non-active drainage system (including the Acid Drain). However, they were probably fewer in number and released into a different area of the marine environment, more likely contributing primarily to the Foreshore.

2.4.13 This analysis is in accordance with empirical findings of particles in the environment as discussed in Chapters 4 and 5, which also consider the movement and longevity of discharged particles.

Chapter 3

HEALTH EFFECTS

3.1 Potential Doses and Risks from Fuel Particles

3.1.1 This section draws on material prepared by the Health Protection Agency, Radiation Protection Division (HPA-RPD) (formerly the National Radiological Protection Board) on behalf of SEPA and by the University of Birmingham (UB) on behalf of UKAEA. A detailed description of the work has been published (Harrison et al. 2005).

Characteristics of fuel particles

Radionuclide composition

3.1.2 Generally, fuel particles can be conveniently characterised by their ^{137}Cs content via the photon emissions from its short-lived decay product ^{137m}Ba. The exceptions are those deriving from stainless steel, which essentially contain only ^{60}Co, which also emit gamma-rays and so can be identified in a non-destructive manner. However, ^{137}Cs-containing fuel particles originating from both MTR and DFR also contain ^{90}Sr and its decay product ^{90}Y. These radionuclides emit beta particles and, for MTR fuel particles, are the most important contributors to contact doses (SEPA 1998; COMARE 1999). However, they can only be determined by destructive radiochemical techniques. The ^{90}Sr and ^{90}Y contents of a relatively small number of fuel particles have been determined by various laboratories. The results are summarised in terms of radionuclide activity ratios in Table 3.1. Data for some isotopes of plutonium are also shown.

3.1.3 The ^{90}Sr:^{137}Cs ratios for MTR particles are generally reasonably consistent. The two exceptions, MTR particle no.132 and MTR no. 138, these particles also have Pu:^{137}Cs ratios that are more consistent with those observed for DFR particles, and may well have been wrongly attributed. Measurements of skin dose rates have been carried out for a further set of 27 particles considered to be of MTR origin. The results are summarised in Figure 3.1 (reproduced from Harrison et al. 2005). Most of the measured values are reasonably consistent with the calculated values of dose rate based on a ^{90}Sr:^{137}Cs ratio of about 0.9 (0.89 in Figure 3.1). Taking the results in Table 3.1 and Figure 3.1 together, a ratio of 0.9 was used in the assessment of doses from MTR particles (Harrison et al. 2005).

3.1.4 From Table 3.1, the ^{90}Sr:^{137}Cs ratio for 9 of the 11 DFR particles studied is lower than 0.9. The data for a further 10 particles of DFR origin (Figure 3.1) are consistent with this view, since the measured values are lower than those calculated for MTR particles that assumed a ^{90}Sr:^{137}Cs ratio of 0.9. Consequently, dose assessments based on the ^{137}Cs content and the default radionuclide ratios for MTR particles are generally expected to be cautious if applied to DFR particles.

3.1.5 The data for ^{137}Cs in Table 3.1 have been derived from measurements on solutions, *i.e.* after the fuel particles have been dissolved. Measurements made on the particles themselves are subject to additional uncertainties because of possible differences in the geometry of the sample relative to the detector. SEPA has commissioned work to investigate this problem, and has concluded that direct measurements are generally expected to be within a factor of 2 of the value obtained following dissolution.

Table 3.1 Radionuclide activity ratios

Particle	$^{90}Sr : ^{137}Cs$	$^{238}Pu : ^{137}Cs$	$^{239}Pu : ^{137}Cs$
MTR	1.0	0.01	0.004
MTR	0.9	0.003	0.008
MTR	0.8	0.0009	0.0005
MTR*	2.0	0.003	0.001
MTR 101	0.9	0.007	0.0004
MTR 109	0.9	0.001	0.0002
MTR 154	0.9	0.003	0.0004
MTR 157	0.9	0.006	0.0006
MTR 002	1.4	0.003	0.0006
MTR 113	0.5	Not calc'd	Not calc'd
MTR 132	0.04	0.00001	0.00005
MTR 138	0.05	0.000003	0.00004
DFR 055	0.2	0.000002	0.00001
DFR 082	0.2	0.00009	0.0005
DFR 098	0.2	0.00002	0.0001
DFR 106	0.1	0.00003	0.0001
DFR 111	1.3	0.00002	0.00007
DFR 107	2.9	0.00004	0.0002
DFR 125	0.3	0.000004	0.00002
DFR 128	0.2	0.00006	0.0002
DFR 134	0.04	0.0000004	0.000001
DFR 135	0.3	0.000002	0.000007
DFR 136	0.5	0.0005	0.005

* Mean of data for three fuel particles

3.1.6 The calculations of doses from MTR particles summarised later in this chapter were based on the assumptions that the fragments were spherical with a homogenous elemental composition of uranium and aluminium (15% U) and a specific activity of 2 GBq $^{137}Cs\ g^{-1}$ (Darley *et al.* 2003). The assumed activity ratios were 0.9 for $^{90}Sr:^{137}Cs$, 0.003 for $^{238}Pu:^{137}Cs$, and 0.001 for both $^{239}Pu:^{137}Cs$ and $^{241}Am:^{137}Cs$.

Particle solubility and intestinal absorption of radionuclides

3.1.7 SEPA commissioned the National Nuclear Corporation to carry out a series of *in vitro* experiments to evaluate the potential solubility of particle-associated radionuclides in the gut. The results have been published as part of the SEPA work, together with a detailed account of complementary *in vivo* experiments carried out by NRPB (Harrison *et al.* 2005). In most cases, for all of the radionuclides studied the percentage taken into solution was very small. The data from both sets of experiments were used to derive default values for absorption to blood for use in the dose calculations (Table 3.2).

3.1.8 The values in Table 3.2 have been used to estimate doses to body tissues from radionuclides absorbed to blood following the ingestion of a fuel particle. Although the majority of the particles studied exhibited low solubility, there was one notable exception, particle MTR 113. This fragment dissolved readily under the conditions of the *in vitro* extraction, and for all of the radionuclides studied about 50% of the activity went into solution in simulated gut fluids. With the exception of particle MTR 113, all of particles shown in Table 3.1 required rigorous dissolution conditions. Particle MTR 113 may not, however, be unique because only a relatively small number of particles have been taken into solution. A separate dose assessment has therefore been carried out for particles having these characteristics. In May 2006, DPAG was informed by UKAEA that a possible reason for this exception was that rather than originating from the U/Al alloy, this particle was of uranium oxide.

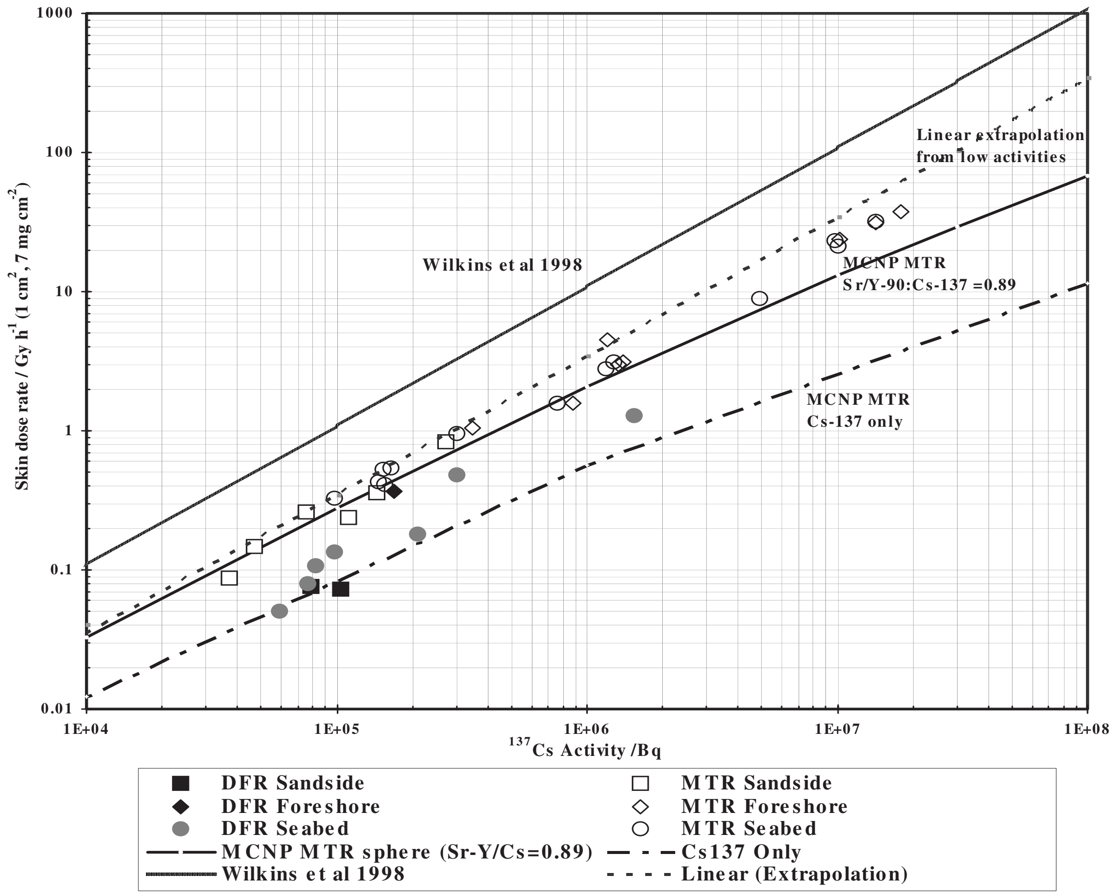


Figure 3.1 Skin dose rates for MTR and DFR fuel particles (reproduced from Harrison *et al.* 2005).

Self-attenuation

3.1.9 The study published by SEPA in 1998 cautiously took no account of attenuation of beta particle energy within the matrix of the particle itself - the process of self-attenuation. For the work summarised here, potential doses to the skin, to the gut following ingestion, and to the lungs following inhalation, were calculated taking account of self-attenuation within particles. The effect of self-attenuation is most important for those particles of highest activity and size, for which surface dose rates can be substantially reduced. This is illustrated in Figure 3.1, where the measured values for the higher activity particles are less than would be expected on the basis of a linear extrapolation. The calculated values were based on the assumption of spherical particles and uniform distribution of activity noted earlier, an approach that maximises the effect of self-attenuation. However, comparison between the measured and calculated values in Figure 3.1 indicates that the difference is around a factor of 2 or less.

Table 3.2 Values derived from *in vitro* and *in vivo* data for radionuclide absorption to blood following ingestion of a fuel particle

Particle type	% of ingested activity absorbed to blood		
	^{137}Cs	^{90}Sr	^{239}Pu
MTR	1 (0.02 - 2)	0.01 (0.001 - 0.03)	0.001 ($5x10^{-5}$ – $5x10^{-3}$)
DFR	0.03 (0.001 - 0.05)	0.003 (0.001 - 0.02)	0.001 ($5x10^{-5}$ – $5x10^{-3}$)

3.2 Dose Assessment Methodology

3.2.1 The dose-assessment methodology has been described in detail elsewhere (Harrison *et al.* 2005). Briefly, local doses to skin were estimated for an area of 1 cm^2 and a depth of 70 μm, in accordance with the recommendations of ICRP (1991). Doses to the ear and to the cornea of the eye were assessed in the same way. Estimates of doses following ingestion made use of a new ICRP Human Alimentary Tract Model (HATM) which is not yet published, but has been approved by the ICRP Main Commission. An important development in this model is the explicit calculation of doses to a target layer of tissue in the wall of the various regions of the alimentary tract. Doses were calculated for the rectosigmoid region of the large intestine, which receives higher doses than other regions because of the longer transit times for this part of the gut. The possibility of inhalation was also considered, making use of the ICRP human respiratory tract model (ICRP 1994). In each case, the main emphasis was the possibility of the occurrence of deterministic effects after exposure to particles of different activities; that is, the possibility of acute tissue damage. However, equivalent and effective doses were also estimated to assess risks of stochastic effects; that is, cancer and hereditary effects.

Doses to the skin and the eye

3.2.2 Figure 3.1 shows measurements of surface dose rates from selected MTR fuel and DFR fuel particles that were made by the University of Birmingham. These are represented by points on the graph. The Figure also shows calculated values of dose rate as a function of ^{137}Cs activity, represented by lines on the graph. In each case, the dose rate is estimated to 1 cm^2 at a depth of 70 μm. For higher activity MTR particles, measured values fall between values calculated taking account of self-attenuation of beta particle energy within spherical particles (central solid line) and values calculated taking no account of self-attenuation (dotted line). Measured dose rates for DFR particles are lower than those for MTR particles having the same ^{137}Cs activity content and are closer to calculated values assuming no $^{90}Sr/^{90}Y$ content (dashed line). For comparison, Figure 3.1 also shows the more conservative approach to the estimation of dose rates used in earlier work. These were based on more limited data available at the time, which gave a ^{90}Sr:^{137}Cs activity quotient of 2 (SEPA 1998a).

3.2.3 When considering irradiation of the skin from particle contact, the important effect is acute ulceration. Most of the available information on the effects of particle irradiation of skin comes from studies using pigs; although some limited human data are also available. Together, these data allow the estimation of an ED_{50} value[2] (measured for 1 cm^2 of skin, at a depth of 70 μm) for acute ulceration of about 10 Gy and a threshold of about 2 Gy. It is clear from these data, together with data for larger area skin exposures, that the effect will be dissipated when a particle moves during skin contact, by even a few mm, and when dose rates are low. Taking no account of this amelioration of their possible effect, Table 3.3 provides a summary of the time taken for particles of MTR origin to deliver doses of 2 Gy and 10 Gy. The ranges in time for the larger particles are based on differences in the shape of particles, with shorter times for non-spherical particles because of reduced self-attenuation.

[2] The ED_{50} is the dose that would be expected to produce an observable effect in 50% of cases. The likelihood of producing an observable effect depends on dose rate as well as on the cumulative dose.

Table 3.3 Estimates of time taken for MTR particles to deliver doses corresponding to the threshold and ED_{50} for acute ulceration

Activity Bq ^{137}Cs	Dose rate Gy h^{-1}	Threshold: 2 Gy	ED_{50}: 10 Gy
10^4	0.03	3 days	2 weeks
10^5	0.3	7 hours	33 hours
10^6	2 – 4	0.5 – 1 hour	2 – 5 hours
10^7	15 – 30	4 – 8 minutes	20 – 40 minutes
10^8	70 – 140	1 – 1.5 minutes	<10 minutes

3.2.4 The most active MTR particles found in the environment around Dounreay contain about 10^8 Bq ^{137}Cs. The short exposure period needed for these particles to cause ulceration illustrates the high probability of such damage in the event of contact. The dose rates produced by these particles are such that exposures of a few hours duration would give rise to serious ulceration. Lesions would occur that would be visible within 1-2 weeks. These would extend over areas of up to 1 cm^2 and take several weeks to heal, probably with some scar formation. In such cases infection would be a possibility and medical treatment might be needed.

3.2.5 For MTR particles containing 10^6 Bq ^{137}Cs, the period of stationary contact needed for the ED_{50} value to be approached is a few hours. Such contact times are credible for people spending time on beaches. Consequently, MTR particles with a ^{137}Cs content of 10^6 Bq have been taken by DPAG to be broadly the lower level at which deterministic effects from contact with the skin might be expected, i.e. fuel particles of some radiological significance. Consequently, DPAG has termed fuel particles containing greater than 10^6 Bq ^{137}Cs *significant*.

3.2.6 For MTR particles containing 10^5 Bq ^{137}Cs, *i.e.*, typical of the most active particles found at Sandside Bay, stationary contact for more than 7 hours would be required before any ulceration would be expected to occur. For exposure periods of several hours, the dose rates produced by such particles are unlikely to be sufficient to cause ulceration, although a particle trapped against the skin for longer periods of a day or two may cause a small effect. An exposure from such a particle corresponding to the ED_{50} value, which implies stationary contact for 33 h, might produce a small lesion that would be visible within 2-3 weeks. However, this would heal within a further 2-4 weeks with normal personal skin care. For open areas of the skin, such residence times are considered unlikely. Consequently, DPAG considers that, if an individual came into contact with fuel particles of the activity found so far at Sandside Bay, observable effects would be unlikely to occur. DPAG has termed fuel particles with ^{137}Cs contents in the range 10^5 - 10^6 Bq *relevant*.

3.2.7 The above estimates of the time taken to cause skin damage and considerations of the possible severity of ulceration apply to all sites including the ear. The possible residence time of a fuel particle in the ear can be long and could be sufficient for fuel particles containing around 10^4 Bq ^{137}Cs to give rise to observable effects (Harrison *et al*. 2005). However, the probability of a fuel particle entering the ear is extremely low, less than 1 in 100 million for the beach at Sandside Bay (Smith *et al.* 2005). On this basis, DPAG considers that fuel particles containing less than 10^5 Bq ^{137}Cs are very unlikely to give rise to a radiological problem and so has termed them *minor*.

3.2.8 A particle entering the eye requires separate consideration because it is necessary to consider the possibility of induction of cataracts in the lens as well as ulceration of the exterior corneal surface. However, the mechanism of cataract formation involves damage to cells around the whole periphery of the lens, at a depth of at least 2 mm from the surface of the eye over a wide age range in children and adults. For a particle on the corneal surface, the average dose to this equatorial region of the lens will be at least two orders of magnitude less than the skin dose rates given in Table 3.2. Damage to the cornea is therefore considered to be of primary concern.

3.2.9 The most active fuel particle found at Sandside Bay up to February 2006 (3 x 10^5 Bq ^{137}Cs) would deliver a dose rate to skin or the cornea of ~ 1 Gy (1 cm^2, 70 µm) per hour. Such a particle would have a diameter of about 0.4 mm, similar to that of a medium-sized grain of sand. It would seem reasonable to expect that toleration of particles of this physical size would not usually extend for more than a few hours. Consequently, early biological effects from fuel particles of the activity found so far at Sandside Bay would be unlikely. In a thorough review of particle effects, NCRP (1999) concluded that protection of the cornea should be considered on the same dose criteria as protection of skin. Dose rates to the cornea are likely to be reduced due to particle movement around the eye, and movement of eye lids and eye ball: this movement will increase the threshold for observable effects, in the manner described earlier for damage to the skin. Extended corneal exposure to higher activity fuel particles could produce corneal ulceration, which may require medical intervention and treatment. However, the more active particles are also likely to be physically larger, which might mean that stationary contact times in the eye would be relatively short. In addition, the probability of a fuel particle entering the eye is very small, about 1 in 100 million at Sandside Bay.

Doses from inadvertent ingestion

3.2.10 Estimated doses to the rectosigmoid region of the large intestine are summarised in Table 3.4. Again, values have been estimated as a function of the ^{137}Cs activity and based on the properties given in Section 3.1, assuming no loss of activity from particles due to dissolution in gut fluids. In each case, two sets of values have been given. The first is an expectation value corresponding to random movement of the particle through the lumen of the rectosigmoid. The second is a maximum value, based on the cautious assumption that the particle remained in contact with the wall of the rectosigmoid throughout transit.

3.2.11 The effect of using the new ICRP HATM model and taking account of self-attenuation of beta particle energy within particles can be seen from a comparison of the results in Table 3.4 with those from the earlier study (SEPA 1998). For particles containing 10^8 Bq ^{137}Cs, the estimated dose for an adult male based on random transit was about 0.3 Gy, with a maximum value of 1.2 Gy for movement in contact with the intestinal wall. The corresponding value in the earlier study was about 7 Gy. At the lower end of the activity range, the differences between the maximum values in Table 3.4 and those in the earlier study were less because self-attenuation in smaller particles would be less important. However, for a particle containing 10^5 Bq ^{137}Cs, the difference between the random value in Table 3.4 and that in the earlier study is a factor of about 7.

Table 3.4 Estimated doses to the rectosigmoid, mGy

Particle Activity, Bq ^{137}Cs	Particle diameter, µm	Adult male		Adult female		One year old child	
		Random transit	Maximum	Random transit	Maximum	Random transit	Maximum
10^3	67	0.01	0.08	0.01	0.1	0.04	0.2
10^4	150	0.1	0.7	0.1	1	0.4	2
10^5	310	0.9	6	1	8	3	16
10^6	680	7	40	10	60	27	110
10^7	1300	46	230	67	340	185	640
10^8	3100	290	1200	420	1800	1200	3500

3.2.12 The study by Harrison *et al.* (2005) evaluated the possible effect of changes in the assumptions made in the calculations on the resultant doses. The factors considered included the specific activity of the particle, the depth of the target cells in the intestinal wall and the dimensions of the colon. However, the evaluation showed that variations in transit times were of greatest importance. Transit times for the colon might typically increase by factors of 2-3 in individuals suffering from constipation, but increases of a factor of 10 might occur in extreme cases. Doses to the rectosigmoid would be directly proportional to the transit time. In these extreme cases, for a particle containing 10^8 Bq ^{137}Cs, it is possible that doses for adults could be in the region 10 - 20 Gy, with a corresponding value of around 35 Gy for one-year old infants. For a particle containing 10^5 Bq ^{137}Cs, the corresponding doses would be less than 100 mGy for adults and about 200 mGy for one-year old children.

3.2.13 On the basis of available animal data, the threshold for acute damage to the colon resulting in death, following protracted irradiation from ingested radionuclides passing through the gut, has been estimated to be about 20 Gy, with an LD_{50}[3] of 35 Gy. Thus it appears unlikely that ingestion of even a particle containing 10^8 Bq ^{137}Cs by an adult would result in death, although in extreme cases the possibility, however small, cannot be ruled out for a one-year old child. It should be emphasised, however, that so far only one particle of this activity has been retrieved from the Dounreay Foreshore and a further two have been found on the seabed. Doses from the most active particles found so far on the beach at Sandside Bay would be around 100 times less than the threshold for lethality.

3.2.14 Since the movement of material through the rectosigmoid region in particular occurs *via* periodic muscular contractions, localised doses were also considered by Harrison *et al.* (2005). The approach adopted was similar to that used for skin. The results indicated that, for a particle containing 10^8 Bq ^{137}Cs remaining at the surface of the lumen for 6 h, the resulting dose would be likely to cause ulceration that might not be easy to repair. Under the same conditions, a particle containing 10^5 Bq ^{137}Cs would be likely to cause localised damage to the lining of the gut that should be repairable by natural regeneration.

Doses from inhalation

3.2.15 Only particles having aerodynamic diameters of around 20 µm or less can penetrate into the deep lung, referred to in the ICRP (1994) HRTM as the alveolar-interstitial (A-I) region. The particles found on Sandside Beach and elsewhere around Dounreay are very much larger than this and have a negligible probability of reaching the A-I region. Therefore, based on observed activity:mass quotients, those particles that would be small enough to reach the A-I region would not be sufficiently radioactive to produce the high doses associated with acute effects in the lung (Harrison et al. 2005).

3.2.16 Larger particles could however deposit in the extrathoracic (ET) airways, and so doses to the anterior nasal passages have been estimated for particles of various activities. The possibility of localised doses was considered important, in a manner analogous to that adopted for the skin. The results indicated that a particle of MTR origin containing 10^5 Bq ^{137}Cs would, if held against the same point on the ET epithelial lining for 12 h, deliver a dose to 1 cm^2 of tissue of about 1 Gy. The corresponding value for a particle containing 10^8 Bq would be about 500 Gy. Again, the doses do not vary in a linear manner because of the increasing importance of self-attenuation in the larger and more active particles. Local doses of around 500 Gy would cause severe acute ulceration that would

[3] LD_{50} - the dose that would be expected to result in death in 50% of cases.

take some time to heal, while doses of around 1 Gy would cause imperceptible damage. It should of course be noted that a 10^8 Bq particle is unlikely to reside in the ET region for very long because of its physical size.

Particles containing only ^{60}Co

3.2.17 Only a small number of particles containing only ^{60}Co have been located so far, and so on this basis the likelihood of such particles being deposited on the beach at Sandside Bay would be low. For this reason, and because the emissions from ^{60}Co are dominated by energetic photons, the report by Harrison et al (2005) contained a less rigorous dose assessment in which the self-attenuation of beta particles within fuel particles was not taken into account. Typically, the estimated doses to the rectosigmoid per unit activity of ^{60}Co were about 70% of the corresponding value for ^{137}Cs in an MTR particle, taking account of the associated activities of ^{90}Sr and ^{90}Y. For present purposes, doses from particles that contain only ^{60}Co can conservatively be taken to be around the same value as those MTR particles having a similar ^{137}Cs activity.

Equivalent and effective doses

3.2.18 The main health effects of concern in considering exposure to Dounreay fuel particles are those discussed above, involving acute tissue damage. However, it is also important to assess doses relevant to the risks of cancer and hereditary effects. The work by Harrison *et al.* (2005) focused on the inadvertent ingestion pathway and distinguished between doses from the soluble MTR 113 and those from other fuel particles. However, potential exposures due to inhalation and skin contact were also considered.

3.2.19 Radionuclides differ in their modes of decay, their radioactive half-life and their biokinetic behaviour, *i.e.* their distribution and retention in body organs and tissues. In addition, individual organs and tissues differ in their sensitivity to radiation. To provide a method for the interpretation of absorbed dose in different organs in terms of the total risk of cancer and hereditary effects, ICRP uses the concepts of equivalent dose and effective dose (ICRP 1991). These have units of sieverts (Sv) to distinguish them from absorbed dose in Gy. The first stage is to calculate absorbed doses to all of the important tissues, using biokinetic and dosimetric models to take account of the distribution and retention of radionuclides and their radioactive emissions. These are then converted to equivalent doses, taking account of differences in the effectiveness of different radiation types in causing cancer. For example, alpha particles are taken to be 20 times more effective per unit of absorbed dose than beta particles and photons. Doses to different tissues and organs are then summed, taking account of their different radiosensitivities, to give a single value of effective dose. The use of effective dose allows the summation of doses from external radiation and from radionuclides having different distributions and emissions.

3.2.20 Effective doses were estimated for the ingestion of MTR particles containing 10^5 and 10^8 Bq ^{137}Cs, based on the intestinal absorption factors for typical particles given in Table 3.2 For an adult male, the resultant doses were 0.1 and 80 mSv respectively, the corresponding values for a one year-old being 0.5 and 300 mSv. In each case, the equivalent doses to the alimentary tract contributed around 70% of the effective dose. As in the case of acute effects, these values would be sensitive to the transit time through the alimentary tract. For a particle containing 10^5 Bq ^{137}Cs, an increase in the transit time by a factor of 2 to 3 would increase the committed effective dose for a one-year old child to about 1 mSv. An increase in transit time by a factor of 10 would give a committed effective dose of about 3 mSv in this unlikely event. For comparison, a typical individual in the UK almost inevitably receives an effective dose of about 2.2 mSv every year from natural sources of radiation (Watson *et al*. 2005).

3.2.21 In the case of ingestion of a particle of 10^5 Bq ^{137}Cs with the solubility exhibited by MTR 113, the committed effective dose to an adult male was estimated to be about 2 mSv. In this case, the high solubility of the particle and intestinal absorption of radionuclides meant that the contribution to the overall committed effective dose from the alimentary tract was only about 15%, while skeletal tissues contributed around 60%. Doses to a one-year old child would be about 2 – 4 times greater than that for an adult male. In short, for a given ^{137}Cs activity, the dose to the alimentary tract from a particle with the characteristics of MTR 113 will be considerably less than that from a particle with the much lower solubility assumed earlier in this Chapter (Table 3.2). In this context, it would be helpful if more data were available on the solubility of particles.

3.2.22 The risks of fatal cancer and total detriment can be broadly estimated by combining the committed effective doses with the risk factors published by ICRP (1991). These risk factors relate to averaged values for the whole population, i.e. both genders and all ages, and are 0.05 per Sv of dose for fatal cancer and 0.07 per Sv of dose for total detriment. Thus an effective dose of 1 mSv corresponds to an overall fatal cancer risk of 5×10^{-5}. The estimated dose of 0.5 mSv to a child that ingested an MTR particle of typical solubility containing 10^5 Bq ^{137}Cs would therefore correspond to a risk of around $2 – 3 \times 10^{-5}$. The corresponding value for a particle with the solubility characteristics of MTR 113 would approach 5×10^{-4}. These estimates of risk should be considered together with the estimated annual probabilities of individuals ingesting a particle containing this amount of activity, which were of the order of 1 in one million million (Smith and Bedwell 2005a). In addition, particles with the characteristics of MTR 113 may not be unique. On the basis of the results in Table 3.1, of the 25 particles studied so far only one has been readily soluble. This may be a reflection of a particle with a composition of uranium oxide rather than uranium/aluminium alloy (see Chapter 2).

3.2.23 Local doses to the skin can be converted to an equivalent dose and thence to an overall risk of cancer using published information (Harrison *et al.* 2005). Equivalent and effective doses from a particle on skin are very small and the associated cancer risk is very low. A risk estimate of 1.6×10^{-4} Sv^{-1} has been derived for low dose rate exposure of the skin. This estimate applies to the general population and takes account of the differing sensitivities of UV-exposed and UV-shielded areas of the skin (Muirhead *et al.* 1993). On this basis, an equivalent dose of 0.1 mSv to the skin of an adult, corresponding to a local dose of 2 Gy to 1 cm^2, implies a risk of fatal cancer of 2×10^{-8}. Skin cancer risk associated with possible exposure to Dounreay particles can be regarded as of low importance in comparison with considerations of local dose and the possibility of skin ulceration. Again, this risk should be considered together with the low probability of incurring the skin dose.

External doses from fuel particles remote from the skin

3.2.24 The discussion of health effects and probabilities set out so far in this chapter refers to close or direct contact with a particle, rather than being within its general proximity. People making use of Sandside Beach might spend time a few metres away from a particle without being in contact with it. The potential importance of this exposure pathway has been evaluated by HPA-RPD using a predictive modelling approach (Smith *et al.* 2005). External dose rates in the environment are usually expressed in terms of microSieverts per hour (µSv h^{-1}). The general value for Sandside Beach is about 0.1 microSieverts per hour (RIFE 2006), which is a typical beach value. For a particle containing 10^5 Bq ^{137}Cs the dose rate to a person standing 1 m away would be about 4 nanoSieverts per hour (Smith *et al.* 2005a). A nanoSievert (nSv) is one thousandth of a µSv, and so the presence of a particle of this level of activity on the beach would have no measurable effect on the external dose rate. Chapter 4 and Appendix G indicate that the presence of *significant* particles cannot be ruled out. On the basis of a cautious approach, a particle containing 10^7 Bq ^{137}Cs would be expected to give dose rates at a distance of 1 m of about 0.4 µSv h^{-1}. However, a person spending a whole day (10 hours) on the beach at this distance from such a particle would then receive an external dose of about 4 µSv, a level considered trivial by the International Atomic Energy Agency, (IAEA 1988).

3.2.25 Overall, therefore, the external dose received by a person standing even a short distance away from a particle is expected to be extremely small. DPAG has not therefore considered this pathway further in this report.

Categorisation of fuel particles

3.2.26 In paragraphs 3.2.5 to 3.2.7, the assessment of the potential effects of fuel particles on skin and in the eye and ear was used to derive categories based on the ^{137}Cs content. DPAG has used these categories throughout this report, but they are summarised here.

- Fuel particles containing greater than 10^6 Bq ^{137}Cs have been termed as *significant.*
- Fuel particles with ^{137}Cs contents in the range 10^5 - 10^6 Bq have been termed *relevant.*
- Fuel particles containing less than 10^5 Bq ^{137}Cs have been termed *minor.*

Chapter 4

OFFSHORE PARTICLES

4.1 Introduction

4.1.1 Radioactive particles originating from Dounreay were first specifically identified on the Dounreay Foreshore in 1983 and on Sandside Beach in 1984, during routine monitoring of both sites. Following this, the monitoring at Dounreay Foreshore was intensified and particles were found and recovered regularly from 1984. Until 1997 it was believed that the Foreshore particles were probably derived from a source on land, perhaps *via* one of several drains which discharge non-radioactive runoff onto the Foreshore from the site's roadways, roofs and paved surfaces, or perhaps as a result of particles that had been buried in soil eroding out from the cliff behind the beach. For some years it was thought that the explosion which occurred in the Shaft in 1977 might have scattered particles across adjacent areas of the site, from which they might subsequently be released by natural weathering of the soil. These ideas were later tested by thorough searches of the site in the 1990's and found to be unsubstantiated. As no further particles were found during routine monitoring at Sandside Beach, it was concluded that the particle found there in 1984 was a unique occurrence, perhaps transported from Dounreay Foreshore in sand adhering to a bird's foot. This idea also was later shown to be unsubstantiated, when two more particles were found in 1997 and improvements in monitoring introduced at Sandside in 1999 resulted in regular finds thereafter.

4.1.2 In 1997, a particle was detected and recovered from sand on the sea bed near the Old Diffuser, during industrial diving operations. A search of adjacent areas of sea bed was immediately instigated and a further 34 particles were found. Since 1997, searches have been made over much wider areas of sea bed, and a total of 929 particles have been recovered up to May 2006. It is now certain that there is a cache of radioactive particles on the sea bed, and that this has supplied the particles identified on Dounreay Foreshore since 1983 and on Sandside Beach. As explained in Chapter 2 of this Report, it is likely that the cache originated during routine discharges and several events primarily in the 1960's and 1970's, when particles are known to have been discharged to the sea *via* the Old Diffuser. Further discharges *via* the Old Diffuser may have occurred in later years up to 1995. Some particles were also discharged *via* drains designed to carry non-radioactive discharges and runoff from the site as discussed in Chapter 2.

4.1.3 Until 2004, all effective searches of the sea bed were made by divers using hand-held gamma detectors to locate particles by their ^{137}Cs activity. Once located, each particle was recovered by the diver digging in the sand with a saucepan while simultaneously monitoring the activity of each pan-full of sand. Once it was established that a pan-full contained radioactive material, it was transferred to a polythene bag and brought onto the dive boat and thence onto the shore. The particle was separated with some sand from the bulk sample onboard the boat prior to transfer to the UKAEA laboratories. There the radioactive particle was isolated by successive splitting of the sand sample, and its radioactivity and the content of gamma-ray emitting radionuclides established. The activity, location and depth of burial of each find was recorded, as was the number of fragments present. All particles recovered until now have been removed from the sea bed by divers in this way. Most finds have also been made by divers, but since 2004 some surveys have been made by a robot device named TROL (Tracked Robotic Offshore Logger), as described in the next paragraph and in Section 4.3.

4.1.4 In 2004, UKAEA began trials with an undersea tracked vehicle equipped with location devices and a gamma spectrometer, which could be used to search systematically the sandy parts of the sea bed to locate particles. In 2005, the device was tested more extensively and divers were deployed to confirm finds and recover the particles. UKAEA intend to use the device to search several areas of sea floor during summer 2006.

4.1.5 DPAG welcomes the development of the TROL, but notes that its deployment has coincided with a reduction in the rate of search and recovery of particles compared with previous years. DPAG also notes that while the ability of the TROL to locate particles reliably has been proven by the trials in 2005, it cannot yet be used to determine unequivocally a particle's activity. The main reason for this is the shielding effect of the sand in which most particles have been found buried. The radioactive count rate received by the TROL may be much the same for a high activity particle that is shielded because it is buried fairly deep, and a lower activity particle on the surface or buried at a shallow depth. UKAEA is exploring techniques for determining both the activity and the depth of burial from the instrument output of the TROL. DPAG strongly supports this aim and notes that until it is achieved, it will not be possible to distinguish *significant* from *relevant* or *minor* particles without the deployment of divers to recover the particles found by the TROL.

4.1.6 In its remaining sections, this Chapter provides an outline of the characteristics of the particles that have been recovered from offshore, considers their numbers and provides an estimate of the total numbers likely to have been present on the sea bed during the years of diving surveys, 1997-2005. The pattern of particle finds is then considered, together with natural processes of sand transport, and this evidence is used to deduce an overall picture (or conceptual model) of the behaviour of particles on the sea bed. The conceptual model provides an explanation of why particles have persisted on the sea bed in the area round the Diffuser for several decades since the first known releases, and demonstrates that those found on the Dounreay Foreshore and on the publicly accessible beaches at Sandside and Dunnet bays have been fed from offshore. It also provides an indication of how rapidly the particles are being reduced in size and radioactivity by fragmentation. The fifth section of the Chapter provides an assessment of a computer-based mathematical model of particle transport on the sea bed which was commissioned by UKAEA from the Hydraulics Research Establishment, Wallingford (HR Wallingford). The Wallingford model agrees with large parts of the conceptual model based on the pattern of particle finds. There are also some important disagreements that limit the usefulness of the Wallingford model as a tool for predicting particle behaviour in the future. The final section of the Chapter discusses the implications of the findings in preceding sections, and draws the important conclusion that particles will continue to occur on publicly accessible beaches for as long as *significant* particles persist on the sea bed around the Diffuser. If no further particles are removed, the Dounreay particle problem is likely to continue for many decades into the future.

4.2 Classification and Characteristics of the Offshore Particles[4]

Classification and origins of offshore particles

4.2.1 A total of 929 radioactive particles has been recovered from offshore up to February 2006. For each particle, the radioactivity has been measured and the radionuclides present have been identified. The particles have been classified into three categories on the basis of their appearance and radionuclide composition in relation to three probable origins. The categories adopted by UKAEA are:

- MTR, derived from the Materials Testing Reactors;
- DFR, derived from the reprocessing of fuel from the Dounreay Fast Reactors;
- SS, irradiated steel particles.

4.2.2 The principal radioactivity in MTR and DFR particles, which were derived from reactor fuel, is from the nuclear fission products ^{137}Cs and ^{90}Sr. Irradiated steel particles lack these radionuclides, but have radioactivity from ^{60}Co which is not present in the MTR and DFR types.

4.2.3 MTR particles are metallic. As explained in Chapter 2 of this report, they were formed by the milling and the cropping and crushing procedures of reactor fuel elements which consisted of an outer aluminium jacket surrounding a core of reactor fuel. The fuel consisted of alloys of aluminium with uranium, chiefly UAl_4. Because they are derived from pieces of swarf, the particles in the sea may be composed of aluminium derived from the jacket, or fuel alloy, or both components. Non-radioactive aluminium particles are very difficult to detect in natural sediment and none has so far been identified; so all the MTR particles considered here are either composed of fuel alloy, or particles that comprise partly fuel alloy and partly aluminium.

4.2.4 DFR particles were formed accidentally during processing of fast reactor fuel. They consist of a sinter- or clinker-like material which sometimes appears porous. Most of their radioactivity is from the fission products ^{137}Cs and ^{90}Sr, in which they resemble MTR particles. However, ^{94}Nb (niobium), if present at measurable levels, provides positive identification of particles derived from DFR processing and allows them to be distinguished from MTR and irradiated steel particles.

4.2.5 Accurate classification of particles by their origin has proved difficult in practice and two distinct sets of criteria have been used by UKAEA: one criterion is the visual appearance of particles when imaged by Scanning Electron Microscope with Energy Dispersive Auxiliary X-ray analysis (SEM/EDAX) this criterion is described in this paragraph. A second criterion is on the basis of the radionuclides that it contains; this is discussed in paragraph 4.2.6. Most particles recovered from the sea bed in 1997 and 1998 were examined by the visual appearance techniques but only a few have been so scrutinised since. The SEM provided high resolution visual images. The additional technique of EDAX provided maps of some images on which colour coding represented different approximate concentration levels for selected elements on the particle surface. EDAX is only capable of detecting elements that are present at fairly high

[4] Data have been provided by UKAEA on 27 June 2006 revising the numbers of particles established by SEM/EDAX, which the Group has been unable to take into consideration due to time constraints.

concentration and the radionuclides ^{137}Cs, ^{90}Sr, ^{94}Nb and ^{60}Co could not be identified in this way. UKAEA have used the appearance of particles under SEM to classify them into MTR, DFR and SS (stainless steel) categories. Of 121 particles classified by appearance, 92 are MTR, 28 are DFR and 1 is SS.

4.2.6 The second criterion for identifying the origin of a particle is on the basis of the radionuclides it contains. All particles have been examined by gamma-spectrometry which allows the content of radionuclides such as ^{137}Cs, ^{94}Nb and ^{60}Co to be determined. Particles that contain measurable activity of ^{60}Co, but not the other two isotopes are likely to be irradiated steel. Particles containing the fission product ^{137}Cs are derived from reactor fuel, but only those derived from fast-reactor fuel would contain ^{94}Nb. Thus particles containing ^{60}Co can be classified as irradiated steel, while those containing ^{137}Cs with ^{94}Nb could be classified as originating from fast-reactor fuel. Particles with ^{137}Cs, but no measurable ^{94}Nb are more difficult to classify unequivocally. They could derive from MTR fuel, but it is also possible that they originate from DFR fuel, but contain insufficient tell-tale ^{94}Nb to be measurable above background levels.

4.2.7 It follows from the preceding paragraph that using gamma spectrometry as a criterion on its own can identify the following categories:

(a) containing ^{60}Co but not ^{137}Cs, positively indicating origin as irradiated steel;

(b) containing ^{94}Nb and ^{137}Cs, positively indicating origin from DFR fuel;

(c) containing ^{137}Cs but no measurable ^{94}Nb, positively indicating origin from spent reactor fuel which at Dounreay could be from MTR or DFR fuels, or could derive from fuels that were imported for reprocessing such as French Pegase fuel; and,

(d) particles with combinations of isotopes that do not fall into any of (a), (b) or (c).

UKAEA have carefully examined and re-counted any particles whose classification initially appeared to fall into (d), and have established that all of the 929 offshore particles recovered up to February 2006 fall into one of (a), (b) or (c).

4.2.8 The two criteria for classification produce results that are broadly compatible. Of the 28 particles classified as DFR by SEM/EDAX exactly half contain measurable levels of ^{94}Nb, and half do not. One particle classified by EDAX as MTR contains ^{94}Nb, and this is the only case in which the two criteria produced conflicting results. Table 4.1 shows the numbers of particles classified by each criterion separately, and an overall classification based on both.

4.2.9 From Table 4.1 the proportion of unequivocally identified DFR particles is 11.6%. However, if the sub-sample of 28 DFR particles classified by SEM/EDAX is representative of the whole group, then the 80 DFR particles that were identified without SEM/EDAX on the basis of ^{94}Nb being present would represent only half of a possible total of 160. Thus, the proportion of DFR particles may be as high as 188 out of 929 (20%). Only 0.9% of offshore particles are of irradiated steel.

Table 4.1 Classification of Offshore Particles by Inferred Origin

Classification by SEM/EDAX		Classification by γ-spectrometry		Combined classification	
Category	**Number**	**Category**	**Number**	**Category**	**Number**
DFR	28	^{94}Nb + ^{137}Cs	107	DFR (positive identification)	108
MTR	92	^{137}Cs alone	814	Fuel particles (mostly MTR but may include DFR)	813
SS	1	^{60}Co	8	Irradiated steel	8

Characteristics of the Offshore Particles

4.2.10 Once in the sea or on beaches, the Dounreay particles will be subjected to the same processes of entrainment, transport and deposition as natural grains of sediment. On the other hand, it is the radioactivity of the particles which is of primary importance with respect to implications for human health. Radioactivity is also the only property that permits the particles to be individually located and recovered, but it has no influence on how the particles behave as man-made sediment grains within the natural environment. The properties that influence the movement and dispersal of sediment grains are shape, size and density.

4.2.11 The shape of Dounreay particles is very variable. Until recently almost all available images were incapable of providing particle size in three dimensions, but in 2006 UKAEA produced microscope images of a small number of *significant* particles taken from three orthogonal directions. These images allow the longest, intermediate and shortest axes of the particles to be measured, which are termed the a-, b- and c-axes respectively. The ratio a:b:c provides a measure of particle form. Two other measurable criteria are the degree of approximation to a sphere and the extent to which corners, edges or faces have been rounded. Few of the Dounreay particles are truly equant in shape (a≈b≈c), *e.g.* spheres or cubes), but some have a rough approximation to prolate or oblate spheroids (a>b≈c and a≈b>c, respectively). Figure 4.1 is an example of a prolate spheroidal shape with a≈1.2b≈1.2c, although it is complicated by a hollow on one side. Figure 4.2 has the shape of a flattened spheroid, with a≈1.2b≈2.3c. Both these particles are rounded, *i.e.* edges or corners are all smoothly curved and lack sharp angles, but vestiges of a former angularity remain in the beak-like end at the left of the “Plan” and “0 Degree” images in Figure 4.1. The particle in Figure 4.3 has a more elongated shape with a non-equant cross section with a≈1.6b≈2.3c. Though the cross section is sub-rounded in the “90 degrees” view, one end is clearly sub-angular in the “plan” view whereas the other appears rounded. An example of an oval disc shape is the particle in Figure 4.4 which has a≈1.7b≈3c and clearly retains traces of an originally flat form. In contrast, the particle in Figure 4.5 has a rod shape with a>>b≈c, with a sub-rounded cross section, but sharp, angular ends. It, too, seems to retain elements of its original form. Figure 4.6 shows a particle which is irregular and angular in shape, with a≈1.5b≈2.4c.

4.2.12 The surfaces of the particles illustrated in Figures 4.1-4.6 are as variable as their shapes. Some show contrasting darker and lighter coloured areas. The lighter areas may represent a different composition or they may be patinas which cover some parts of the particle, but were never present or have been worn away in others. Several particles show re-entrant pits and hollows in their surfaces, which sometimes contain patinas that may display cracks and fissures (e.g. Figure 4.3).

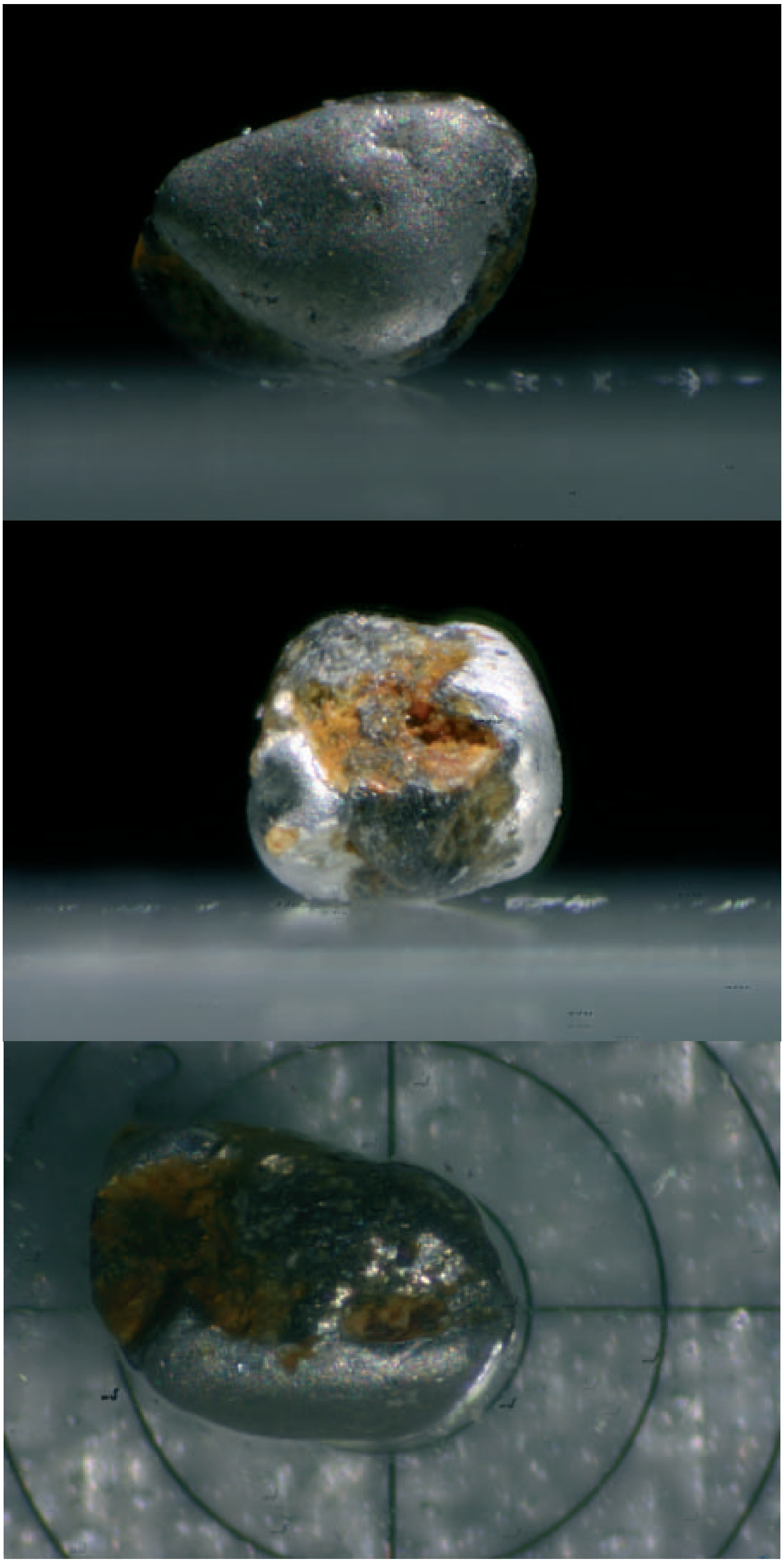


Figure 4.1 Example of a prolate spheroid particle

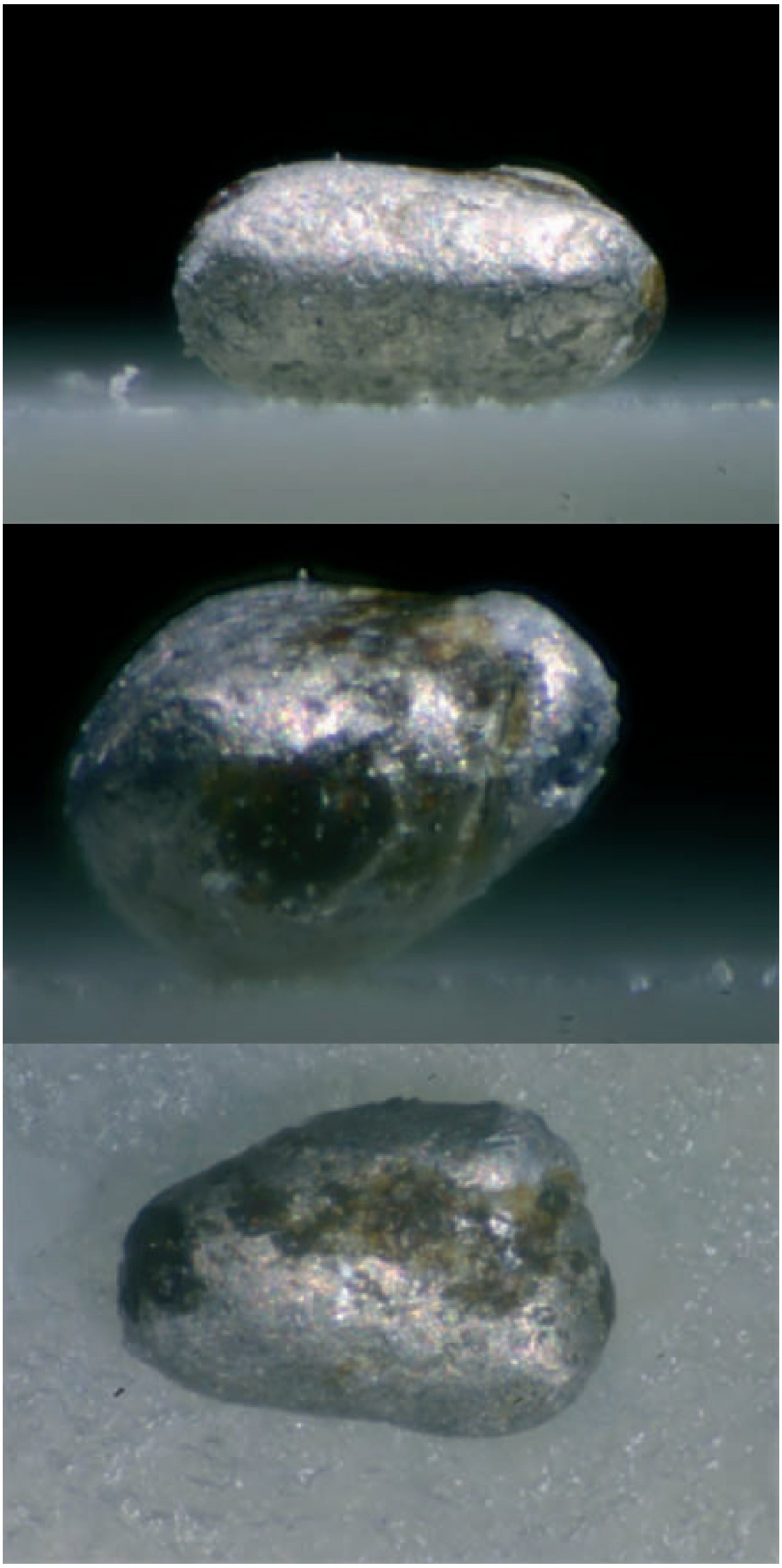


Figure 4.2 Example of a flattened spheroid particle

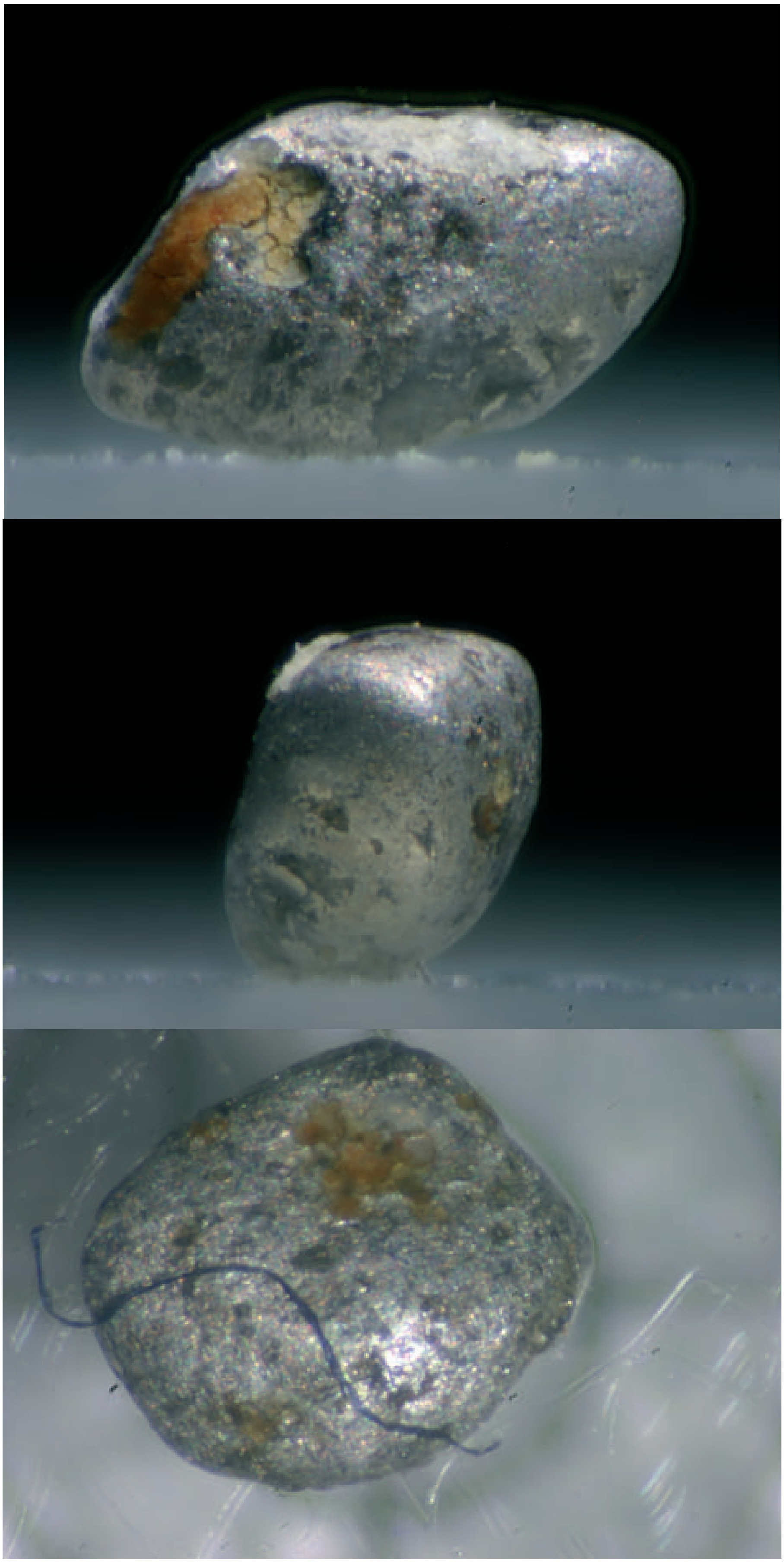


Figure 4.3 Example of a particle with elongated shape and non-equant cross section

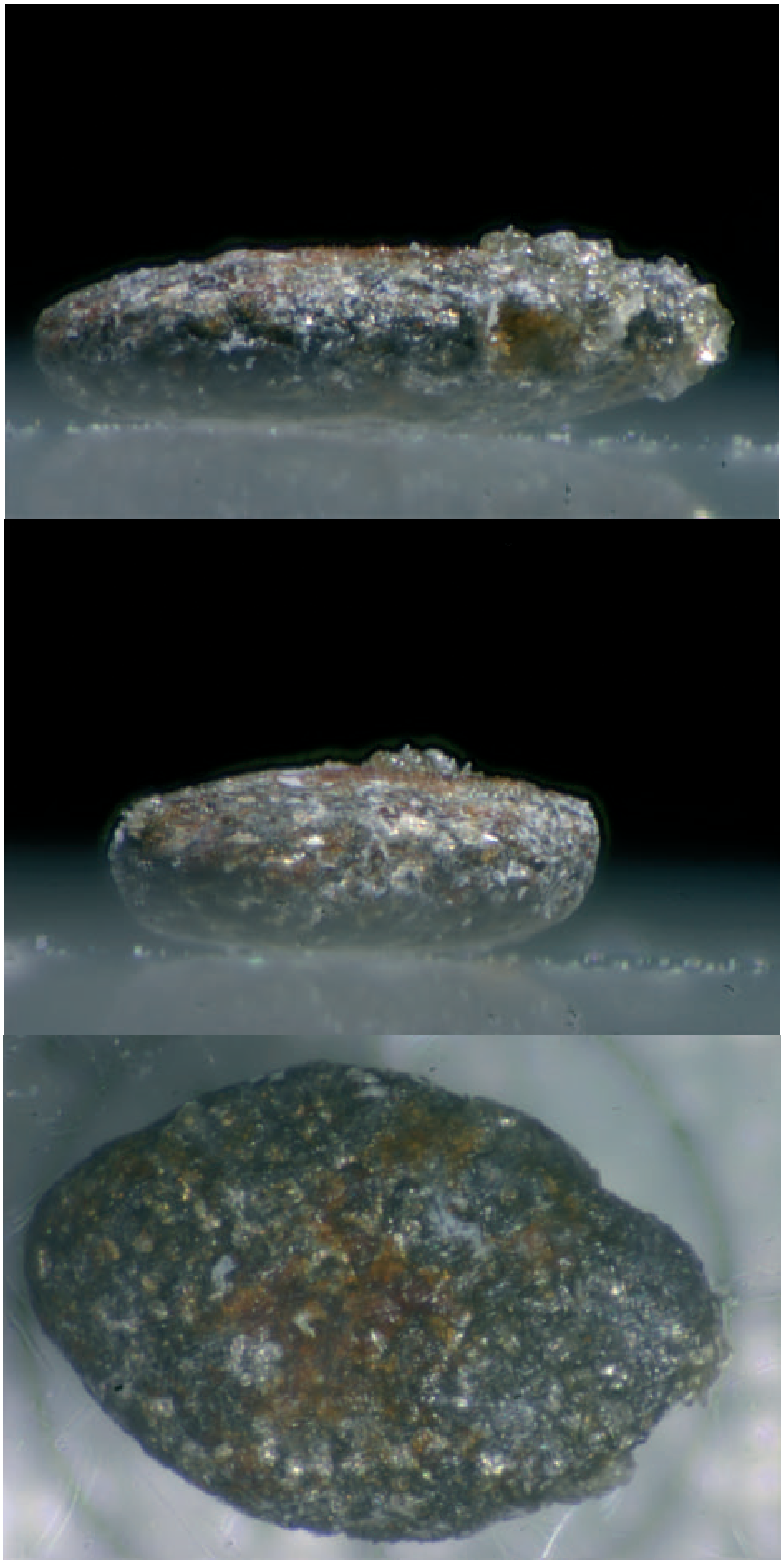


Figure 4.4 Example of an oval disc shaped particle

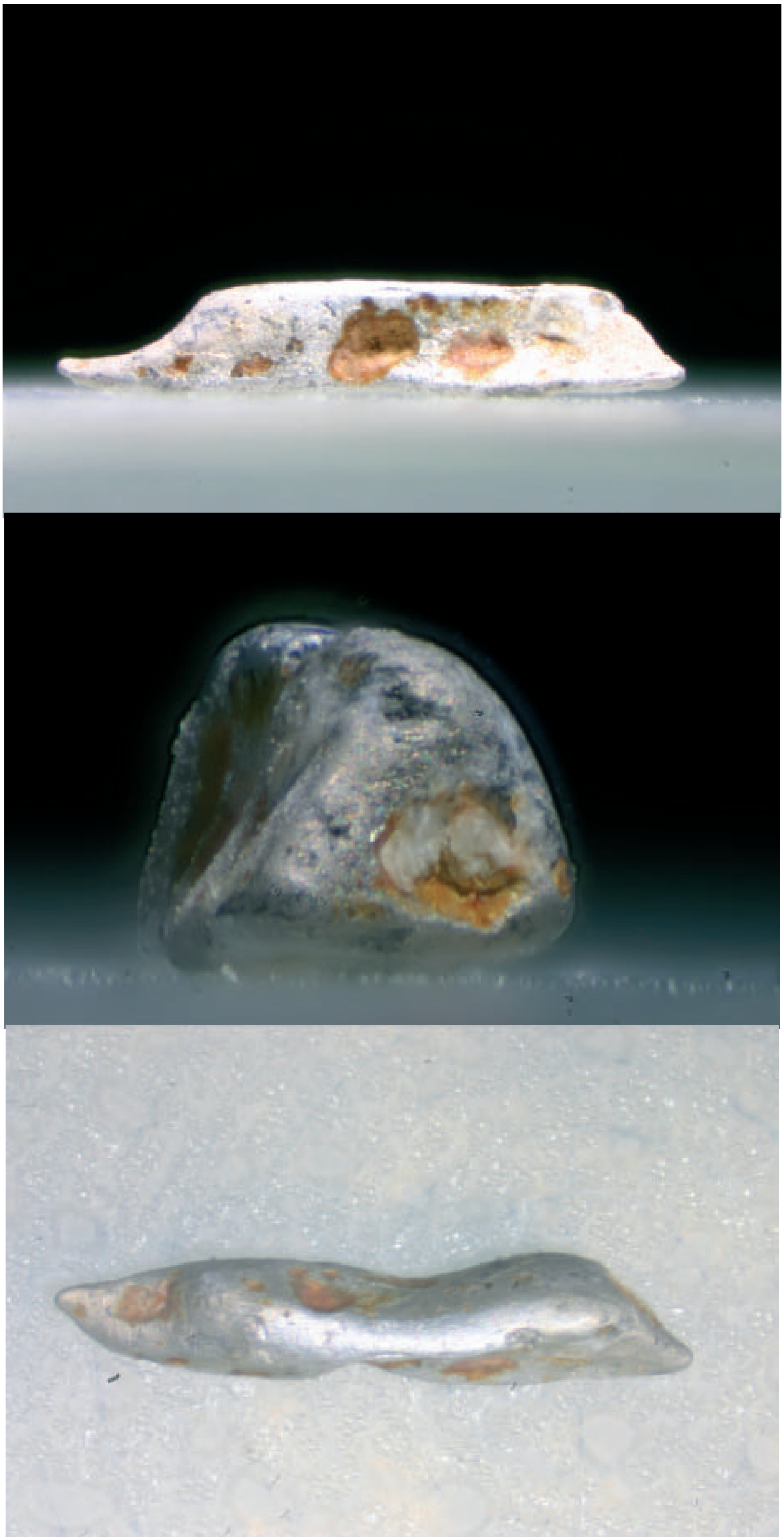


Figure 4.5 Example of a rod shape shaped particle

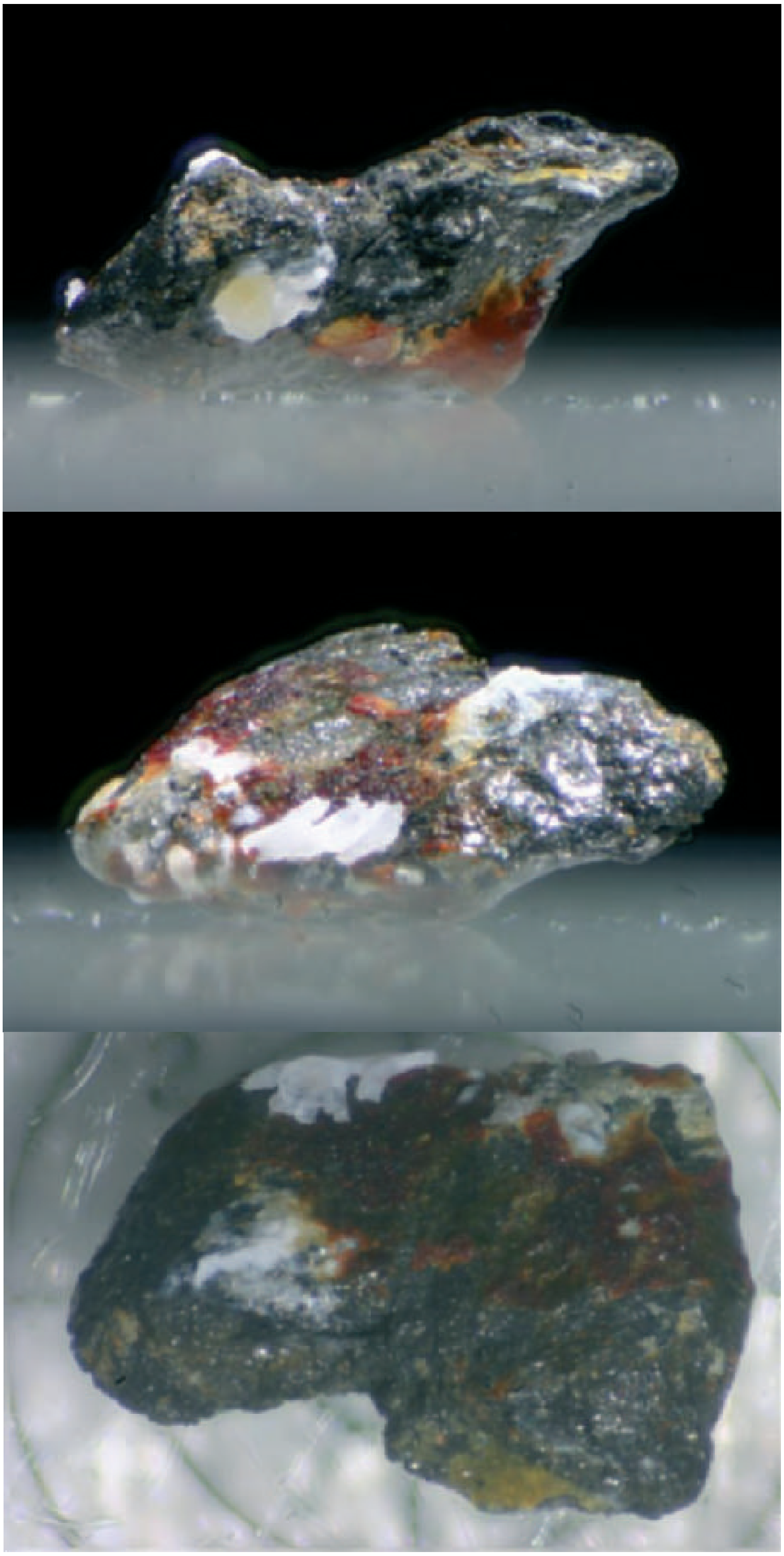


Figure 4.6 Example of an irregular and angular shaped particle

None of the particles illustrated contains an obvious fracture, but c.15% of offshore particles have been found as fragments, while deep cracks have been observed in others. EDAX images have provided clues to the composition of the patinas on some of the particles recovered in 1997-98 (not illustrated here). The patinas contain aluminium and iron, while the darker surfaces adjacent to them contain aluminium and uranium. These compositions are consistent with galvanic corrosion of the particles, forming pits where aluminium has been dissolved, and coatings where it has been co-precipitated with iron from sea water as a mixture of oxy-hydroxides. Iron was not present in the original MTR or DFR fuels, but is abundant in sediment as coatings of iron oxide in cracks or fissures within sand grains.

4.2.13 Two-dimensional images of 166 particles have been made, and the values of a-axis and b-axis for these are plotted in Figure 4.7. All the a:b ratios lie between 1 and 6, but the majority of particles have a ratio between 1 and 2, with a scatter of higher values. A value of 1 is appropriate for spheres, cubes, circular and square discs, or intermediate shapes. A value of 2 represents either laths, oval discs or prolate spheroids. Higher values indicate rod-like forms. In earlier studies, as the third axis was not determined, the exact forms of the particles cannot be inferred from this plot. However, it can be seen that the smaller particles in the sample (with a-axis less than 1 mm) tend to be more equant, whereas aspect ratios exceeding 2 predominate among the few particles longer than 3 mm. This trend may reflect the origin of many particles as ribbons or strips of metallic swarf, most of which have by now broken into shorter lengths. There appears to be little or no differentiation between Offshore and Foreshore particles as far as the two-dimensional shape ratio a:b is concerned and the lack of information regarding the ratios of these two axes to the third prevents any further deductions on the question of whether particles in different locations have any tendency towards differentiation by shape (but see 4.2.11 above).

4.2.14 Particle sizes are illustrated by Figure 4.7 and Figure 4.8. The largest particles lie in the range from 3 mm up to 7 mm in length, but these comprise less than 10% of the sample of 166. The basis for selecting the particles used to construct these diagrams is not clear. However, it appears from Figure 4.8 that the distribution of a-axis values is a roughly symmetrical histogram for offshore particles, provided that the logarithm of size values is used as a scale, rather than the values themselves. The 115 Offshore particles in the sample, span over two orders in size, from very fine sand or silt (~0.06 mm) to gravel (~8mm). Dounreay Foreshore particles tend to be longer than the Offshore population with a size distribution that has the commonest particles in the coarse sand grade (~ 2 mm), but also shows a tail towards medium sand (~0.2 mm). The sample of Sandside particles is very small, only 10, but demonstrates a narrow range centred on the 0.6 mm category.

4.2.15 The mass of individual particles is easily established by weighing on a modern microbalance. Figure 4.9 is a plot of mass *versus* a-axis length for 115 offshore particles. If shape were constant across all particles in this plot, mass should increase with the third power (cube) of length. The obvious scatter in the data can be attributed to the wide variation that exists in particle shapes, and also to possible variations in density; these are discussed below.

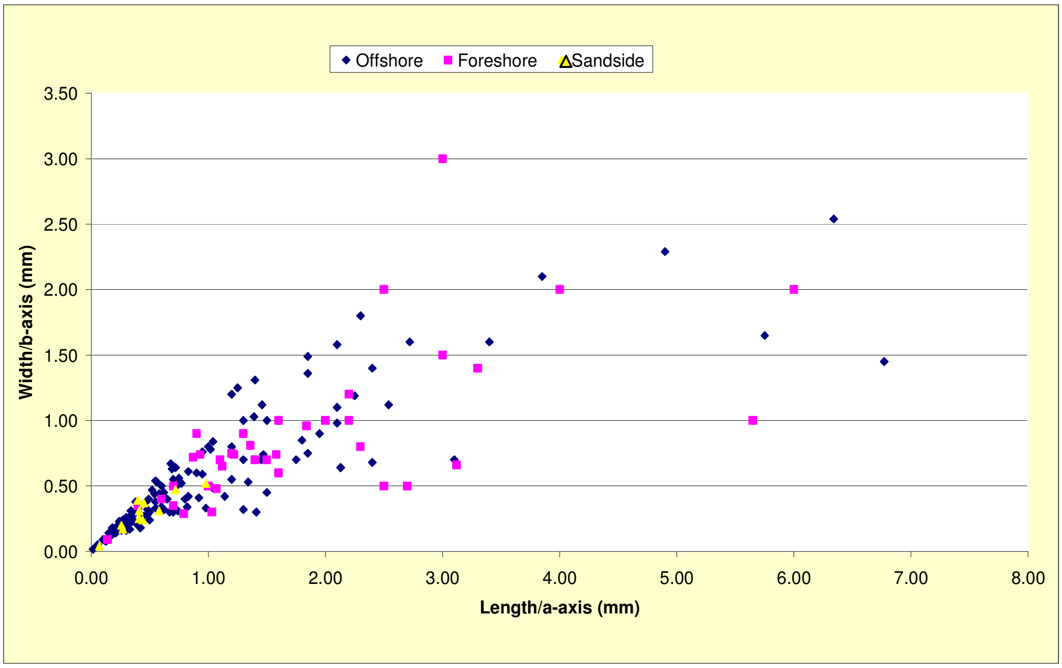


Figure 4.7 Particle dimensions (sourced from UKAEA Data)

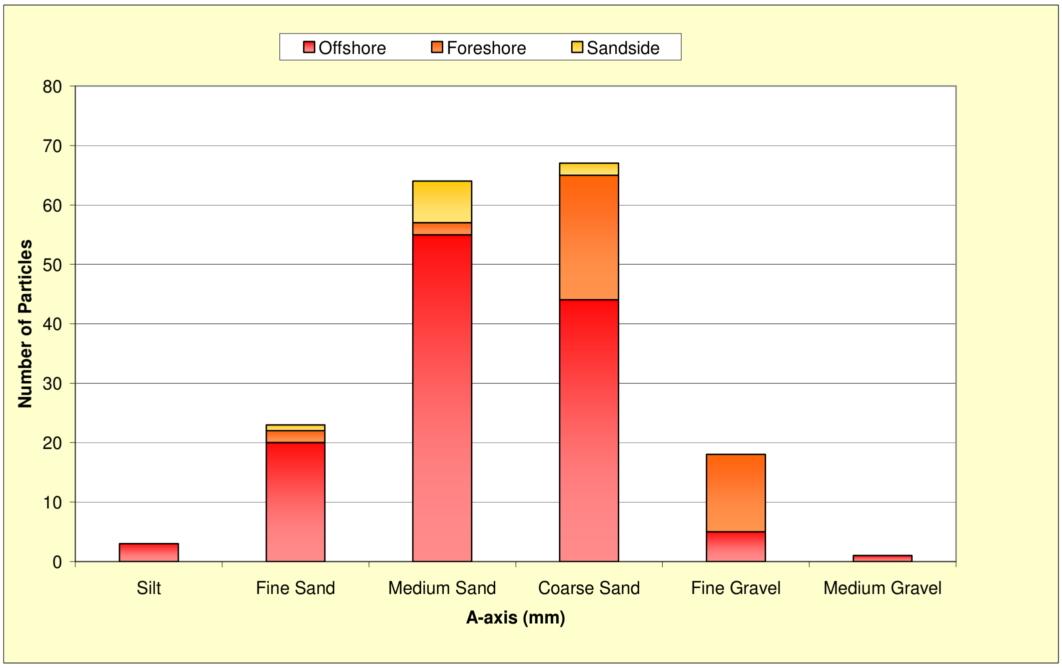


Figure 4.8 Particle Size Distribution (source UKAEA)

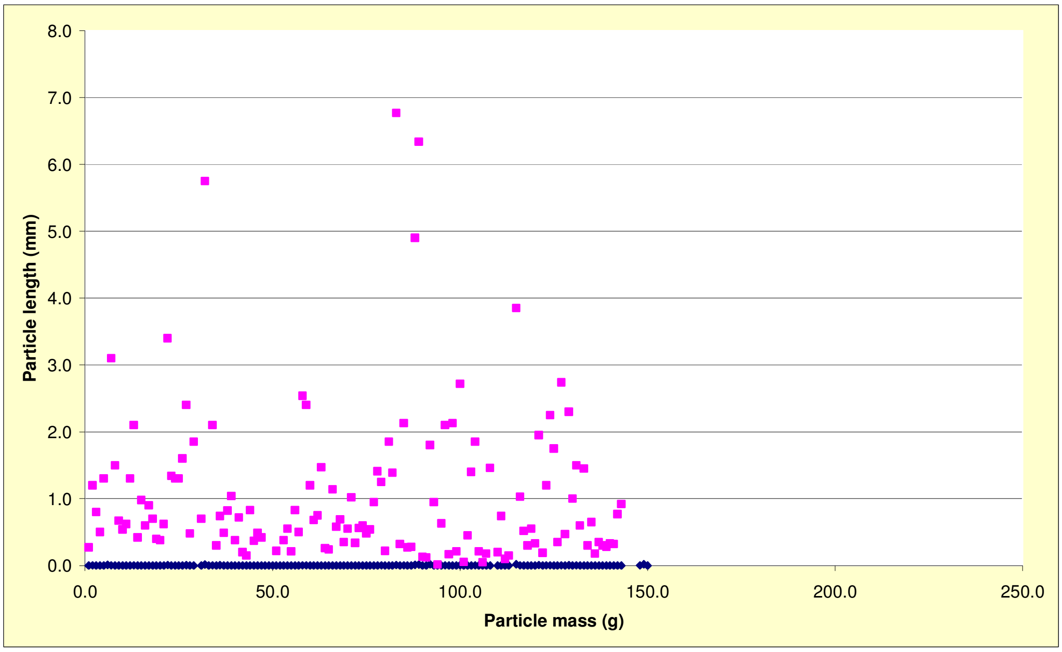


Figure 4.9 Particle Mass *versus* a-axis length

4.2.16 The density of Dounreay particles, although a critical property controlling transport and deposition, has proved frustratingly difficult to establish through measurement. In theory, the density of non-porous particles formed from U-Al alloy should be in the range 3.0 to 3.4 g/cm^3, depending on the exact uranium content. The density of pure aluminium is 2.75 g/cm^3. For comparison, the density of quartz, the main mineral in beach and sea bed sands at Dounreay, is 2.65 g/cm^3. The simplest method for measuring particle density would be to place each particle successively into a range of heavy liquids with different densities and to determine the liquids in which the particle just sank and just floated. The particle density would lie in the range between the two liquid densities. This methodology merits further consideration. UKAEA are currently pursuing an alternative approach based on constructing 3-D images of particles through microscope photography from different angles, with estimation of particle volume by a computer algorithm which performs a 3-D triangulation. Mass of the particle can be easily established by weighing and the density calculated from the ratio of mass to volume. This technique has been piloted on nine particles including the six illustrated in Figures 4.1 to 4.6, and a sample of pure aluminium wire. Densities that overlapped the expected range (within error) were obtained for three of the particles and the wire, but for the remaining six particles the computed densities were much lower than expected, with the most irregularly shaped particles (*e.g.* Figure 4.6) giving the lowest values. A possible explanation is that the number of photographs taken of each particle was too small for accurate 3-D reconstruction, so that the volume estimation consequently failed to take into account the numerous pits and re-entrant hollows that are an obvious feature in the photographs. All of the particles studied in this way so far have been of MTR type. Many DFR particles appear to be porous and the 3-D technique will inevitably underestimate the density of their solid parts, although it may eventually provide reasonably accurate estimates for overall bulk density. Until the accuracy of measurements can be more convincingly assured, it must be supposed, by default, that the densities of most Dounreay particles lie within the range 2.7 to 3.4 g/cm^3.

4.2.17 The main gamma-emitting radionuclide in the Dounreay particles is ^{137}Cs. Figure 4.10 shows the distribution of ^{137}Cs activity among all 929 offshore particles that have been recovered. The distribution among recovered particles may not represent the true distribution of activities among all particles in the environment, for several reasons. High-activity particles are easier to find and low-activity particles may be undetectable if buried, so recovered particles may show a bias towards large activities. An opposite bias may result from the fact that 227 recoveries were made during re-surveys of the Repopulation Areas (circular patches of sea-floor which had previously been carefully cleared of all detectable particles). The activities of the finds made during re-surveys are systematically lower than those made from the same areas on initial survey. The distributions of activity among particles within different areas of the sea bed are considered further in Sections 3 and 4 of this Chapter. In these Sections, allowances have been made to compensate for these sources of bias.

4.2.18 Radioactivity due to gamma-ray emitters, usually ^{137}Cs, is the only characteristic that has been measured on every one of the Dounreay particles found in the environment. For those in the sea and on beaches the factors that determine their behaviour as sediment grains are shape, size and density. As discussed above, these are known very imperfectly and only for sub-sets of particles which were selected on arbitrary grounds and so do not necessarily constitute a representative sample of either the recovered particles or the overall population in the environment. The remainder of this Chapter discusses the behaviour of particles in the environment and of necessity uses ^{137}Cs activity as a surrogate for the other particle characteristics. At this point, therefore, it is appropriate to examine the relationships between ^{137}Cs activity and particle size and mass, using the arbitrary sub-sets of data that are available.

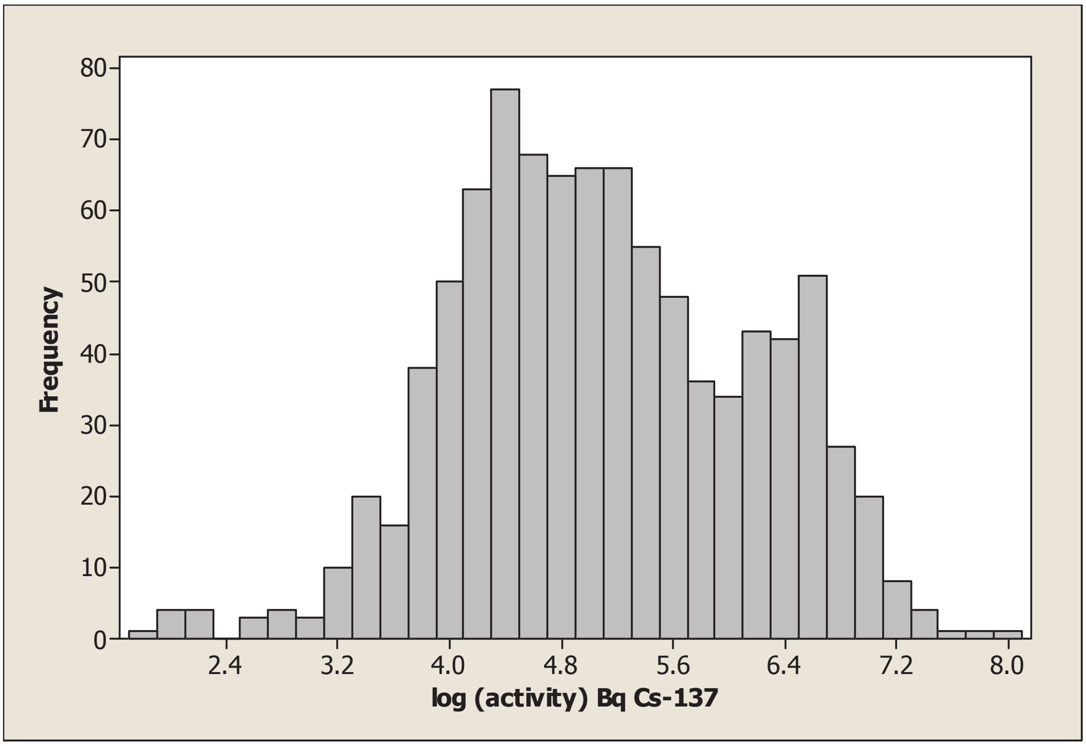


Figure 4.10 Histogram of activity for the 929 offshore particles

4.2.19 Figure 4.11 is a scatter plot of particle activity against a-axis length, with finds from Offshore, the Dounreay Foreshore and Sandside Beach distinguished. Among the Offshore particles there is a clear tendency for activity to increase with particle size, but the trend is non-linear and convex-upwards. A simple increase in activity with particle volume would produce a convex-downwards trend, so other factors must determine the observed relationship. The sub-set of particles plotted does not include the very highest activities found offshore, which exceed 10^8 Bq ^{137}Cs, so the appearance of an upper limit to activity in relation to particle size in Figure 4.11 may be illusory. However, it seems likely that the smaller rate of increase of activity with length among particles longer than 1 mm may reflect some features of the original process of production, perhaps a tendency for activity to be concentrated at one end of a ribbon of swarf when a milling or cutting machine entered the fuel itself.

4.2.20 The small sample of particles from Sandside Beach plot within the scatter of offshore data in Figure 4.11. The Sandside particles all have a-axis lengths of less than 1 mm, and the majority cluster in the range 0.3 to 0.5 mm. The members of this cluster have activities around 10^5 Bq ^{137}Cs. It is important to note that some offshore particles in the upper part of the Sandside size range (a-axis) have activities exceeding 10^6 Bq ^{137}Cs. The implication of this is that *significant* particles exist offshore which are of a suitable dimension to be transported onto Sandside Beach. The distribution of activities for offshore particles with a-axes smaller than 1 mm in Figure 4.11 suggests that about 15% of suitably sized particles may be *significant*, but, as this sample is not known to represent accurately the true offshore population, this figure should be treated with caution, especially as the number of Sandside particles in the Figure is so small.

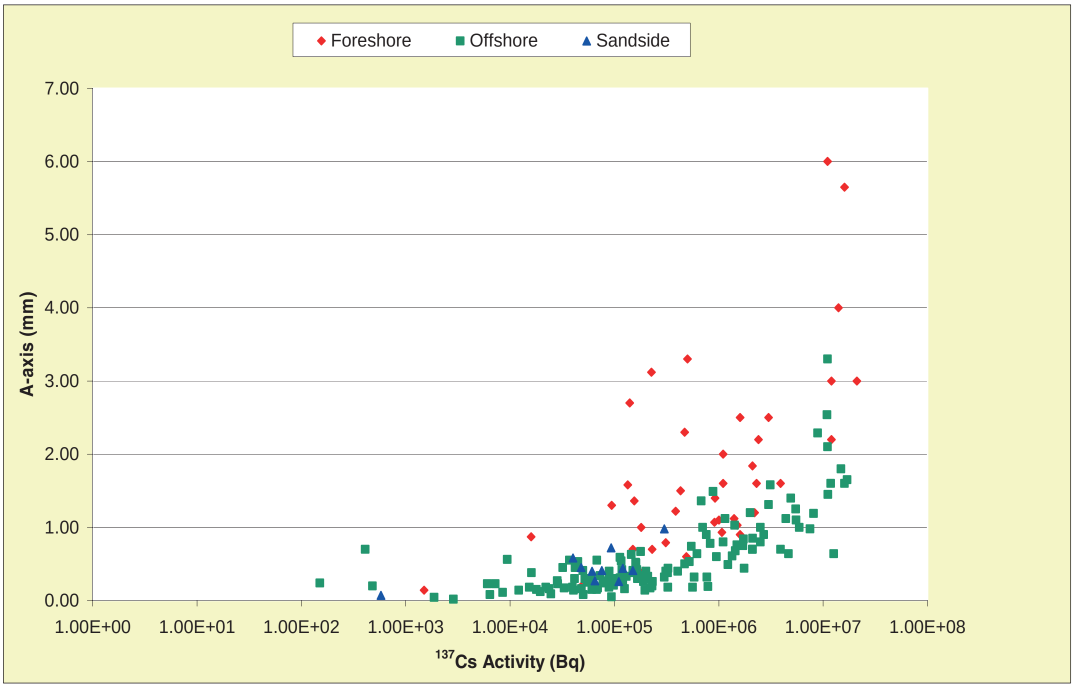


Figure 4.11 **^{137}Cs activity *versus* a-axis (source UKAEA)**

4.2.21 The a-axis sizes of those Dounreay Foreshore particles plotted in Figure 4.11 are generally larger than those of the offshore set. As the Foreshore particles are probably derived from the offshore population, this difference in size should reflect sorting by sedimentary processes as discussed further in Section 4 of this Chapter. More striking is that the Foreshore data in Figure 4.11 mostly plot outside the field of offshore data. The Foreshore group is therefore quite distinctive in both size and activity. This must reflect sedimentary selection for some variable other than size that not only determines the particles' behaviour as sedimentary grains, but is also correlated with activity. Density is the most likely candidate. It can be expected to show some relation to ^{137}Cs concentration because particles with higher uranium content will be denser and, as ^{137}Cs is a fission product, its activity should be proportional to the amount of uranium present. The burn-up history of the particular fuel from which the particle is derived will also have an influence. The lower activities displayed by Foreshore particles compared with similar sized Offshore particles suggests that there is a selection for lower density during transport onto the Foreshore. This idea agrees with what would be expected on the basis of normal sedimentary processes, but the influence of particle shape is also a possibility. There is also a possibility that particles originating from the non-active drains discharging close to shore could have contributed to this local population.

4.2.22 The relationship between ^{137}Cs activity and particle mass is presented in Figure 4.12. Statistical analysis of the data in this Figure shows that the mean activity for particles of the same mass is significantly different between Foreshore and Offshore particles (Appendix G). In both groups the gradients of the trends between activity and mass are the same. Figure 4.12 appears to confirm the conclusion already drawn from Figure 4.11, *i.e.* that some unmeasured characteristic which is positively associated with activity is being selected as particles are transported and deposited onto the Foreshore. Again, density appears the most likely candidate, but shape may also play a part. The particles in both environments show similar ranges of mass, so there is no evidence from these data that mass itself is being selected during transport or deposition of Foreshore particles. Section 4.4 of this Chapter discusses sedimentary selection and sorting in more detail.

Summary of the Characteristics of Offshore Particles

4.2.23 Offshore particles display a wide range of shapes and sizes, but these are imperfectly known because of the shortcomings of existing photographic and SEM imagery. Among particles that have been imaged in two dimensions and are less than 1mm long, the ratios between long and intermediate axes mostly lie between 1 and 2. Larger particles tend to have higher ratios and are more rod-shaped, possibly reflecting their origin as ribbons of swarf.

4.2.24 Density is very poorly characterised, but a few estimates based on 3-D analysis of orthogonal photographs suggest that densities of MTR particles are either within the theoretical range of 2.75 to 3.4 g/cm^3, or may lie below it. There is no evidence so far that particle densities might exceed this theoretical range. There is no information on the density of DFR particles.

4.2.25 The ^{137}Cs activity of Offshore particles increases with particle size (a-axis length) and with mass. Both relationships show considerable scatter, but indicate that activity could be employed as a crude surrogate for size and/or mass. This is fortunate, as ^{137}Cs activity is the only characteristic that has been measured for all recovered Dounreay particles. A small set of Sandside particles appears to conform to the general relationships seen between activity and size or mass among the Offshore data. On the other hand, a sample set of the Dounreay Foreshore particles shows distinct differences from the offshore set with respect to both activity and size, but not with respect to mass. This may be due to the selection of large but less dense particles from the offshore population during different stages of transport and deposition on the Foreshore.

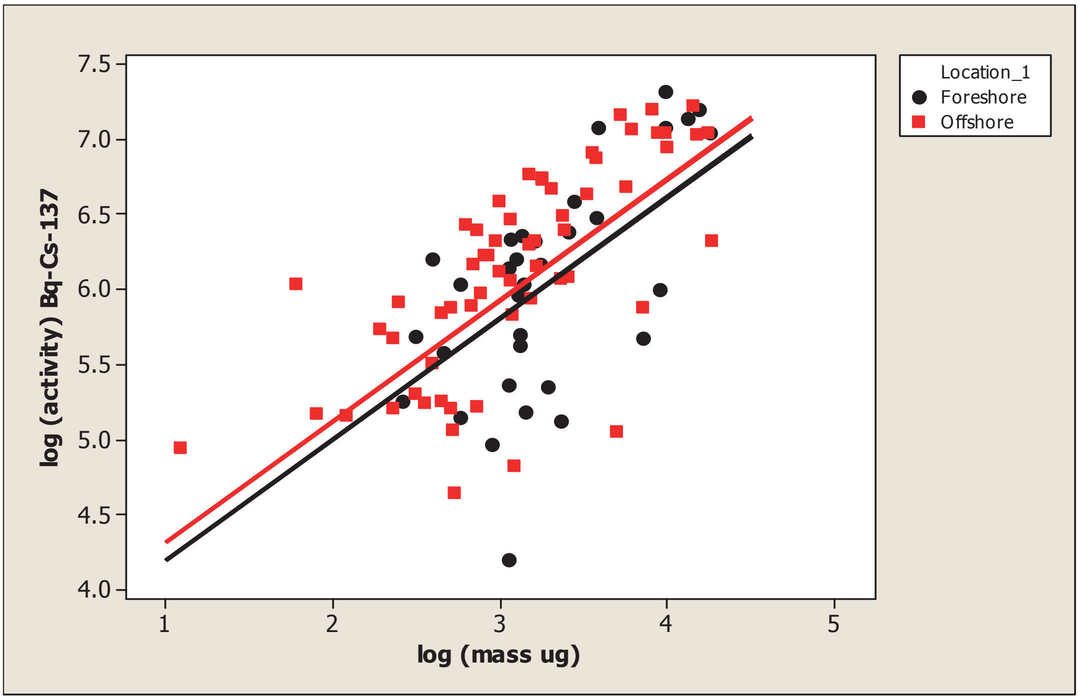


Figure 4.12 ^{137}**Cs activity and particle mass (source UKAEA)**

4.3 <u>The Distribution of Particles on the Sea Bed and Estimation of Total Numbers Present</u>

Diver Surveys and other data on the distribution of particles

4.3.1 Although particles have been recovered from the Dounreay Foreshore since November 1983, nothing was known of their offshore occurrence until one was identified during diving work close to the Diffuser in 1997. This immediately led to a more extensive survey and 34 were found and recovered. Since then, diving surveys have taken place each summer, although the areas surveyed have varied, as have the specific aims and procedures in each diving campaign.

4.3.2 Diver surveys have followed four main procedures. Initial work in 1997 was unsystematic, with few precautions taken to avoid going over the same areas several times or to ensure that the whole of a designated area was covered. In 1998 and subsequently, search areas were much more systematically designated and recorded using GPS coordinates of the dive-boat's position and controlling the search pattern on the sea floor. Despite some shortcomings, the data from these dives allow the calculation of the numbers of finds per unit area of sea bed.

4.3.3 The second search mode was undertaken only in the years 2000 and 2001. A series of lines was laid out over the area between the Diffuser and the shore. Divers followed the lines measuring the electrical conductivity of the sea water and searching for particles in a swathe approximately 2 m wide.

4.3.4 In 2000 the third mode of search was initiated, being designed to reveal the amount of particle movement on the sea bed by studying the repopulation of a cleared area. Initially seven sites were selected at varying distances west and east of the Diffuser. A further five sites were added in subsequent years, the full twelve being known as the Repopulation Areas. With the exception of Repopulation Area 9, each site consisted of a circular area with a metal pin driven approximately 600 mm into the sea-bed sediments at its centre. The position of the Repopulation Sites is not adequately plotted on any of the maps in this Report.

Reference to Table 4.2 which relates their position to the hectare grid squares shown on Figure 4.17 enables their approximate position to be determined. A rope could be attached to the central pin on each visit by a diver and, when held in tension, this would define the radius of each circle (28.2 m), and its area of 2500 m^2. At four of the repopulation sites (#2, 3, 4, 5) an outer annular area has also been surveyed, with 50 m radius and total area 7855 m^2 including the inner circle. Site (hash) 9 is exceptional. It is very close to the Diffuser in an area of outcropping rock and intervening sand basins. Five sand basins were surveyed and are designated 9E, 9W, 9S, 9C1 and 9C2. In all Repopulation Areas the whole area was intensively and systematically searched for particles which were all removed. The initial surveys thus cleared each area of all detectable particles, although some lower activity particles may have remained because they were buried too deeply for detection. Each Repopulation Area was subsequently re-surveyed and all detected particles were again removed. The number of re-surveys varied from site to site, with two sites established in 2004 so far lacking any re-survey and one site (#4) having been visited eight times in all, *i.e.* seven re-surveys.

Table 4.2 Repopulation Areas

Repopulation Site Number	Hectare Squares (part)	Shore parallel distance from diffuser (metres)	Mean Water Depth (metres)
#1	330 m SSW of origin	1960 W	18
#2	F 12; G 12	430 W	23
#3	G 16; G 17	80 W	18
#4	I 17; I 18; J 17; J 18	160 E	22
#5	L 22	690 E	20.5
#6	O 24; O 25	1070 E	22
#7	S 26	1440 E	27
#8	G 17; G 18	80 W (inshore)	15
#9 (C1)	H 17; I 17	60 E	22
#9 (C2)	I 16; I 17	60 E	22.5
#9 E	H 17	0	21
#9 S	H 17	0	20
#9 W	H 16	40 W	22
#10	I 16	80 E	23.5
#11	Q 25	1250 E	24
#12	X 31	2150 E	29

4.3.5 The particles found in repopulation surveys may, therefore, be classified into initial finds, *i.e.* those made on previously un-searched areas, and re-survey finds. Most of the latter must be particles that had migrated into the cleared area from the surrounding sea bed. (A few re-survey finds may be particles that escaped detection on previous searches because they were too deeply buried. If such particles could be identified, the fact that they had migrated to depths that were shallow enough for detection on re-survey would allow one to estimate the minimum depth to which sediment had been disturbed in the interim).

4.3.6 The latest mode of searching for and recovering particles was initiated in 2005. A robotic device known as the TROL has been developed by UKAEA for searching the sea floor and recognising particles. It distinguishes them from natural background radioactivity by their gamma energy spectrum characteristics and provides an unequivocal identification, unlike the FITS device used in a previous survey in 1998-1999 (DPAG, 2001). The TROL device was first deployed in 2004 but no attempt was made in that year to use diving to confirm the “strikes” it made. In 2005, however, divers were employed to search for, confirm and remove the particles found by the robot. The TROL’s search mode is systematic, consisting of successive passes back and forth across an area of sea bed rectangular in shape at times when boat drift is absent.

4.3.7 Figures 4.13 and 4.14 show all of the areas searched by divers between 1997 and 2005 plus the areas covered by TROL in 2004 and 2005. No distinction is made between areas in which particles were found and those where none was located.

4.3.8 Figure 4.15 shows the location of recovered particles as dots and Figure 4.16 shows the same information at larger scale with the offshore particles colour-coded according to their activity. Onshore finds are shown undifferentiated by activity. Re-survey finds from Repopulation Areas are excluded from these diagrams.

4.3.9 The divers detected particles by their radioactivity, using hand-held scintillator counters to detect gamma rays from ^{137}Cs. The detection limit under water is about 250 Bq for a particle resting on the sediment surface. For a buried particle the sediment provides shielding and reduces the count level at the diver's instrument. Table 4.3 gives approximate detection limits as a function of depth of burial. However, these are not exact limits, as a diver operating carefully can decide to follow up an observation of a slight increase in count rate by placing the instrument closer to the sea bed, or could make a trial excavation to see if the count rate increases when sediment is removed. A few high-activity particles that were recorded as very deeply buried by the divers who found them may have been initially detected in this way. In general, however, the maximum depths at which particles of various activities are recorded as having been found are all in good agreement with the detection limits in Table 4.3.

4.3.10 The detection limits in Table 4.3 imply that *minor* particles ($<10^5$ ^{137}Cs) are likely to remain undetected if they are buried deeper than about 200 mm in sediment. Some *relevant* particles (10^5 – 10^6 Bq ^{137}Cs) may pass undetected if buried deeper than between c.350 mm to c. 520 mm, whereas *significant* particles ($>10^6$ Bq ^{137}Cs) are detectable at greater depths, depending on their activity. The maximum depth at which divers have reported finding *significant* particles is 1000 mm, although this may be an overestimate of the true depth. The largest activity of any offshore particle so far recovered is 1×10^8 Bq ^{137}Cs, which would be detectable at 800 mm.

Table 4.3 Approximate limits of detectable ^{137}Cs activity for particles buried at various depths.

Depth in sediment (mm)	Minimum detectable activity (Bq)
0	2.51×10^2
100	1.26×10^3
200	6.30×10^3
300	3.16×10^4
400	1.66×10^5
500	7.94×10^5
600	4.37×10^6
700	2.0×10^7

(Data from Fig.10 in M.Scrirea 2000).

4.3.11 Normal diving operations are limited to c. 30 m depth. Therefore the majority of particles have been found beneath depths of water that were less than this. The only reliable data from greater depths comes from the TROL surveys of 2004 and 2005.

4.3.12 In 1998-1999 a towed large area plastic scintillation detector device known as FITS was used in an attempt to explore how far the distribution of particles might extend into water deeper than could be explored by divers. Maps showing peaks of activity were obtained and published (DPAG 2001), but careful analysis since has indicated that most peaks were the effect of natural boulders or rock buried in or beneath the sea-bed sediments. In a small area where diving and FITS surveys overlapped, it could be shown that the FITS signal indicating a real particle was quite distinct from that due to natural radioactivity. There were very few indications of particles on the sea floor or in the sediments to seaward of the 25 m depth contour and the FITS data gave little sound reason to suspect that any more than a very few particles exist there.

4.3.13 Further important limitations of both the FITS and the TROL data are that neither give any indication of the depth at which a particle represented by a definite "strike" may be buried. The FITS data are difficult to interpret and are now best set aside. The TROL data on their own can record the definite presence of a particle from its ^{137}Cs spectral characteristics, but the count rate that is recorded could represent any one of many combinations of particle activity with depth of burial. At present these two factors can only be resolved if the particle is recovered by a diver, although further development of the TROL device may make it possible to estimate activity in combination with depth of burial (see paragraph 4.1.5).

The distribution of particles on the sea floor

4.3.14 During the years 1997 – 2005, 694 particles have been detected and recovered by divers from initial surveys including the TROL trials, and a further 235 from revisits to repopulation areas. The overall pattern of surveys has yielded a somewhat unsystematic sampling of the offshore zone, with more searches between 15 and 29 m water depth than in shallower water.

4.3.15 The pattern of particles found (Figures 4.15 and 4.16) and of areas that were searched, but yielded no finds (Figure 4.13 and 4.14) shows that the particle distribution takes the form of a plume, dispersed roughly parallel to the shore. There are few particles close to the shore, which is rocky with little sand apart from the beach area of the Dounreay Foreshore. The seaward limit of the diver finds is at c. 25 m depth and is determined to some extent by the procedures for diving. However, while some robot TROL "strikes" have been made beyond this limit, the frequency of strikes per unit area drops off sharply across the 25 m depth contour not shown on this figure suggesting that the true edge of the plume lies only a short distance to seaward (see Figure 4.18).

4.3.16 The visual impression provided by Figures 4.15, 4.16 and 4.18 is that the frequency of particles per unit area of sea bed declines continuously away from the Diffuser. The decline appears steeper to the west and less marked to the east, in agreement with the predominantly eastwards direction of tidal transport.

4.3.17 The distal parts of the plume have been searched much less intensively than the areas nearer the Diffuser. The beach and the rocky part of the Dounreay Foreshore lie opposite the central part of the plume where the frequency of particles on the sea bed is highest. The onshore finds have been made on a 1 km length of this shore. The activities of these finds are much higher than at Sandside and Dunnet Beaches. The Group considers that the Dounreay Foreshore finds are particles derived from the central part of the plume, which have been driven onto the shore by wave action.

4.3.18 The part of the plume west of the Diffuser extends as a narrow ribbon of finds into Sandside Bay. Part of the floor of this bay has been searched, but few particles have been found there (see Figure 4.16). It may be inferred from this that the 59 particles found so far on Sandside Beach to February 2006 (starting with a single particle in 1984, but with all but two of the other finds following after a series of improvements in monitoring that began in 1999) had all moved into the bay as part of the plume and were carried onto the beach by wave action.

4.3.19 Northeast of the Diffuser the plume extends parallel to the shore for over 2 km (Figure 4.16). Robot TROL surveys of three small areas lying seaward of the distal part of the plume proved wholly negative, suggesting that its seaward boundary lies close to the 25 m depth contour, as the pattern of the finds themselves also suggests.

4.3.20 Diving on two small areas east and west of the Brims Ness headland resulted in nine particle finds. The only sea-bed searches made further east from these two areas have been by robot TROL in Dunnet Bay. They proved negative. However in 2005, a "Low Activity" metallic radioactive particle was located by means of its ^{137}Cs activity during a systematic survey of Dunnet Beach. These distant finds are undoubtedly derived from Dounreay, and demonstrate that the particle plume extends eastwards beyond Brims Ness. However, particle frequencies per unit area may be very low in this part of the plume. No particles have yet been found on the beaches at Scrabster and Thurso, despite regular monitoring of these two sites for many years.

4.3.21 Almost all the particles that have been recovered from the sea bed have been located in areas of sand. Only on the Dounreay Foreshore have particles commonly been found on rocky outcrops. Even here the finds are usually associated with small pockets of sand in hollows or crevices which may temporarily trap sediment swept onto and off the shore by breaking waves. Very few particles have been found on rock outcrops on the sea bed and those that have were trapped in crevices and sand filled gullies.

Estimation of total numbers of particles present on the sea floor

4.3.22 To estimate the total numbers of particles on the sea bed, it is necessary to smooth and interpolate particle frequencies per unit area, between the irregularly distributed patches of ground that have been surveyed. The method that has been adopted for doing this is based on squares of 1 hectare (ha) area (a square 100 m x 100 m has an area of 1 ha = 2.471 acres). A grid of these squares is shown on Figure 4.17, and Figures 4.19 to 4.22 are based on this grid. Reference in the text to individual hectare squares are based on a combination of letters (A-Z south to north) and numbers (1-31 west to east)

4.3.23 In estimating total numbers of particles, the *significant* (>10^6 Bq) particles, as defined in terms of potential radiological impact, are treated separately from those with activities less than 10^6 Bq. The latter comprise *relevant* and *minor* particles with activities of 10^5 - 10^6 Bq and <10^5 Bq respectively. Chapter 3 in this Report describes the derivation and importance of these categories.

4.3.24 In Figure 4.19 the numbers of actual finds of *significant* particles are shown for each hectare square. The colour coding of the squares indicates the proportion of the sand-floored area within the square that has been searched. Squares in which no search has been made are distinguished from those in which 0-25%, 26-50%, 51-75% and 76-100% of the sand area has been searched.

4.3.25 The actual finds can be extrapolated to provide an estimate of the total number of *significant* particles in each square. This has been done by dividing the numbers found by the fraction of the sand area that was searched. The reason for using only the sand-floored portion of each square is that almost all recovered particles were found in sand, whereas all the rocky areas surveyed were almost devoid of particles. Figure 4.20 shows the resulting estimates of the numbers of *significant* particles in each square.

4.3.26 The colour coding in Figure 4.20 is related to the degree of uncertainty of the estimates for the total numbers. If we make the assumption that the detailed distribution of particles within the sandy parts of each square is essentially random in relation to the areas searched, then the expected uncertainty related to a certain number of actual finds is given by the square root of that number. In other words, if we imagine the particles being restored to their position on the sea bed, and a second random search conducted, the number that might be found might differ from that found the first time. The uncertainty is the magnitude of this difference, or to be exact it is the average magnitude of the differences among many such repeated searches. Of course we have only one search to consider, so the estimate of uncertainty is what matters and this is given by the square root of the number actually found. To take this a little further, if the number of particles found in a square is N, and these are found in a search of fraction F of the sand area, the expected total in the square is N/F and the 1-standard deviation error in this estimate is $100/\sqrt{N}$, expressed as a percentage. In Figure 4.20 the squares are shaded according to whether the percentage uncertainty in their estimated total is <25%, 26-50%, 51-75%, or 76-100%.

4.3.27 The next step in estimating the total number of significant particles is to contour the scattered estimates for each hectare square. The contoured map shown in Figure 4.20 has been constructed according to the assumptions that the plume is continuous and the frequencies of particles per unit area of sea bed decline fairly regularly away from the Diffuser. This is the pattern which would be expected if the plume had arisen from a single deposition of particles onto the sea bed near the Diffuser at some time prior to 1984. An alternative possibility is that there were several emissions of particles onto the sea bed at different times. This issue is discussed in Chapter Two. Multiple sources in time might have produced uneven distribution of particles, and might be the basis for an alternative scheme of contouring in which closed contours would be drawn to represent peaks that had migrated down-drift from the Diffuser. Relatively high estimated numbers in squares H20, L20, O25, S27 and T28 might at first glance appear to justify this procedure. However, all of these high estimates (and also that in Q22) are in fact based on very small numbers of particles found, and very small fractions of the sand area in each square actually surveyed. The relative percentage errors for these squares are very large, so the values shown should be interpreted cautiously. The true figure may be much lower than that shown, but could equally be much higher. The contouring procedure adopted has given greatest weight to squares with low relative errors, and less weight to those where the errors are large. The aim was to produce contours for a smoothly varying particle frequency on the sea bed.

4.3.28 In Figure 4.20 the plume of *significant* particles (>10^6 Bq ^{137}Cs) is bounded by the estimated position for the contour of 1 particle per ha (1 ha^{-1}). The total area enclosed within this contour is 62 ha. The total number of particles was estimated by integration across the whole plume area within this contour. Graphs of particle frequency per unit area versus distance were drawn for regularly spaced lines orientated at right angles to the plume axis. The number of particles represented by each cross section was calculated and the total summed over the whole length of the plume.

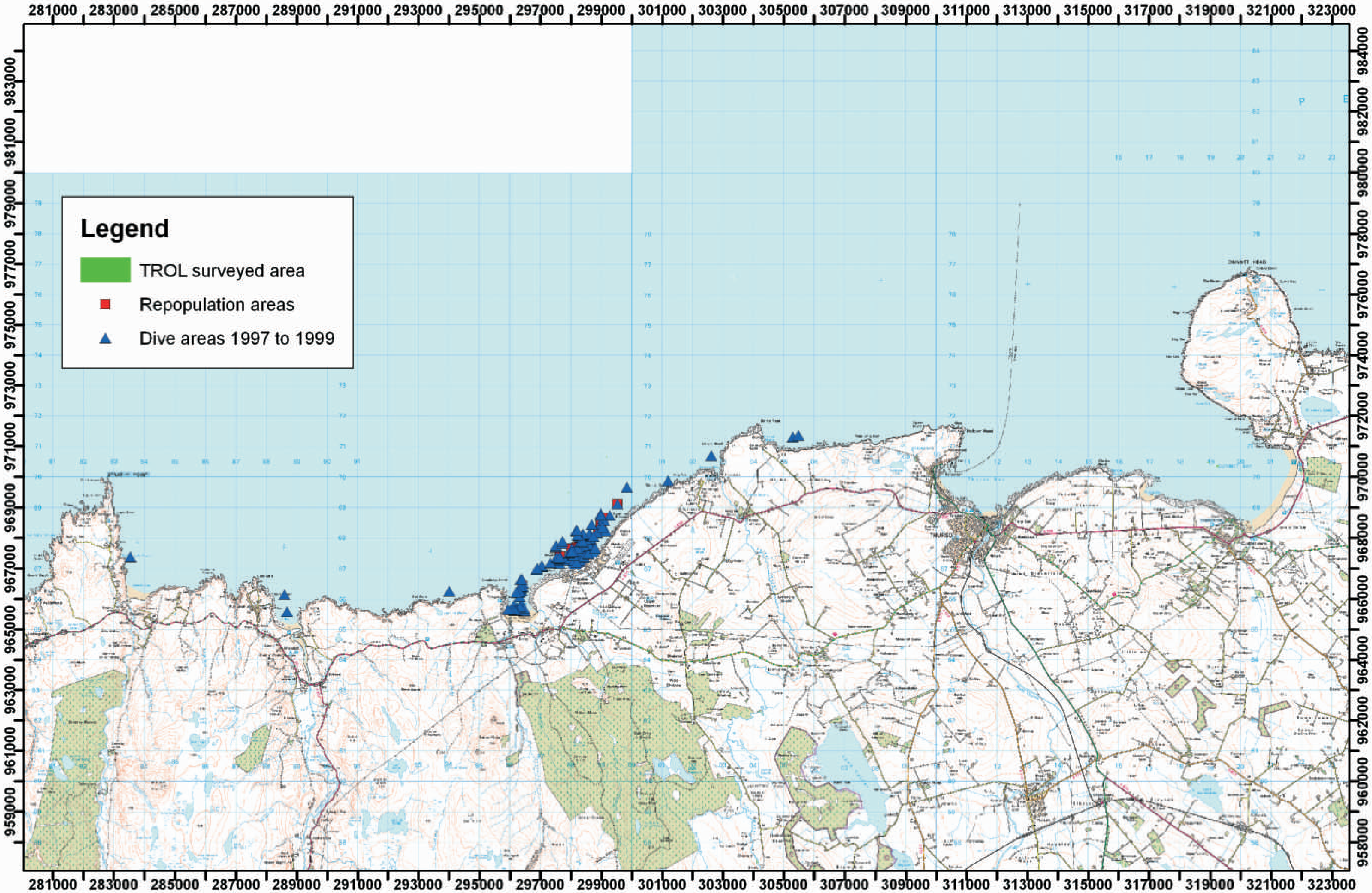


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Figure 4.13 Distribution of Surveys, Strathy Point to Dunnet Head

0 2 4 Kilometres

SEPA Scottish Environment Protection Agency

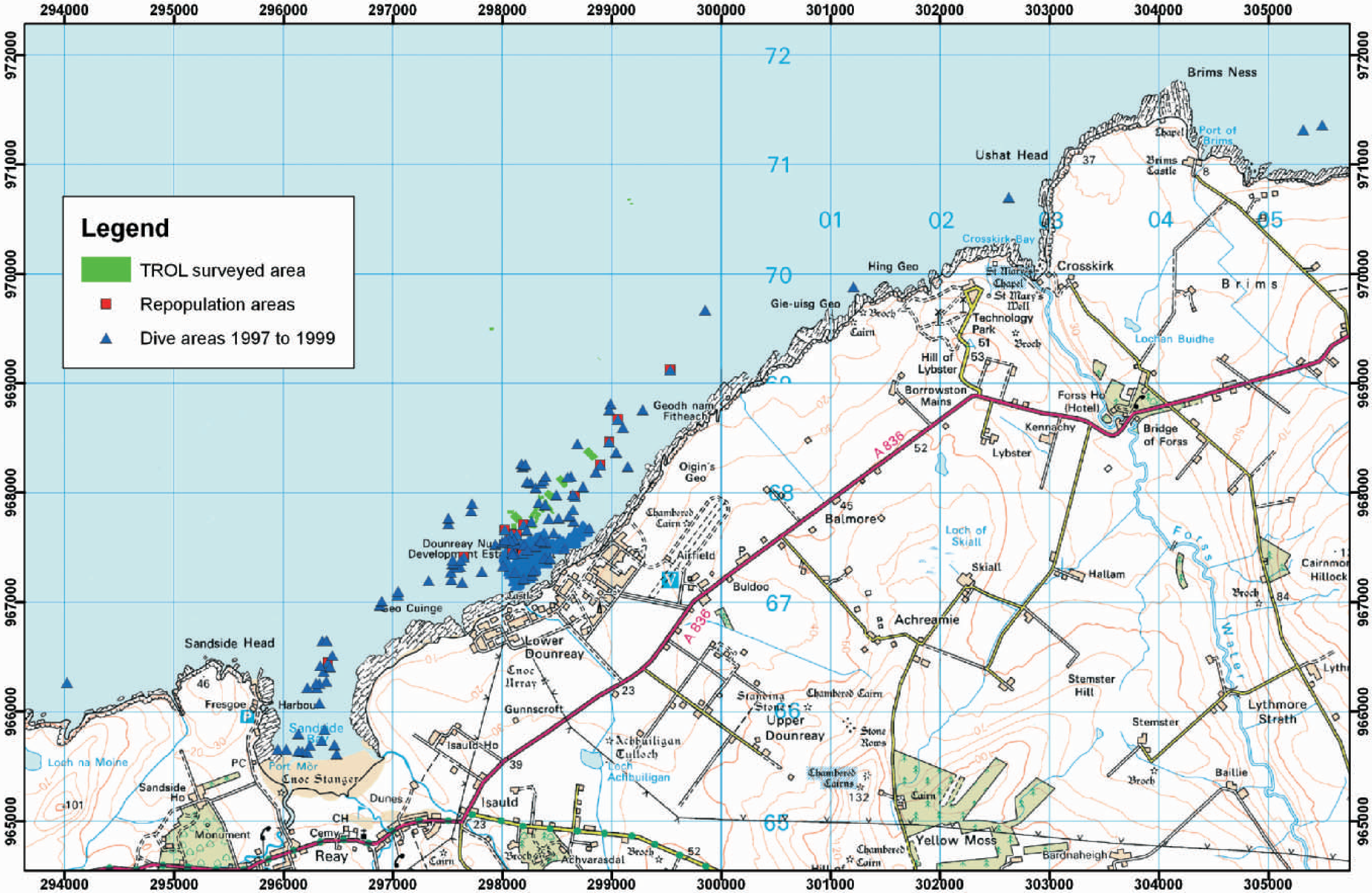

Figure 4.14 Distribution of Surveys, Sandside Bay to Brims Ness

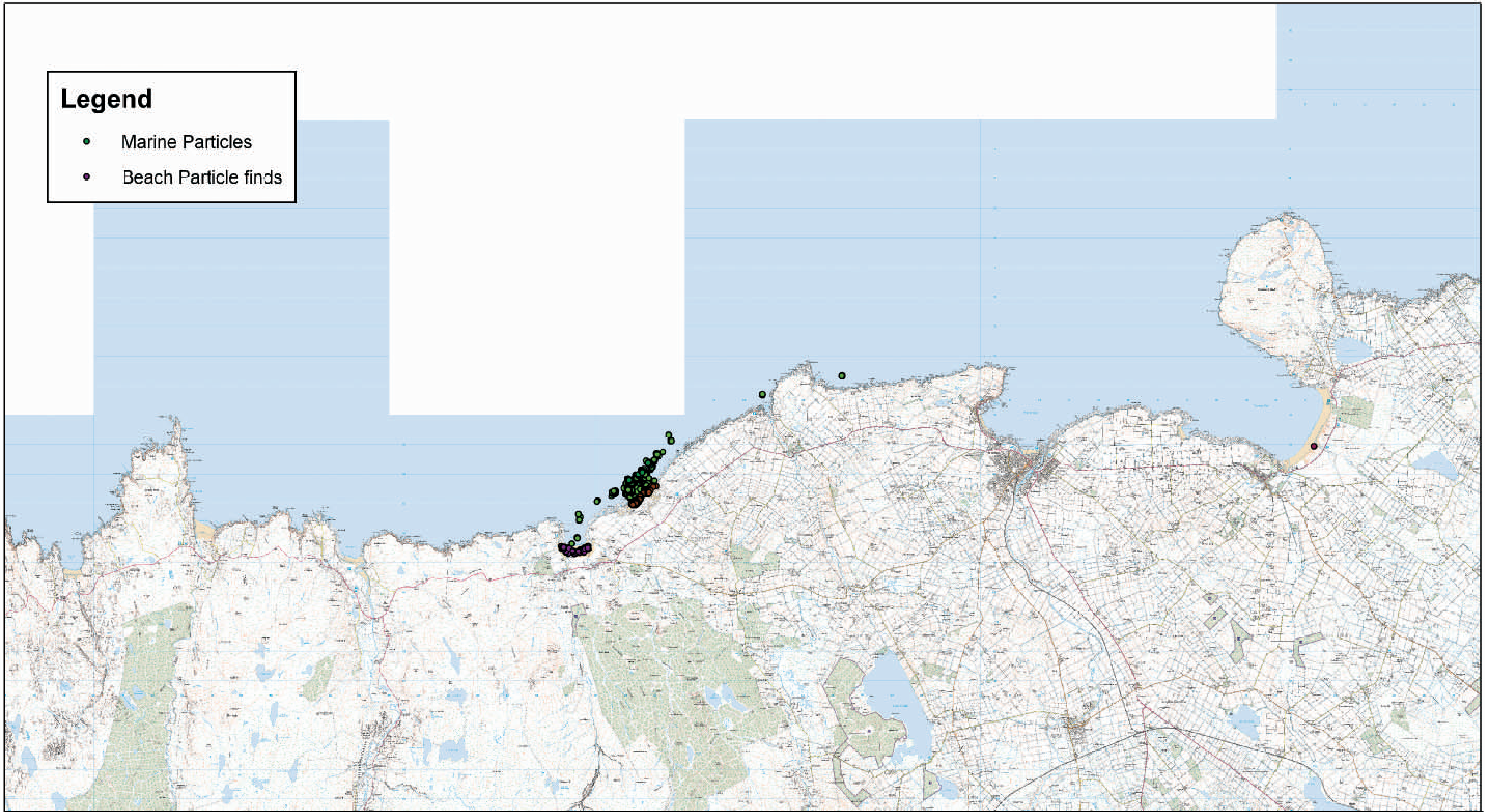

Figure 4.15 All particles recovered around Dounreay
Strathy Point to Dunnet Head

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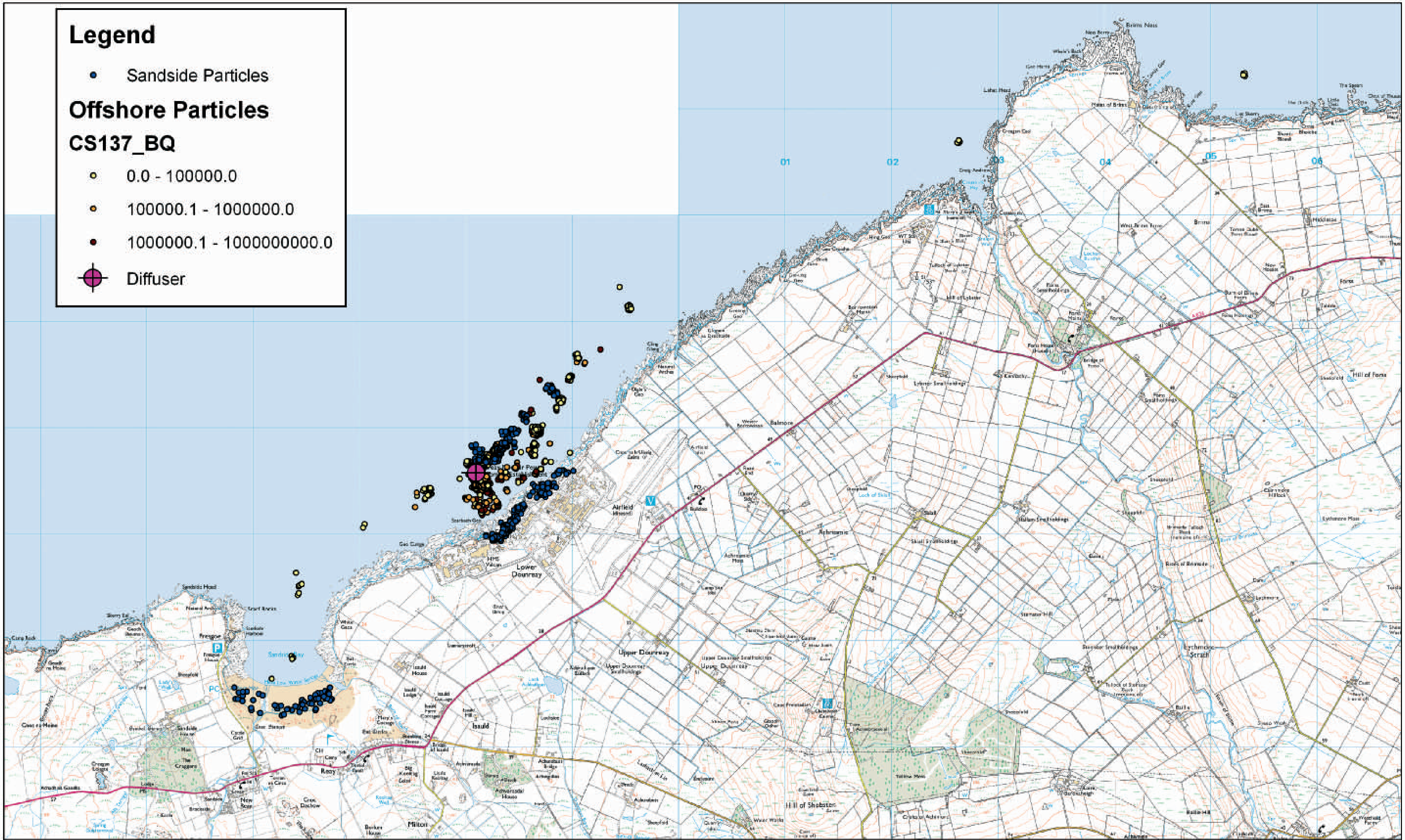
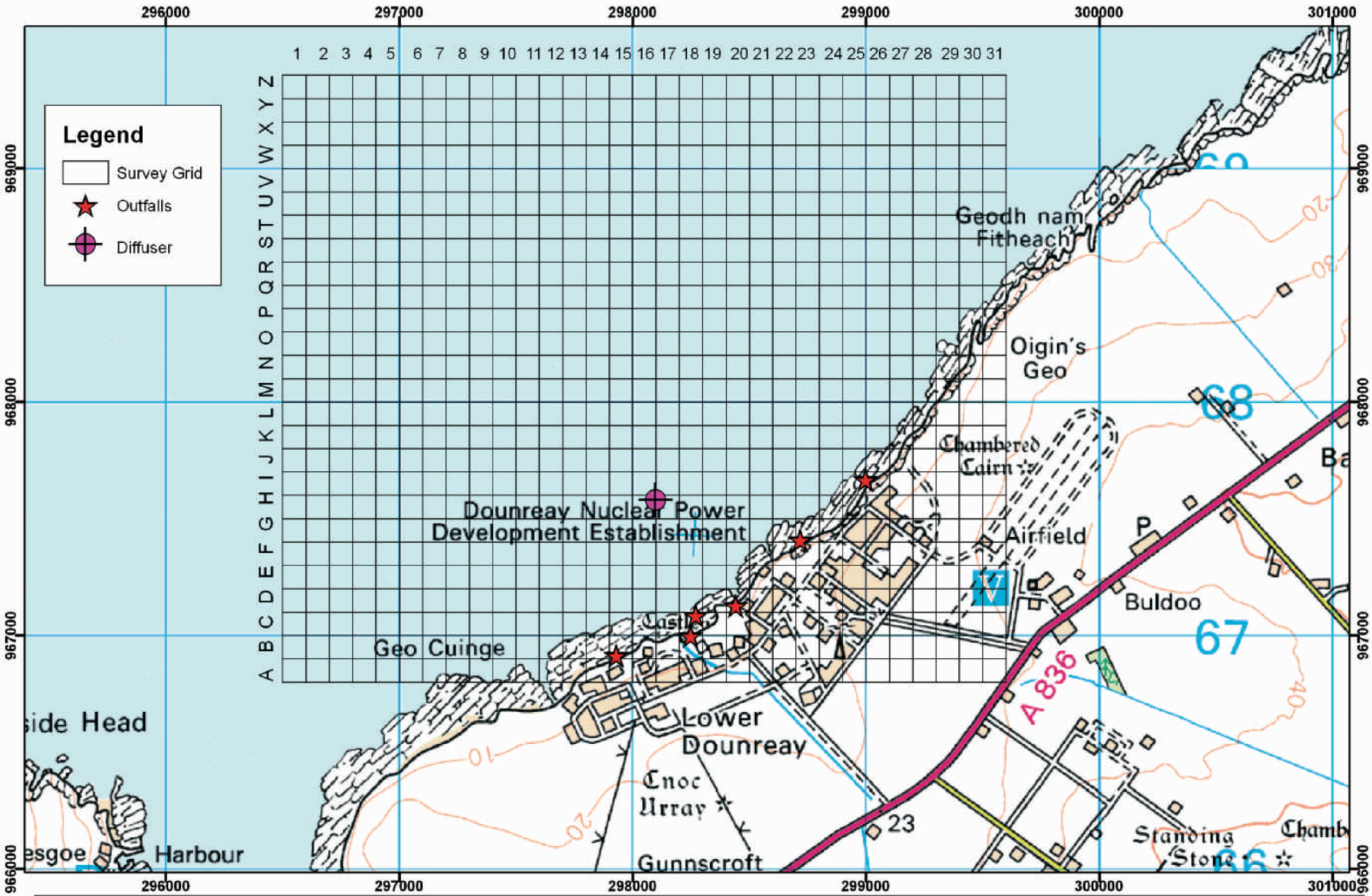


Figure 4.16 Particles detected close to Dounreay. Offshore Particles differentiated by activity, foreshore and beach particles undifferentiated.

SEPA Scottish Environment Protection Agency



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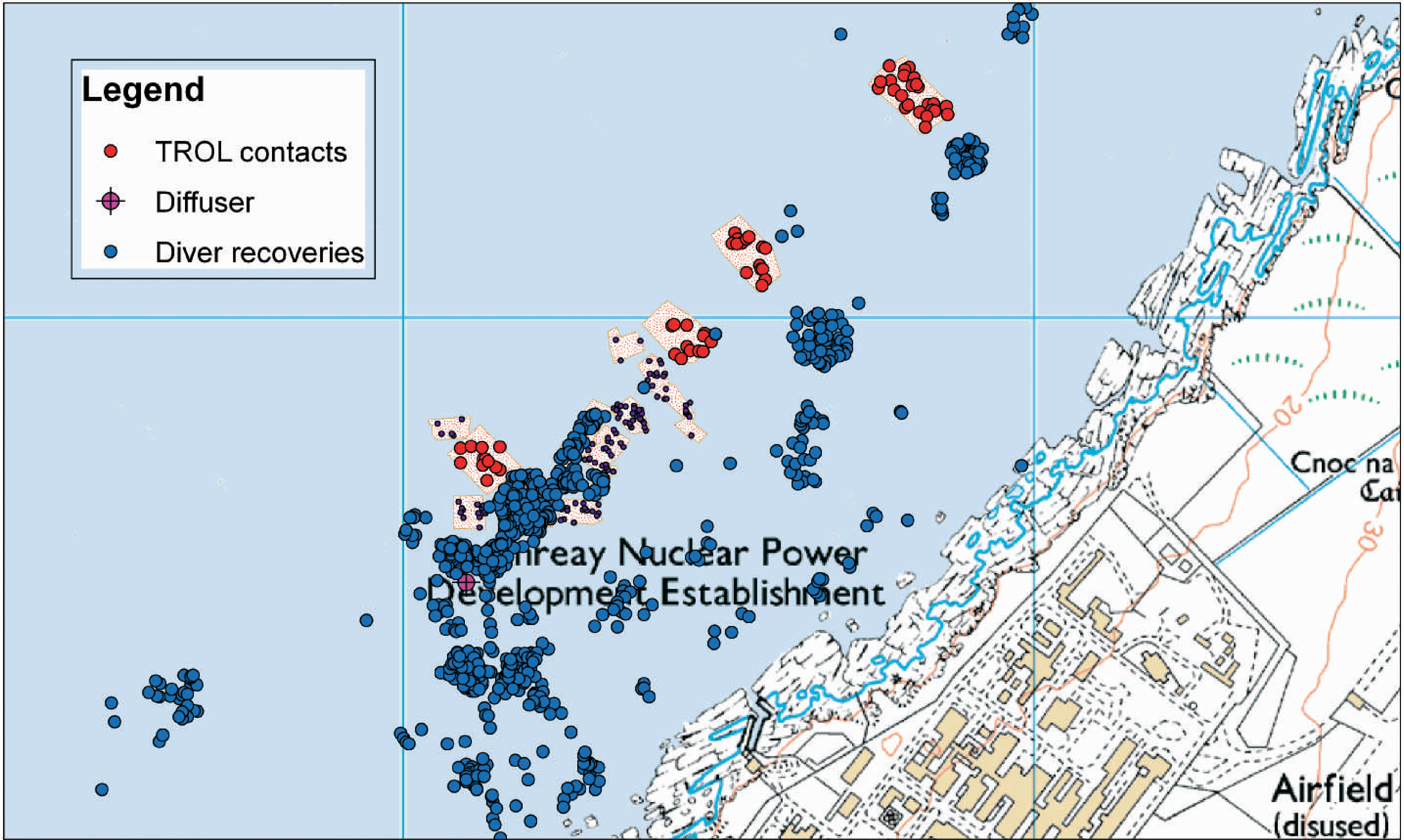
0 0.5 1 Kilometres

Figure 4.17 Location of Dounreay Outfalls Diffuser and Survey Grid Extent

SEPA Scottish Environment Protection Agency



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1:5,500,000

Figure 4.18 TROL surveys and particles detected in 2004 and 2005 together with diver recovered particles

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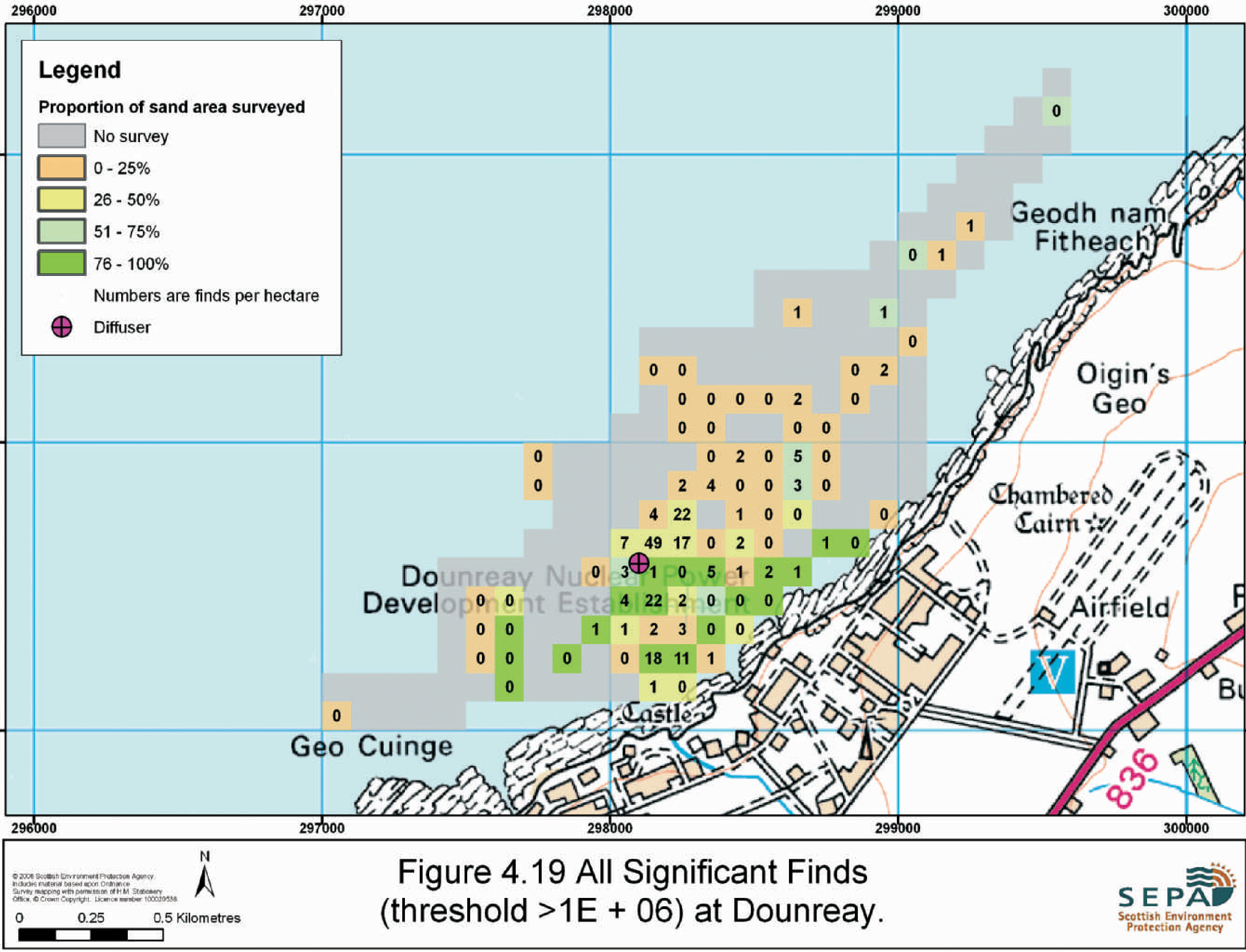

Figure 4.19 All Significant Finds (threshold >1E + 06) at Dounreay.

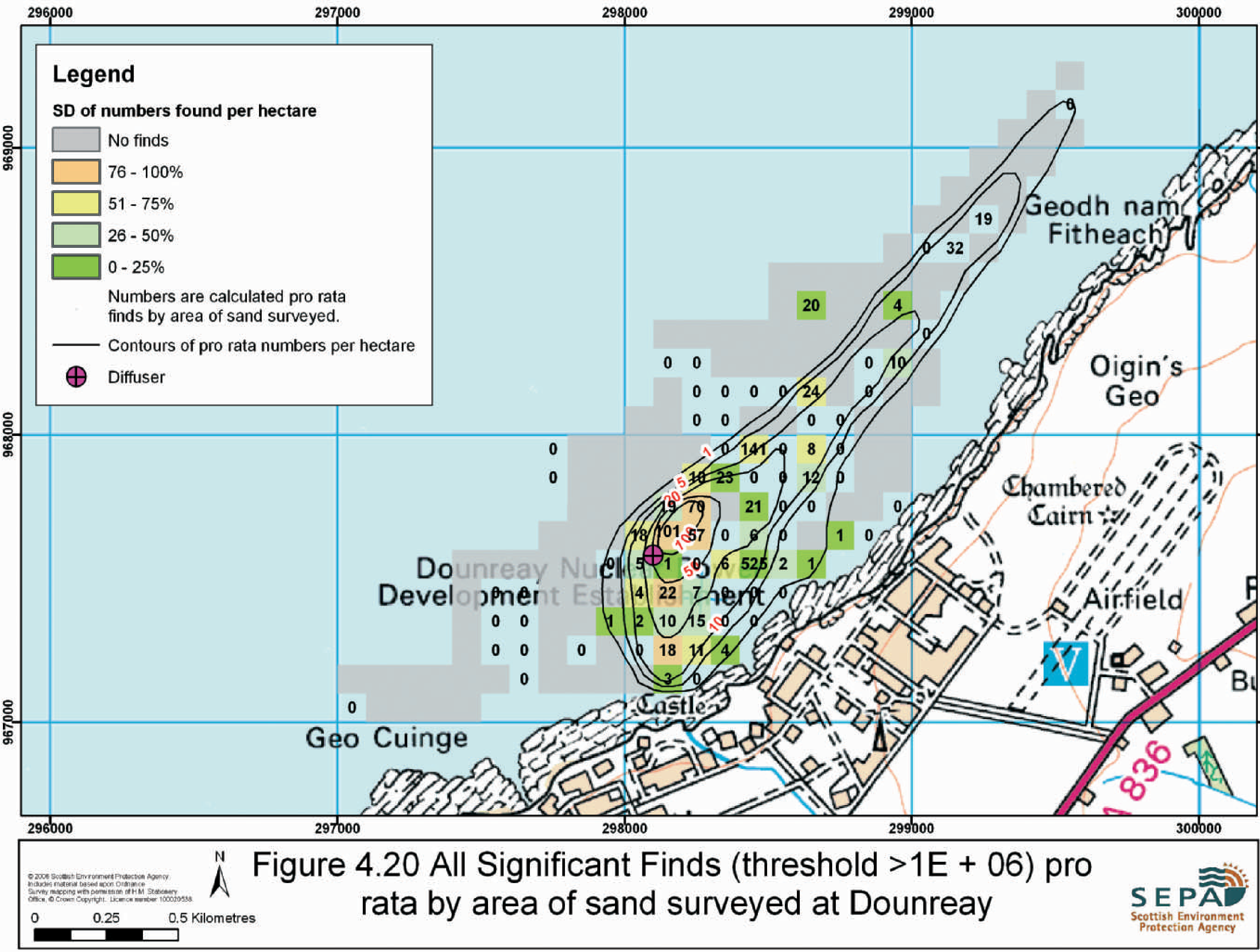

Figure 4.20 All Significant Finds (threshold >1E + 06) pro rata by area of sand surveyed at Dounreay

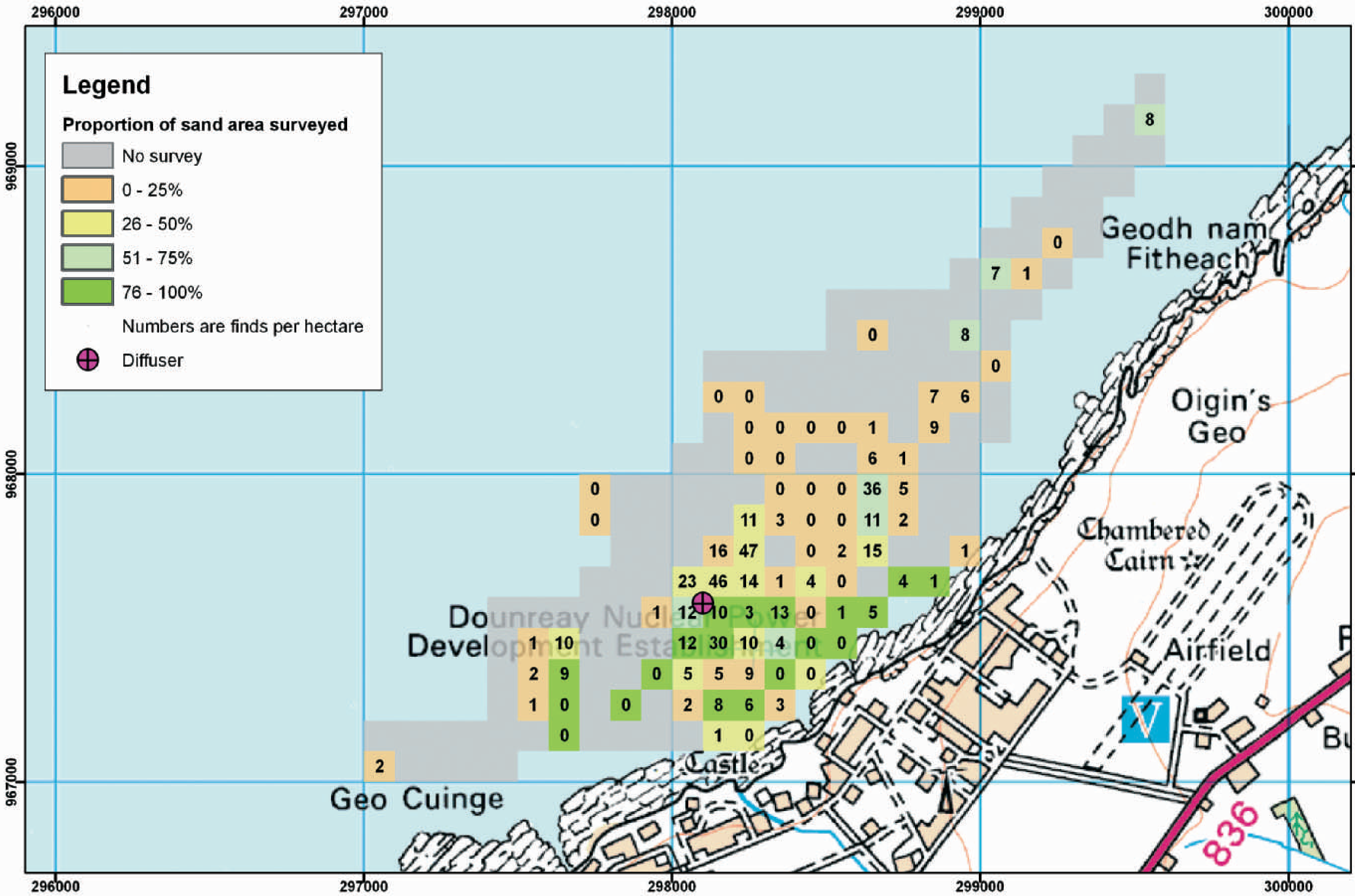

Figure 4.21 All Small Finds (threshold <1E + 06) offshore at Dounreay

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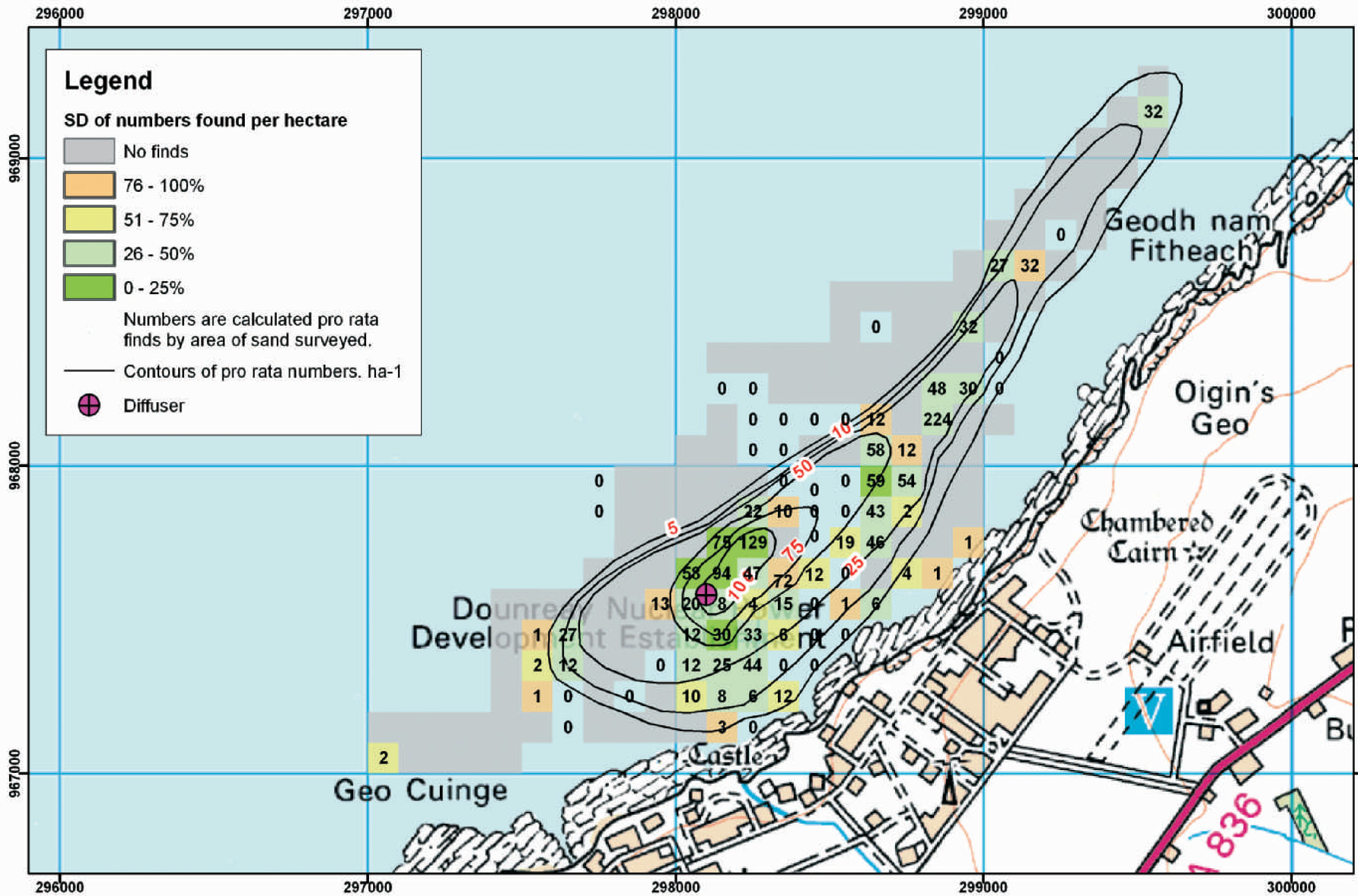

N

0 0.25 0.5 Kilometres

Figure 4.22 All Small Finds (threshold <1E + 06) pro rata by area of sand surveyed at Dounreay.

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4.3.29 The total number of *significant* particles found by this procedure is 1300. This estimate is based on a subjective contouring procedure; therefore it is not possible to make exact estimates of all the uncertainties to which it must be subject. The uncertainties on numbers for individual squares are mostly large, because the actual numbers of finds are small. The relative error on the total number of actual finds is $100/\sqrt{N}\%$, and with N = 197 for *significant* finds, the 1 standard deviation error may be estimated as ± 7%. Further uncertainties arise from the estimation of sand areas in each square, from interpolation and from the subjective choice of contour construction. These errors are difficult to estimate but are unlikely to be individually as great as the counting/sampling error of 7%. If they are conservatively estimated as being collectively slightly greater than the counting/sampling uncertainty, then (with 95% confidence), the number of significant particles on the sea bed is highly likely to lie between 870 and 1700, with 1300 being the best estimate (overall uncertainty at 2 sigma of 33%).

4.3.30 A similar procedure can be applied to all particles with ^{137}Cs activities <10^6 Bq. These include both of the categories defined as *relevant* and *minor*. Unfortunately they cannot be distinguished and estimated separately by means of the contouring technique used for the *significant* particles. The reason for this is that study of the statistical distribution of activities among particles in different parts of the plume (summarised in Section 4.4) has shown that 10^6 Bq ^{137}Cs is roughly the cut-off point between different types of hydrodynamic behaviour among particles. The >10^6 Bq ^{137}Cs group can be treated separately because the evidence shows that they behave in a different way from other particles with lower activities. The <10^6 Bq ^{137}Cs group comprises a single population with a continuous statistical distribution of activities. This distribution appears to have resulted from the complex interaction of a number of processes, with particle break-up, differential transport, and varying wave and tidal conditions all playing a part. The definition of *relevant* particles as having activities between 10^5 and 10^6 Bq ^{137}Cs was made on the basis of potential health effects on humans. The 10^5 threshold in particular has no significance with respect to the distribution of the less active group in the environment, so it is doubtful if the contouring technique used above for *significant* particles would be valid for the *relevant* category. Instead, a more roundabout method is followed in the succeeding paragraphs.

4.3.31 Figure 4.21 shows actual numbers of finds with activities <10^6 Bq ^{137}Cs. Figure 4.22 presents estimates of the total numbers in each 1 ha square, calculated by the methods described above for *significant* particles. The contours are also drawn using the same principles as before. The bounding contour in this case is for 5 particles ha^{-1}, in contrast to 1 ha^{-1} for the >10^6 Bq ^{137}Cs group. The total area enclosed within this contour is 113 ha with 27.5 ha of this lying west of the Diffuser. As will be discussed below, many *minor* and some *relevant* particles have been located within a distribution which is widely spread from Sandside Bay to Dunnet Bay. These particles all lie outwith the bounds of the plume as shown in Figure 4.22.

4.3.32 The further factor that must be taken into account is that the radioactivity from some particles may be completely shielded from detection because they are buried too deeply in sediment. These particles will have gone undetected by the divers' surveys. However, their numbers can be estimated from those that were recovered, providing account is taken of the depth at which each particle was buried (which is known), and it is assumed that the statistical distribution of activities among particles with <10^6 Bq ^{137}Cs is the same at all depths of burial. The statistical distribution of particles' activities in the near-surface sediment (0 – 100mm depth) is known, as are the detection limits for different depths of burial. Because the statistical distribution can be shown to vary with the depth of water, this factor must also be accounted for. Table 4.4 sets out some of the calculations required.

Table 4.4 Calculation of numbers of particles < 10^6 Bq ^{137}Cs present beneath different water depths in the Dounreay plume, allowing for buried particles.

Water depth (m)	Estimated number of particles <10^6 Bq ^{137}Cs present	Factor for non-detected particles	Revised number of particles <10^6 Bq ^{137}Cs present	Fraction that are *relevant*	Number of *relevant* particles	Number of *minor* particles
>20	2065	1.53	3159	0.19	600	2559
15-20	1095	1.15	1260	0.41	516	744
10-15	255	1.41	359	0.44	158	201
0-10	70	1.10	77	0.63	48	29
TOTALS	3485		4855		1322	3533

4.3.33 Based on these calculations, the total number of particles with <10^6 Bq ^{137}Cs activity in the plume defined by Figure 4.22 is estimated to be c. 4900.

4.3.34 The uncertainty in this initial estimate was evaluated by the same arguments as used for *significant* particles, bearing in mind that the number of actual finds was 426 particles. This leads to an evaluation that the true value is highly likely (95% confidence) to be between 3600 and 6100 particles (an overall uncertainty at 2 sigma of 95%).

4.3.35 To determine the proportion of these particles that fall into the category of *relevant*, i.e. 10^5 to 10^6 Bq ^{137}Cs, it is necessary to turn again to the statistical distributions of activities among actual finds, in relation to water depth. These distributions are described in more detail in a later section, but the proportions of particles <10^6 Bq ^{137}Cs that fall into the *relevant* category are shown in the fifth column of Table 4.3. Multiplying the entries in the column headed "Revised number of particles" by these factors gives the numbers of *relevant* particles for each interval of water depth. These numbers are summed at the foot of the sixth column to yield the total number of c. 1300 *relevant* particles within the plume defined by Figure 4.22. The approximate range of uncertainty in this estimate is likely around ± 33%, *i.e.* between 870 and 1700.

4.3.36 It follows that the number of *minor* particles (<10^5 Bq ^{137}Cs) in the plume is c. 3500 with lower and upper range limits of 2400 and 4700 respectively.

4.3.37 Table 4.5 summarises these estimates for the numbers of particles of each category – *significant*, *relevant* and *minor* – in the plume offshore from Dounreay.

Table 4.5 Estimated total numbers of radioactive particles in the plume offshore from Dounreay.

	significant	*relevant*	*minor*
Definition of ^{137}Cs activity	>10^6 Bq	10^5 – 10^6 Bq	<10^5 Bq
Best estimate	1300	1300	3500
Approximate lower bound	870	870	2400
Approximate upper bound	1700	1700	4700

4.3.38 The estimates in Table 4.5 define the magnitude of contamination of the sea bed sediments close to Dounreay. An important further point is that these estimates were based on the numbers of particles found by divers and that these particles were removed during the successive campaigns of 1997-2005. Including the re-surveys of Repopulation Areas, a total of 929 particles have been removed up to the end of 2005, which is about one sixth of the total numbers in Table 4.5. Those which came from within the bounds of the plume, as defined by the outer contour in Figure 4.20 numbered 894, comprising 217 *significant,* 275 *relevant* and 402 *minor* particles. Subtracting these numbers from the values in Table 4.5 provides an indication of how many particles remain within this area, as shown rounded to 2 significant digits in Table 4.6.

Table 4.6 Estimates for the numbers of particles remaining within the main plume* offshore from Dounreay

	significant	*relevant*	*minor*
Number estimated as remaining in the main plume (based on Best estimate in Table 4.4)	1100	1000	3100
Approximate lower bound (based on 67% of Best estimate)	650	610	2000
Approximate upper Bound (based on 133% of Best estimate)	1500	1500	4300

* The "main plume" comprises the 113 ha area bounded by the outer contour in Figure 4.22.

4.3.39 The plume edges defined in Figures 4.20 and 4.22 are not sharp boundaries. Beyond them, particles are thinly scattered across a wide area of sea floor. Figure 4.16 shows that a narrow train of particles extends westwards from the Diffuser and into Sandside Bay. On the seaward side of the main plume a few particles have been located by robot TROL, but none of these have been recovered by diving so their activities and depths of burial are not known. (In the early stages of investigation, 1998-1999, it was thought that the FITS towed-sensor data indicated large numbers of particles in this area, but this interpretation has since been shown to be spurious, the apparent particle strikes being in fact due to local variations in natural background radioactivity.) To the northeast of the main plume, small numbers of particles have been found on the sea bed near Crosskirk and east of Brims Ness headland. One particle has also been recovered from Dunnet Beach east of Thurso. Thus, the overall extent of potential contamination by radioactive particles has now been demonstrated to extend from Sandside Bay to Dunnet Bay, but the main identified concentration is located off the Dounreay Foreshore.

4.3.40 Making accurate estimates of the numbers of particles present in these distal parts of the overall plume is extremely difficult. West of the Diffuser, the pattern of searched areas and of actual finds allows very approximate boundaries to be placed on the extent of the plume that extends to Sandside Bay. Within these boundaries, 5 particles have been found in an area of 7 ha searched, giving a crude estimate of 0.7 particles ha^{-1}. When multiplied by the area of the plume (68 ha), a very tentative estimate of about 50 is obtained for the number of particles of any activity on the sea bed between the west end of the main plume and Sandside Beach.

4.3.41 The distribution of ^{137}Cs activities among 30 sea-bed particles recovered from the Sandside plume suggests that 10% of particles may be *relevant* and the remainder *minor*. Thus the Sandside plume is likely to contain c. 5 *relevant* particles and 44 *minor* ones. No allowance has been made for undetected, buried particles but they are very unlikely to raise these rough estimates by a factor greater than 2. The Sandside plume will continue to be replenished from the main plume.

4.3.42 To the northeast of the main plume the data are much sparser than towards Sandside Bay. Eighteen particles have been found outwith the plume boundaries on Figures 4.20 and 4.22 within Repopulation Area #12 and off Crosskirk and Brims Ness. Two of these were >10^5 Bq ^{137}Cs, and the best-fit statistical distribution for the group as a whole suggests that about 15% of the distal particles east of the main plume might belong to the *relevant* category. These are probably not solely confined to the part of the plume near Dounreay, as one particle at Crosskirk had an activity of 9.5 x 10^4 Bq ^{137}Cs, on the threshold of the *relevant* group.

4.3.43 A few *significant* particles have been found at the extreme northeastern end of the main plume, one during initial survey in square T28 and another beyond the plume in Repopulation Area 12 during the re-survey of March 2005. Thus, there is a possibility that *significant* particles may eventually be transported eastwards beyond the boundary of the area presently mapped as the main plume in Figure 4.20.

4.3.44 The Dunnet Bay find was a *minor* particle, as were all but one particle mentioned above at Crosskirk and Brims Ness. Therefore, it seems likely that the most distal parts of the plume east of Brims Ness will contain mostly *minor* particles and possibly rather rare *relevant* particles. Only further surveys can confirm this.

4.4 Offshore Particles – Patterns and Interpretation

Approaches to Understanding the Dynamic Behaviour of the Offshore Particle Plume

4.4.1 The offshore particle plume has been described and analysed in the preceding section as if it were almost static. However, the real plume is evolving and changing over time, and the compression of eight years' data on particle finds into a single snapshot is a necessary simplification for making estimates of the total numbers of particles present. Several lines of evidence show that the sandy sediments on the sea bed are moved quite frequently by wind-induced waves and tidal currents, and that many of the radioactive Dounreay particles are moved with them. These movements have been responsible for the spread of the plume to its present shape from what must have been an initial concentration of particles in the immediate vicinity of the Diffuser, and they will also govern the future evolution of the plume. As the offshore particles feed the supply of radioactive particles to beaches at Dounreay, Sandside and Dunnet Bay, it is clear that understanding the evolution of the plume is crucial for estimating how long the problem may continue.

4.4.2 Tidal currents are capable of moving the smaller radioactive particles for small distances each day. The larger particles probably require the additional currents created by wind-induced waves to move them, with the result that they move less often (but still several times per month), and their net transport is in a different direction from that induced from tides. Storm waves, which occur several times per year, will mobilise all sizes of particle as the sea-bed sediments are first scoured and suspended, then re-deposited as the storm wanes. The overall effect of these various movements, repeated by the thousands of tides and many storms which have occurred during the last four decades, has been to spread the smallest *minor* particles very widely along the sea bed near the coast, with the most distant find made so far being on the beach at Dunnet Bay, 25 km east of the Diffuser. The more radioactive particles have not been located at such great distances, but some found on the beach at Sandside Bay have been in the *relevant* category. The Sandside particles have been transported 3 km westwards from the Diffuser and the Crosskirk- Brims Ness particles are 9 – 11 km along the coast to the east. *Significant* particles, which tend to be larger than the less radioactive categories, have mostly been found within 1 km of the Diffuser, although a few have been recovered from the sea floor between 2 and 3 km to the east.

4.4.3 This pattern, in which *minor* particles have apparently travelled the greatest distances, *relevant* particles are widespread, and *significant* particles are mostly restricted to within 1 km of the Diffuser, is mirrored by the contrast between finds made on Dounreay Foreshore and those from the beaches at Sandside and Dunnet Bay. Of all finds made on the Dounreay Foreshore up to February 2006, 60% were *significant* (>10^6 Bq ^{137}Cs), 31% *relevant* (between 10^5 and 10^6 Bq ^{137}Cs), and 9% *minor* (<10^5 Bq^{137}Cs). These finds all came from a 1 km section of Foreshore which lies directly adjacent to the core of the sea-bed plume where *significant* particles are common. No particles have been found on monitored beaches beyond the limits of this 1 km section, except on Sandside Beach in the west and Dunnet Beach in the east. At Sandside, no *significant* particles have been found at all so far, with 15% of the total of 59 finds being in the *relevant* category. The majority of Sandside finds are *minor* particles, with 8.2 x 10^3 Bq ^{137}Cs being the lowest activity yet detected there. The single metallic particle found at Dunnet Beach had 8.9 x 10^3 Bq ^{137}Cs activity.

4.4.4 These patterns suggest that a process of differential transport affects the distribution of radioactive particles. As discussed in Section 4.1 of this Chapter, the more radioactive particles tend to be heavier and are probably also larger, and therefore are likely to be less easily and less frequently moved by currents. Smaller, mostly less radioactive particles are likely to be moved more frequently and therefore to have travelled further. Such differential transport is normal for natural sediments. Its cumulative effects are termed sorting because natural sands in different locations often show differences in their grain size distributions. For example, the sands found on the Foreshore at Dounreay are much coarser than those at Sandside Beach. Table 4.7 summarises grain sizes of sediments on beaches and the sea bed.

Table 4.7 Sand sizes found in different locations near Dounreay

Location	**D_{50} in mm**	**D_{90} in mm**
	(50% of grains are smaller)	(90% of grains are smaller)
Dounreay Foreshore [1]	0.46 (minimum)	0.7 (minimum)
Dunnet Beach[2]	0.3	
Sandside Beach[1]	0.18 – 0.3	0.3 – 0.5
Offshore zone (inshore from Diffuser)[1]	0.21 – 0.6	0.45 – 1.27
Offshore zone (seaward of Diffuser)[1]	0.21 – 0.28	0.32 – 0.63

(Sources: [1]UKAEA paper EPTG(00)P04, *Summary Assessment of Available Grain Size Distribution Data for Beach and Offshore Sediment Samples from near Dounreay*. [2] J.Hanson, University of Glasgow, *pers.comm.*)

4.4.5 There are two general approaches that can be taken to develop an understanding of the dynamics and evolution of the plume. One is to study the occurrence and characteristics of the radioactive particles themselves, and to use such clues as they provide to interpret the processes taking place. This might be termed the “sand tracer” approach, as the radioactive particles are marked grains of sediment whose movements should reflect the dynamic processes affecting sand-sized sediment in general. By its nature, this approach must look backwards, using the evidence of the snapshot picture of the plume provided by the surveys of 1997-2005 to infer the processes involved up to that time. Once these processes are properly understood it may be possible to project their effects forward in time and make an informed estimate of the longevity and scale of the plume, and its potential future impact on beaches.

4.4.6 The second approach is more fundamental. It starts from a general understanding of the physical principles of currents on the sea bed, the influences of tides and waves, and of how particle transport takes place. With these principles expressed in mathematical form, a computer model of the situation can be constructed. Such a model can then predict the development of the plume following an initial release of particles. This "numerical modelling approach" has been taken by HR Wallingford, under contract to UKAEA. They have formulated a three-stage model of the currents and tides off the north coast of Scotland, with fine detail for the Dounreay region, and including a particle tracking routine which predicts the whereabouts of particles for different times after they have been released into the model.

4.4.7 The two approaches complement one another. A computer model cannot be constructed without first deciding what processes must be included and how to represent them mathematically. Thus the writing of computer code must be preceded by consideration of all available data and by the formulation of a conceptual model that may be expressed verbally, in diagrams or equations, or in a mixture of all three forms. Translation from conceptual to mathematical model is by means of equations, including unknown parameters, which must be estimated. The reliability and hence uncertainty of model predictions depend on many factors; model conceptualisation and prior scientific knowledge, translation to the mathematical form, parameter estimates and the process of model calibration. The conceptual model formulated by HR Wallingford as the precursor to their computer model was based on early information on particle finds *plus* data from instruments deployed on the sea bed for periods of a few weeks to measure currents and sediment movement. The "sand tracer" approach leads to a fuller conceptual model of particle dynamics, which is described in this Section. Later sections describe and assess the performance of the HR Wallingford model and compare the two approaches.

4.4.8 Both types of approach rely upon a general understanding of the marine environment, including currents, tides, waves and weather, and of how the transport of particles and sand grains is determined by these various factors. Therefore the sections that follow will begin with a brief outline of these general principles.

Particle transport and physical processes on the sea floor

4.4.9 Sand is moved on the sea bed by the action of waves and currents. As the Dounreay particles are mostly in the sand-size range (0.06 – 2.0mm diameter), they will be subject to the same processes as those that move natural sand grains.

4.4.10 Individual sand grains are set in motion by the movement of water immediately above them. Where the sea water is moving in a current, the flow just above the bed will be in the same general direction as the overall current. Sea water near the bed also moves in response to waves travelling across the surface, but in this case the movement oscillates, first in the direction of wave movement, then back again. A sand grain may be initiated into motion by means of the mechanisms described below. The current near the bed exerts a horizontal drag force on the grain which may slide or roll it across the bed. Movement in which the particle does not leave the bed is called traction. However, the water flow near the bed contains irregularities in velocity and pressure which cause a lifting force on any particle which projects from the bed. Where the flow is eddying, causing random fluctuations in velocity (the technical term for this is turbulence, for instance wind gusts are a familiar example of turbulent fluctuations in the atmosphere), the lifting force may be momentarily greatly increased. The effect can be to lift the particle off the bed and into the layers of moving fluid above it, where the drag force accelerates the grain and carries it horizontally for some distance before it falls back again to the bed. This hopping mode of movement is called saltation. It transports grains much farther and faster than sliding or rolling. When the flow is very turbulent, sand grains may be held in suspension for lengthy periods. In such conditions they do not follow the simple arc-like paths involved in saltation, but are irregularly moved along complex paths by the eddies in the water. Extreme turbulence caused by large waves combined with a strong unidirectional tidal current produce ideal conditions for suspending large concentrations of sand grains, eroding the bed. Individual grains may be moved distances of many metres while in suspension, and the total movement of a grain during a single storm could be hundreds of metres.

4.4.11 The rate of grain transport depends on the velocity of the water flow and on the properties of the grains themselves. The crucial properties are diameter and density, although grain shape also exerts an influence. For grains of a fixed shape, for example spheres, each grain's diameter determines its volume, and its volume and density combine to determine its mass. However, it is the product of diameter and density that determines the threshold value that the velocity of the water must exceed in order to initiate grain movement. If the velocity is less than this threshold, the grain will not move. If it exceeds the threshold the grain may first slide or roll, then at higher velocities it may commence saltation. Each mode of transport requires progressively higher velocities, from traction through saltation to suspension, and larger, denser grains require higher velocities at each threshold than smaller, less dense grains.

4.4.12 The fact that threshold velocities depend so strongly upon grain size leads to differential transport. A current of water may move smaller grains, but be too weak to move larger ones; it will tend therefore to separate these two sizes. Such separations may also arise from other mechanisms and these are described briefly later. The overall separating of grains by their diameter is known as sorting and can be highly complex in its effects, even though it is simple in principle. Suppose that an idealised sediment contains spherical grains of just two diameters, coarse and fine, and that the grains all have the same density. The threshold water velocities for traction, saltation and suspension will all differ between the two types of grain. If there is a directional current, but it is very slow, neither type of grain will move. If the current increases, the smaller grains will begin first to slide or roll, while further increase may start the larger grains moving also. Critically, once the current speed increases so that the smaller grains begin saltation while the larger grains remain on the bed, there will be a large difference in the transport velocities between the two. Small grains will be removed from the deposit and carried away down-current. If this condition persists, almost all the small grains near the surface of the sediment may be removed, leaving a surface layer composed nearly entirely of large grains. Thus the difference in diameter, combined with the prevailing current conditions, will have promoted sorting of the original mixture of grains into two separate fractions, namely a transported fine fraction and a residual coarse fraction. This type of sorting, by initiation of transport, is known as winnowing and the residual coarse fraction is known as a lag.

4.4.13 A second group of sorting processes depend on the fact that larger grains settle through water more quickly than smaller, while denser grains settle faster than less dense. In saltation, the vertical settling rate dictates how long it takes for a lifted grain to fall back to the bed. During its fall it is swept along by any horizontal current present, so will travel further on each “jump” if it settles slowly than if it settles quickly. Thus, even when fine and coarse grains are saltating together in the same current, the fine grains will be transported faster and further than the coarse, because they remain in motion for a higher proportion of the time. This process of differential transport tends to separate grains by size and density and is a powerful mechanism for sorting.

4.4.14 A third mechanism of sorting is through differential settling which operates most strongly on grains with widely differing grain size and settling velocities. For example the waves on a beach will carry sediment of all sizes landward as they break on the beach slope. As the up-rush of each wave ceases and the back-wash begins, sand grains that have settled to the bed may be rolled or saltated to seaward. Finer silts, which settle more slowly, will not be deposited at all but remain in suspension and be carried back into the surf zone. Thus, the beach will consist of the sand grains that are too large to be removed by the backwash. Finer sand grains will be found in deeper water to seaward of the beach, and silts and clays will be largely absent. Any silts and clays that do occur will tend to be transported in suspension elsewhere along the coast, to settle as mud in sheltered parts of bays or estuaries or out to sea in water too deep to be disturbed by waves.

4.4.15 The various processes of sorting act in combination and will vary in relative importance according to conditions. Their overall effect, acting over time, is to separate the countless sediment grains present in the coastal zone according to their size and density and to concentrate grains of one size in one location and grains of larger size in another. The separation is not perfect, and, in any case, is countered by mixing which occurs when conditions fluctuate, and sediments of one grain size are transported into a region dominated by a different size and deposited there. Nevertheless, the grain size distribution of sediment in a given location tends to reflect the energy of the most frequent (or most recent) currents that occur there. In a location subject to high current velocities and strong turbulence, such as the surf zone of a beach, sediments tend to be relatively coarse and may show a small range of grain sizes, *i.e* be well-sorted. The less energetic environment of the sea bed in deeper water has weaker currents for most of the time, so average grain size there may be finer. These differences are reflected by the grain sizes for different environments near Dounreay shown in Table 4.7 which indicates finer grain sizes (both median and 90-percentile) in deeper water than in shallow and finer sediment on sheltered beaches at the rear of Sandside or Dunnet bays than on the exposed coast at Dounreay.

4.4.16 A further factor in sorting is how often currents and waves are strong enough to move particles of different sizes. Particles of a given size will be initiated into movement less often in deep water because of the declining effect of waves with depth. Calculations made from the records of instruments deployed on the sea bed off Dounreay in 2000-2001 suggest that fine sand grains are moved by a combination of tidal currents and waves several times per week in 20 m depth of water, but only once per month at 50 m. Most radioactive Dounreay particles have been found beneath water less than 30 m deep, so movement is probably frequent for the smaller sizes. Large storm waves mobilise all of the sediment roughly once per year at 20 m depth, but much less often at 50 m, possibly less than once every 5 years. Thus, large particles are likely to be moved much less frequently than small particles, and so are likely to have slower rates of average transport.

4.4.17 At Dounreay, wave-driven currents strong enough to move large particles tend to have a different direction from the tidal currents that move only small particles. This results in a difference in transport direction for particles of different size. Large particles tend to be driven on-shore because large waves come only from an off-shore direction (northwest and north). These conditions also move small particles on-shore. However, in the periods between storms, when the bottom currents are due to tides and small waves, only the small particles will move and the dominant directions of transport are parallel to the coast. These effects may account for the fact that the *minor* and *relevant* particles in the plume are spread along the coast to both west and east of the Diffuser, whereas the *significant* particles have remained close to the Diffuser and are concentrated on its shoreward side.

The patterns of sorting observed among Dounreay particles

4.4.18 The only characteristic that has been measured for all Dounreay particle finds is the level of radioactivity from ^{137}Cs. Unfortunately this property has no direct bearing on the particles' behaviour as sediment grains. However, there is a correlation between activity and mass, as demonstrated in Section 4.1 of this Chapter. Particle mass is indirectly related to hydrodynamic behaviour through its connection with particle diameter and density. For spherical particles,

$$mass = \rho . \pi . \frac{d^3}{6}$$

where d = grain diameter and ρ = particle density. There should therefore be a tendency for the more radioactive particles to behave similarly to larger sand grains, and less radioactive particles to resemble fine sand in their behaviour.

4.4.19 There are definite indications of sorting among Dounreay particles from different locations, in terms of their radioactivity. The particles found in each environment and location have a characteristic distribution of activities, which often conforms approximately to the log-normal curve (*i.e.* the frequencies of values for the logarithms of activity conform to the bell-shaped curve known as the "normal" or Gaussian distribution function). Natural sand grains usually show log-normal distributions of diameter, suggesting that the log-normal distribution of Dounreay particles may be due to the same processes of sorting as affect the natural grains.

Variation in particle activity with water depth

4.4.20 Figure 4.24 shows the variation of activity with water depth among offshore particles found in the top 100 mm of sediment. The sea becomes progressively deeper with distance from the Dounreay coast, so water depth is also an indicator of distance offshore. The diagram indicates the mean log-activity of the particles found in each depth category, with a vertical bar extending to two standard deviations above and below this value. The highest activity particles are found in shallow water. As the water depth increases, mean log-activity becomes less, but the range indicated by the vertical bars remains much the same. This pattern is consistent with particles of all sizes being driven into shallow water by waves, and finer ones being returned seawards into deeper water while coarser ones tend to remain in the near-shore zone.

4.4.21 In water depths greater than 15 m the sediment is disturbed by waves less frequently. Analysis of the particles found in these depths has shown that they belong to two overlapping populations, both with a roughly normal distribution of log-activity. The mean and 2-standard deviation ranges of the particles found on the surface and in the top 100 mm of the sediment are shown in black on Figure 4.23. These particles are known to be frequently disturbed, as instrument records show that the surface level of the sediment can fluctuate through a ±100 mm range over short periods. However, buried at depths greater than 100 mm is a population of high activity particles which is quite distinct from those found near the surface. Almost all of the particles in this population belong to the *significant* category (*i.e.* >10^6 Bq ^{137}Cs). The mean log-activities and 2-standard deviation ranges of the High Activity Population (HAP) are shown in red on Figure 4.23.

4.4.22 At shallow water depths (<15 m) there is no difference in the distributions of activities for particles in the top 100 mm of sediment and those buried more deeply. This presumably reflects the relatively frequent movement of the entire bed by waves, keeping the sediments well mixed through the depth range from which particles can be detected (*c.* 500 mm).

4.4.23 The buried particles from the HAP comprise roughly 13% by number of the particles in water depths greater than 15 m. Due to their higher individual activities, this group contains about 80% of the total radioactivity in the zone. The lower margin of activity in the buried particle group coincides with the 10^6 Bq ^{137}Cs boundary between the *significant* and *relevant* categories.

4.4.24 Figure 4.23 suggests, therefore, that in water more than 15 m deep the less radioactive, presumably smaller particles are disturbed every few days along with a layer of sediment about 100 mm thick, while a cache of *significant* particles is buried within the deeper layers of sediment. Cores of sediment recovered from the sea bed provide a clue to the possible origins of the cache. They show a layered structure, with the sand in each layer being slightly coarser towards the bottom of the layer and slightly finer at the top. The layers represent disturbance and re-deposition of the sea bed by large storm waves. The deepest layers (down to about 500 mm depth, the approximate length of the cores) represents the oldest storm recorded by the sediment, which must also have been the largest because it disturbed the sand to a depth that has not been equalled since. The next layer up represents the largest storm that has occurred in the period since the first layer was formed. The third layer in turn represents the largest storm since the second layer was formed, and so on. It is known that the bed is disturbed to depths of about 100 mm several times per month, and that the storm which occurs roughly once per year may disturb the bed down to about 400 to 500 mm, so the deeper layers must reflect annual or less frequent disturbance in response to large storm waves. Every time such deep disturbance occurs, some of the Dounreay particles present on the bed will be mixed down into the re-deposited sediment.

4.4.25 Just after particles were released from the Diffuser they would all have been located on the surface, or in the frequently disturbed top layer 100 mm thick. Storms would have occurred and each storm would have stirred the bed and mixed particles into the layer it disturbed. Though the heights of storm waves, and the depths to which they mixed the bed, would have occurred in an essentially random sequence, the size of the largest storm to have occurred since the particles were first released would inevitably increase as time went by. Thus, in the early history of the plume, the successive exceedance of each “largest” storm by a later one would have buried a fraction of the particles to a greater depth than before. This essentially stochastic process would establish a cache of particles the residence time of which,since they were last disturbed and re-buried increases with depth. The deeper parts of this cache are disturbed only very infrequently, but shallower parts are reworked more often as they can be reached by smaller storms. Each time a layer is reworked, some of the high activity, (*i.e. significant*) particles are brought up to the surface, while less radioactive particles from the surface layer are buried deeper down.

4.4.26 In shallow water (<15 m deep) smaller waves will disturb the bottom sediment more effectively and mix the sand layers more frequently. This is reflected in the lack of difference in particle activity distributions between the top 100 mm of sand and the deeper sediment. Nevertheless, the overall distribution of activities in this zone has a higher mean, and the zone contains significant particles, both buried and in the surface sediment.

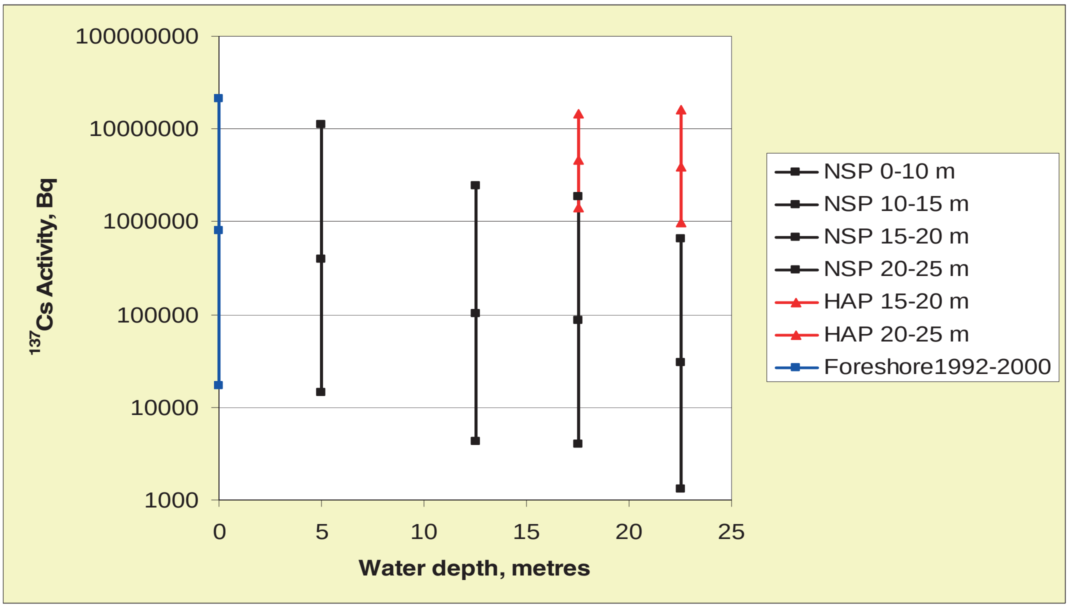

Figure 4.23 Particle Activity distributions *versus* water depth

4.4.27 The upper limit of particle activity in water less than 10 m deep is ~10^8 Bq ^{137}Cs, which is similar to the upper limit in the buried cache located further offshore. Though a slightly lower limit occurs in depths of 10-15 m, the general pattern in Figure 4.23 is consistent with a scenario in which *significant* particles are mobilised from the cache by storms from time to time, transported by wave action together with smaller particles into shallow water, and retained there once the storm waves have died down. Winnowing and offshore transport during calmer weather removes many of the smaller, less radioactive particles from the shallow water population.

4.4.28 The shallow water cache (0 -10 m depth) is the source for the particles found on the Dounreay Foreshore. The distribution of activities in the Foreshore group is approximately log-normal, but has a tail of low activity particles that are more numerous than would be expected in a truly log-normal distribution. Figure 4.23 shows the log-mean and range for particles recovered in the period 1992-2000, *i.e.* before the annual numbers of finds began to drop after divers removed particles from the near-shore zone. The vertical bars for this group extend upwards to the activity level of the most radioactive particle recovered in the period, and downwards to 2 standard deviations below the mean. The small proportion of particles <10^4 Bq ^{137}Cs found on the Foreshore may represent fragments broken from larger particles in the high energy environment provided by breaking waves.

4.4.29 This paragraph summarises the variation in activity with water depth which increases with distance offshore. In water deeper than 15m, the plume of particles is made up of two populations. One, the Near-Surface Population, shows a broad spread of activities with an approximately log-normal distribution. All the particles in the surface sediment belong to this population, in which only a very small proportion have activities >10^6 Bq ^{137}Cs, *i.e.* are *significant* particles.

The second population comprises high-activity particles that are buried in sediment at depths below 100 mm. Their activities range up to ~10^8 Bq ^{137}Cs, and they are much more abundant than would be expected in proportion to the lesser particles found in the same sediment. These *significant* particles form a buried cache in water >15 m deep which is disturbed comparatively rarely. When it is disturbed, this cache supplies *significant* particles to the surface sediments. These can then be driven shorewards into waters <15 m deep, where the sediments are kept well mixed and *significant* particles are found at all depths of burial within the sand, as well as on the surface. The particles found on the Foreshore are supplied from the shallow water population, which has a preponderance of *significant* and *relevant* particles.

Variation of activity with distance from the Diffuser

4.4.30 In 2000 UKAEA established 7 "Repopulation Areas" for making repeated particle surveys, as described above (Section 4.2). The majority of these were circular areas of 2500 m^2, although some were later enlarged to 7855 m^2 by the addition of an outer *annulus*. The outer *annuli* of 2, 3 and 5 were surveyed once, and the outer *annulus* of 4 was surveyed twice. Two areas were added in 2002, and a further three in 2004, bringing the total of the repopulation areas to 12 (see Table 4.3). Systematic, exhaustive searches were made for particles in each area, and all of those found were removed. Most of the areas received at least one re-survey, in which the numbers, activities and depths of finds were recorded. This method of searching implies that when a particle was found on re-survey, it must have either migrated into the circle since the previous search, or have been disturbed and brought to a higher level in the sediment than it had occupied previously. This implication rests on the assumption that the only particles to have been overlooked on each survey were those buried so deeply that their radioactivity was effectively screened by the sand overlying them. This is a reasonable assumption, given the thoroughness of the search.

4.4.31 The numbers and activities of particles found during the initial surveys of the Repopulation Areas provided information on the undisturbed populations of particles at different distances from the Diffuser and provide a check on the contouring methodology used to define the overall shape of the plume in Section 4.2 of this Chapter. Figures 4.24 and 4.25 show the results of initial surveys and re-surveys, expressed as numbers found per ha and plotted in relation to the distance of each Repopulation Area from the Diffuser. Figure 4.24 illustrates the plume east of the Diffuser and Figure 4.25 shows the areas west of the Diffuser.

4.4.32 Numbers of particles per ha fall off rapidly away from the Diffuser in both directions, but much more steeply to the west than to the east. Figure 4.24 shows a concave-upwards curve of declining numbers, from around 200 per ha close to the Diffuser to about 50 per ha at a distance of 1500 m, and flattening to ~20 per ha at 5 to 8 km. This pattern broadly confirms the contour maps in Figures 4.20 and 4.22.

4.4.33 To the west of the Diffuser, Figure 4.25 indicates that numbers per ha on initial survey had declined to around 50 per ha within a distance of 200 m from the Diffuser, and to ~20 per ha within 500 m.

4.4.34 The data for re-surveys, also plotted in Figures 4.24 and 4.25 show a rather different contrast between the west and east arms of the plume. In the west, the rather sparse data available indicates that the cleared areas were repopulated with particle numbers similar to the original surveys. In contrast, in the eastern plume the repopulation is almost always with much lower numbers of particles than were found originally. Whereas in the initial surveys around one third of finds were *significant* particles, this proportion dropped to less than 7% on re-survey. The distribution of activities among the re-survey finds is similar to that of particles in the top 100 mm of sediment, and lacks the excess *significant* particles that are found buried more deeply in sand beneath water depths of more than 15 m. (All but one of the repopulation areas lie in water depths >15 m; Table 4.2).

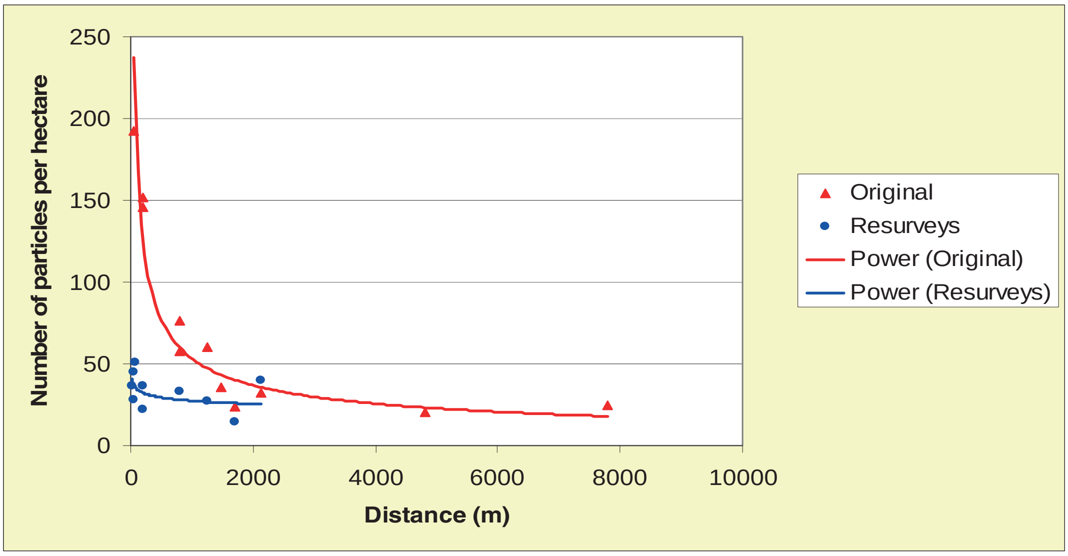

Figure 4.24 Repopulation data (east of the Diffuser)

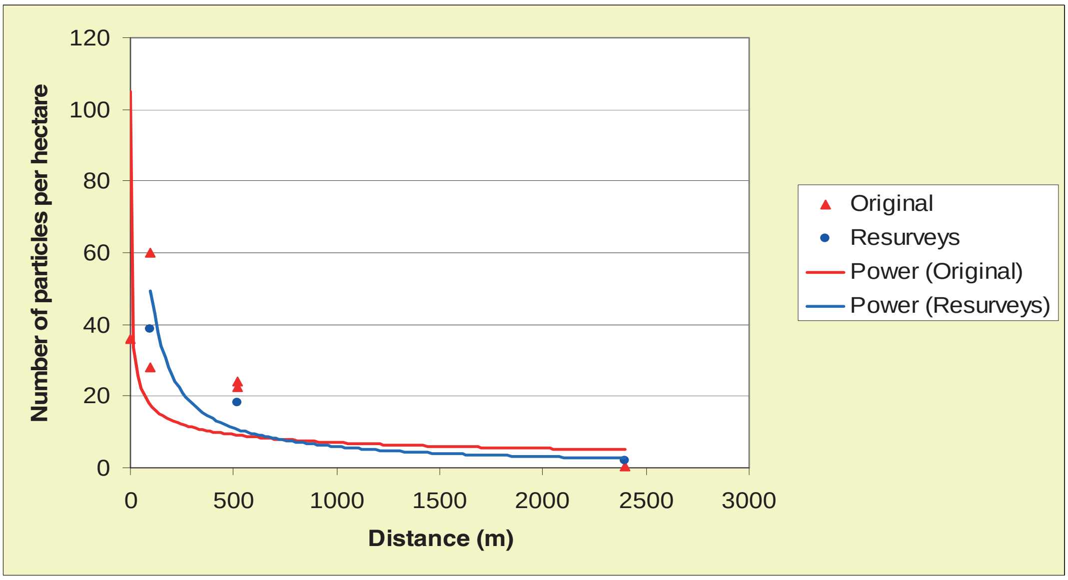

Figure 4.25 Repopulation data (west of the Diffuser)

4.4.35 These findings corroborate Section 4.2 in suggesting that the western branch of the plume lacks any large store of buried *significant* particles, at least at distances over ~200 m from the Diffuser. The relatively rapid recovery of particle numbers following clearance suggests that there is a continuing feed of particles from the densest part of the plume near the Diffuser, along the western branch towards Sandside Bay.

4.4.36 In the east, the large reduction in numbers of particles found on resurvey is a reflection of the importance of the initial buried cache as a proportion of total numbers in the plume. Half of the finds made on initial surveys were buried below 100 mm in the sediment, whereas on re-surveys the proportion was less than a quarter. This suggests that re-population of cleared areas is quite rapid for particles that are moving within the frequently disturbed top 100 mm of sand (which as Figure 4.23 shows are mostly below 10^6 Bq and likely to be smaller than 1 mm long, according to Figure 4.11). However, burial of particles from the immigrating population is incomplete, indicating that a longer period than the average 6-8 months between surveys may be required before full restoration of the buried population would be achieved.

4.4.37 The curve in Figure 4.26 shows the mean log-activity of initial survey finds for the east branch of the plume. Close to the Diffuser the mean activity is almost 10^6 Bq, but this falls rapidly with distance, to less than 10^5 Bq at about 1000 m. Beyond 2 km, however, the average activity shows little further downward trend with distance, but remains essentially constant at values around ~10^4 Bq as far as 8 km from the Diffuser. Apparently a sorting process of some kind affects the Dounreay particles in a down-plume direction, whereby high activity particles tend not to reach such large distances from the Diffuser as lower activity (smaller) particles.

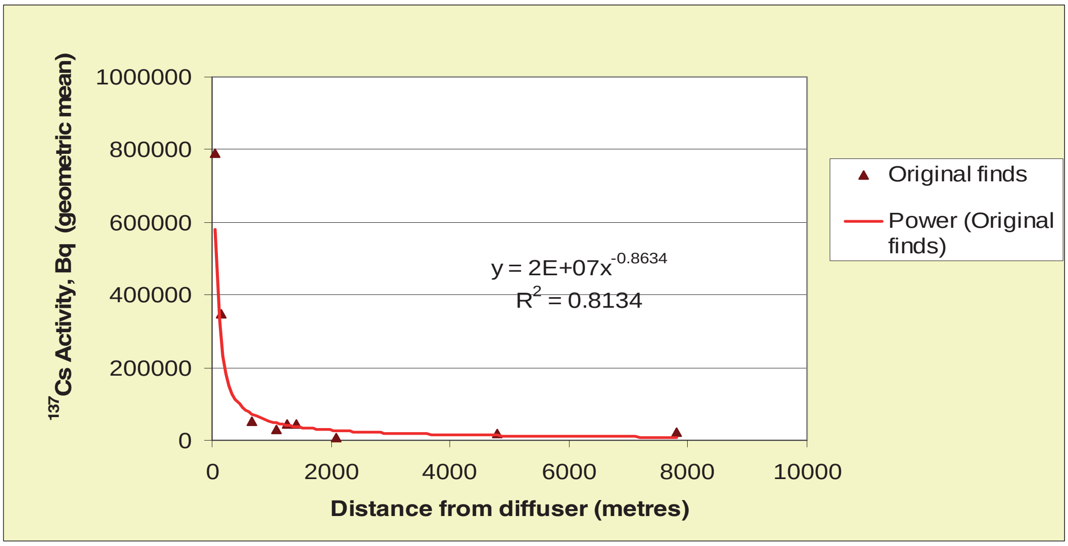

Figure 4.26 Change along northeast plume

4.4.38 This simple picture of differential transport of greater and lesser activity particles in a down-plume direction is complicated by the re-survey finds (not illustrated). High activity particles were found in re-surveys of Repopulation Areas 6 and 12, at distances of 1070 and 2100 m respectively. These may simply have been smaller particles than average for their activity (see Figure 2.1), but their presence indicates that a few *significant* particles can be transported somewhat further from the Diffuser than the curve for initial survey finds in Figure 4.26 would suggest.

Storm frequency, disturbance of sand and burial of particles deeper than 100 mm

4.4.39 Wave heights in the open sea off Dounreay have been estimated by HR Wallingford using data on wind velocities and durations for the period 1969-2003. Figure 4.27 shows the relationship between wave height and return period, the latter being the average time that elapses between occurrences of waves that equal or exceed a given height. The annual wave height (*i.e.* the height that can be expected once per year on average) is 7.5 m, whereas the largest storm in the period had an estimated wave height of 10.5 m which Figure 4.27 suggests has a return period of around 45 years.

4.4.40 The data from Repopulation Areas permits a broad correlation to be made between the depth of disturbance and wave height. For each resurvey, the depth of burial of the deepest particle found provides an indication of the minimum depth to which the sand has been disturbed since the previous survey. The records of wind speed allow the maximum wave height in the intervening period to be estimated. Figure 4.28 shows the comparison of wave height with estimated depth of disturbance. Although there is considerable scatter there is a positive correlation in which depth of disturbance is proportional to approximately the square of wave height. The best-fit line would suggest that the sediment is disturbed down to 100 mm by waves only 3.5 m high, which are expected to occur quite frequently. This is quite compatible with the finding from particle activity distributions, and observations from sea-bed instruments, that the bed is frequently disturbed to this depth. On the other hand the data suggest that the bed may be disturbed to a depth of 400 or 500 mm by waves around 7.5 m high, which occur about once per year according to Figure 4.28.

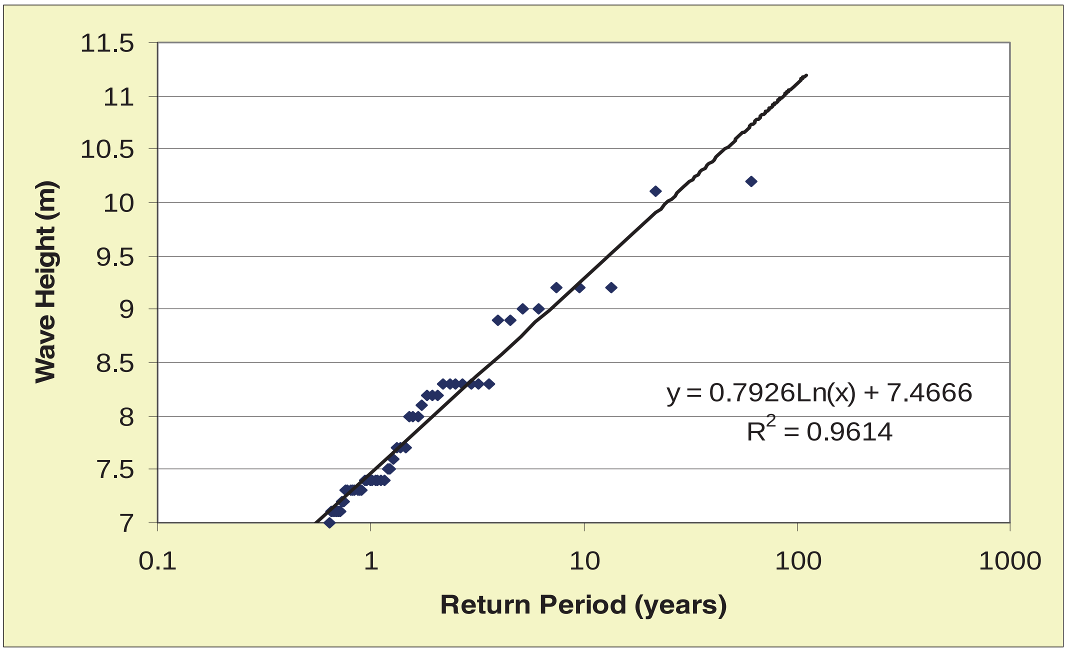

Figure 4.27 Dounreay Wave Height Return Periods

4.4.41 It might be expected that water depth would also influence the depth of sediment disturbance. To some extent this is supported by the data in that for a given wave height the disturbance is less in the Repopulation Area with the deepest water (27 m, Area 7) than for the shallowest (15 m, Area 8). Most of the Repopulation Areas lie beneath water with a narrow depth range of 18 to 22 m, however, and among these water depth appears to exert little influence on estimated disturbance for any given wave height. Figure 4.28 plots the greatest estimate of disturbance among all areas for each wave height. It follows from the methodology that this provides the best estimate of the depth of sediment disturbance, but it ignores any influence exerted by water depth.

4.4.42 The data in Figures 4.27 and 4.28 are rather scattered, but the relationship they suggest between depth of bed disturbance and return period implies that the sediment in the repopulation areas may be disturbed to considerable depths roughly every year or two. This is broadly consistent with the intervals of somewhat less than a year between re-surveys of Repopulation Areas (though a few re-surveys occurred two years after previous surveys). While some particles were introduced or disturbed down to depths of several hundred mm, this is unlikely to have occurred more than once or twice during the intervals between re-surveys, and this would be insufficient to restore the full population of buried particles. This is probably why the proportion of buried particles in re-surveys is not as great as in the initial surveys.

4.4.43 There is little direct information on the disturbance of sediment at the sea bed. The anecdotal evidence of divers is that they perceived no obvious change in the appearance of the stakes that mark the centres of Repopulation Areas over the time between their establishment in summer 2000 and the surveys of 2004. In spring 2005, two of the stakes, in Areas 3 and 8, were missing. This followed a notable storm in January (for which wave height data are unfortunately not yet available) and the most probable explanation is that waves disturbed the bed sufficiently for these two stakes to fall over and become buried. However, Area 3 had not been visited since 2002 and furthermore it lies within an area entered illegally by a fishing vessel which was operating a trawl net on an occasion during the period May 2004 – March 2005. It cannot be ruled out that the loss of this stake was due to the trawl net uprooting it, but the stake in Area 8 was not within the area visited by the fishing vessel and its disappearance can be put down to natural causes. Area 8 had been visited the previous year, as had Areas 4, 6 and 12 in which the stakes were all intact. The depth into the sand to which stakes were driven was not recorded, but is said by divers to be ’over two feet’, *i.e.* 600 mm. The implication is that the January 2005 storm may have disturbed the bed in Area 8 to such a depth, with presumably somewhat smaller disturbances elsewhere. Conversely, the largest waves that occurred in the period August 2000 to May 2004 were 7.2 m high, and the fact that none of the stakes was disturbed indicates that these waves must have disturbed the sand around them to substantially less than 600 mm depth. Finally, divers making the initial searches for particles in 1997-98 observed that in the rocky areas close to the Diffuser the levels of sand abutting against rock had changed substantially in some places. No figure for the magnitude of this change can be given, but the observation appears to be soundly based, in that the divers emphasized that they were referring to particular places where particles had been found buried in sand adjacent to rock outcrops in 1997 and which they were searching again the following year. Wave heights did not exceed 7 m in the winter of 1997-98, suggesting that somewhat smaller waves than this were capable of scouring sand to noticeable depths close to rock outcrops. All of this circumstantial evidence is in broad agreement with the implication from the burial depths of Repopulation Area finds, that the sea-bed sand may be sporadically disturbed to depths of 400 – 500 mm every year or two on average.

Fragmentation of particles

4.4.44 The first offshore particle was recovered as a chance find during diving operations near the Diffuser in 1997. On return to the laboratory it was found to be in two fragments. Since then nearly 12% of the particles recovered have been found to be in two or more fragments when examined in the laboratory. By examining sequential groups of 100 particles in the order in which they were found, this proportion varies between 5 and 19%, but shows no trend over the years since 1997. The average number of fragments is 2.8. Sixty-three per cent of fragmented particles have two fragments, with the larger containing on average 85% of the radioactivity of the original. Across all fragmented particles, regardless of the numbers of pieces into which they have split, the most active fragment contains on average 80% of the original particle activity. Table 4.7 shows the average proportion of activity remaining in the largest fragment, in relation to the number of fragments into which the parent particle has split.

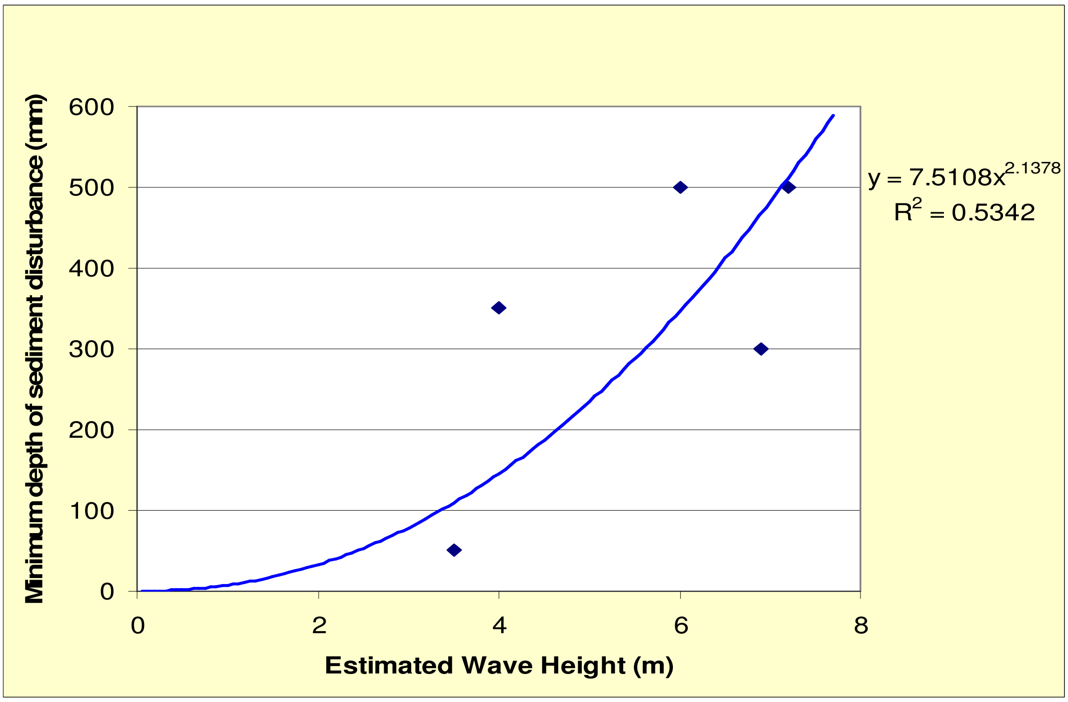

Figure 4.28 Repopulation Areas: Estimated depth of sediment disturbance *versus* wave height

4.4.1 Particles that have been securely identified as DFR (by their ^{94}Nb activity) break up more readily than other particles which are mostly MTR. Almost 20% of the 103 DFR particles identified were in fragments. The effect of taking these into account is to lower the proportion of MTR particles that are found in fragments to 10.5% (see footnote on page 33).

4.4.2 The proportion of particles found in a fragmented state shows no systematic trend with depth of burial. Roughly similar proportions, ranging from 6.5 to 17% were found as fragments at all depths down to 500 mm.

Table 4.7 Relative activities of particle fragments in relation to number

Number of fragments	**Number of cases**	**Mean activity of largest as% of total**
2	67	85
3	18	71
4	5	81
5	5	66
6	6	65
7	2	95
8	1	37
9	0	-
10	1	30
ALL CASES	105	80

4.4.3 The cumulative effect of fragmentation on the size, activity and numbers of particles offshore can be gauged only if it is known how rapidly fragmentation occurs. The repopulation data provide clues to this. Most of the recoveries from resurveys were found within a year of the previous survey. The proportion of particles found as fragments in resurveys is 30 out of 208 or 14.4%. This may be compared with the proportion found as fragments in the initial surveys of the same areas, 43 cases out of 276, or 15.6%. As fragments will normally be separated if they are disturbed and transported, the splitting of the re-survey finds must have occurred since the previous survey, and also since the particles entered the

Repopulation Area in which they were found. The conclusion is that breaking of particles into fragments must occur quite rapidly, generally within less than a year of arrival within the cleared areas. Thus, the rate of breakage can be roughly estimated at 15% per year.

4.4.4 The cause of splitting in MTR particles is likely to be electrochemical corrosion causing pitting and fissures along crystal grain boundaries. The particles are multi-metallic alloys – Al and UAl_4 – and therefore differences in electro-negativity will occur among crystal grains within the particles. These differences will result in a flow of electrons from the crystals with low electron affinity towards grains with high electron affinity, with a corresponding flow of charged ions into solution in seawater to complete the circuit. The fact that the proportion of finds in a fragmented condition is as great among deeply buried particles as on or near the surface suggests that chemical attack is a necessary precursor to fragmentation, even though the actual splitting may be triggered by physical disturbance.

A conceptual model of plume development, based on the "sand tracer" approach

4.4.5 The plume is considered to have originated from one or more releases of particles *via* the Diffuser during the 1960s, 1970s and possibly on more recent occasions (see Chapter 2).

4.4.6 Since release, the larger and generally more radioactive particles have been transported towards the shore into the area between the Diffuser and the coast, and also northeastwards parallel with the coast. Tidal currents are predominantly parallel to the coast, so the coast-parallel nature of the plume reflects their influence. Tidal currents act in both directions as the tide runs back and forth, but the flow is not exactly equal on ebb and flood tides, so that a small residual current exists over each tidal cycle. On the north coast of Scotland this acts in a generally eastward direction. However, the presence of headlands along the coast creates local gyres or circular structures in the tidal residual current. It is one of these, created by flow around Strathy Point to the west, that is probably responsible for the southwestwards movement of particles from the Diffuser area to Sandside Bay. The main extension of the plume to the northeast of the Diffuser reflects the regional tidal residual current, which produces a nett transport of water towards the Pentland Firth. However, tidal currents acting alone have velocities that are too slow to move large particles (Figure 4.11) shows that *significant* particles offshore generally have a-axes longer than 0.5 mm). The plume of *significant* particles has so far been found only to the northeast of the Diffuser. This asymmetry indicates that additional forces are involved, and these are provided by wind-induced waves. Waves cause oscillating movements of water down to depths of five or six times the wave height, which can transport particles in the same direction as the wave itself is travelling. The coast at Dounreay itself is aligned northeast-to-southwest, whereas the general coastline of the north of Scotland follows an east-west trend. Thus, the fetch for wind-induced waves is greatest in the quadrant between west and north. Within this quadrant, winds from west and northwest are more frequent than those from directions closer to north. The most frequently occurring winds therefore create waves that will tend to move particles along the shore to the northeast. Winds directly from the northwest, which are also fairly frequent, would drive particles from the Diffuser closer to shore. The only winds that would move large particles to the southwest are those coming from close to north, and these are probably not sufficiently frequent for their effects to outweigh those of the westerlies. It is the asymmetry in wind direction that is reflected in the asymmetry of the plume of *significant* particles.

4.4.51 A corollary of the argument in the previous paragraph is that a prolonged period of strong winds from the north might have the potential to move *significant* particles southwestwards towards Sandside Bay. However, it would require a general predominance of northerly winds for this transport to be other than purely temporary, and for the same particles not to be driven back again when the normally prevailing pattern of westerlies resumed. The complete lack of any findings of *significant* particles at Sandside Bay appears to be a result of differential transport that is, in turn, due to the prevailing wind pattern.

4.4.52 Turning to the smaller and generally less radioactive particles: these form a bidirectional plume, with branches extending both southwest and northeast from the Diffuser. The sea bed west of Sandside Bay has not been thoroughly searched, so it is not known whether this branch of the plume extends further. What is certain is that this branch is responsible for the feed of particles to Sandside Beach. The main reservoir source feeding the arrival of Sandside Beach particles is likely to be the core of the main plume, i.e. the area around the Diffuser and between the Diffuser and the shore where the greatest frequency of *relevant* and *minor* particles per hectare are found.

4.4.53 The fact that the southwestern branch of the plume is composed exclusively of particles <10^6 Bq ^{137}Cs indicates that tidal currents are probably capable of moving some or all of these particles without the aid of wind-induced waves. However, waves from all directions between west and northeast undergo refraction around the headlands at the mouth of Sandside Bay, and it may be that the additional transport they provide is responsible for steering the plume into the bay.

4.4.54 An important implication of Figure 2.1 (particle activities *vs* mass) that should be noted is that it does not rule out the possibility that *significant* particles might arrive on Sandside Beach in the future. The four particles from Sandside that are shown on Figure 2.1 are among the most active recovered from this beach. However, among the offshore particles in the sample shown in Figure 2.1, 10 out of 28 in the same mass range as the Sandside four possess activities greater than 10^6 Bq ^{137}Cs. The sample of particles was not random , therefore this proportion cannot be relied upon as representative of the whole population of offshore particles. It should also be borne in mind that density and size, not mass, are the factors that determine particle sorting. Nevertheless, relatively light particles with *significant* activity undoubtedly exist within the offshore plume, and have masses similar to the most active particles that have so far been found on Sandside Beach.

4.4.55 The branch of the plume that extends northeast contains the majority of the *relevant* and *minor* particles (<10^6 Bq ^{137}Cs). Their frequency per ha drops off within 2 km of the Diffuser to a roughly constant value of ~20 per ha, beyond which the plume extends at much the same frequency for at least 10 km, rounding the headland between Brim's Ness and Crosskirk (Ushat Head). Searches of the sea bed further to the east have been too sparse for the plume to have been detected on the sea bed there. However, it must be present in some form, as a metallic particle was recovered from Dunnet Beach in 2005, indicating an overall plume length of 25 km. Two plastic items, one radioactive, originating from Dounreay have also been found on Dunnet Beach in 2005 and 2006, confirming the general direction and extent of transport. It is possible that the Dunnet Beach items may have floated for all or part of their journey.

4.4.56 It is clear that the northeasterly plume of less radioactive particles is much longer than the corresponding plume of *significant* particles. Some form of differential transport must be taking place between particles of different activity, presumably through the correlation between activity and particle mass. Differential transport is also suggested by the decrease in average activity with distance from the Diffuser.

This may be due to the physically smaller particles, which will tend also to be less radioactive, being moved by tidal currents on almost every tide, whereas the *significant* and larger *relevant* particles may only be moved when favourable wind-induced waves augment the tides. There is also the influence of water depth. Tidal velocities at the sea bed will be less where the plume enters deeper water. Even the smaller particles may then require waves to augment the tides in order to migrate significantly further along the coast in deeper water, and larger particles may move more slowly or be trapped until they break down to a suitable size.

4.4.57 The actual rate of particle migration is impossible to estimate accurately from the distribution of the particles themselves, because the observations are not detailed enough, and do not cover a sufficient number of years for the evolution of the plume shape to be revealed. The measurements of currents on the sea bed made by UKAEA from short-term deployments of instruments on a Minipod frame indicate that the natural sand is in frequent movement under a 20 m water depth. These observations were confirmed by calculations made by Cambridge University, based on the Minipod data, and by the rates of particle migration simulated by the Wallingford model. The model shows very rapid migration of some particles across the sea bed traversed by the actual plume, with some reaching the eastern boundary within 30 days after release. Though it would be unwise to take model results completely literally, all these lines of circumstantial evidence agree in suggesting that the lesser *relevant* and *minor* particles migrate quite quickly. Furthermore, the Wallingford model suggests that even large diameter particles should migrate quite fast, with the majority being found at large distances from the Diffuser after 30 model years, *i.e.* at a time corresponding to the likely age of the real plume.

4.4.58 The discrepancy between the likely rate of migration of particles moving freely in the surface layers of sediment, and the concentration of *significant* and other particles around the Diffuser suggests very strongly that other factors have influenced the evolution of the plume. The only data that provide clues to the plume's evolution prior to 1997 are the time-series of finds made on Dounreay Foreshore illustrated in Table 5.1 and Figure 5.2 in Chapter 5. Although there was considerable variability in arrivals from year to year, it is clear that the feed of particles from the sea bed to the Foreshore was almost continuously greater than 10 per year between 1984 and the commencement of offshore removals by divers in 1997. Since then the annual numbers of Foreshore finds have been consistently less, with the exception of 1999, when 11 particles were found. This reduction in Foreshore finds was particularly marked following the diving campaign of 2001, when particles were removed from the sand-covered depressions between rock outcrops which are the route by which sand is transported onto and removed from the Dounreay Foreshore by waves. This removal of particles from the feeder route appears to have depressed the rate of Foreshore finds to between 3 and 5 per year for a couple of years afterwards. In 2004 – 2005, the rate recovered somewhat but was still lower than it had been before diving operations first began. No finds have been made on Dounreay Foreshore from the end of January 2005 up to February 2006[5] .

4.4.59 Before 2001, the average activity of particles found on the Foreshore had shown a slowly declining trend, although this was not statistically significant in comparison with the scatter in the data from year to year. Taken together with the impact of diver removals and the relative constancy of numbers of Foreshore finds per year

[5] In June 2006, DPAG was informed by UKAEA that less than the entirety of the Foreshore was being monitored with effect from July 2002. In addition, the monitoring systems subsequently employed had different efficiencies of detection and it is, therefore, difficult to interpret time-series data.

up to 2001, this suggests that (a) the reservoir of freely migrating particles available to feed the beach was probably quite small, (b) that once emptied the same reservoir of particles took several years to become replenished, and (c) that the average activity of particles in the reservoir may have declined slowly over time.

4.4.60 The factor that is most likely to be responsible for the small size of the reservoir of freely moving particles is that the majority of larger particles appear to be buried. *Significant* particles are preferentially buried when the bottom is disturbed by waves in water over 15 m deep, whereas in shallower water there is no tendency for high-activity particles to be more commonly buried than less active particles. At all depths the bed of the sea is scoured and re-deposited during storms that occur from time to time, with the largest storms affecting the greatest depths of sediment. When the disturbed sand settles to the bed as the waves die down, most of the *significant* particles that have been released by scour will become buried once again. A few, however, will remain on the sediment surface. It is these, located where the water depth is less than 15 m which constitute the reservoir of particles from which the Dounreay Foreshore finds were directly derived.

4.4.61 Particles which spend most of their time buried in sand will migrate along the length of the plume much more slowly than if they were always at the sediment surface. Disturbance of the bed occurs to depths below 100 mm several times per year and this may extend down to 400 – 500 mm about once every one or two years on the evidence of re-population finds. Such frequent burial retards the migration of all particles, and is probably the main factor responsible for the >30-year longevity of the patch of *significant* particles found within 1 km of the Diffuser.

4.4.62 The lifetime of the wider plume of less radioactive particles must also be prolonged by burial, as about half of these particles are immobilised for most of the time. However, an effect of burial is to retard the migration of large and small particles by the same factor. If, for the sake of argument, large particles migrate at one tenth the rate they would have done if they were always at the surface, so too would the small particles be retarded to one tenth of their free migration rate. Thus, the smaller particles should have migrated much faster than the larger, and over the lifetime of the plume it might be expected that they would have been completely removed from the area round the Diffuser. In fact, this area is where particles of all activities are found in greatest abundance. So the persistent presence of easily transported *minor* and *relevant* particles around the Diffuser for so long must be explained by some other factor than either burial or differential transport.

4.4.63 The missing factor appears to be particle break-up. Around 11% of all particles that have been recovered were in fragments, and the re-population experiments indicate that the rate of break-up of particles that have recently moved may be 15% per year. The cause of fragmentation is not known for certain, but electrochemical corrosion producing pits and cracks is strongly suspected. The rate of ~15% per year implies that particles have a mean lifetime of about 6.7 years before they break into two or more fragments. The largest fragments average 80% of the total activity of each particle before it broke up. This implies that about ten fragmentation events are required for the largest surviving particle to be reduced to one tenth the activity of the original. The time required for this number of fragmentations would be, on average, 67 years. In the 30 or 40 year lifetime of the plume, each original particle should therefore have declined to between one third and a quarter of its original activity due to fragmentation, and also undergone radioactive decay to roughly half its original value. Thus, fragmentation is probably somewhat more effective than radioactive decay in mitigating the particle problem by reducing the radioactivity of the largest particles.

4.4.64 The average number of fragments produced when a particle breaks up is 2.8. Thus, the numbers of less radioactive particles may be maintained, in the vicinity of the Diffuser, by the break-up of larger *relevant* and *significant* particles. In the core region of the plume, there may be a balance between particle production by fragmentation and particle loss by transport down-plume. As particles migrate down plume they will be retarded by burial and eventually will probably break up into smaller particles. Once the smallest fragments are of silt size (60 µm or smaller), they will be efficiently transported as suspended load and dispersed.

4.4.65 DPAG has considered the possible fate of silt-sized particles being dispersed in suspension, as well as that of very fine sand that might be transported along the sea bed. (HR Wallingford, 2001; 2002; 2005). The Pentland Firth is the sea-way that lies between the southern-most Orkney Islands and the Scottish mainland, just east of the Dounreay region. The residual current produced by tidal water flows will carry particles to the western end of the Firth. It is this residual current that has already transported at least one particle to Dunnet Bay, and others can be expected to be carried around Dunnet Head, which lies to the north of this bay, and into the western end of the Pentland Firth. (This pattern is also confirmed by particle transport runs of the outer area Wallingford model which is described in Section 4.5 (R.Wild, oral presentation to COMARE Dounreay Working Group, 7.7.05)). Tidal currents through the Pentland Firth are very strong and would transport sand-sized particles back and forth on each tide. However, there is a net flow of water eastwards, and eventually all the fine sand or silt particles derived from Dounreay are likely to be transported through the Firth and into the North Sea. Just east of the Firth the sea bed contains large sand banks known as Sandy Riddle, consisting of natural sediment that has been transported by the fast currents through the narrow part of the sea-way and then deposited as the current becomes slower in more open water. Fine sand-sized particles from Dounreay might be deposited here, but silt -sized material is more likely to be carried further east, eventually to settle to the bottom of the North Sea in areas where the sea bed is muddy. All of these particles will be highly dispersed over a large area of sea bed, and because their individual activities will be very low (less than 10^3 Bq ^{137}Cs) they will present no hazard to human health.

4.4.66 To sum up, evidence from divers' finds and observations in the field suggests that many of the particles that were released initially had activities in the range 10^6 – 10^8 Bq ^{137}Cs. A proportion of these particles were buried by storm waves and sediment disturbance shortly after their release from the Diffuser, and now form a cache of *significant* particles in the sea bed. The bed is disturbed frequently in shallow water, down to ~15 m depth, and probably somewhat less often at 20 – 29 m depth. The population of particles in sediment beneath shallow water forms the feedstock for finds on the Foreshore, but also exchanges particles with the populations in deeper water further offshore. This exchange is promoted by wind-driven waves transporting the larger particles towards the shore, whereas the bottom currents that compensate for the pile-up of water against the shore also effect the return transport of particles. In this way, the arrival of particles on the Dounreay Foreshore has been maintained at a rate which has declined only slowly since 1984.

4.4.67 The store of *significant* particles further offshore is mostly buried under normal conditions. Storm waves are required to disturb the store and bring part of it to the sediment surface. Particle fragmentation by chemical corrosion occurs at roughly equal rates among buried particles and those freely migrating on the surface, with a mean lifetime between fragmentation events of 6 or 7 years. The smaller daughter particles produced are transported down-plume more quickly than their larger siblings, causing a reduction in average radioactivity of particles in a down-plume direction. Sixty or seventy years are required to reduce particles to one tenth of their original radioactivity, during which time radioactive decay will also have caused a roughly four-fold reduction in ^{137}Cs.

4.4.68 The longevity of the plume is due to the burial of *significant* particles beneath water depths of 15 to 29 m, where they may be disturbed once per year or less frequently, but still often enough for fragmentation and excavation to the surface to offset transport down-plume and maintain the numbers of *relevant* and *minor* particles within the area near the Diffuser at roughly constant levels. *Relevant* and *minor* particles are more effectively transported by tidal currents, they therefore spread both southwest and northeast from the Diffuser, with northeasterly transport being augmented by prevailing winds and the waves that these induce. *Minor* particles have spread up to 25 km to the northeast, and particles in the lower part of the *relevant* range are found at Sandside Beach, 3 km from the Diffuser to the southwest.

4.4.69 This model of the plume has certain important implications. The most important is that the future radioactivity of the largest *significant* particles, with activities between 10^7 and 10^8 Bq ^{137}Cs at the present time (2006) can be expected to remain above 10^6 Bq for decades. The longevity of the plume as a whole may be much longer than this, because of the effects of burial on slowing particle transport and dispersal. The time that will be required for fragmentation and radioactive decay to reduce and finally eliminate all *significant* particles is discussed in Section 4.6 of this Chapter.

4.5 Assessment of the Wallingford Model

The Wallingford Model

4.5.1 HR Wallingford Ltd was commissioned by UKAEA to develop a numerical model of water movements and sea-bed currents around Dounreay, and to use it to predict the movements of particles. The model is described in a series of reports to UKAEA, which have been made available to DPAG (HR Wallingford, 2000; 2001; 2002). This section is an assessment of the latest and final version of the Wallingford model, which is described in HR Wallingford (2005).

4.5.2 The Wallingford model contains three main components:

- The "Outer Model" is a 2-dimensional (depth averaged) hydrodynamic model of a large area that includes southern Orkney and the whole north coast of mainland Scotland east of the Kyle of Tongue. The eastern boundary lies in the North Sea, 25 km east of the Pentland Firth.
- The "Inner Model" is also a purely hydrodynamic model, but it is 3-dimensional, in that it includes variation with depth) while it covers an area that extends only from Ardmore Point in the west to Holborn Head in the east, and considers the sea bed within 10-15 km of the coast. This model generates detailed water velocities close to the sea bed for 20-minute time-steps, and takes into account the effects of tides, winds and waves. It is driven by the historical times series of winds and computed astronomical tides since 1969, and has been calibrated against water levels observed at tide gauges, and observations of currents made by UKAEA and others on the sea floor. The results from these instrument deployments were reported by Lyndhurst Oceanographics Ltd (1999a; 1999b).

- The "SandTrack Model" is a particle-tracking routine which uses the output from the Inner Model and predicts the positions of individual particles for different times after release at any location. By repeating runs for ~1000 particles, SandTrack can simulate the development of a particle plume in the form of a series of snapshots showing particle locations after release at the Diffuser.

4.5.3 The Outer and Inner Models are based on well established principles and produce results that agree well with observations and with other hydrographic modelling of tidal flows around the British coast. DPAG sees no reason to doubt the general veracity and value of these two components of the overall Wallingford model.

4.5.4 SandTrack is innovative in that it uses a particle-tracking approach that is unconventional for sediment transport in the sea. However, this approach is well established in other contexts, notably groundwater flow and contaminant transport. SandTrack uses simple, but realistic equations to portray how currents move particles of different size and density across the sea floor. The current velocities are taken from the 20-minute time-steps of the Inner Model. In terms of sand dynamics, SandTrack is essentially similar to more conventional models that are used to estimate bulk fluxes of sand movement in situations where the supply of sand is unlimited. When tested against the general distribution of sandy sediments on the sea floor, SandTrack tends to move particles to the areas known to be sandy, and to remove them from areas that are rocky. These comparisons give a general level of confidence that the particle-tracking approach is physically realistic in its predictions of the way particles may, over time, disperse across the sea bed.

4.5.5 Although the transport predictions made by SandTrack seem realistic in terms of where particles are moved to, this component of the model predicts such a large average velocity for individual grains that many grains reach the edge of the modelled area within a short time. Moreover, few remain in the area of the Diffuser for periods of the order of 30 years. This discrepancy was noted when Phase 3 of the Wallingford Model had been completed. One of the aims of Phase 4 was to improve the representation of particle trapping, so as to slow down the dispersion of particles to rates that might match the observed distribution of finds in the sea bed from 1997 to 2004.

4.5.6 Based on monitoring data, particles have been found buried in sediment down to depths of 700 mm to 1 metre. Normal disturbance of sediment by waves and currents extends downwards only a few centimetres, so these deeply buried particles are, in effect, held immobile until a storm occurs that is large enough to scour the bed down to their burial depth. The buried particles may then be released for transport, or alternatively they may become buried again when the sediment settles as the storm wanes. Unfortunately there is very little evidence of the relationship between storm severity, as indicated for example by the heights of waves, computed from records of measured winds, and the depth to which the bed may be scoured or mobilised and then re-deposited. Such evidence as exists has been reviewed in Section 4.4. This, together with general reasoning, suggests that particles buried at shallow depth may be re-excavated at short intervals, whereas deeply buried items may remain immobile for far longer. Clearly, the overall effect of infrequent burial and excavation is to retard the average rate of particle migration. The final version of SandTrack attempts to model this by means of a particle-trapping routine.

4.5.7 Two approaches to modelling particle retardation have been tried in successive generations of SandTrack. Earlier versions attempted to model the processes of burial and excavation explicitly, but came up against the practical difficulty that a large number of parameters were required to make the model physically realistic, and that values for very few of them were reasonably constrained. In such circumstances, model calibration can only proceed by guesswork and it is desirable to reduce the number of parameters. The second approach achieved this by abandoning the goal of realistic physical representation of burial and excavation in favour of the generalised concept of trapping and release of particles. At the end of any given time step a particle may be in one of two states, trapped (T) or free to move (F); in the next time step it may either continue in the same state or change. These possibilities give rise to four possible transitions from time-step to time-step: T-to-T, T-to-F, F-to-F, F-to-T, each of which can be assigned a probability of occurrence. In the model, these probabilities are made to depend upon the speed of the water current above the particle, using an arbitrarily chosen equation. The parameters of this equation are purely mathematical and must be calibrated against real data in order to use the model in a practical way. This was done by using the model to predict the numbers of particles that would migrate over time into a circle of 2500 m^2 area that had been cleared of all particles, and comparing the results with the actual numbers found in repeated experiments of this type at Repopulation Area #4. Fitting was by trial and error. Following this calibration, SandTrack's particle-trapping routine was tested by comparing model predictions with known outcomes for other Repopulation Areas.

Comparison of particle finds with predictions from the Wallingford Model

4.5.8 The model has been used to predict dispersion of quartz particles with diameters of 0.25, 0.5, 1, 2, 3, 3.5 and 4 mm released at the Diffuser. Predicted initial movement is rapid for all sizes, predicting spreading along the coast for several kilometres within just one month. By the time that 30 model years have elapsed, roughly equivalent to the age of the real plume, half or more of particles in all size categories have left the Inner Model's eastern boundary, which is located to the west of Holborn Head. In practice, only one particle has been found east of Holborn Head, on Dunnet Beach in 2005. This was a *minor* particle, so probably corresponds to one of the smaller sizes in the model. Only small areas of sea bed have been searched this far east, but these have not so far yielded any practicles.

4.5.9 Larger particles in the model are transported to the northeast in the long term. Although initially some particles migrate southwestwards along the coast, the importance of northwesterly winds and waves in moving large particles ensures that this trend is reversed over time, and the nett migration for sizes greater than 2 mm is exclusively northeastwards after the first 10 model years. This feature is in good agreement with particle finds, as no *significant* particles have been found from areas to the west of the Diffuser.

4.5.10 The model predicts that the particle plume will mainly remain close to the shore, with relatively few particles being transported into water deeper than 50 m. This also agrees well with the distribution of particles found, which appear to be mainly restricted to a well defined plume that lies parallel to the shore northeastwards from the Diffuser. Smaller particles in the model were dispersed southwestwards as well as to the northeast. Some modelled particles enter Sandside Bay, but as there is no mechanism to entrap them there, they may leave the Bay again and join other particles that are predicted to migrate past Sandside. By the time that 30 model years have elapsed, particles are distributed as far west as Strathy Point where accumulations form in the gyres formed by water currents east and west of the headland. These predictions are only partly substantiated by particles found. Westward transport to Sandside is a prominent feature of the real plume, and only involves the *minor* and less active *relevant* particles. In this, the agreement between model and real world is excellent. However, so far, no particles have been found in the course of limited searches on the sea bed near Strathy Point, or anywhere west of Sandside Bay; so these aspects of the model remain unverified.

4.5.11 A striking agreement between model and reality came when diving took place on two areas of sea floor off Crosskirk and Brims Ness, which were chosen because the model predicted that particles would accumulate in small gyres at these locations. A small number of *minor* particles was found in both sites, with some just below the threshold of the *relevant* category. However, no *significant* or more active *relevant* particles were located, despite the model's prediction that these should also have accumulated.

4.5.12 From these comparisons it can be seen that there is general agreement between the directions of dispersal predicted by the model, and the places where particles have been found. The model predicts that the main plume will remain close to the shore, and this is where almost all particles found have been recovered. The model predicts that transport will be predominantly northeastward, and it is. The model predicts that particles will occur well to the east of Holborn Head, and one has been. The model predicts transport of smaller grains to Sandside Bay, and only less active particles have been found there. These agreements give confidence that the model has captured most of the processes causing particle dispersion across the sea bed.

4.5.13 Despite this success, some very important discrepancies remain. Of these the principal one is that the overall patterns of geographical distribution among the particles in the model bear very little relation to what has been established on the real sea bed. The modelled particles, after 30 years, have either left the area of the Inner Model altogether, or are loosely concentrated many kilometres away from the Diffuser, along the coast to the east of Brims Ness, and between Sandside and Strathy Point. In contrast, monitoring data show that particles are strongly concentrated close to the Diffuser and the abundance of particles per unit area of sea floor declines very steeply 2 - 3 km away from the Diffuser in both directions. This lack of agreement is especially serious for the *significant* and larger *relevant* particles, when compared with model particles of 1 - 4 mm diameter. No *significant* particles have been found more than 2.3 km from the Diffuser and almost all finds of these have been within 1 km of it.

4.5.14 DPAG considers that the particular lack of agreement between real and modelled particle patterns is a serious shortcoming of the model. The situation seems to be that the model's hydrodynamic and particle transport elements are correct, as these are the components which determine locations to which particles will migrate. However, the average rate of migration in the model appears too fast, so there must be processes occurring in the real world which are either not represented at all in the model, or represented in a way that differs substantially from reality. Two such processes are particle fragmentation and ultimate destruction, and particle burial and release. Study of the particles found provides strong evidence that both of these episodic processes are important, as already described in Section 4 of this chapter. Fragmentation of larger particles into smaller will limit the distances over which big particles can travel, if it proceeds at such a rate that they break up before they have gone very far. However, fragmentation is not represented in the model.

4.5.15 Burial and release of particles are represented in the model, through SandTrack's trapping routine. Although it is an elegant solution to the problem of devising a simple model that can be calibrated using the Repopulation data, the simple probabilistic approach adopted is open to criticism on several grounds.

4.5.16 The model has been validated using sparse data, presented graphically in the Wallingford Report which notes good general agreement with the numbers of particles predicted and those found in Repopulation Re-surveys, especially for cases involving large numbers of particles. However, all the cases with large numbers involve the outer rings of Repopulation Areas (#3, #4, #5) and, with the exception of hash4 these have never been resurveyed after initial clearance. The agreement on the large numbers shown in the report is with the numbers found during the initial clearance of each area. In effect, this is a very weak test of the model's performance and should not be used as significant evidence of successful validation.

4.5.17 Plotting all the data that are independent of the calibration process in the form of predicted *versus* numbers of particles found reveals that the model predicts on average only half as many finds as were made. While there is scatter in the data, this result nevertheless suggests that the calibration may not be particularly robust, and that different best-fit parameters might have been obtained from a different choice of calibration data set.

4.5.18 A fundamental criticism of the trapping routine is that it includes no reservoir of buried particles. The transitional probability for becoming free is the same for all trapped particles, of a given size and in a particular time-step, regardless of burial depth. Obviously, this is not true in reality. It has the corollary that every particle has a finite chance of being moved whenever the water currents are fast enough. Even particles which are, in reality, deeply buried will be moved from time to time by the model. The trapping routine attempts to deal with this by making the probabilities of movement depend on the particle's size and on the prevailing currents. However, the way the routine is constructed means that it is fundamentally unable to represent the fact that some particles spend very long periods buried, and should have a probability of zero for moving until a storm occurs that will excavate them. The probability of such a storm is completely unrelated to the threshold probability for a particle being moved once it is free to do so. DPAG suspects that the inadequacy of the trapping routine in retarding larger particles sufficiently to agree with the real distribution of *significant* finds may lie in this aspect of the model's construction.

4.5.19 In calibrating the model, data on particles that are mobile have been used, since these are the ones that have migrated into positions previously cleared in Repopulation Area #4. The model's construction includes a fixed relationship between the probabilities of a trapped particle becoming free and a free particle being trapped. This fixed relationship has the advantage of reducing the number of parameters that must be fitted to sparse data from 3 to 2, but it is probably unrealistic to fix it as part of the model structure, especially as it cannot be accurately determined from surveys because of the shielding effects of sand on detection of buried particles. Overall, the use of mobile particles and short term data to calibrate the model, however necessary in practice, the parameters chosen may have introduced bias against any representation of long-term trapping by burial at depth.

4.5.20 The variation in probabilities of trapping and release with increasing speed of current is represented in SandTrack by convex-upwards curves that have maximum values when currents increase and the bed becomes mobile. A concept of an upward limit to probability is thus built into the model equations. A fundamental objection to this is that real buried particles are only likely to be released when waves and wind are violent enough to mobilise the whole bed. A mobile bed is also more likely to trap free particles within a sediment profile if conditions ameliorate from one time step to the next. These considerations militate strongly against the idea that transition probabilities might have an upper limit and suggest that a different function, perhaps a power law, could have been chosen, as this would have involved the same number of parameters without imposing upper limits to probability.

4.5.21 In summary, the trapping routine in the final version of SandTrack may be criticised from several standpoints. DPAG recognises that other modelling approaches were tried and found to be impractical. However, SandTrack fails in the fundamental test of successfully predicting the observed distribution of particle frequencies on the sea bed. The Model is successful in predicting the general directions of dispersion; nonetheless the mismatch of patterns of frequency must be due to failure in the model to determine the correct average rates of movement. This points to the modelled dispersion being too fast, which is probably attributable, at least in part, to the structure and calibration of SandTrack's trapping routine. The omission of particle fragmentation may also play a part.

Conclusions on the Wallingford Model

4.5.22 DPAG considers that the Wallingford Model provides a useful and largely accurate simulation of the directions of particle dispersion. However, it fails to capture the rates of dispersion because retardation is a process that occurs in reality, but is not fully represented, while fragmentation is not represented at all. Despite these limitations, the model is likely to prove very useful in suggesting those areas of the sea bed that should be searched for particles. DPAG recommends that future deployments of the TROL vehicle or its successors should be made in areas where the model predicts accumulations of particles far from the Diffuser at 30 model years. Deployments should also be made in areas where the model predicts either no particles or sparse populations of particles, in order to confirm or refute these conclusions. With its limitations kept in mind, the model is a good tool for predicting where to look for particles. It provides a pessimistic estimate of possible longer-range transport.

4.5.23 By contrast with its strength in predicting where particles may occur, the model is much weaker as a predictive tool of when events may occur. A critical question is whether it could be used to forecast the length of the period over which particles are likely to persist on the sea bed. It predicts that some particles would remain within the modelled area for both 30 year and 70 year timescales, which does suggest that the problem may persist for many decades. Because it has been derived solely from the model, DPAG has little confidence in the validity of this prediction. The poor match between predicted and known patterns of particle distribution undermines the model’s credibility in representing rates of movement and, hence, rates of plume evolution.

4.5.24 DPAG considers that fragmentation and long-term burial are likely to be important processes that may determine the longevity and distribution of particles within the plume. These processes are not represented, or not fully represented in the model. This may account for its shortcomings as a forecasting tool.

4.6 Conclusions and Implications

The state of current understanding of the particle plume on the sea bed.

4.6.1 The Wallingford Model and the conceptual model presented in Section 4.4 of this Chapter, based on the evidence provided by the particles themselves, both indicate that the offshore particles are subject to transport by tidal and wind-induced currents. These combine to induce differential transport between larger and smaller sand-sized particles moving within the upper 100 mm of frequently disturbed sand on the sea bed. Larger particles are transported almost exclusively northeastwards, forming a plume that lies parallel to the shore. Smaller particles are transported much further and by implication much faster, because they can be moved by tidal currents alone, without the additional water movements provided by waves. The plume of smaller particles has two branches extending for 25 km eastwards from Dounreay to Dunnet Beach, and 3 km southwestwards to Sandside Beach. The influence of wind-induced waves is seen in the asymmetry of these two branches, and in the smaller numbers of particles inferred to be present in the southwestern branch. This is because the prevailing wind directions and the limitations on fetch provided by the shape and orientation of the coastline result in a predominance of waves that augment tidal currents transporting particles to the northeast, but oppose transport to the southwest. The general directions of particle transport have been successfully predicted numerically by the Wallingford model, although some aspects of its predictions, ,for example, transport beyond Sandside Bay in the west, remain to be tested by more extensive surveys of the sea bed.

4.6.2 The offshore plume was initiated over 30 years ago and has certainly been present since 1984. The plume is still centred on the Diffuser and the concentration of particles on the sea bed is greatest in the area of sea bed opposite the Dounreay site. This longevity contrasts with what would be predicted from simple hydrodynamic transport of the particles that has been simulated in the Wallingford Model.

4.6.3 The longevity of the *significant* particles that are concentrated in the central part of the plume is due to burial and periodic re-excavation of these particles by scour and replacement of sand on the sea bed. Only the top 100 mm or so of the sand is in frequent movement whereas the layers of sand beneath are disturbed by wave action during storms. Particles buried in the deeper layers are immobilised until such time as they are re-excavated. Re-excavation releases some of the buried particles to the surface layer but buries some of those that were formerly free to move. Because large particles are released, re-excavation renews the supply of large particles at the sediment surface. Burial, on the other hand, restricts their average rate of transport. Hence, they have travelled much shorter distances than similar particles that were entirely free to move in response to the combined forces of winds and tides.

4.6.4 *Relevant* and *minor* particles, being generally smaller than *significant* particles, are transported more rapidly during the periods when they are free to move. This causes a progressive change in the numbers and average activities of particles in a down-plume direction, with values having declined to ~20 particles per ha and ~10^4 Bq about 2 km from the Diffuser but remaining approximately constant at greater distances as far as 10 km eastwards.

4.6.5 The greatest numbers of *relevant* and *minor* particles are found in the central part of the plume in which *significant* particles are also concentrated. This is probably because the lesser particles are created, and their numbers renewed, by the physical break-up of *significant* particles. Electrochemical corrosion is probably the agent responsible for weakening particles so that from time to time they break into fragments when physically stressed, either by natural disturbance or during excavation by divers. About 15% of particles break up per year, a figure which implies an average lifetime of 6 or 7 years between fragmentation events. On average 2.8 fragments are produced in each event, with the largest containing on average 80% of the radioactivity of the original. The *significant* particles remain concentrated near the Diffuser and, therefore, their break-up forms a supply of fragments which serve to maintain the numbers of smaller *relevant* and *minor* particles in the central part of the plume. These are transported down-plume at much the same overall rate as they are generated by fragmentation, and this feeds and maintains the more distant parts of the plume.

4.6.6 The ultimate fate of the radioactive material that makes up the particles in the plume is, of course, radioactive decay. However, fragmentation appears to be more effective than decay in reducing, over time, the radioactivity found among individual particles. This reduction has the further consequence that the physical size of particles declines over time. The particles in the more distant parts of the plume continue to be buried and released, to undergo chemical attack and fragmentation, and to be progressively reduced in both activity and size. Once these particles reach silt size, they will remain in suspension in turbulent water and may then be much more efficiently transported over long distances in the sea. Probably the ultimate fate of the particles is to be reduced to silt size and then be carried through the Pentland Firth and into the North Sea (see paragraph 4.4.65) where they will ultimately be deposited with muddy sediments, where they are likely to remain until radioactive decay makes them indistinguishable from the surrounding sediment.

The future of the particle plume and implications for the problem of contamination on beaches

4.6.7 The time taken for a particle to be reduced to one tenth of its initial activity by fragmentation alone can be calculated as 60 – 70 years. This places a rough limit on the duration of time for which *significant* particles may persist in the marine environment and continue to come ashore on the Dounreay Foreshore. The largest particles found on the sea bed have ~10^8 Bq of activity, but the approximate median for the *significant* group is nearer 10^7 Bq. It would take 60-70 years for fragmentation alone to reduce all 10^7 Bq particles to less than 10^6 Bq. However, radioactive decay of ^{137}Cs also contributes to this process, and if taken into account it shortens the time required to ~40 years. Thus, 40 years from now, the numbers of *significant* particles in the plume can be expected to have roughly halved, and after 80 years even the largest *significant* particles present today will have been reduced to the *relevant* category.

4.6.8 For much of this time the numbers of smaller particles will be augmented and maintained by fragmentation in the region where *significant* particles still occur. This region will spread, as transport moves *significant* particles further down-plume in between lengthy periods of burial. It is not certain how far the central region of the plume will spread, but given that the plume is already 30 – 40 years old, it is unlikely that in another 80 years the area of *significant* particles will extend much more than three times further from the Diffuser than it does today. This suggests that the edge of the area might be 6 km from the Diffuser to the east, but remain less than one km in the west. However, this is subject to great uncertainty as particle transport is not influenced by radioactivity, and it is possible that a few smaller *significant* particles than average may be transported rather further than these estimates suggest. Even so, this probably would not be enough to bring any *significant* particles onto publicly accessible beaches to the east, where Crosskirk is the nearest, 8 km from Dounreay. However, in the west it is conceivable that a few *significant* particles could reach Sandside Beach in the future.

4.6.9 The supply of *relevant* and *minor* particles from the central part of the plume is responsible for feeding the arrivals on Sandside Beach, as well as the single particle found so far on Dunnet Beach. It can be expected that Sandside Beach will continue to be contaminated by radioactive particles at levels similar to the present for another 40 years, and for contamination then to gradually decline for another 40 years. Only after ~80 years would we predict a more rapid natural amelioration of the contamination of public beaches, unless mitigating actions were taken.

4.6.10 The numbers of fragments produced is greater than the number of parent particles, thus the numbers of *relevant* and *minor* particles in the plume can be expected to rise somewhat in the future, with the increase being greatest for the *minor* category. This may lead to increases in the rate of arrivals on the more distant beaches, such as Dunnet Bay, possibly including Scrabster and Thurso which are both fine sand beaches on which no particles have so far been found, but which lie within the length of coast with which the plume is parallel.

4.6.11 The dynamics of burial combined with differential transport directions for large and small particles appear to have ensured so far that *significant* particles do not travel southwestwards from the Diffuser. However, there is a large overlap in mass range between *significant* and *relevant* particles, so it is possible that physically smaller or less dense *significant* particles may be transported over greater distances in the future than has happened so far. The upper activity range at Sandside Beach overlaps with the lower part of the mass range of *significant* particles, and there seems no apparent reason in our present state of knowledge why a very few *significant* particles should not reach Sandside Beach within the next 40 – 80 years. However, it is very unlikely that more than a very few would do so.

4.6.12 *Significant* particles predominate on the Dounreay Foreshore and can be expected to continue for some time, although their mean activity and numbers will probably decline slowly in the long term. The intensive diving activity and particle recovery during the years 1999-2002 appear to have had a significant effect on the rate of particle arrival on Dounreay Foreshore (but see footnote 5). In 2001-2 divers removed particles from the near-shore zone, in water depths as little as 5 m. The rate at which particles were found on Dounreay Foreshore decreased for several years. It increased in 2004-5, although the adoption of a new instrument by UKAEA (a vehicular version of Groundhog Evolution) may have improved the efficiency of search at much the same time. Since February 2005, no particles have been detected on the Foreshore. It may be that removing particles from the source reservoir – in this case the intermediate reservoir of particles in sand in the near-shore zone – does reduce or cut off the supply of particles to the Foreshore.

Possible strategies for mitigation, and implications for monitoring

4.6.13 The ultimate source of all the beach particles between Sandside and Dunnet is the cache of *significant* particles in the central part of the plume. The total number of these is not large, between 650 and 1500 (see Section 4.2 of this Chapter), and a determined campaign using a TROL to locate these particles and their subsequent removal would undoubtedly have a very significant effect on the plume. The numbers of smaller particles reaching public beaches might begin to decline over a period of years, whereas numbers of *significant* particles reaching Dounreay Foreshore would be cut almost to zero very rapidly, with a steep reduction in average activity of those particles that did continue to be swept onto the Foreshore and lodge there. However, such a strategy would require further development of the TROL so that it could distinguish between large particles buried deeply and small particles near the surface of the sand on the sea bed. It would probably not be cost-effective to use divers to recover all particles irrespective of their activity, because the total to be located and recovered would be five times greater, and, furthermore, many smaller particles would go undetected without multiple searches of a large area over several years. *Significant* particles can be detected down to at least 500 mm depth, so search by a modified TROL could in principle be very efficient.

4.6.14 Our current understanding of the formation and likely future evolution of the offshore plume has implications for the strategy of relying on monitoring of beaches to protect the public. Radioactive particles can be expected to continue to arrive on Sandside and Dunnet Beaches for the next 40 to 80 years. Their activities will mostly be in the *minor* and *relevant* ranges, but a few *significant* particles may arrive on Sandside Beach in the same period. Dounreay Foreshore is likely to continue to receive *significant* particles. There is a possibility that sporadic appearances of particles may occur on beaches other than Sandside, Dounreay and Dunnet. In particular, Thurso and Scrabster Beaches have fine sand that may behave in a similar manner to the smaller *relevant* and *minor* particles that are present in the plume, and so afford a suitable host sediment for their deposition.

4.6.15 Dunnet Beach has been monitored once, following repeated recommendations by DPAG, RWMAC and COMARE that this be done. A radioactive Dounreay metallic particle was found on this survey, and the clear implication of this find, combined with our understanding of the plume feeding to this part of the coast from Dounreay, is that monitoring should be conducted annually.

4.6.16 Similar caution should be applied in relation to Thurso and Scrabster beaches. These are currently monitored three times each year. Both beaches lie within the stretch of coast traversed by the particle plume *en route* to Dunnet Bay. Both are composed of finer sand than either Dunnet or Sandside, reflecting their sheltered position and the low energy of the waves that reach them. Thus, it is expected that if particles do reach these beaches, they are likely to be physically smaller in size than the average for the plume, and therefore to belong to the *minor* category or be in the lower end of the *relevant* range. Detection of *relevant* particles, if they are present on these beaches, is desirable for the reassurance of the public and also to improve understanding of the extent and evolution of the plume.

4.6.17 On the basis of the above arguments, DPAG recommends that serious consideration should be given to the targeted removal of *significant* particles from the marine environment. Such action should reduce the potentially protracted duration of this problem.

Chapter 5

BEACH MONITORING

5.1 Introduction

5.1.1 This chapter presents an evaluation of the monitoring equipment and its operational performance (*e.g.* Figure 5.1) and a review of the particles found on the beaches of Caithness. A comparison of the two Groundhog monitoring systems was necessary to determine whether differences in the number of particles detected can be attributed to changes in the method of detection. There is a discussion of the numbers, distribution and types of particles found offshore, their transport and potential sources. Recommendations are also presented, regarding detector deployment and minimum detectable particle activities for future monitoring. The relevance of these results on the probability of encountering a particle is considered in Chapter 6.

Figure 5.1 Evaluation of beach monitoring capability: Groundhog Evolution on Sandside Beach, April 2006.

The geomorphological characteristics of Caithness Beaches

5.1.2 Knowledge of the dynamic nature of the Caithness beaches routinely monitored is limited by the scope of the investigations that have been pursued in recent years. Here we will confine the discussion to beaches where particles have been detected.

Sandside Beach

5.1.3 Sandside Beach is a typical bay-head beach, shaped by the range of waves (height, wavelength and crest alignment) able to reach the beach from a broad northerly direction. Waves, including swell from the west and north are refracted into the bay. The grain size of the sand (c. 0.33 mm) determines the smooth curvature of the beach and the gentle and consistent slope.

5.1.4 The general behaviour of bay-head beaches is that they tend to increase in volume above LWMOT (Low Water Mark of Ordinary Tides) in the quieter summer months and lose volume during and especially towards the end of the stormier winters. However, exceptionally stormy summers and/or quiet winters can reverse this trend. It is generally thought that the overall volume of sand in the bay remains constant and offshore bars develop during the winter, which are then brought back shorewards by waves and a summer ridge of sand (berm) or swash bar migrates across the beach building it up by perhaps 200 to 300 mm. Over a period of decades or even centuries there may have been a nett increase in the volume of sediment in the bay, which may, in part, together with the sediment supply from the stream that feeds into Sandside Bay, account for the increase in dune volume.

5.1.5 Changes in beach orientation, a result of sand being built up on one side and combed down on the other, are controlled by the variations in the energy balance between the northeasterly swell and broadly northerly storm waves. Given the low slope of the beach, these changes in orientation require large volumes of sediment to be moved. This in itself would require energy provided by waves from a constant direction persisting probably over several weeks.

5.1.6 Particles are likely to be transported to Sandside Beach in a nearshore eddy, induced by the projection of Strathy Point to the west. In the near-shore zone, the wave induced currents are thought to maintain a movement of sediment to the west, which diverges offshore to join the general easterly flow of sediment and to carry sand and any associated particles into Sandside Bay. From here particles are likely to have been moved up onto the beach by the landward progression of swash bars, which individually are unlikely to add more than c. 300 mm of sand to any part of the beach in any month. Any active particles are therefore likely to be found in this depth range. Particles may also be buried or exposed by the disturbance of large waves breaking on the beach. According to King (1972), a 1 m wave is likely to disturb beach sand to the depth of 50 mm, and the relationship between wave height and disturbance is linear.

Dunnet Beach

5.1.7 Dunnet Beach is one of the largest bay-head beaches in northern Scotland, extending over 4 km and, like Sandside, the beach is composed predominantly of sand (c. 0.31 mm). It has a westerly aspect and thus faces the westerly swell, responsible, at least in part, for particle transport and the beach acts as a sediment trap (Ritchie and Mather 1984). The high sandstone cliffs of Dunnet Head to the north and the low flagstone platform to the south refract incoming waves such that they are parallel to the arc-shaped beach. The beach is flanked by rock platforms, where adjacent sediments in the upper part of the beach can be as coarse as shingle. The beach is also backed by dunes, which show signs of erosion by storm waves.

5.1.8 The almost ubiquitous sandy bottom-sediment within Dunnet Bay implies generally good sediment supply that can be transported from offshore, and the occurrence of a particle on the beach confirms that sediment accretion on the beach is active. Its greater distance than Sandside Beach from Dounreay suggests that fewer particles are likely to be found than on Sandside Beach, although the location of Dunnet, being east of Dounreay, makes it more likely that particles will migrate here, rather than westward to Sandside, because of the predominantly easterly direction of sea-water flow. However, the proximity of Sandside to the Dounreay Site compared to the beach at Dunnet is probably the most important factor.

Dounreay Foreshore

5.1.9 Continuous access combined with interest in the relationship between changes in the quantity of sediment and the pattern of particle finds have led to a pattern of surveys of the Dounreay Foreshore which gives a far more quantitative understanding of the way in which this beach changes over time as compared with those at Dunnet and Sandside. In August 1996, the west side of the Foreshore which holds almost all of the sand was excavated and particles extracted. Thus when particle detection resumed its normal course within a few months, this established beyond doubt that the finds from the beach over the years had arrived at most several weeks before most of them were found. Natural processes were therefore moving particles onto and, presumably, off the beach.

5.1.10 Most volume changes of this beach involved the arrival or removal of between 10 and 100 m^3 of fine to coarse sand. Any material that had arrived in one month was likely to have been lost in the following month. This reflects the high energy level of this exposed beach, and its steep, unstable nature. The open exposure of the beach resulting in higher wave energies, compared with Sandside and Dunnet, result in coarser sediment, ranging from sand to large pebbles. The sand component, relevant for the discussion of particles, typically ranges from 0.46 to 1.67 mm. The mean beach depth is estimated to be around 600 mm and the volume of sediment between 3500 and 4000 m^3.

5.1.11 Analysis showed that there is no simple correlation between the arrival of large volumes of sand on part of the beach and the pattern of finds, nor between areas of most rapid changes and the frequency of finds. Analyses showed that the more sand free zones of the beach are most likely to yield finds of particles, often between pebbles and particularly on the uppermost part of the beach. This may be related to the shoreward movement of particles under storm conditions, throwing up sand and particles onto the beach. Many will be combed back down by backwash but some will remain. This is unlikely to be the process operating on Sandside and Dunnet.

5.1.12 Overall, it is rare for the beach as a whole to be built up or combed down and usually about half of the beach is involved in appreciable changes. Unlike the bay-head beaches, the varying dominant wave directions are less affected by refraction as they move into shallow water and as a result the relatively small shifts in wave orientation are reflected in quite considerable transfers of sediment from one side of the beach to the other.

Summary of the history of beach monitoring

5.1.13 The first well documented beach particle was found in November 1983 through a routine radiological survey of the Foreshore of the Dounreay site. Since this discovery, routine strandline monitoring for particles at Sandside Bay, Scrabster, Melvich, Oigin’s Geo and Thurso was implemented although the methodology used for that monitoring was not designed specifically to detect the presence of particles.

5.1.14 A joint report, issued by SEPA and NRPB in 1998, recommended that more rapid and less manual beach monitoring techniques should be employed so that larger areas of these beaches could be covered more frequently. Similar views had been put forward by RWMAC and COMARE in their joint report on Dounreay, by SEPA in collaboration with HSE (1998), and by the European Union within a report from an Article 35 group (EC 1999). Furthermore, the Secretary of State for Scotland had, on 31 December 1998, requested that SEPA should ensure that "*there is sufficient monitoring in place to ensure that any particles finding their way to the beach at Sandside Bay are promptly detected and removed*."

Dounreay Foreshore

5.1.15 The Dounreay Foreshore is effectively closed to the public. Routine bi-weekly strandline monitoring has been carried out on the Dounreay Foreshore since 1983. Beta/gamma monitoring was carried out by means of hand-held Geiger-Muller tubes until June 2002. Since then, the surveys have been carried out using a hand-held single detector system based on the Groundhog Mk 1 system, as well as beta surveys using a large area beta detector. In October 2004, Groundhog Evolution was introduced. Since October 2004, the Dounreay Foreshore has generally been monitored fortnightly the exception being during the four months of the tern nesting season.

5.1.16 Up to February 2006, 239 particles have been found; these will be discussed further in paragraph 5.1.20. Four of the particles contained only ^{60}Co activity.

Other Beaches of Caithness

5.1.17 The first well documented particle found at Sandside Beach was in 1984. No other particles were discovered on Sandside until 1997 when two further particles were located. These finds led to an increase in the frequency of strandline monitoring from once every two weeks to once every week (alternately γ and β/γ) at Sandside Beach; this was consistent with advice given by COMARE in 1995. Particles have continued to be found, retrieved and recorded at Sandside Beach the total up to February 2006 being 59. The Groundhog Mk 1 gamma detector system was first introduced in 1999 and replaced by Groundhog Evolution in 2002. Prior to Groundhog, a beta/gamma probe system was used. In 2005, following a survey at Dunnet Beach, a small number of radioactive items was found. These included several stones with elevated concentrations of naturally occurring radioactivity, a DFR particle of around 8 x 10^3 Bq ^{137}Cs and a piece of plastic containing c. 2 x 10^4 Bq ^{137}Cs. Other beaches have been surveyed, but no other particles had been detected up to February 2006.

The Technical Implementation Document (TID)

5.1.18 A schedule specifying the beaches to be monitored and the frequency of surveying was issued by SEPA in February 1999 as part of its decision on the application by UKAEA to dispose of radioactive wastes from Dounreay. was issued in February 1999. It is presented in Appendix H.1 (Technical Implementation Document, TID). Following a review in 2000, a revised TID was implemented in 2001. This is also detailed in Appendix H.2. The main difference between the two TIDs is the detection criteria set. The new (2001) TID stipulated a more challenging detection criterion of '*at least 10^5 Bq ^{137}Cs at 100 mm depth*', to be achieved at higher monitoring frequency.

5.1.19 UKAEA started routine monitoring of Sandside Beach in July of 1999, using the Groundhog Mk 1 system. This was replaced in May 2002 by the Groundhog Evolution system. Following preliminary calculations of the detection capability of the Evolution system, the TID was revised on October 2003, as summarised in Appendix H.3. Instead of requiring detection limits, the new TID requires the system to maintain a mean operating velocity of 1 ms^{-1} and also requires that no account should be taken of any measurement when the equipment is operating in excess of 1.2 ms^{-1}. In addition, the requirement to monitor Dunnet Beach was added. The supporting documentation also indicated that UKAEA should strive to achieve better detection sensitivities.

Summary of beach particle finds

Dounreay Foreshore finds

5.1.20 Table 5.1 presents a summary of the particles found (number of particles, mean activity and range) in each year since 1984 on Dounreay Foreshore. Up to February 2006, 239 particles had been found (note no particles had been found between February 2005 and February 2006) with a mean activity of 5.6 x 10^6 Bq ^{137}Cs. Four particles had no detectable ^{137}Cs activity and contained only ^{60}Co activity. The mean in the previous sentence excludes the ^{60}Co activity. A number of particles found shows a decreasing trend over the period 1984-2003 (Figure 5.2), but a small increase in 2004 and 2005 is apparent which may be related to the introduction of the Groundhog systems on the sediment-covered areas of the western Foreshore. The eastern Foreshore, which is not accessible to Groundhog Evolution has not been effectively monitored since June 2002[6]. Figure 5.2 illustrates an apparent association between a reduction in the rate of particle finds and offshore- and inshore-diving to remove particles from the seabed. No particles have been found on Dounreay Foreshore since February 2005. Figures 5.3 and 5.4 show the mean, and minimum and maximum activities, including and excluding a particle of 2 x 10^8 Bq. There is evidence of a decrease in both the mean and maximum activity of particle finds, but with little evidence of any trend in the minimum activity. There are significant inter-annual variations. It should be noted, however, that no particles have been found since February 2005.

Sandside Bay

5.1.21 By February 2006, 59 particles have been found and their activity is summarised in Table 5.2. It is more difficult to comment on the pattern of finds at Sandside Bay than on those on the Dounreay Foreshore because of extended periods when monitoring could not be undertaken because access to the beach was denied. Formal access was granted from February 2001 to June 2002, when permission was denied. Access was reinstated in November and December 2002, removed for January 2003, and reinstated from February 2003 until April 2004. From May 2004 until December 2004, access was again denied, but was reinstated from January until March 2005. Access was denied from April until June 2005 and was reinstated in July 2005 until February 2006 when it was again denied.

[6] In June 2006, DPAG was informed by UKAEA that less than the entirety of the Foreshore was being monitored with effect from July 2002. In addition, the monitoring systems subsequently employed had different efficiencies of detection and it is therefore difficult to interpret time-series data.

Table 5.1 Summary of particle finds on Dounreay Foreshore ($\times 10^6$ Bq ^{137}Cs)

Year	Number of particles	Mean activity	Min	Max
1983	1	56	-	-
1984	27	9.2	0.000067	92.5
1985	11	5.2	0.63	22.2
1986	18	3.8	0.011	9.9
1987	10	9.3	0.04	45
1988	11	7.3	0.43	21
1989	15	7.7	0.1	49
1990	11	2.1	0.21	7
1991	13	20	0.5	200
1992	4	0.04	0.009	0.16
1993	13	2.9	0.1	6
1994	14	4.5	0.17	20
1995	11	5.9	0.5	21
1996	20	1.9	0.0018	14
1997	10	2.1	0.0014	16
1998	6	0.47	0.016	1.6
1999	11	3.3	0.0038	14
2000	6	4.5	1.07	7.6
2001	3	2.7	0.068	7.7
2002	5	1.3	0.74	3
2003	3	2.4	1.7	3.2
2004	9	0.34	0.082	0.8
2005	7	1.4	0.043	5.9
2006(Feb)	0	-	-	-

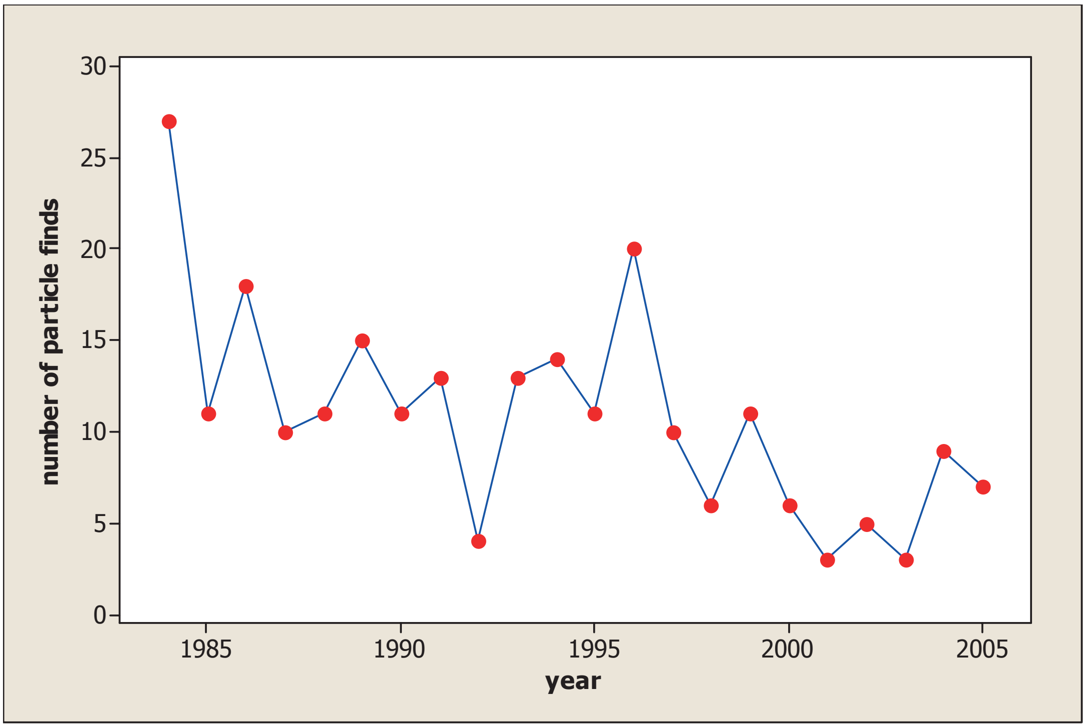

Figure 5.2 Change in the number of particles detected on the Dounreay Foreshore with time

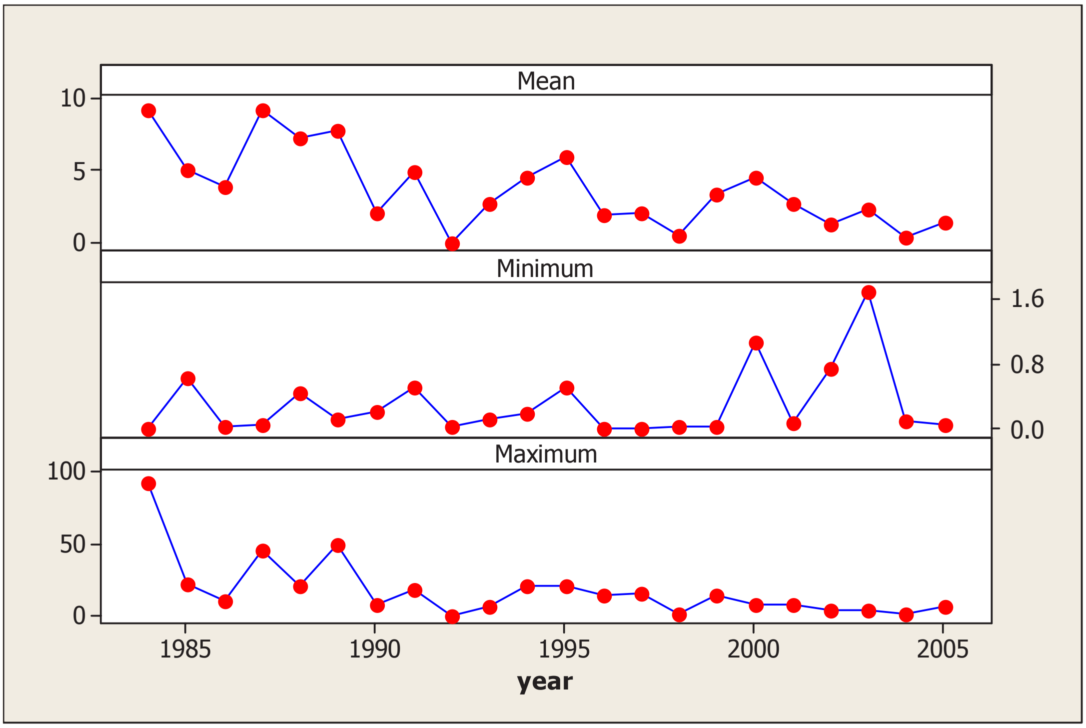

Figure 5.3 Scatterplot of arithmetic mean, minimum and maximum activity (x 10^6 Bq ^{137}Cs) at Dounreay Foreshore

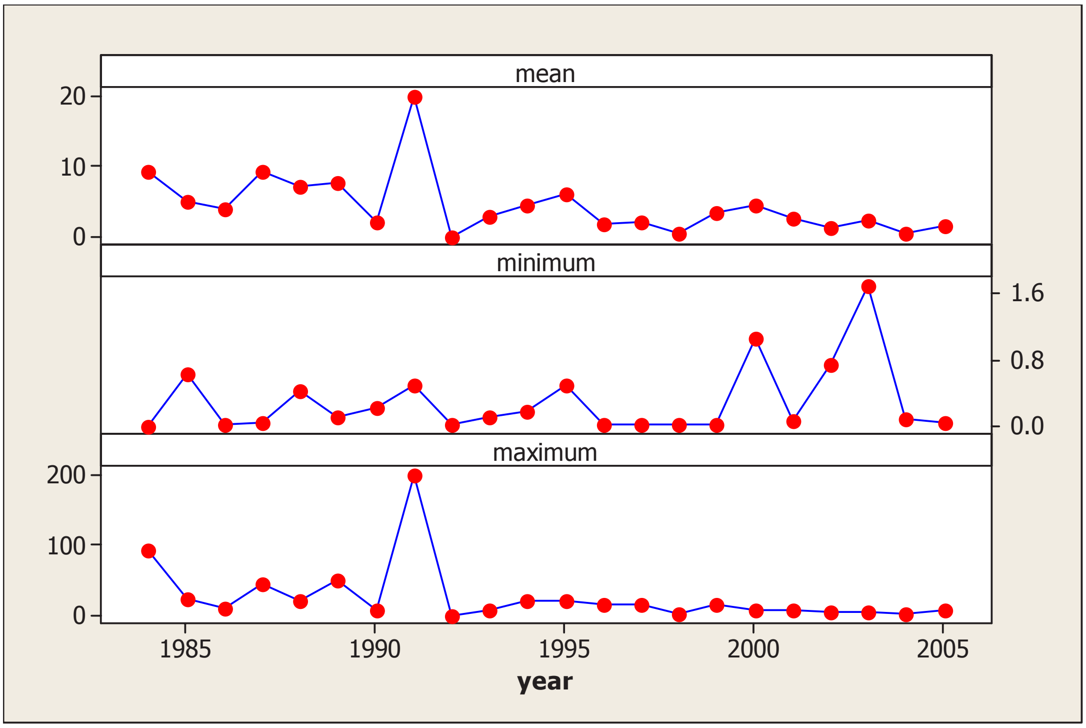

Figure 5.4 Scatterplot of arithmetic mean, minimum and maximum activity (x 10^6 Bq ^{137}Cs) (one particle at 200 x 10^6 Bq omitted) at Dounreay Foreshore

Table 5.2 Summary of particle finds at Sandside Bay

Year	Mean activity ($x\ 10^4$) Bq ^{137}Cs	Min and max ($x\ 10^4$) Bq ^{137}Cs	Mean (max) depth (mm)	Number of finds	Survey Status	Months of Monitoring Effort
1984	20		10.0 (10)	1	Beta/gamma	
1997	8.25	1.5, 15	25.0 (50)	2	Beta/gamma	
1999	14	6.1, 30	48.0 (100)	5	Groundhog Mk 1 from Jul 1999	6
2000	6.54	4, 12	40.0 (100)	6	Mk 1	11
2001	7.27	5.7, 10	78.3 (130)	3	Mk 1	12
2002	7.86	3.9, 11	120 (150)	5	Evolution(2)/Mk 1(6)	8
2003	5.0	0.8, 28	82.7 (200)	24	Evolution	11
2004	5.8	1.4, 9.7	66.0 (100)	5	Evolution	4
2005	3.13	1.1, 6.4	91.7 (150)	6	Evolution	9
2006	1.41	0.8, 2	30.0 (50)	2	Evolution	2

5.1.22 Groundhog Mk 1 was first used on Sandside Bay in July 1999, and this system was replaced by Groundhog Evolution in May 2002. The mean activity of particles found was 6.4 x 10^4 Bq ^{137}Cs (with minimum 8.2 x 10^3 and maximum 3 x 10^5 Bq ^{137}Cs). The mean depth of finds shows a general increase for 2003, 2004 and 2005, the period over which Groundhog Evolution was deployed. The number of finds in 2003 was exceptional, with 7 and 6 finds in March and April respectively, following a 2 month gap in surveying and a period when the beach was being eroded. This suggests that these particles may have been derived from a historical cache of particles previously buried too deep for detection. Table 5.2 and Figure 5.5 show little evidence of a trend in the number of finds.

5.1.23 If it is assumed that the density distribution of particles (number of particles per unit area) was uniform over both time and space, adjustment for incomplete sampling can be made. Figure 5.5 also shows the corrected (for sampling effort) numbers of finds. The correction applied is based on the number of months sampling effort with information only available since the introduction of Groundhog Mk 1. The predicted total number of particles from 1999 to 2006 would be 88 compared with the 56 actually found. Figures corrected for sampling effort will be returned to in Figure 5.9. It is worth noting that the method of estimating the risks of exposure took account of these factors.

5.1.24 Figures 5.5 and 5.6 summarise the particles found; they show no evidence of a decline in numbers of particles found, but show that the mean activity is declining in a linear fashion. This may be a reflection of detection systems recovering particles with lesser activities. The mean activity is declining by approximately 0.8 x 10^4 Bq y^{-1}.

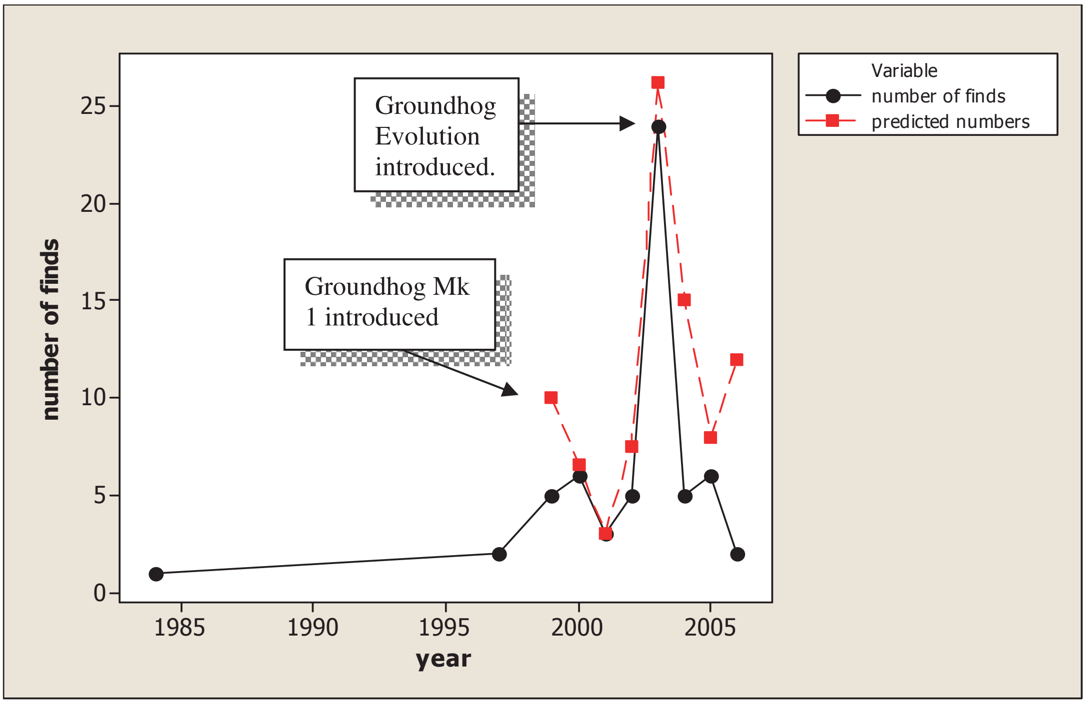

Figure 5.5 Number of particles found at Sandside Bay (corrected for sampling effort)

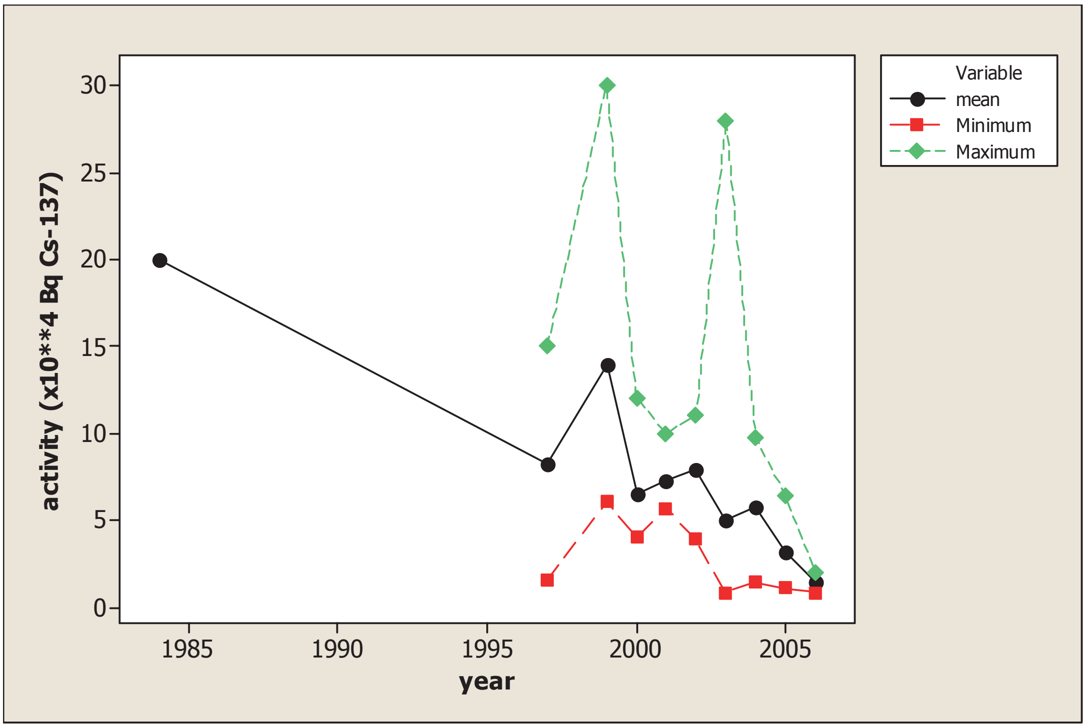

Figure 5.6 Mean (minimum and maximum) activity (x10^4 Bq ^{137}Cs) at Sandside Bay

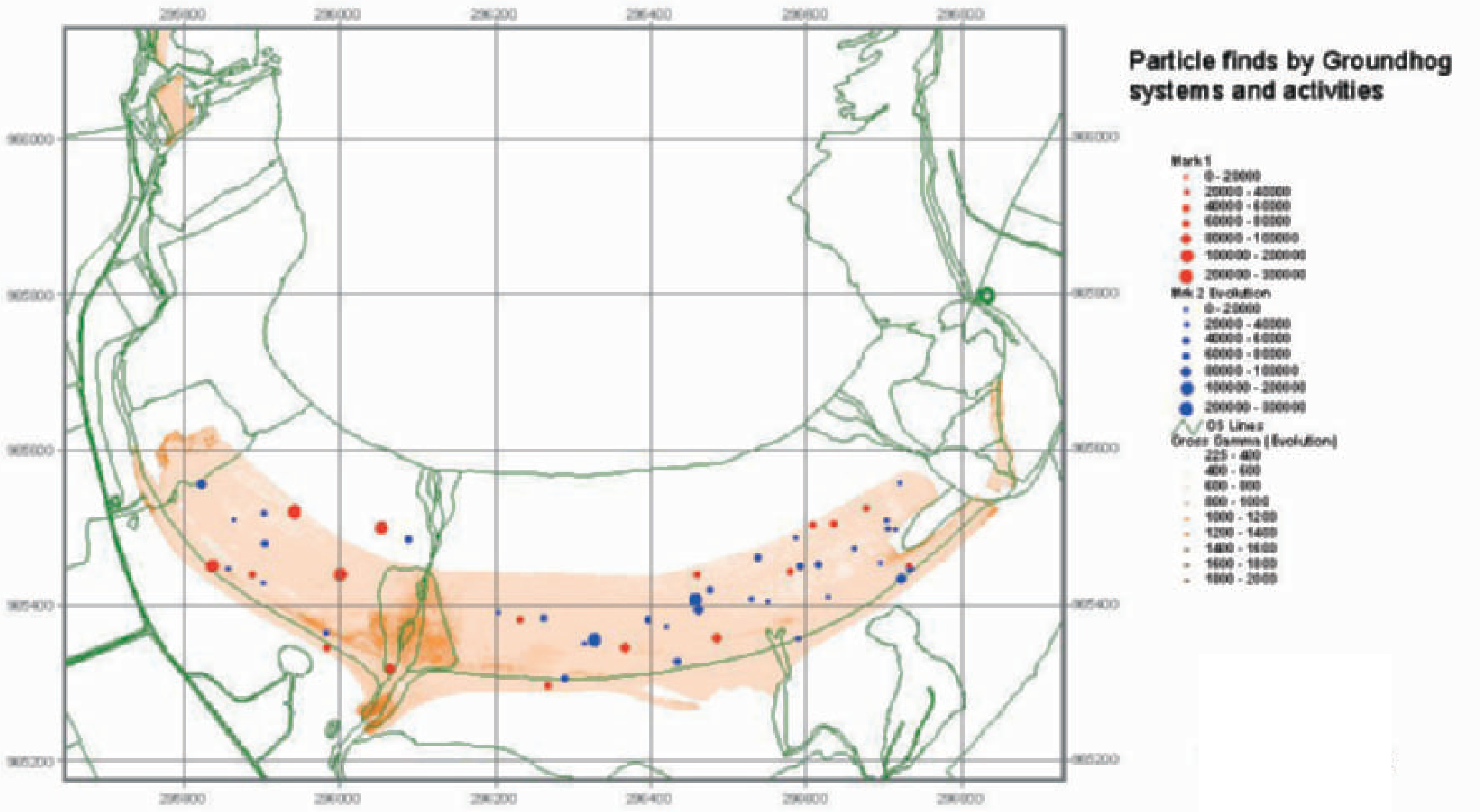

Figure 5.7 **The distribution of Groundhog Mk 1 and Evolution finds across Sandside bay. Particle activities proportion to symbol size expressed as Bq. Particles superimposed on a gross gamma image layer to demonstrate the variation in the natural radiation field.**

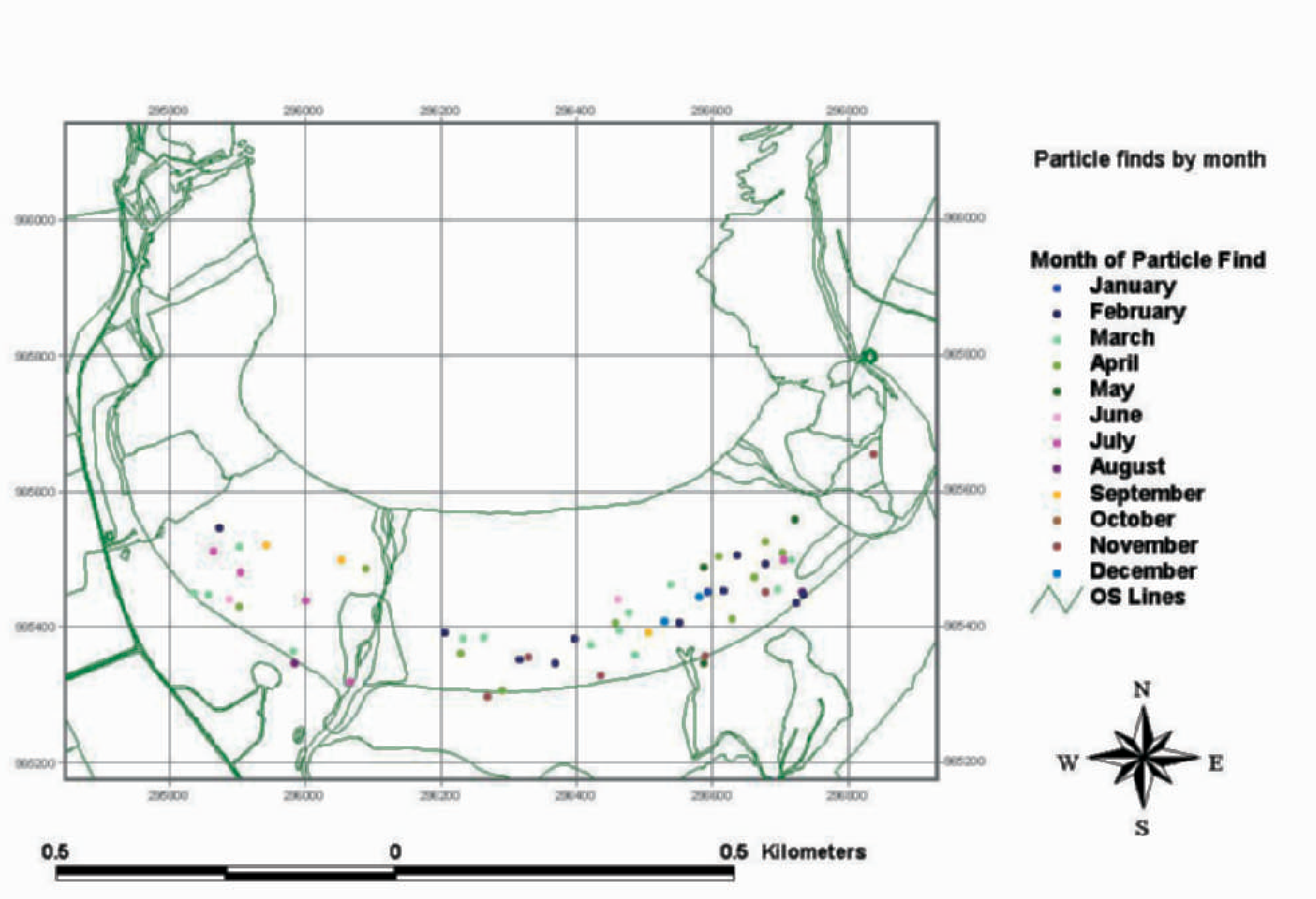

Figure 5.8 Particle distribution by month of a find.

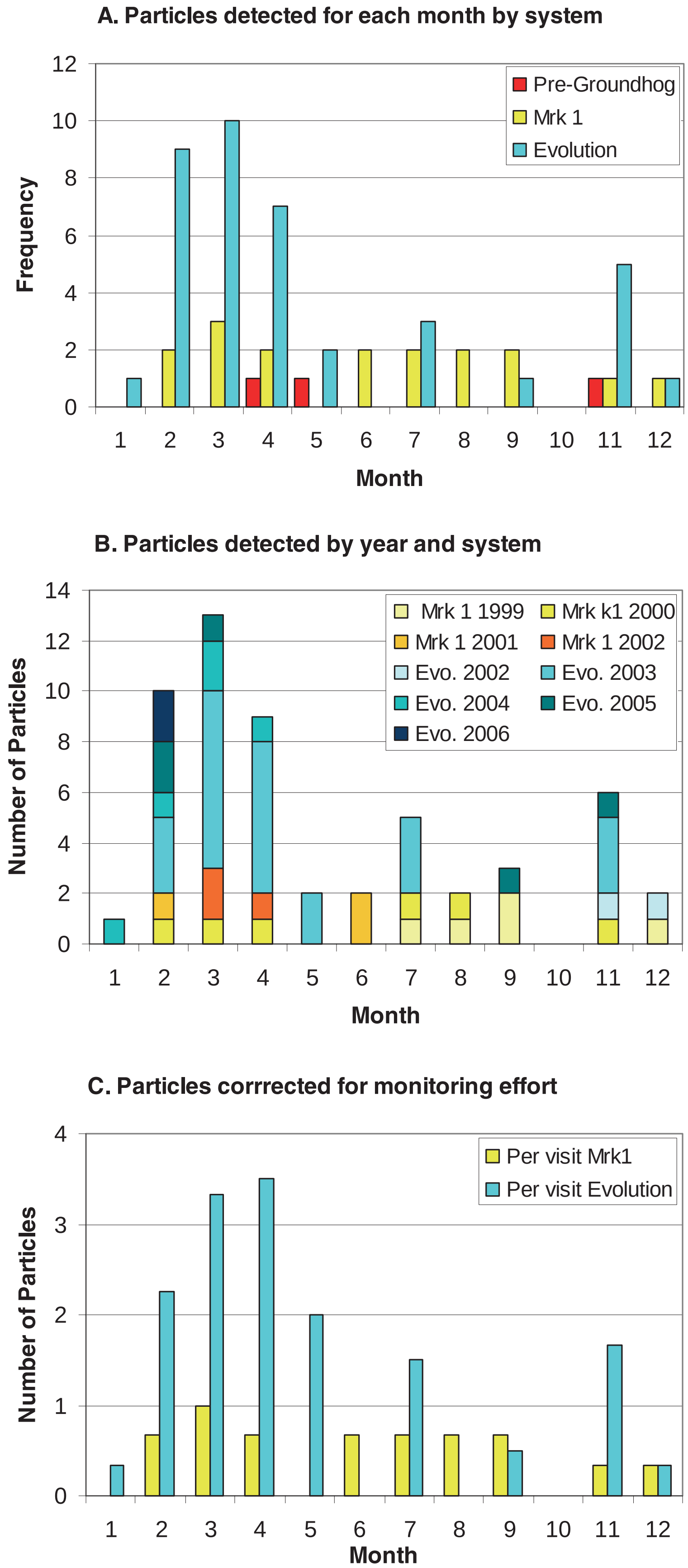

Figure 5.9 Histograms of Sandside particle Finds: A. By calendar month for particles found before Groundhog Monitoring, Groundhog Mk 1 and Groundhog Evolution; B. Particle finds separated by system and calendar year; C. Particle finds corrected for monitoring effort.

5.1.25 Figure 5.7 shows the spatial distribution of all particles found since 1999 and their specific activities are shown relatively as size of circle. These data are superimposed onto a map of the total counts, as measured by a Groundhog Evolution survey in May 2003, to illustrate the typical survey area and the variation in the natural background observed across the beach at Sandside. Figure 5.8 shows the particle locations by month of find and includes the pre-Groundhog 1984 and 1997 finds. The data, which have not been corrected for monitoring effort, suggest that the particles to the east of the beach burn are dominated by winter and early spring finds, whilst mid-summer and early autumn finds are predominantly found on the beach to the west.

5.1.26 The histogram, Figure 5.9A, clearly shows a marked difference in the particle finds by month of monitoring for the three types of monitoring systems. By plotting the same data but separating the finds by year, Figure 5.9B suggests that the finds in 2003 are exceptional, especially in the first few months of the year. Whilst this almost coincides with the introduction of Groundhog Evolution, the first surveys at the end of 2002 did not reveal similarly high numbers of particles. Thus, the exceptional number of particle finds may be attributed to the storms in the early months of 2003, from which anecdotal evidence suggests that the beach at Sandside had been unusually strongly scoured, suggesting that a cache of particles had been exposed. For those months where monitoring occurred after 2003, the number of particle finds per month appear to have returned to a level similar to that of the pre-2003 finds and it is noteworthy that this period includes the introduction of SEPA's TID requirement to reduce Evolution's monitoring speed to 1 ms^{-1} in October 2003, thereby improving detection capability further (see Appendix H6). Unfortunately, the lack of consistency in monitoring effort restricts any definitive conclusions here. However, the influence of the exceptional finds in early 2003 is still seen when corrections are made for monitoring effort (Figure 5.9C).

5.2 A review of the capabilities of Groundhog Mk 1

5.2.1 In March 1999, UKAEA tested a vehicular (Unimog) mounted gamma ray detection system (Groundhog Mk 1) on the beaches at Thurso and Scrabster. It utilised four independently operated 76 mm x 76 mm thallium-doped sodium iodide scintillation detectors (NaI(Tl)). The detectors were operated at about 200 mm above the surface of the beach and spaced 500 mm apart and supported from the front of a four-wheel drive Unimog (Figure 5.10), which was occasionally substituted by a Land Rover. The speed of the vehicle was to be maintained at around 1 ms^{-1}. Following a detailed internal review, the vehicle velocity was reduced to 0.8 ms^{-1} from June 2001 (UKAEA 2002). The detection criteria are summarised in Appendix H.2.

5.2.2 In July 1999, following discussion with SEPA, this system was brought into routine operation to fulfil the requirements of the TID. This system located 17 particles on Sandside Bay. The theoretical capabilities were originally published in DPAG (2003) and are here reproduced in Appendix H.3. To provide a spatial context and to provide a comparison with the next generation of monitoring (Groundhog Evolution and successors), the detection capabilities have been calculated spatially for each beach measurement and are mapped for each of the beaches monitored in the TID.

Figure 5.10 Groundhog Mrk 1 system, with four 76 x 76 mm diameter NaI(Tl) Detectors

Theoretical detection capability

5.2.3 The first review of the UKAEA's monitoring of public beaches took place during the summer of 2000 (SEPA, 2000) and concluded that the monthly performance routinely bettered the detection criterion of 10^7 Bq ^{137}Cs, but that the more challenging 10^5 Bq ^{137}Cs detection criteria of the TID was not strictly being met. SEPA and UKAEA estimated independently that a detection level of 1.4×10^5 Bq ^{137}Cs was more realistic for particles lying between the detectors at 100 mm depth.

5.2.4 Both the NRPB (now the HPA-RPD), COMARE and DPAG reviewed the Groundhog system independently. NRPB and DPAG came to very similar conclusions, as reported in DPAG's second interim report (DPAG, 2003) and Youngman and Etherington (2003 and 2005), specifically that the detection capabilities were optimal under average background conditions and deteriorated when background was increased or decreased. COMARE (2002) recommended that further improvements could be made to the current monitoring strategy and equipment to ensure that the majority of the *relevant* particles were being found.

The Spatial reconstruction of Groundhog Mk 1 response

5.2.5 One of the limitations of the Groundhog Mk 1 system has been its potential inability to cope with a varying background signal. Whilst this has received some recognition, no data appear to exist on the potential influence of the heterogeneity in the background radiation field on the detection limits of the system. Given the limited knowledge of the detection capabilities of Groundhog Mk 1, especially in response to a heterogeneous natural background, the response capabilities of the detector are estimated for each individual measurement to enable the spatial response characteristics to be estimated. Beach Monitoring Modelling (BMM) Software, commissioned by SEPA, has been developed to reconstruct the detection limits and detection probability of Groundhog Mk 1 to a particle of known activity, nominally 10^5 Bq ^{137}Cs particle at 100 mm depth, although the probabilities of detecting different source activities at the surface, 50 mm depth and 200 mm depth can also be calculated for both the worst- and best-case scenarios and an overall detection limit and detection probability estimated. These data can then be displayed through a Geographical Information System (GIS).

Assumptions

5.2.6 The detector response to a 10^5 Bq particle across a range of particle proximities and depths in sand was derived from data supplied by RWE NUKEM through UKAEA.

5.2.7 Detector response to a particle of known activity has been modelled to derive an estimate for vehicle speeds between 0.2 and 2 ms^{-1} for the worst-case (approaching or leaving a particle) and best-case scenarios (particle passes underneath the detector at the mid point in the one second integration time) for a particle buried at 100 mm depth and with a 0 mm, 100 mm and 250 mm lateral displacement from a detector.

5.2.8 The acquisition start times of the detector array are assumed to be synchronised.

5.2.9 The detector response was derived from validated Monte Carlo simulations supplied by RWE NUKEM through UKAEA (Youngman and Etherington (2005)) and the stated detection criteria were used (Davis 2002).

Evaluation of system performance

5.2.10 The focus of system performance evaluation has been on Sandside Beach to enable potential particle abundance to be estimated, as discussed in Section 5.5. The mean detection limits and probability of detection for a particle at 100 mm are given in Figures 5.11 and 5.12. The influence of elevated natural background radiation field on the mean detection probability can be seen (compare with the areas of elevated background in Figure 5.11). At 100 mm depth the mean probability of detecting a 10^5 Bq ^{137}Cs particle is clearly very variable. The detection probability falls to zero at 200 mm depth. The variation in detection probability and detection limits with monitoring velocity is illustrated in Appendix H.4. The sensitivity of detection capability with vehicle velocity shows that the detection limits at a 95% level of confidence is 4 x 10^5 Bq ^{137}Cs for a mean vehicle monitoring velocity of 1 ms^{-1} and a depth of 100 mm.

5.2.11 The data are in line with the original calculations undertaken by DPAG (2003) and NRPB (2002), but here the entire data set is used encompassing the full range of natural background observed on Sandside. The mean values given are therefore a function of the dominance of background characteristics and lower monitoring speed of 0.8 ms^{-1}, compared with 1 ms^{-1}, the latter forming the basis of the original calculations. The range in detection limits encompasses the best of the best-case scenario detection limits to the worst of the worst-case detection limits for a particle at the mid point between detectors at 100 mm depth.

5.2.12 Based on the theoretical evaluation of the system, the results indicate that for a 10^5 Bq particle at 100 mm depth the mean probability of detection was 0.88, but that over the beach this probability ranged from 0 to 1.

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5.2.14 Based on the theoretical evaluation of the system, the results indicate that for a 10^5 Bq particle at 100 mm depth the mean probability of detection was 0.88, but that over the beach this probability ranged from 0 to 1.

Table 5.3 The mean probability of detection and detection limits for Groundhog Mk 1 across Sandside Beach, based on monitoring data recorded in July 2001. Figures given are estimated from the BMM software. Mean vehicle speed = 0.8±0.2 ms^{-1}, n = 794,057

	Mean Probability of detecting 10^5 Bq ^{137}Cs *Mean across the detector array and best and worst case scenarios*			**Mean Detection Limits (10^3 Bq ^{137}Cs)** *Mean across the detector array and best and worst case scenarios*			**Detection limit range from best to worst case (10^3 Bq ^{137}Cs)**
Depth	**Mean**	**1 σ**	**Range**	**Mean**	**1 σ**	**Range**	
0 mm	1	0.0004	0.86-1	20	5	11 – 100	9.7 – 120
50 mm	0.997	0.029	0.06-1	47	13	23 – 260	20 – 300
100 mm	0.88	0.17	0-1	96	27	46 – 550	40 – 670
200 mm	0.019	0.019	0-0.13	500	140	250 – 2,900	220– 3,000

5.3 A review of the capabilities of Groundhog Evolution

System description

5.3.1 The new 'Groundhog Evolution' system incorporates 5 larger volume (76 mm x 400 mm) detectors mounted to provide a contiguous lateral cover of 2 m, representing 6.7 times increase in detector volume over the old Groundhog system (Figure 5.1). The system electronics are very similar to the original Groundhog Mk 1, the counts from the detectors are recorded in a 'below ^{137}Cs window', '^{137}Cs window' and 'above ^{137}Cs window'. The detectors are mounted on a Hillcat vehicle in an array maintained at around 200 mm above the sediment surface, although this geometry can change to avoid irregularities on the beach. The system became fully operational on Sandside Beach in February 2003 and a second replicate system was introduced about one year later. The detection criteria are detailed in Appendix H.5.

5.3.2 The original system employed a standard GPS. Following a preliminary review of the system and in view of the need to gain information on the variation in beach profile height between surveys and estimate the net erosion and deposition to be estimated, DPAG recommended that a kinematic DGPS be used. The kinematic DGPS, with nominal vertical accuracy of 50 mm, could enable distinction between particle finds as either recent arrivals or a function of beach erosion based on their relationship to changes in beach profile since the previous survey.

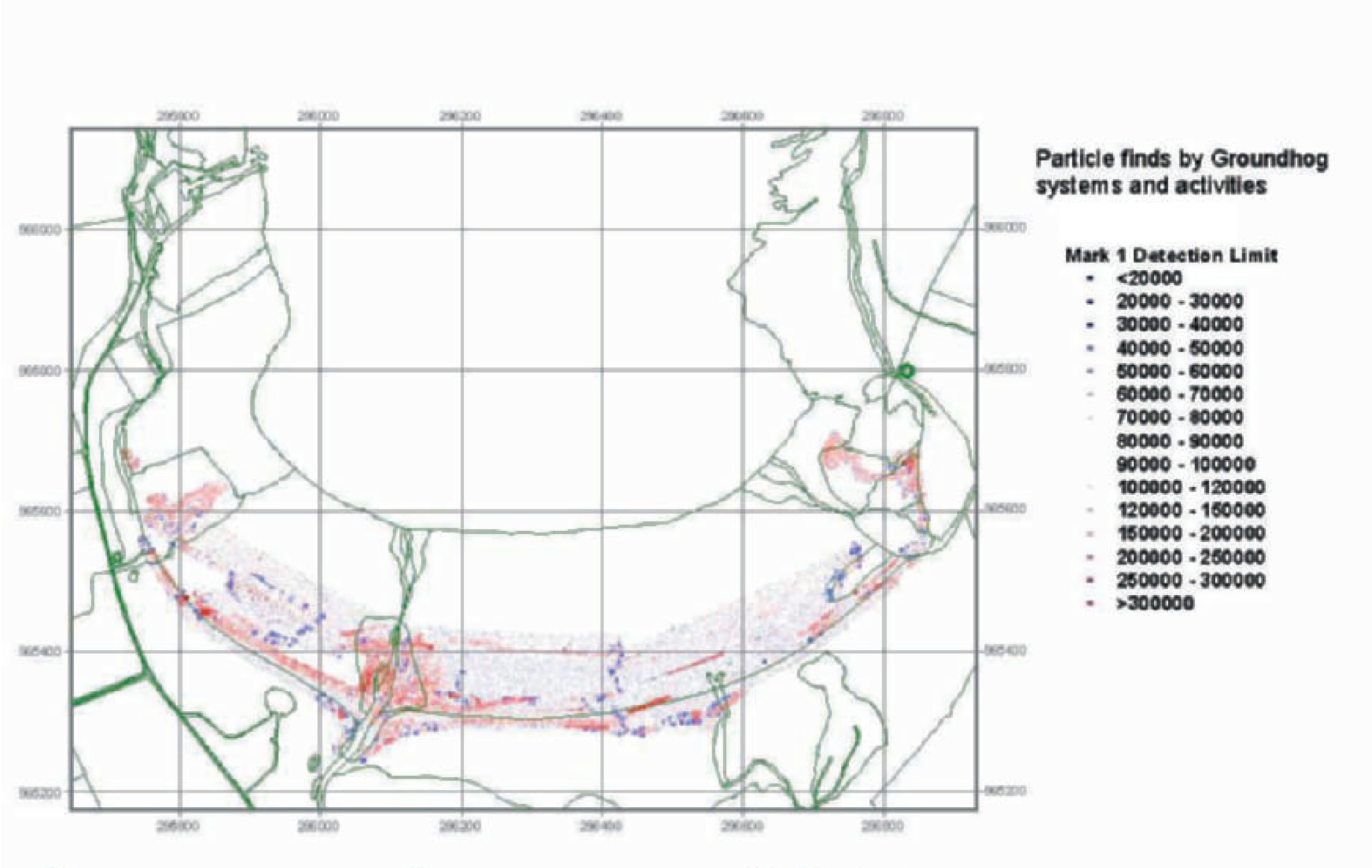

Figure 5.11 The mean detection limits (Bq) for a particle at 100 mm depth across Sandside Beach with Groundhog Mk 1 (Based on monitoring data from July 2001).

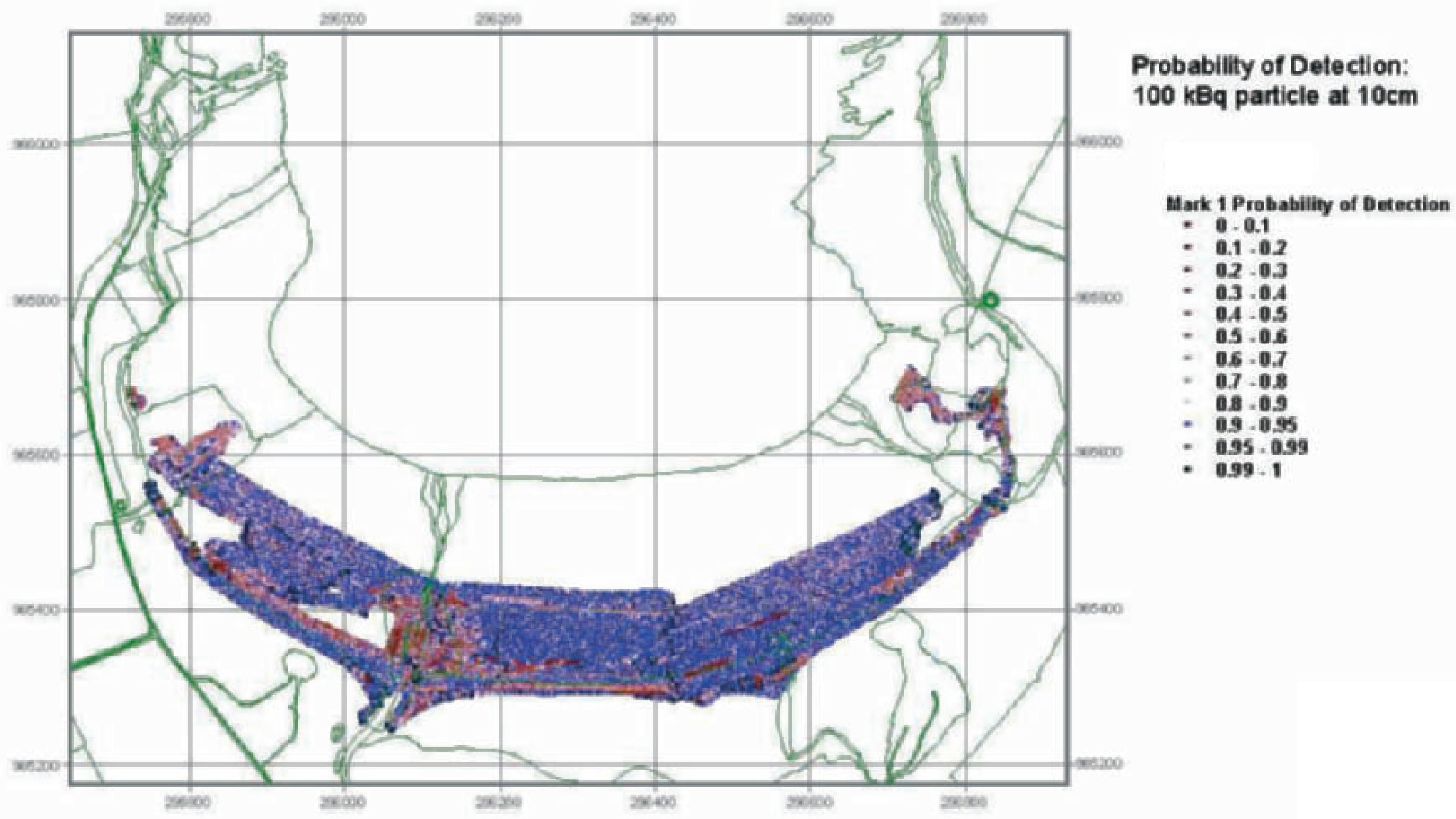

Figure 5.12 The probability of detecting a 10^5 Bq particle at 100 mm depth across Sandside Beach with Groundhog Mk 1 (Based on monitoring data from July 2001).

Theoretical Detection Capability

5.3.3 SEPA-commissioned software (BMM) was also developed to aid SEPA's regulatory review of the performance of the beach monitoring around Dounreay, undertaken by RWE NUKEM. The detector response characteristics were taken from Davis (2003)) following clarification with UKAEA Dounreay. The programme characterises the response capabilities of the detector on the Groundhog Evolution system using the actual data collected and the triggering mechanisms detailed in RWE (2003). The response capabilities are quantified in both detection limit and probability of detecting a 10^5 Bq ^{137}Cs particle at 100 mm depth. This is calculated for both the worst- and best-case scenarios (defined below) and a mean estimate can be derived.

5.3.4 A summary of the results are presented in Table 5.4 for monitoring undertaken in June 2003. The range of detection capability from the worst of the worst case detection limits to the best of the best-case detection limits is also shown. As with Groundhog Mk 1 (Appendix H.4), the detection capability is also dependent on monitoring velocity as summarised in Appendix H.6. Although 10^5 Bq particles are confidently detected at 100 mm depth, Appendix H.6 shows that at 200 mm depth, detection capability is perhaps more strongly influenced by monitoring velocity than other influences, such as the variation in natural background. In contrast to Groundhog Mk 1 the theoretical capability for Evolution shows that for a 10^5 Bq particle at 100 mm depth, the probability of detection ranges from 0.89 to 1.

Table 5.4 The mean probability of detection and detection limits for Groundhog Evolution across Sandside Beach, based on monitoring data recorded in June 2003. Data are estimated from the BMM software. Mean vehicle speed = 1.2±0.18 ms^{-1}, n = 841,298

Depth	**Mean Probability of detecting 10^5 Bq ^{137}Cs** *Mean across the detector array and best and worst case scenarios*			**Mean Detection Limits (10^3 Bq ^{137}Cs)** *Mean across the detector array and best and worst case scenarios*			**Detection limit range from best to worst case (10^3 Bq ^{137}Cs)**
	Mean	**1 σ**	**Range**	**Mean**	**1 σ**	**Range**	
0 mm	1	0	1-1	17.5	2.5	8 – 33	6.7 – 38
50 mm	1	0	1-1	25	4	11 – 49	8.7 – 61
100 mm	1	0.0008	0.89-1	42	7	19 – 82	15 – 100
200 mm	0.401	0.162	0.0008-0.99	140	23	65 - 280	52 – 325

Spatial analysis of system capability

5.3.5 The data summarised in Table 5.4 have been mapped for Sandside Beach. Figure 5.13 and Figure 5.14 summarise the probability of detection for a 10^5 Bq particle at 100 mm depth and the detection limits at 100 mm depth. The data show that the Groundhog Evolution system is able to detect 10^5 Bq particles to 100 mm depth. Detection limits are typically much better than 10^5 Bq although dependent on the natural background.

Detection Capabilities on other Caithness Beaches

5.3.6 The detection capability of Groundhog Evolution depends on the natural background characteristics and detector velocity. Appendix H.7 presents a summary of the evaluation of the other beaches. The mean detection limits on both Scrabster and Thurso are well within the 10^5 Bq requirement at 100 mm depth. Both Crosskirk and Brims Ness are monitored with the single detector Evolution system, and whilst the data presented in Appendix H.7 indicate that the system operates close to the requirement of the TID, the spacing between the survey transects leaves the detector runs at least 500 mm apart. The detection capability for particles occurring in this gap is unlikely to meet the requirements of the TID. The monitoring of these beaches should therefore be reviewed to ensure compliance.

5.4 Empirical validation

UKAEA Harwell Sand Pit Trials

5.4.1 The Beach Monitoring Steering Group (BMSG), a consultancy group advising UKAEA on the selection of the next generation of beach monitoring equipment, designed a sand pit to evaluate equipment performance (Figure 5.15). At the same time, the existing Groundhog Evolution system was tested and two detectors from the original Groundhog Mk 1 were reconfigured to demonstrate the performance of the original Groundhog Mk 1 system. The facility was designed to provide similar conditions throughout the trials and comprised a sand bed measuring 10 m long by 6 m wide and 0.4 m deep with a moving platform which allowed the systems under test to be traversed at constant speed (between 0.5 and 1.5 ms^{-1}) along the length of the test bed. The test bed allowed for a variety of source and background scenarios to be explored. Twelve trials for each source and depth configuration were calculated to be optimal to enable comparison between systems and provide sufficient capability to achieve a range of objectives (Appendix H.8)

Figure 5.13 Photograph of the sand pit used for trials undertaken at UKAEA Harwell.

Groundhog Mk 1

5.4.2 Tables 5.5 and 5.6 provide the estimated detector response characteristics for a particle being passed over at the mid point between two Groundhog Mk 1 detectors on Sandside Beach using the BMM software. The range in values indicates the influence of the variation in natural gamma radiation background and the 2 standard deviation for the skewed data set is only indicative of the central tendency of the data. The results for the detection capability in both the low-background (Table 5.5) and elevated -background (Table 5.6) conditions confirm the conclusions previously derived for the capability of the Mk 1 system (DPAG's 2nd Interim report), in that it is unable to meet the requirements of the TID. In this case, the system appears to be detecting a little over 50% of the 10^5 Bq particles at 100 mm depth. The test results also confirm the output from the BMM software.

Table 5.5 Detection probabilities from the sandpit trials for the low background area.

		Detection probability			
	Mk 1	Mean Velocity = 1 ms^{-1}			
	Depth	**$3x10^4$ Bq**	± 2σ	**^{137}Cs 10^5 Bq**	± 2σ
Trial	0 mm	**0.92**	**0.045**	**1**	
BMM		0.92	0.1	1	0
Trial	50 mm	**0**		**1**	
BMM		0.03	0.25	1	0.02
Trial	100 mm	**0**		**0.42**	**0.082**
BMM		0.008	0.08	0.51	0.22
Trial	150 mm	**0**		**0**	
BMM					
Trial	200 mm	**0**		**0**	
BMM		0	0	0.001	0.024
	Evolution	Mean Velocity = 1 ms^{-1}			
	Depth	**$3x10^4$ Bq**		**^{137}Cs 10^5 Bq**	
Trial	0 mm	**1**		**1**	
BMM		1	0	1	0
Trial	50 mm	**1**		**1**	
BMM		0.94	0.04	1	0
Trial	100 mm	**1**		**1**	
BMM		0.48	0.01	1	0
Trial	150 mm	**0.75**	**0.072**	**1**	
BMM					
Trial	200 mm			**0.92**	**0.045**
BMM		0	0	0.50	0.02

Bold numbers relate to trial results

Groundhog Evolution

5.4.3 Groundhog Evolution was also evaluated on the sand pit, in part to provide an empirical validation of the system performance, but primarily to provide a bench mark against which new beach monitoring systems may be evaluated. The results can also be found in Table 5.5 and Table 5.6, for both the low and elevated background natural conditions. The data confirm that the system provides a significant improvement over the Mk 1 system. In contrast to Mk 1, the elevated natural background reduces the detection capability of the system, confirming the observations derived from the BMM software.

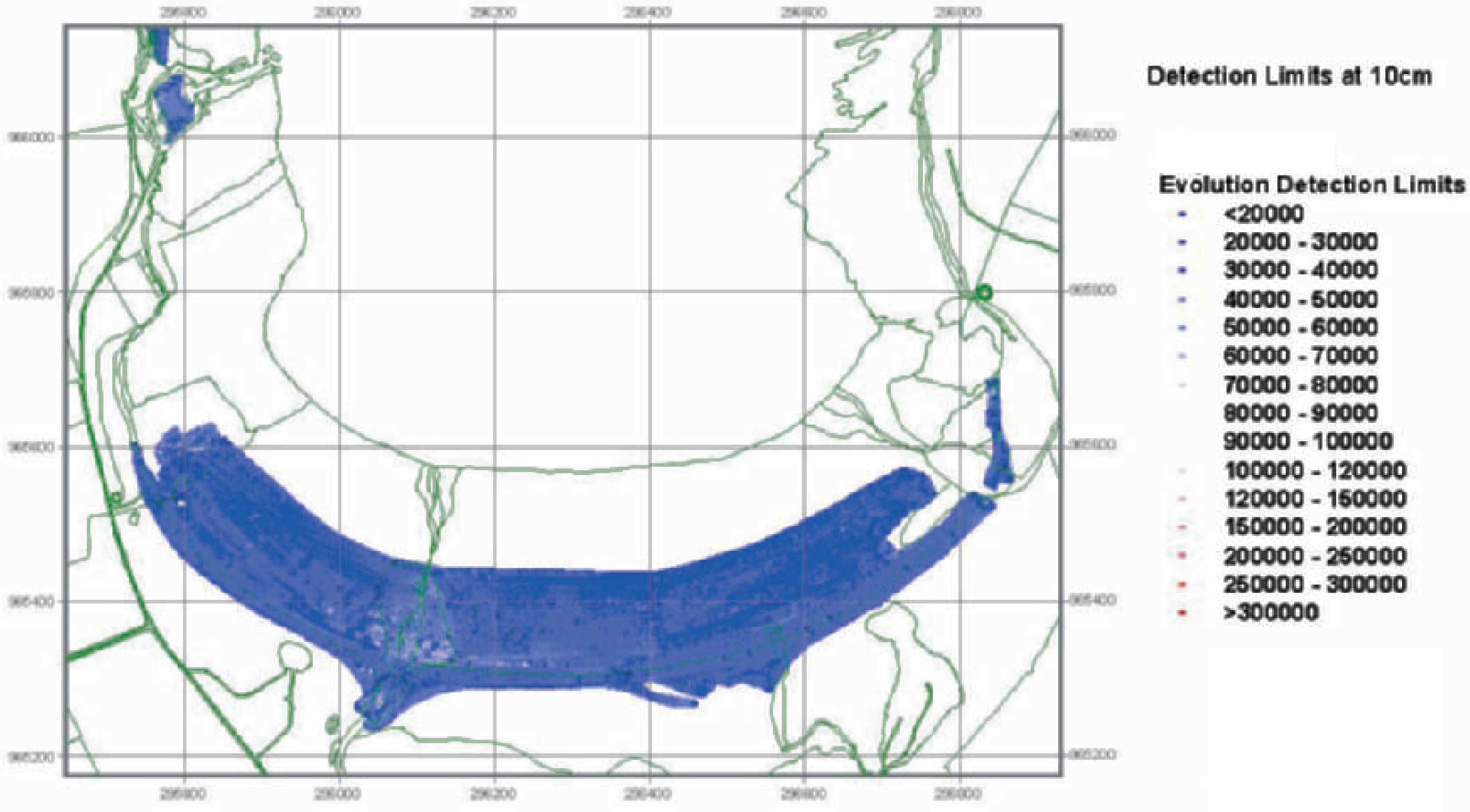

Figure 5.14 The mean detection limits (Bq) for a particle at 100 mm depth across Sandside Beach for Groundhog Evolution (Based on monitoring data from June 2003).

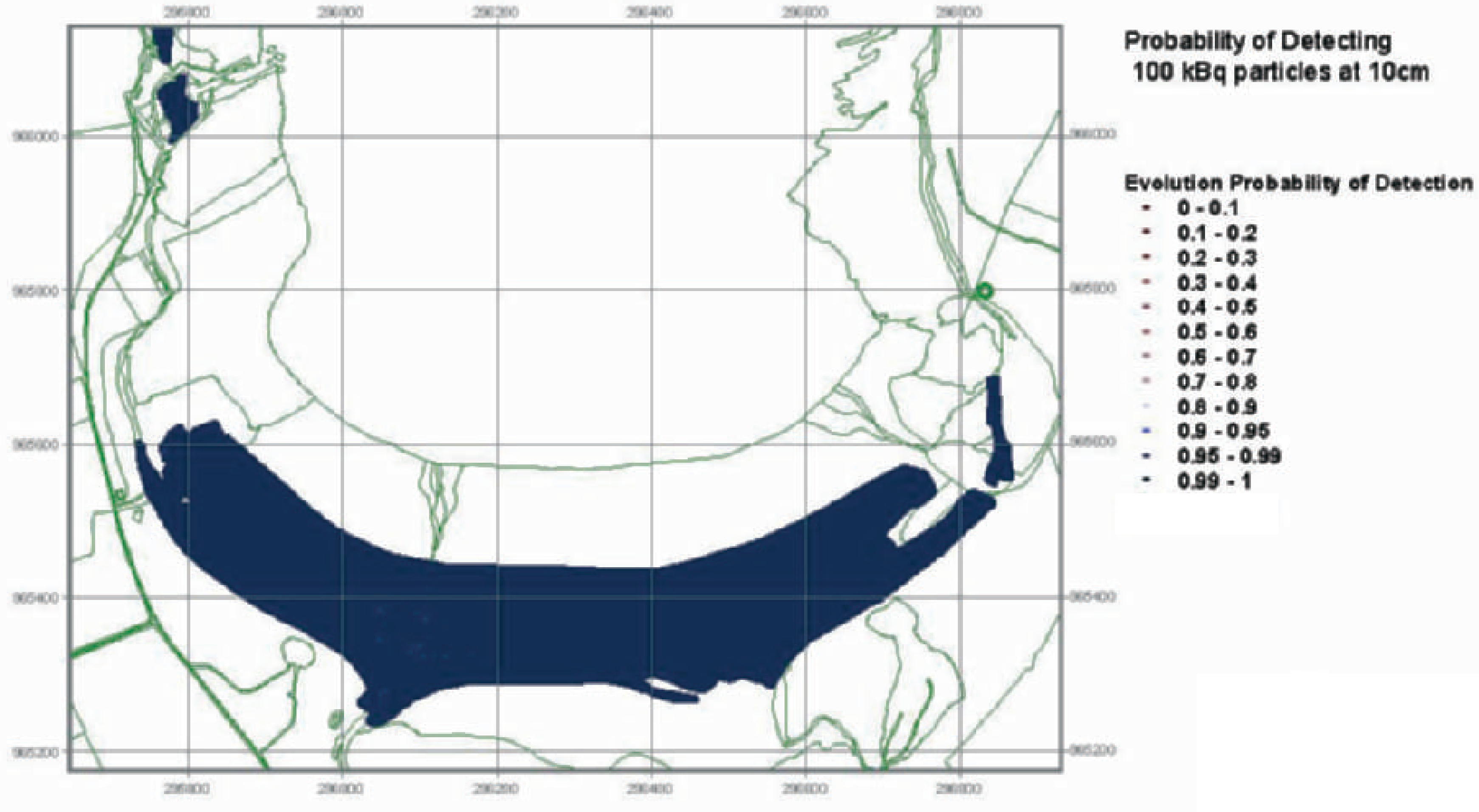

Figure 5.15 **The probability of detecting a 10^5 Bq particle at 100 mm depth across Sandside Beach for Groundhog Evolution (based on monitoring data from June 2003).**

Table 5.6 Detection probabilities from the sand-pit trials for the high and variable background area.

		Detection probability			
	Mark 1	Mean Velocity = 1 ms^{-1}			
	Depth	**$3x10^4$ Bq**	± 2σ	**^{137}Cs 10^5 Bq**	± 2σ
Trial	0 mm	**0.83**	**0.063**	**1**	
BMM		0.92	0.16	1	0
Trial	50 mm	**0.25**		**1**	
BMM		0.09	0.42	1	0.14
Trial	100 mm	**0**		**0.75**	**0.072**
BMM		0.007	0.07	0.51	0.42
Trial	150 mm	**0**			
BMM					
Trial	200 mm	**0**		**0**	
BMM		0	0	0	0.014
	Evolution	Mean Velocity = 1 ms^{-1}			
	Depth	**$3x10^4$ Bq**	± 2σ	**^{137}Cs 10^5 Bq**	± 2σ
Trial	0 mm	**1**		**1**	
BMM		1	0	1	0
Trial	50 mm	**1**		**1**	
BMM		0.96	0.26	1	0
Trial	100 mm	**0.83**	**0.063**	**0.83**	**0.063**
BMM		0.43	0.28	1	0
Trial	150 mm	**0.25**	**0.072**	**0.25**	**0.072**
BMM					
Trial	200 mm			**0**	
BMM		0	0	0.45	0.27

Bold numbers relate to trial results

Beach Trials

5.4.4 Following recommendations of both DPAG and COMARE, SEPA made available the necessary funding to purchase a set of perspex-encapsulated point sources of ^{137}Cs and ^{60}Co. Permission to access the beach at Sandside Bay was obtained from the landowner, together with the agreement of the Scottish Executive, SEPA and UKAEA. The trials were carried out over the period 8 – 10 April 2006 by a small team representing both COMARE and DPAG, together with an observer from SEPA. The beach trials were designed primarily to assess and confirm the detection capabilities of the Groundhog Mk 1 and Evolution system and to provide data with which to validate the theoretical and modelling considerations of detector performance (BMM software).

5.4.5 The specific objectives of the trial were to:

- conduct a test of the monitoring capabilities of both Groundhog Mk 1 and Groundhog Evolution; and,
- verify predictions on their ability to detect particles.

5.4.6 In order to conduct the trials, UKAEA made available two Hillcat vehicles and a reconstruction of the Mk 1 detector array. The latter was towed behind one of the Hillcat vehicles, while the other was configured as the standard Groundhog Evolution system (Figure 5.16). The vehicles were operated by experienced staff of RWE NUKEM, the UKAEA sub-contractor responsible for the routine beach monitoring programme. This ensured that the trials were carried out under exactly the same conditions as routine beach monitoring. Prior to setting up the experimental layouts on each day, the area to be used was surveyed by Groundhog Evolution using standard operating procedures in order to ensure that there were no radioactive particles within the test area. This background survey extended at least 1.5 detector array widths to either side of the source positions and at least to the vehicle turning areas beyond both ends of each layout. Over the three days, some 15,000 m^2 of beach were surveyed and no radioactive particles were detected.

Figure 5.16 Example of Groundhog Evolution (pictured right) and the reconstructed Mk 1 system towed behind the first Hillcat (pictured left).

5.4.7 Test runs were constructed using either 250 m or 150 m lengths of beach, and in total 3 areas of the beach were used (Figure 5.17), with the majority of the exercise focused on area 1 (low natural background) and 2 (elevated natural background). The low background area is representative of most of the beach, whilst the elevated natural background was selected to be at least partly representative of some of the other beaches monitored. A linear array of sources was buried at a given depth, the spacing between sources being 15 m. This distance was chosen in order to accommodate the requirement to reset the detector systems after each detection event.

5.4.8 Over the course of the trials, sources were buried at depths of 50,100, 200 and 300 mm below the surface. The source strengths were 10^4 Bq, 10^5 Bq and 10^6 Bq of ^{137}Cs and 10^5 Bq of ^{60}Co. The level of natural background varies across the beach at Sandside Bay with an area of higher background being situated parallel to the course of the burn (note that the course of the burn has changed from that shown in Figure 5.17).

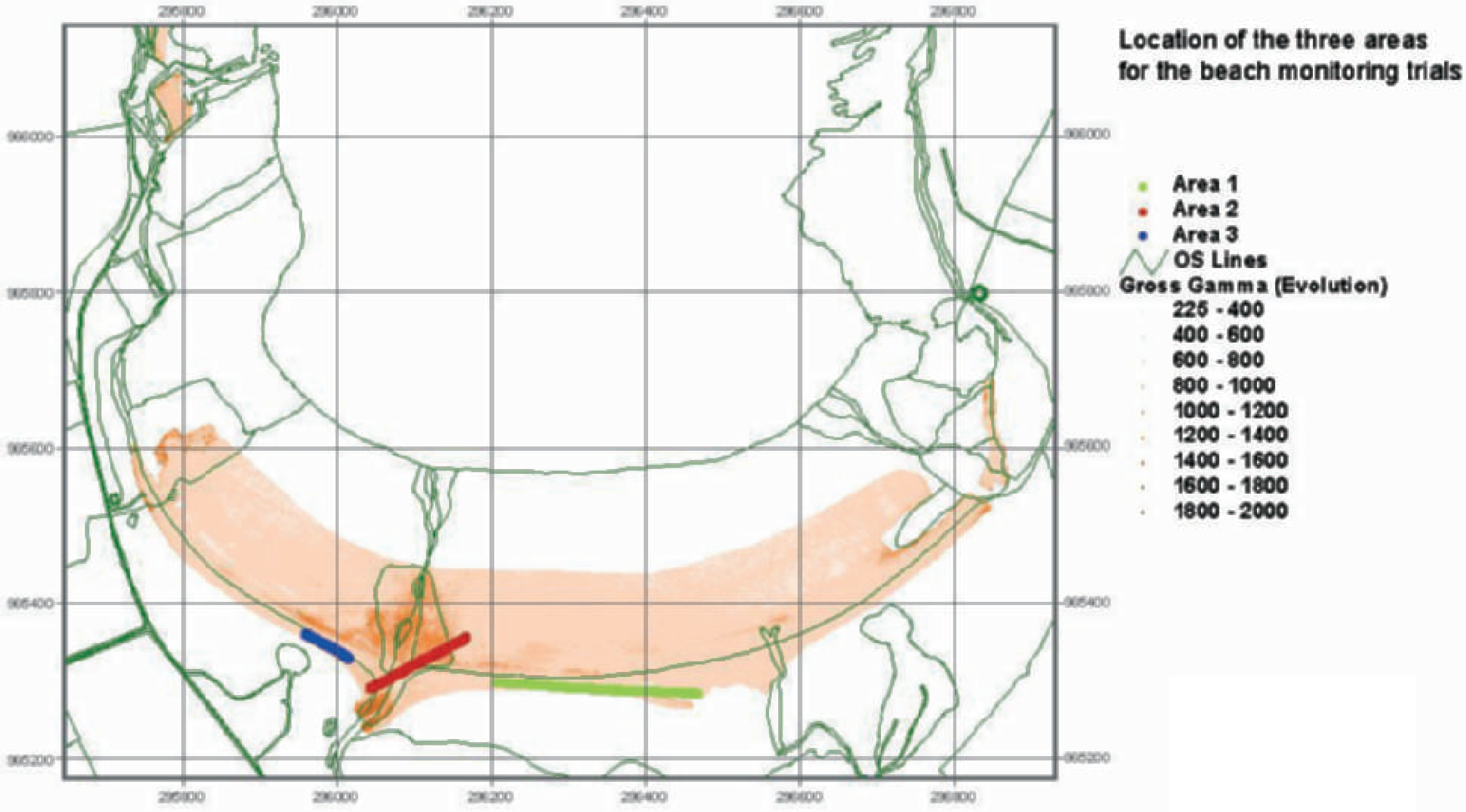

Figure 5.17 Map showing the location of the three monitoring areas during the 2006 beach monitoring trials

5.4.9 The perspex sources were held in a steel holder, retained in place by a clip-on PTFE cover. The position for each source was located by reference to a surveyor's tape laid along the length of each layout and by the use of a differential GPS system. The use of the steel source-holder also permitted location by means of a standard metal detector. The theoretical performance of the detector array may change dependent upon the location of any particle across the field of view. Tests were therefore conducted with the sources located in the centre of transverse field view, with a partial offset and with the sources offset to the edge of the detector field of view.

5.4.10 The vehicles were operated at the speeds specified by the TID; Groundhog Mk 1 travelled at 0.8 ms^{-1}, while Groundhog Evolution travelled at 1 ms^{-1}. On each run, there was a lead-in blank area to ensure that the vehicle was at the correct operating speed on reaching the first target. It was estimated that 25 measurements were required for each source/depth/background/lateral position combination in order to obtain statistically-significant results. This was obtained in most cases, although bad weather during the test period necessitated some curtailment of the programme.

Table 5.7 Detection probabilities from the beach trials for the low-background area (areas 1 and 3; Typical of Sandside). The modelled estimates are given beneath with two standard deviations. Probability is estimated as the proportion of successful detections out of 25 observations in most cases.

		Detection probability							
	Mk 1	Mean Velocity = 0.80 ± 0.06 ms^{-1}							
				^{137}Cs				**^{60}Co**	
	Depth	**10^4 Bq**	± 2σ	**10^5 Bq**	± 2σ	**10^6 Bq**	± 2σ	**10^5 Bq**	
Trial	50 mm	**0.027**	**0.013**	**1**		**1**		**0**	
BMM		0.001	± 0.007	0.99	±0.005	1	± 0		
Trial	100 mm	**0**		**0.88**	**0.026**	**1**		**0**	
BMM		0	±0.0002	0.42	± 0.27	1	± 0		
Trial	200 mm	**0**		**0.067**	**0.020**	**1**		**0**	
BMM		0	±0	0.001	± 0.005	1	± 0		
Trial	300 mm	ND		ND		**0.8**	**0.032**		
BMM									
	Evolution	Mean Velocity = 0.98 ± 0.08 ms^{-1}							
				^{137}Cs				**^{60}Co**	
	Depth	**10^4 Bq**	± 2σ	**10^5 Bq**	± 2σ	**10^6 Bq**	± 2σ	**10^5 Bq**	
Trial	50 mm	**0.76**	**0.034**	**1**		**0.96**	**0.016**	**0.5**	**0.200**
BMM		0.036	± 0.08	1	± 0	1	± 0		
Trial	100 mm	**0.165**	**0.030**	**1**		**0.973**	**0.013**	**0.775**	**0.167**
BMM		0	± 0	1	± 0	1	± 0		
Trial	200 mm	**0.013**	**0.009**	**0.88**	**0.026**	**1**		**0.6**	**0.196**
BMM		0	± 0	0.58	± 0.1	1	± 0		
Trial	300 mm	ND		ND		**1**			
BMM									

ND – not done
Bold numbers relate to trial results

5.4.11 Table 5.7 presents the mean results across a detector array from areas 1 and 3 (low background) and Table 5.8 presents the results from area 2 (elevated background) from both Groundhog Mk 1 and Evolution. The results demonstrate that a 10^6 Bq particle can be reliably detected by both systems to depths of at least 200 mm for Mk 1 and deeper for Evolution. The results also confirm that Mk

1 is not detecting 10^5 Bq particles at 100 mm depth reliably and is not able to detect small particles (10^4 Bq) or ^{60}Co particles of at least 10^5 Bq. Groundhog Evolution had a probability of around 0.5 of detecting 10^5 Bq ^{60}Co source down to at least 200 mm depth. However, neither system was specifically configured to detect this radionuclide.

Table 5.8 Detection probabilities from the beach trials for the elevated-background area are given in bold. The modelled estimates are given beneath with two standard deviations. Probabilities are proportion of successful detections out of 24 observations in most cases.

		Detection probability					
	MK 1	**Mean Velocity = 0.75 ± 0.18 ms^{-1}**					
				^{137}Cs			
	Depth	**10^4 Bq**	± 2σ	**10^5 Bq**	± 2σ	**10^6 Bq**	± 2σ
Trial	100 mm	**0.014**	**0.010**	**0.736**	**0.037**	**1**	
BMM		0.03	± 0.0004	0.86	± 0.3	1	± 0
Trial	200 mm	**0**		**0.125**	**0.028**	**1**	
BMM		0	± 0	0.01	0.02	0.994	± 0.03
	Evolution	**Mean Velocity = 1.02 ± 0.11 ms^{-1}**					
				^{137}Cs			
	Depth	**10^4 Bq**	± 2σ	**10^5 Bq**	± 2σ	**10^6 Bq**	± 2σ
Trial	100 mm	**0.083**	**0.023**	**1**		**1**	
BMM		0	± 0	1	± 0	1	± 0
Trial	200 mm	**0.028**	**0.014**	**0.903**	**0.025**	**1**	
BMM		0	± 0	0.40	± 0.20	1	± 0

Bold numbers relate to trial results

5.4.12 The introduction of Groundhog Evolution has made a substantial improvement on particle detection capability with 10^5 Bq ^{137}Cs particles being detected with almost 90% confidence to 200 mm depth. Evolution also demonstrates a low probability of detecting the 10^4 Bq ^{137}Cs particles and the influence of the elevated background reduces this probability further. The low background results are also in broad agreement with the low-background sand-pit trials.

5.4.13 As with the sand-pit trials, the results also show an acceptable level of agreement for the Mk 1 beach trial results and estimates derived from the BMM software output. The same can be said for Evolution at high degrees of detection probability. The modelled Groundhog Evolution capability underestimates the experimental data, suggesting that the theoretical detector response, derived from RWE NUKEM Monte Carlo simulations, provides a conservative estimate of either the photon fluence from buried particles or the detection capability. This detection capability was derived from RWE NUKEM Monte Carlo simulation of the detector response, and forms the basis of the BMM software. Therefore, if this software is to be used in the future, it is important to review the data used in the software to estimate beach monitoring performance.

5.5 Lessons from particles found (Sandside Beach and Dounreay Foreshore)

Dounreay Foreshore

5.5.1 The various methods of monitoring have generally been consistently applied at least until 2002 on the Dounreay Foreshore and there have been no gaps in monitoring except during the tern nesting season. Therefore there is a valuable data set to establish change on the western Dounreay Foreshore. From June

2002, Groundhog has been used, with Evolution since October 2004 - present. It is of interest here to consider whether there has been any change in the pattern of finds following the extensive offshore diver campaigns in 1997 when a large number of particles were removed. Although subsequently there have been other removals of offshore particles, they have not been as extensive. It is also important to note that the Dounreay Foreshore was systematically stripped to recover particles in 1996.

5.5.2 In Table 5.1 slight increases in the number of particles found (linked to lower mean activity and greater mean depth) in 2004 and 2005, are consistent with the improved detector sensitivity of Groundhog Evolution.

5.5.3 Table 5.9 shows the number of offshore particles removed by divers from 1997 till 2005. The survey periods were generally May through September and in total 928 offshore particles have been removed over this period.

Table 5.9 Table summarising offshore removals

Year	Mean activity (10^6Bq ^{137}Cs)	Number of finds
1997	2.38	35
1998	1.45	88
1999	2.22	15
2000	0.74	115
2001	1.55	122
2002	1.82	342
2003	0.70	56
2004	0.71	72
2005	0.55	83

5.5.4 The Dounreay Foreshore finds can be divided into two periods (pre- and post - offshore diving removal) and Table 5.10 summarises the finds in these two periods. It is noticeable that there appears to have been a marked decrease in the mean particle activity and also in the number of finds post 1997, coinciding with the removals of particles from the offshore environment. Assuming an annual rate of 6 per year, the probability of no particle finds in a one year period is 0.0025. Thus, February 2005 to February 2006 is a highly unlikely occurrence.

Table 5.10 Table summarising Dounreay Foreshore finds (particle of 2 x 10^8 Bq ^{137}Cs omitted)

Period	Mean activity (10^6 Bq ^{137}Cs)	Number of finds	Mean number of annual particle finds
Pre1997 (14 years)	4.98	178	13
1997 and later (9.5 years)	2.1	60	6

Sandside Bay

5.5.5 Sandside Bay has been monitored only intermittently because of access restrictions. Table 5.11 shows the particle finds divided into the two periods (Groundhog Mk 1 and Groundhog Evolution) and also corrected for sampling effort.

5.5.6 As indicated earlier in Section 5.1, detailed interpretation of these data are not possible. Significantly more particles have been found in a shorter period of time (although, of course, one must consider the periods when no monitoring took place) and the mean activity is roughly 50% of the Groundhog Mk 1 finds, even though the maximum activity found is comparable. The mean depth of finds for Evolution is 80 mm while it was 63 mm for Mk 1.

Table 5.11 Descriptive Statistics: Radioactivity (10^4 Bq ^{137}Cs)

	Number of finds	**Corrected total number of finds**	**Mean activity**	**Minimum activity**	**Maximum activity**
Mk 1 (5 years)	17	21	9.3	4.0	30
Evolution (3.5 years)	39	56	4.7	0.84	28

5.5.7 There appears to be evidence of a decrease in the mean activity of finds and although the number of particles found has increased, on average they are less active and at greater depth.

5.6 Reconstruction of Particle Abundance at Sandside Bay

5.6.1 From the initial assessment of the Groundhog Mk 1 and Evolution time series data, it is clear that more *minor* particles have been detected and at greater depth with Groundhog Evolution than Groundhog Mk 1. However, the question remains as to whether this can be accounted for by the change in detection system or due to some other change in the natural system. In addition, can we reconstruct particle abundances from Groundhog Mk 1 and Evolution detection capabilities and make a useful comparison to conclude information on the change in particle characteristics and arrivals since effective monitoring began in 1999?

5.6.2 The particle abundances presented here represent DPAGs best estimate. Those for Groundhog Mk 1 use the BMM-derived detection probability for the location of each particle for Groundhog Mk 1, and those for Evolution are derived from a combination of the probability of detection interpolated from the sand-pit data and beach trials. All particle abundance estimates have been rounded up to the nearest integer. A sensitivity analysis was undertaken of the possible uncertainty of the estimate of particle depth of the probability of detection and thus particle abundance estimates. The results showed that an uncertainty of 20 mm can have a substantial influence on the particle abundance estimates when the probabilities of detection are small, especially when the probabilities are of the order of 0.1 or less. However, the likely error on the depth of particles found will depend on the nature of the beach sand during particle excavation.

Groundhog Mk 1

5.6.3 Taking all the particles founds into account, and their likely detection probability, Table 5.12 and 5.13 represent the particle abundance estimated by DPAG and the NRPB (now the HPA-RPD) over the period of Groundhog Mk 1 monitoring (1999 to 2002). Whilst there is good agreement for the r*elevant* particles, there are clear differences for the *minor* particles. Whilst the differences may be explained by the ways in which they were estimated, the important message is that there are likely to have been many *minor* particles over the monitoring period that were not detected by Groundhog Mk 1.

Table 5.12 Mk 1 estimated particle abundances (DPAG)

Minor **Particles**			***Relevant*** **Particles**	
Depth	$1x10^4$-5 $x10^4$ Bq ^{137}Cs	>5 $x10^4$ <$1x10^5$ Bq ^{137}Cs	>$1x10^5$ Bq ^{137}Cs	Total
<50 mm	**3**	**3**	**1**	**7**
5-200 mm	**5**	**60**	**5**	**70**
Total	**8**	**63**	**6**	**77**

Table 5.13 Mk 1 estimated particle abundances (HPA-RPD)

Minor **Particles**			***Relevant*** **Particles**	
Depth	$1x10^4$-5 $x10^4$ Bq ^{137}Cs	>5 $x10^4$ <$1x10^5$ Bq ^{137}Cs	>$1x10^5$ Bq ^{137}Cs	Total
<50 mm	5	3	2	10
50-200 mm	82	29	5	116
Total	**87**	**32**	**7**	**126**

Groundhog Evolution

5.6.4 The data for Groundhog Evolution are presented in Tables 5.14 and 5.15 for the monitoring period 2002-2005 (March). DPAG estimates have been revised with detection probabilities based on the empirically derived estimates.

5.6.5 Again there is good agreement for the *relevant* particles and the 2 x 10^4-10^5 Bq range of particle activities. However, there is less agreement below 2 x 10^4 Bq. It is possible that the numbers observed at the surface could be extrapolated with depth which would improve the comparison. In either case, the numbers predicted for Groundhog Mk 1 are not dissimilar to those predicted from the Evolution measurements. The likely explaination for the difference between the DPAG and NRPB estimates is that the latter were derived using theoretical predictions.

Table 5.14 Groundhog Evolution Predicted Particle Abundances (DPAG)

Minor **Particles**					***Relevant*** **Particles**	
Depth	<10^4 Bq ^{137}Cs	10^4-2 x 10^4 Bq ^{137}Cs	2 x 10^4-5 x 10^4 Bq ^{137}Cs	5 x 10^4 -10^5 Bq ^{137}Cs	>10^5 Bq ^{137}Cs	Total
<50 mm	2	6	4	2	2	**17**
50-100 mm		16	7	3		**26**
100-200 mm			4	8		**12**
Total	**2**	**22**	**15**	**13**	**2**	**54**

Table 5.15 Groundhog Evolution Predicted Particle Abundances (HPA-RPD)

Minor **Particles**				***Relevant*** **Particles**	
Depth	10^4-2 x 10^4 Bq^{137}Cs	2 x 10^4-5 x 10^4 Bq ^{137}Cs	5 x 10^4 -10^5 Bq ^{137}Cs	>10^5 Bq ^{137}Cs	Total
<50 mm	11	4	2	2	**19**
50-100 mm	23	7	4		**34**
100-200 mm	33	10	9		**52**
Total	**67**	**21**	**15**	**2**	**105**

Mean monthly abundance

5.6.6 The above theoretical calculations provide non-temporally scaled abundances, *i.e.* over the total sampling period. By this we mean that there is no concept of a particle detection rate in time, nor an abundance per time interval. An approach to derive mean monthly abundances is required, based on the probabilities of detection and actual finds. One other complication concerns the dynamic nature of the pool of particles on the beach at any given time.

5.6.7 To make such a calculation, we need to make assumptions concerning the population of particles. The simplest approach would divide the abundance of particles by the number of times the beach had been surveyed, which is approximately once a month, when access was permitted, and taking account of times when access to the beach was not permitted.

5.6.8 Figure 5.18 illustrates the mean monthly abundance of particles for each activity range for Sandside based on probability of detection data derived from Groundhog Mk 1 and Evolution. It is interesting to note that the abundance distribution for particles having activity in excess of 4 x 10^4 Bq is similar using either detection system. The smaller minor particles detected by Evolution are also likely to have existed during the period monitored by Mk 1, but remained undetected. Given the statistical uncertainties on the data, there is insufficient evidence to suggest that there is any difference in the likely monthly abundance of particles on Sandside since monitoring started in 1999. Similarly, by grouping the particles into *minor* (<10^4 Bq, 10^4-4 x 10^4 Bq and 4 x 10^4-10^5 Bq) and *relevant* (>10^5 Bq), as shown in Table 5.16 there is very little difference between the mean monthly abundance for particles >4 x 10^4 Bq.

5.6.9 Table 5.16 indicates that in any given month there might be around 3 particles on the beach, although there is a greater than 95% probability that they will be in the *minor* category.

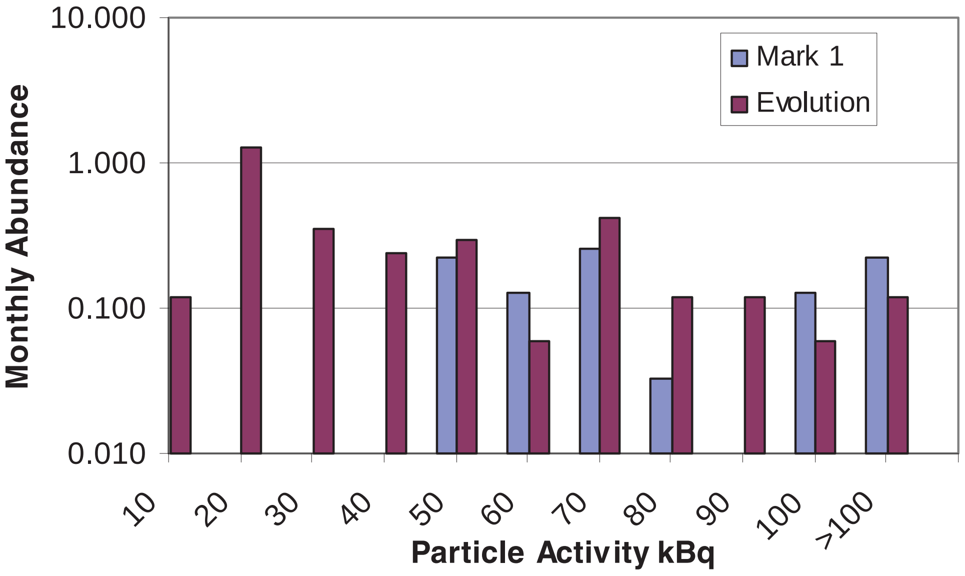

Figure 5.18 Comparison of probable particle monthly abundances, corrected for Groundhog Mk 1 and Evolution detection capabilities

Table 5.16 Summary of mean monthly particle abundances (ND = Not Detected)

Particle category	Activity	Groundhog Mk 1	Groundhog Evolution Calculated using mean probabilities
Minor	$<10^4$ Bq ^{137}Cs	ND	0.12
	10^4- 4 x 10^4 Bq ^{137}Cs	ND	1.88
	4 x 10^4- 10^5 Bq ^{137}Cs	0.77	1.06
Relevant	$>10^5$ Bq ^{137}Cs	0.23	0.12
All	Total	1.00	3.18

Beach-height monitoring

5.6.10 UKAEA fitted high-accuracy kinematic DGPS systems to the Groundhog Evolution systems, following a DPAG recommendation, to enable the beach height to be monitored and to provide a likely depositional context for any particle finds. The DGPS has a nominal vertical accuracy of ± 50 mm and thus should be able to monitor beach-height variation between monitoring periods of greater than 100 mm. Figure 5.19 shows changes between monitoring months, which is illustrated more clearly in the transects shown in Figure 5.20.

5.6.11 Most importantly, the transects show that beach elevation can vary by between 200 and 300 mm between monitoring events. The example shown on Figure 5.19 shows consecutive months of sediment accretion on the beach. Reference to these types of data coupled with knowledge of the depth of particle find will enable particle finds to be identified as a probable new arrival or a particle that may have existed in the sand for long periods of time. A longer time series of data, through periods of summer accretion or winter erosion will enable improved interpretation of particles detected and their likely arrival times.

5.6.12 These data provide the important evidence that stipulated requirement to monitor to 100 mm of sediment depth is inadequate and would not monitor the complete thickness of recently deposited sediment. It is, therefore, recommended that future monitoring be required to provide a minimum of 200 mm of depth coverage and where possible strive to achieve greater, *e.g.* 300 mm, of monitoring depth for 10^5 Bq particles. Beach and Foreshore monitoring systems must be capable of detecting particles containing 10^6 Bq ^{137}Cs or 10^6 Bq ^{60}Co to a minimum depth of 300 mm.

5.7 <u>Summary and conclusions</u>

Particle arrivals on Beaches

5.7.1 Both the Groundhog Mk 1 and Evolution systems have demonstrated the capability of detecting *significant* particles to at least 200 mm depth. The only beach on which *significant* particles have been found is the Dounreay Foreshore. It is important to note that no *significant* particles have been found on any of the other beaches monitored. *Relevant* particles have only been detected on Sandside, as well as Dounreay, albeit rarely. The majority of the particles found, including that found on Dunnet Beach, are *minor* particles.

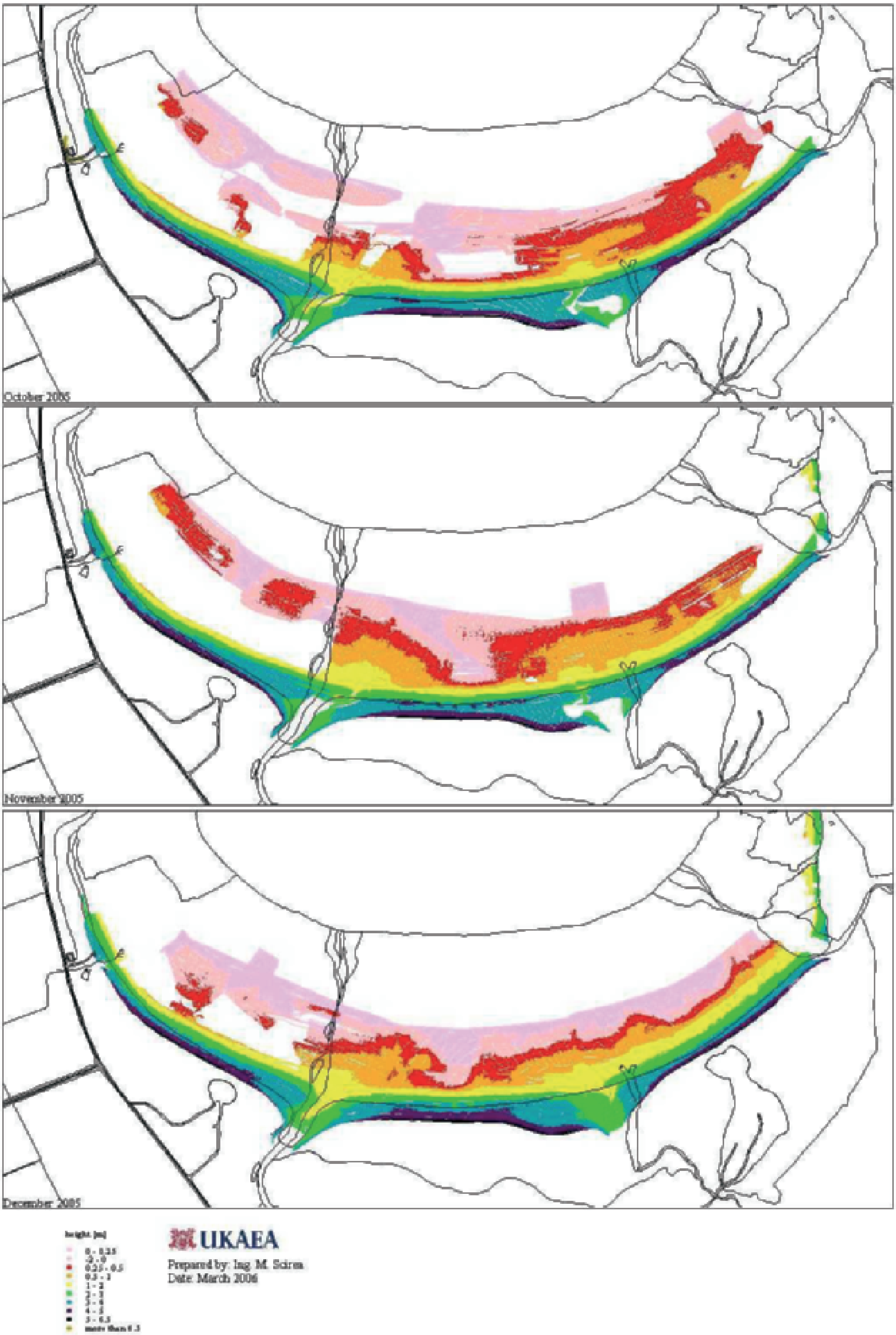

Figure 5.19 Example of beach height for three consecutive surveys in late 2005. Maps reproduced courtesy of UKAEA.

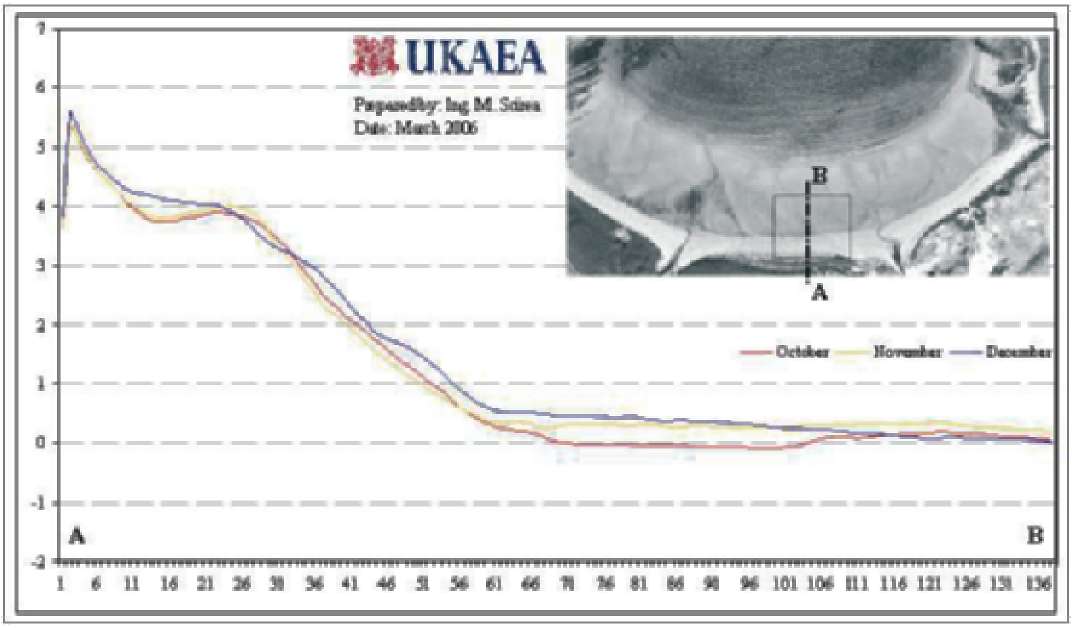

Figure 5.20 Example of three transects drawn S-N across the central portion of Sandside beach for three consecutive surveys in late 2005. Both horizontal and vertical scales are in metres. Data reproduced courtesy of UKAEA.

5.7.2 There is very little evidence to suggest that the mean activity and number of particles found on Sandside are declining with time once the effects of monitoring and detector efficiency have been taken into account. This is not the case for the Dounreay Foreshore, where the effort to clear particles offshore may have had an effect on the range of activities and arrival rate on the Foreshore.

5.7.3 The work suggests that on average over the monitoring period since 1999, there may be as many as 3 particles in the top 200 mm of sand on the routinely monitored areas of Sandside in any one month. The results also indicated that there would be a >95% chance that these will be *minor* particles. Consideration of the coverage could mean that in any one month around 6 particles could be present on the entire beach including parts that are exposed only at extremely low tides. There is a lack of data enabling the rate of particle arrival to be estimated.

Beach Monitoring

5.7.4 Re-analysis through theoretical calculation and empirical measurement has confirmed earlier conclusions that Groundhog Mk 1 was not able to meet the requirements of the TID under all conditions. The detection capability also varied significantly according to the potential position of the particle to be detected relative to the start and end location of each detector's acquisition time (*i.e.* best case *versus* worst-case scenarios). The inability to cope effectively with variations in the natural backgrounds coupled with rigid trigger mechanisms, results in higher detection limits when applied to beaches with higher natural backgrounds. These are the two principal limitations of the Groundhog Mk 1 system. Consequently, detection criteria as defined by SEPA were not met by the Groundhog Mk 1 system under all conditions. Under some conditions, *i.e.* higher natural background and vehicle speeds of 1 ms^{-1}, detection limits may be up to about 4×10^5 Bq. Groundhog Mk 1 was not configured to detect ^{60}Co.

5.7.5 Groundhog Evolution, however, is capable of meeting the current requirements of the TID and at a monitoring speed of 1 ms^{-1} extend these to depths of 150 mm or more. As with Mk 1, Evolution was not configured to detect ^{60}Co, although subsequent modifications might enable the background alarm to indicate the presence of ^{60}Co. Nevertheless it is not able to detect 10^5 Bq ^{60}Co particles reliably, should they exist in the environment.

5.7.6 The incorporation of beach-height monitoring should enable a data base to be built up to provide some interpretation of whether particle finds are associated with recently deposited sand or are derived from a historical store within the beach. More importantly, the initial beach height monitoring data indicate that sediment accumulation of between 200-300 mm between surveys, which are currently about one month apart, is not unusual for large areas of the beach. It is important therefore that the recently deposited sediment is monitored in its entirety.

5.7.7 The position of low water and high water on the beach varies with changes in beach morphology. Monitoring effort should be made to time surveys with tides to optimise coverage. Given the more dynamic nature of the intertidal zone, routinely missed by surveys, it is difficult to compensate for beach area in the particle abundance figures estimated for Sandside. For Crosskirk and Brims Ness the implementation of the wheelbarrow based Evolution system requires careful consideration to enable the 10^5 Bq particle detection requirement to be reached.

5.8 Recommendations

5.8.1 DPAG recommends that Dunnet, Melvich, Murkle and Peedie beaches should be monitored annually for the foreseeable future.

5.8.2 Scrabster and Thurso should be monitored three times per year.

5.8.3 Brims Ness and Crosskirk should be monitored six times per year.

5.8.4 Monitoring of the entire Dounreay Foreshore should be conducted fortnightly for the foreseeable future.

5.8.5 For beach monitoring at Sandside:

- Efforts should be made to undertake monitoring down to the mean low water neap tide during all completed surveys and that the area to the mean low water spring tide be monitored bi-annually. Efforts should be made to coordinate monitoring with the tides to achieve the maximum possible coverage.
- Beach monitoring coverage should be increased to fortnightly surveys to maximise the chance of detecting any recently arrived particles.

5.8.6 For beach monitoring:

- Particle activities of 10^5 Bq ^{137}Cs should remain the priority activity for detection
- 10^5 Bq ^{60}Co should also be included in the monitoring requirement
- The minimum depth for detection of particles containing 10^5 Bq ^{137}Cs should be increased to 200 mm, and where reasonably possible UKAEA should strive to achieve greater detection depths, e.g. 300 mm. Beach

and Foreshore monitoring systems must be capable of detecting particles containing 10^6 Bq ^{137}Cs or 10^6 Bq ^{60}Co to a minimum depth of 300 mm.

- When commissioning new monitoring systems, an independent empirical validation of the system performance should be undertaken allowing direct comparison with the performance of precursor systems.
- The Regulator should stipulate a probability level for the detection and removal of a particle of a given minimum activity and to a maximum depth over any beach.

Chapter 6

IMPLICATIONS FOR HEALTH AND PROCEDURES

6.1 Principles of Radiological Protection

6.1.1 The International Commission on Radiological Protection (ICRP) is the primary international body concerned with the formulation of recommendations on radiological protection standards. Its most recent recommendations for an overall system of protection were issued in 1990 as ICRP Publication 60 (ICRP 1991). The present system distinguishes between two categories of exposure, namely practices and intervention.

6.1.2 Practices are situations where the exposure of individuals is being increased in a planned manner. In terms of protecting people, emphasis is placed on the control of the source of the exposure. Generally, this can be planned before the practice commences. Examples of practices are the generation of electricity by nuclear power and the production of radioisotopes. ICRP recommends an annual limit on effective dose of 1 mSv for members of the public as an overall result of practices that are subject to control. In the UK, discharges are regulated by the Environment Agencies and licensed nuclear sites are required to carry out environmental monitoring to demonstrate compliance with the dose limit.

6.1.3 Interventions are situations where the sources, pathways and exposed individuals are already in place when a decision on control is taken. In such situations, control can only be achieved by intervention, i.e., by removing or modifying the existing sources or exposure pathways or by reducing the numbers of people exposed. A decision on the most appropriate form of intervention is a process of optimisation, with the aim of doing more good than harm. For this reason, dose limits do not cur apply in intervention situations.

6.1.4 In the case of the occurrence of fuel particles in the environment around Dounreay, the fuel particles of concern have already been discharged from the site and so control at source is no longer possible. Protection of people can be achieved only via an appropriate level of intervention. Consequently, under the ICRP system of protection the radiation dose limits that apply to practices are not applicable.

6.1.5 The requirement placed on SEPA by the Secretary of State for Scotland was as follows:

"SEPA ensure that there is sufficient monitoring in place to ensure that any particles finding their way to the beach at Sandside are promptly detected and removed."

6.1.6 This led to the more widespread monitoring of beaches specified in a series of Technical Implementation Documents (Chapter 5). From the radiological protection point of view, the periodic monitoring of beaches around Dounreay and the requirement to remove promptly any active particles that are detected should be regarded in combination as an intervention strategy.

6.2 Fuel Particles of Radiological Relevance

6.2.1 DPAG has set out the classification of *minor*, *relevant* and *significant* fuel particles earlier in this report. The discussion in this section is based on MTR particles, since these give rise to a higher dose per unit of ^{137}Cs activity than particles of

DFR origin (Chapter 3). The dose assessment indicated that, for contact with the skin or following inadvertent ingestion, particles containing around 10^4 Bq ^{137}Cs or less would be very unlikely to give rise to any short-term observable effects. The effective doses would be substantially less than 1 mSv. Residence times in the ear might be sufficient to give short-term effects with particles of this level of activity, but the probability of entrapment is extremely small, less than one in one million million (Appendix D). From the radiological protection point of view, therefore, a formal requirement for the monitoring equipment reliably to detect particles with activities of 1 x 10^4 Bq or less under all circumstances at Sandside Bay would be disproportionate to the probability of causing any effect. There is considerable uncertainty in the probability of detection for fuel particles of this level of activity (Chapter 5). However, on the basis of current evidence the probability of entrapment in the ear is extremely small and even if it were shown that a large number of low activity (*minor*) particles had gone undetected at Sandside it is unlikely that the conclusion reached here would be affected significantly.

6.2.2 Fuel particles containing 10^5 Bq ^{137}Cs could give rise to observable, but transient effects if they were left in stationary contact with tissue for periods of around 1-2 days (Section 3). This is conceivable if such a particle became trapped under a fingernail, but very much less likely in terms of contact with open skin. In contrast, a particle containing 10^6 Bq would give rise to observable effects if left in stationary contact with tissue for periods of a few hours. As noted earlier, in terms of potential doses, it would be reasonable therefore to regard MTR particles containing around 10^6 Bq ^{137}Cs or above as being of some radiological significance. However, to provide a suitable degree of caution, it would also be reasonable to expect any monitoring procedure employed to be able reliably to detect particles containing 10^5 Bq ^{137}Cs. Whatever value is chosen, the criterion on detection limits must have an associated criterion specifying the probability of detection (Youngman and Etherington 2003).

6.3 The Potential for Radiologically Significant Fuel Particles to be Deposited

6.3.1 The fuel particles in the beach at Sandside Bay are brought in with sediment from the sea. The transport of particles in the marine environment depends upon mass and density and not on activity. Most of the particles retrieved so far from the beach at Sandside contained ~10^5 Bq ^{137}Cs or below, the maximum value to the end of February 2006 being about 3 x 10^5 Bq. Until recently, the published data on activity:mass quotients for MTR particles indicated that these may range over factors of up to about 5, most values being in the range 1 - 4 x 10^9 Bq g^{-1} (SEPA 1998) and consistent with the typical value of 2 x 10^9 Bq g^{-1} adopted in this study. UKAEA has now carried out more measurements (SEPA 2005b). Most of the data relate to particles retrieved from the seabed or from the Foreshore, with only a few values available for particles retrieved from the beach at Sandside Bay. DPAG has carried out a statistical analysis of the mass:activity quotients available so far (Appendix G). The majority of the results seemed to give activity:mass quotients that are reasonably consistent with the earlier typical values of around 10^9 Bq ^{137}Cs g^{-1}. The limited data for fragments from the beach at Sandside Bay gave quotients of around 10^8 Bq g^{-1}, which is at the lower end of the range observed previously (SEPA 1998b). Particles of the same mass as those from the beach at Sandside Bay found on the Foreshore and the seabed had much higher activities. Using the relationships derived for the offshore and Foreshore particles, the predicted activities in the particles from Sandside could have been in the range 6.3 x 10^4 Bq – 1.3 x 10^7 Bq based on the 95% prediction intervals.

6.3.2 On the basis of the statistical analysis carried out by DPAG, the possibility of more active particles arriving on the beach at Sandside cannot be ruled out. This provides no justification for stopping the programme of monitoring and retrieval. It is equally important, however, to place this finding in perspective by extrapolating the data used in the evaluation of Groundhog Evolution carried out by HPA-RPD (Smith *et al*. 2005). This evaluation indicated that particles containing 10^6 Bq ^{137}Cs should be detected reliably at depths of up to 300 mm. The corresponding value for particles containing 10^8 Bq was about 600 mm. These predictions are consistent with the results of the field trials (Chapter 5). Had they been present near the surface of the beach, particles containing these levels of activity should have been detected very easily with either of the Groundhog systems. The possibility of particles containing 10^6 Bq ^{137}Cs being present at Sandside Beach must therefore be very unlikely because no such particles have been detected since widespread monitoring began in 1999. In addition, during monitoring of the seabed, most of the particles retrieved that contain 10^6 Bq ^{137}Cs or more have been found to the northeast of the Diffuser within 1 km of the outfall (Chapter 4). In a westerly direction, particles containing this level of activity have been found almost entirely within 0.2 km of the outfall. This finding may, however, be revised as more data on particle distribution in the seabed become available.

6.3.3 The relationship between mass, activity and density merits more detailed study. For example, more data for particles retrieved from Sandside Bay would be useful. In addition, MTR and DFR particles with the same ^{137}Cs content have differing radiological impacts (Chapter 3). Any differences in activity:mass quotients and the implications for transport in the sea should therefore be elicited, although the friability (i.e. tendency to break apart) of many DFR particles may make the gathering of data on mass more difficult.

6.4 The Probability of Coming into Contact with a Fuel Particle at Sandside Bay

6.4.1 The effectiveness of the two Groundhog systems to detect fuel particles at Sandside Beach has been evaluated by both DPAG (Chapter 5) and by HPA-RPD (Etherington and Youngman, 2005; Youngman and Etherington 2003). The results from both of these studies have been used to estimate the numbers of fuel particles that might be present on the beach. Values derived by DPAG are given in Chapter 5, and those by HPA-RPD have been published (Walsh *et al*. 2005; Smith and Bedwell 2005a). For lower activity particles, the estimated values differed considerably, a consequence of the uncertainties in detection capability and the sensitivity of the approaches to assumptions about the depth of particles found (Chapter 5). However, the results for those particles considered by DPAG and HPA-RPD to be *relevant* or *significant* were consistent (Chapter 5).

6.4.2 Estimates of the likelihood that people will come into contact with a fuel particle require information on the usage and occupancy of the beach, *i.e.,* what individuals do while on the beach and how long they spend doing it. This information is commonly referred to as habit data. For the purposes of radiological assessments, habit data are often subdivided into “typical” and “high-rate” subgroups. Thus, for example, people who spend time on a beach may be divided into “typical” users such as tourists, or “high-rate” users such as local residents who use the beach frequently, for instance for dog-walking. Different types of usage that may affect the likelihood or route of exposure may be considered separately. Thus for example those who use a beach to dig for bait might be considered separately from those who use the area for more general leisure purposes.

6.4.3 In support of its general radiological assessment capability, SEPA commissions habits surveys on a regular basis around each licensed nuclear site in Scotland. The most recent survey around Dounreay took place in 2003 (Tipple *et al*. 2004). The results from this and previous surveys were used by HPA-RPD to estimate the likelihood of coming into contact with a fuel particle for a range of habits, including time following leisure pursuits such as walking and beachcombing and time spent digging for bait (Smith and Bedwell 2005b).

6.4.4 The data used in the HPA-RPD study are summarised in Appendix D. Whenever possible, the data used were specific to Sandside Beach. However, the habit data for other local beaches were similar and their use would have made little difference to the results.

6.4.5 HPA-RPD then combined the habit data with information on other factors such as the amounts of sediment that might adhere to skin to provide an estimate of the probability of an individual coming into contact with a fuel particle. These probabilities were estimated for various ranges of ^{137}Cs activities in fuel particles. Where appropriate, the age of the individuals (adult, child or infant) was also considered. The results are summarised in Appendix D and in all cases relate to higher-than-average times spent on the beach.

6.4.6 Estimates of the numbers of *minor* particles in the beach at Sandside made by DPAG differed from the values derived by HPA-RPD (Chapter 5). However, from the radiological point of view the main concern of DPAG is the potential for coming into contact with *relevant* and *significant* fuel particles, for which the two studies gave comparable results. The values given here relate to *relevant* and *significant* particles, and have been taken from the HPA-RPD study. In this discussion, probabilities have been expressed in terms of chance (that is, for example, 1 in one million) and are given as rounded values. It should be emphasised that these probabilities refer to direct contact with a particle, rather than being within its general proximity. This is because any potential hazard to health requires an individual to come into close contact with a particle. General external dose rates on the beach at Sandside Bay are monitored routinely by SEPA, and the proximity of a particle containing 10^5 Bq ^{137}Cs would have no discernible effect on the measured dose rate (Chapter 3, paragraph 3.2.24). Even if a particle of 10^7 Bq ^{137}Cs were present, the dose received by an individual spending 10 h a short distance away would be at a level considered trivial by IAEA. DPAG does not, therefore, consider the external dose pathway to be of any radiological significance (Smith *et al.* 2005).

6.4.7 The results of the HPA-RPD study indicated that the population group most likely to come into contact with a fuel particle were adults who spent higher than average amounts of time on the beach in general leisure pursuits. The amount of time that such people might spend on the beach is, however, still small, around 300 hours each year (Tipple *et al.* 2004). However, this value is the same as that obtained for surveys elsewhere. On the basis of the HPA-RPD estimates of the numbers of fuel particles on the beach at Sandside, the probability of encountering a particle containing more than 10^5 Bq ^{137}Cs was about 1 in 80 million per year. The corresponding data derived by DPAG in Chapter 5 would have given a very similar value. Contact with the skin was the most likely route of exposure. The chance of a particle becoming trapped under a fingernail was about 100 times less likely, with the chance of inadvertent ingestion being about 100 times less likely again. The chances of a fuel particle entering the eye or the ear were very much less than that for contact with the skin. The HPA-RPD study indicated that the chance of an infant inadvertently ingesting a particle containing more than 10^5 Bq ^{137}Cs was about 1 in one million million.

6.4.8 As noted in Chapter 5, the uncertainties in the estimates of the numbers of *minor* particles on Sandside Beach are considerable. These have obvious implications for estimates of the probability of people coming into contact with such particles. As an example, for an adult spending higher than average amounts of time on the beach at Sandside, the chance of coming into contact with a particle having a ^{137}Cs content of less than $2x10^4$ Bq was around 1 in 3 million, based on the data derived by HPA-RPD. However, it must be emphasised that fuel particles containing this level of activity are well below the level that would be expected to give rise to observable health effects.

6.4.9 People are exposed to risks all of the time. For example, the annual chance of death in a motor vehicle accident is about 1 in 17,000, while that for death following an accident in the home is about 1 in 15,000 (NRPB 1998). As noted earlier, the chance of coming into close contact with a *relevant* particle is at least about 1 in 80 million, and even if this did occur the resultant exposure would not prove fatal. To take the converse approach, this implies that over the year there is roughly a 99.999999% chance of not coming into contact with a *relevant* particle while on the beach at Sandside Bay.

6.5 Performance Criteria for the Detection System

6.5.1 Chapter 5 of this report sets out the scientific basis for deriving performance criteria for beac-monitoring systems. Fuel particles that have been deposited recently in the intertidal area of the beach might generally be expected to reside close to the surface of the sediment within a relatively mobile layer. GPS data for Sandside Beach show that altitudes can vary by 200-300 mm between monitoring events, which might mean a period of about one month (Chapter 5, paragraph 5.5.20). This is consistent with published data for a beach in Cumbria in northwest England, where the depth of surface sediment that was mobilised was mostly less than 100 mm in one week and almost always less than 200 mm (Green and Wilkins 2005). Taken together, these results suggest that over a period of a week or two, a mobile layer of sediment would be up to about 200 mm deep. Consequently, if one of the objectives of the monitoring programme was to provide a reasonable expectation of detecting recently deposited fuel particles, intimated by the letter to SEPA from the Secretary of State for Scotland, then a performance criterion of 10^5 Bq ^{137}Cs should be applied to a minimum depth of 200 mm. Compared with the earlier criterion of 100 mm, this is also a more realistic value in terms of the depth to which a child may dig. Efforts should be made to improve the detection capability towards 10^5 Bq ^{137}Cs at 300 mm depth to encompass a greater range of beach accretion possibilities.

6.5.2 As noted in Chapter 5, the system must also be able to detect 10^5 Bq ^{60}Co to a minimum of 200 mm in real time.

6.6 The Extent and Frequency of Monitoring

6.6.1 The extent and frequency of monitoring also need to be considered in the development of an overall strategy. Monitoring should include as much of the intertidal area of the beach as possible. In practice, access to the area close to the Mean Low Water Springs (MLWS) will be limited. Monitoring should therefore focus on the intertidal area above the Low Water Neap (LWN) line, since this is where people will spend most of their time while on the beach. As noted above, the likely depth of sediment movement would typically be less than 100 mm in a week and almost always less than 200 mm over the same period. Provided that the performance criterion applied to a depth of 200 mm, then most of the mobile sediment on the beach would be monitored if surveys were based on a 2-week cycle. In turn, this would mean that, for fuel particles containing at least 10^5 Bq ^{137}Cs, most of those that had been brought on to the beach since the previous survey should be detected. It is recognised, however, that surveying is constrained by the hours of daylight, especially during the winter months, as well as by the tides.

6.6.2 The present TID is specified in terms of an overall area to be surveyed, which in practice might mean that some parts of the beach are surveyed more than once within a short time. It would be preferable to specify the precise geographicl area which is to be covered and to require that only once all of this has been surveyed should the cycle begin again. The area between the LWN and MLWS could be monitored less frequently, provided that the whole of the area was surveyed over a 3-4 month period. This approach should, by these means, provide a reasonable method of detecting *relevant* fuel particles that have been deposited recently in the intertidal area. The effectiveness of the programme does however depend crucially on the continuity of monitoring. For example, predictions of arrival rates require continuity and consistency of monitoring. Therefore, either a sound working relationship needs to be maintained between those carrying out monitoring on behalf of the site operators and the owners of the beach, or the regulator must have the ability to ensure that monitoring takes place.

6.6.3 In addition to Sandside Bay and the Dounreay Foreshore, DPAG has introduced recommendations on the frequency of monitoring of other publicly accessible beaches in the area (Chapter 5, paragraphs 5.7.1 – 5.7.3). For completeness, these are repeated here. Dunnet, Melvich, Murkle and Peedie beaches should be monitored annually for the foreseeable future. Scrabster and Thurso should be monitored three times per year, with Brims Ness and Crosskirk being monitored six times per year. As far as practicable, in all cases, the publicly accessible areas of each beach should be monitored. The choice of frequency will be influenced by factors such as extent of usage of each beach and the location of any fuel particles both on the beaches and offshore. Consequently, the structure of the monitoring programme should be kept under regular review.

6.7 Assessment of the Current Programme and Equipment

6.7.1 The extent and frequency of monitoring are interlinked with both the sensitivity and the criteria on depth. It is recognised that the rate of coverage and the criteria on sensitivity and depth recommended here exceed those currently adopted. Improvements in the current detection capability by reducing vehicle speed in isolation would not seem to be viable. For example, reducing the operating speed of Groundhog Evolution to 0.5 m s^{-1} would only improve the detection capability by about a factor of 2 and increase the time needed by a factor of 2 (Chapter 5). The use of more monitoring units or different monitoring equipment might then need to be considered.

6.7.2 Most of the particles retrieved from the beach at Sandside Bay have a ^{137}Cs activity of less than 10^5 Bq and some of these particles were reportedly found at depths of up to 180 mm. The beach trials reported in Chapter 5 showed that Groundhog Evolution is capable of detecting 10^5 Bq particles to depths greater than 100 mm. These results were also confirmed by the Harwell test-bed trials. However, the probability of detecting lower activitiy particles at these depths is substantially less than 1. Discussions with a monitoring crew indicated that every effort is made to record an accurate depth. In the rare incidences of excavation in water-logged sand, for example, the possibility of particles moving to a greater depth in the sediment before being located cannot be ruled out. This may therefore result in considerable uncertainties in the particle abundance reconstruction numbers reported in Chapter 5.

6.7.3 The ability of the Groundhog system to detect ^{60}Co also deserves comment. Neither Groundhog Mk 1 nor Evolution have been configured to detect ^{60}Co, although the latter could be modified such that the background alarm might indicate the presence of this radionuclide (Chapter 5, paragraph 5.6.5). Nevertheless, the results of the practical evaluation indicated that Groundhog Evolution was not able to detect particle containing 10^5 Bq ^{60}Co reliably, should they exist in the environment. On the basis of the number of finds on the seabed, the probability of particles containing ^{60}Co on the beach at Sandside Bay must be very small. However, it is important to demonstrate the absence of such particles. Consequently, both the Groundhog Evolution and any future monitoring system should have a data-processing capability that enables particles containing 10^5 Bq ^{60}Co to be detected reliably in real time.

6.7.4 The rocky areas of the beach are not amenable to vehicle-based monitoring. The amount of unconsolidated sediment among the rocks means that the probability of coming into contact with a fuel particle will be small. Such areas therefore merit only infrequent monitoring with hand-held equipment.

6.8 Monitoring after Storms

6.8.1 Much of the foregoing discussion relates to monitoring in typical weather conditions. However, monitoring in the immediate aftermath of storms has in the past merited specific mention within the TID. Storms often result in the rapid erosion of large quantities of sediment, as was observed qualitatively at Sandside Bay in 2003. As a result, any fuel particles that have previously been buried at depth may now be near to the newly exposed surface of the beach. It is also possible that fuel particles may be contained within swash bars of sediment as they migrate up the beach. If the frequency of monitoring recommended earlier in this section was adopted, these fuel particles should be detected and retrieved; such procedures would avoid the need for additional action to be taken in the aftermath of a storm.

6.8.2 Erosion and accretion may not be uniform across the entire beach and it would be very helpful to follow changes in beach altitude with time after a period of storms. A global positioning system (GPS) with a suitable altitudinal resolution is already in use as an adjunct to Groundhog Evolution and should form part of any future monitoring scheme.

6.8.3 The present TID requires monitoring of the strandline to be carried out after storms. Since the fuel particles behave in broadly the same manner as sand grains, there is no reason to expect them to be deposited preferentially at the strandline. As was noted earlier, storms are likely to result in erosion of sand rather than deposition. The aim of strandline monitoring is to detect larger contaminated items of flotsam and jetsam. This may be a reasonable objective of the overall monitoring programme for the marine and intertidal environments, but it should not be included in the section related to fuel particles.

6.8.4 In the present context, the other important effect of storms is that they may cause disturbance of the seabed, which in turn could mobilise fuel particles. Such particles may be small enough to remain mobile and be transported to nearby public beaches. Alternatively, larger fuel particles may break up and the products may be mobile. There is still considerable uncertainty over the timescales over which such particles might be transported to beaches such as Sandside.

Indications might be obtained in the future provided that monitoring remains at the frequency suggested here and is continuous. Such information would then be of use further into the future if at that time a programme of less frequent monitoring were to be introduced.

6.9 Potential Future Actions at Sandside Bay

General Assessment

6.9.1 The basic principle of intervention is that, whatever action is taken should do more good than harm. The selection of a suitable option must take account of the results of the monitoring and research carried out so far at Sandside Bay. The most active fuel particles retrieved so far from the beach, *i.e.* those containing around 10^5 ^{137}Cs, would probably only result in observable short term, self-remedial health effects in the highly unlikely event of stationary contact with tissue for periods of around 1-2 days (Chapter 3). In addition, the likelihood of an individual coming into contact with a particle is extremely small. The population group most likely to come into contact with a fuel particle is estimated to be adults who used the beach for general leisure purposes at higher than average rates. For this group the estimated chance of coming into contact with any fuel particle is about 1 in 2 million per year. The corresponding value for particles containing 10^5 Bq ^{137}Cs or greater is around 1 in 80 million per year, while that for a particle becoming lodged under a fingernail is about 100 times less likely. The estimated probability of a child inadvertently ingesting a particle of 10^5 Bq ^{137}Cs or greater is around 1 in 1 million million (*i.e.* 1 in 10^{12}). While current circumstances persist, the overall radiological impact on people making use of the beach is very small. However, there are considerable uncertainties in making predictions about future numbers of *relevant* fuel particles in the beach increasing or decreasing. In addition, the data available so far indicate some variability in the activity:mass quotient (Chapter 4 and Appendix G). However, unlikely on the basis of the monitoring carried out so far, and our present understanding of the transport of particles in the marine environment, the possibility that fuel particles sufficiently active to cause deterministic effects could arrive on Sandsideeach cannot be ruled out. For the present, therefore, doing nothing is not a viable option. Some possible remediation options are discussed below.

The stepwise excavation, monitoring and replacement of the entire beach

6.9.2 When such a procedure was implemented on the Dounreay Foreshore in 1997, 4 fuel particles were found. However, more were located subsequently, presumably having been brought ashore from the subtidal zone. The Foreshore at Dounreay is much smaller in area than the beach at Sandside Bay, and in addition the depth of sand is much less. The volume of sand in the beach at Sandside Bay has been estimated to be more than 40 times greater than that at the Dounreay Foreshore. Implementing this type of approach at Sandside Bay would be expensive, time consuming and damaging to the local environment. Moreover, at present it would be reasonable to assume that further fuel particles will be brought ashore. Consequently, this approach cannot provide a permanent solution. Given the low probability of users of the beach coming into contact with a fuel particle and the limited degree of severity of the possible acute health effects that might be incurred from the particles hitherto found, the excavation of the beach cannot be considered an appropriate remediation option.

Remediation of the seabed

6.9.3 It seems likely that the break-up of large particles currently held in the sea bed offshore Dounreay is an important contributor to the less active particles retrieved from the beach at Sandside Bay. In principle, therefore, the removal of the more active fragments from the sea bed should reduce the timescale over which less active particles continued to arrive at local beaches. A major operation involving the systematic removal of very large quantities of sea-bed sediment, examination and removal of particles and return of the residue to the sea bed would be a very expensive undertaking. There would be considerable environmental damage and it is possible that disturbance of the sea bed could cause particles to be mobilised before they could be retrieved. This action may also disturb a situation that is now reasonably well understood and is unlikely to result in harm in the immediate future. The overall uncertainty and cost of this option does not make it viable. A targeted operation to retrieve a high proportion of the existing *significant* particles could have an effect on the numbers of particles arriving on beaches and on the rate of arrival. However, such an operation would be expensive and possibly protracted, while monitoring of the beaches themselves would need to continue until the regulator was satisfied that further arrivals of potential consequence were unlikely. A decision to carry out such an operation would need to balance the costs of the work on the sea bed against the possible long-term reductions in the need for monitoring of beaches, especially if monitoring needed to continue for decades, as would be implied from the analysis in Chapter 4.

Restriction or prevention of access to the beach by members of the public

6.9.4 A simpler option, and one that might outwardly appear cheap to implement, would be to restrict or prevent access to the beach at Sandside Bay by members of the public. Again, however, the probability of an individual coming into contact with a fuel particle is extremely small. Given their size and appearance there is no reason to expect that fuel particles (of a size typical of those currently being detected at Sandside Beach) would be selected preferentially purely on the grounds of visual appeal, as might be the case with larger objects such as shells. Furthermore, the most active fuel particles retrieved so far would probably result only in observable short-term health effects in unlikely circumstances. Taken together, there seems no good reason to restrict access to the beach. However, the results of future monitoring and research programmes need to be kept under regular review. For example, the need for restrictions might need to be reconsidered if fuel particles containing 10^6 Bq ^{137}Cs or greater were being regularly discovered, since such particles could give rise to observable effects with credible stationary contact times of a few hours (Chapter 3). A decision on the need for restrictions would need to take account of the numbers and activities of the particles found and the probability of an individual coming into contact with them.

6.9.5 It should be emphasised that closure of the beach should not obviate the need for monitoring to be continued. Without monitoring data, it would not be possible to determine whether the situation had improved or deteriorated and therefore whether restrictions could be lifted. Closure without an associated monitoring programme would thus result in a permanent loss of amenity.

6.9.6 Restrictions on access might need to be reconsidered if monitoring was no longer possible. Any decision would need to take account of the monitoring data available at that time, together with the results of any supporting research. One important factor would be the uncertainties in any predictions of the numbers of fuel particles present and their likely activities.

Signage

6.9.7 The owner of the beach has erected signs at the most commonly used access point to Sandside Bay. Under present circumstances, the need for such signs is questionable on purely radiological protection grounds, but it can be argued that, if suitably worded, they could enable potential users of the beach to make an informed choice.

Monitoring and retrieval

6.9.8 It is expected that deposition of fuel particles from the sea onto the beach at Sandside Bay will continue for some time to come, possibly for decades. In addition, although unlikely, the arrival on the beach of particles active enough to give rise to deterministic effects cannot be ruled out. On the basis of the low probability of coming into contact with a fuel particle while on the beach and the potential health hazards posed by the particles currently being found, an ongoing programme of monitoring and particle retrieval seems to be the most suitable form of intervention. However, the objectives of such a programme need to be identified and the benefits balanced against the costs and other factors such as any decline in the amenity value of the beach.

Recommendations for a future strategy of monitoring and retrieval

6.9.9 The underlying principle of intervention is that whatever action is taken should do more good than harm. In this case, the first step would be for the regulator and the site operator to agree the precise objectives for the programme of monitoring and retrieval. These might include the following:

- Providing a means by which fuel particles that are considered of radiological relevance are detected promptly and removed, i.e. fulfilling in practical terms the requirement placed on SEPA by the Secretary of State in 1998;
- Providing information on the numbers of such fuel particles in the beach surface within a given time period, together with their activity, thereby informing decisions on any need for changes in the intervention strategy;
- Providing reassurance to the public that the radiological hazards associated with using the beach at Sandside are currently very small, and that any change in this situation would be identified promptly.

6.9.10 When deciding on the most appropriate strategy, the factors to be considered would include the detection capability required of the equipment, the extent of the area surveyed and the frequency with which surveys should be carried out. The need for appropriate monitoring of other public beaches in the area should be taken into account. These and other factors have been discussed in Chapter 5.

Longer Term Implications

6.9.11 Although a fuel particle was first detected on the beach at Sandside Bay in 1984, in the period between the start of reprocessing and the start of widespread monitoring others could have arrived. Fuel particles are still present on and in the sea bed, and many hundreds have been removed as part of an ongoing research programme. Nevertheless, fuel particles are still being detected in the beach in Sandside Bay. Decisions on the need to modify monitoring of Sandside Beach have to be made on the basis of the number of finds in the beach itself, together with their characteristics.

6.9.12 Of the 59 retrieved from the beach at Sandside Bay up to February 2006, 9 had activities in the range 1-3 x 10^5 Bq. As noted earlier, the possibility of particles containing around 10^6 Bq being deposited on the beach cannot be ruled out, On this basis, monitoring and retrieval might need to continue at the level suggested for some decades. The situation does, however, need to be kept under regular review by both the regulator and the site operator.

6.9.13 The above discussion has focused on a strategy of monitoring and retrieval at Sandside Bay. However, the current monitoring programme encompasses other beaches such as those at Thurso, Melvich, Scrabster and Dunnet (Chapter 5). No *relevant* fuel particles have been located at any of these beaches. However, the absence of such finds should not be taken to imply that monitoring can be stopped in the foreseeable future. Beaches such as Thurso are used extensively and it is important to provide a suitable degree of public reassurance.

Chapter 7

OVERVIEW, CONCLUSIONS AND RECOMMENDATIONS

7.1 Background

7.1.1 Earlier work and the progress made since the previous (Second DPAG 2003) report have now reached a stage at which it is possible to bring together present understanding of the diverse scientific aspects of particles in the environment around Dounreay. This comprehensive overview is as definitive as present knowledge permits, while noting and taking into account the major uncertainties that remain. Areas have been identified in which further work is considered essential to underpin or refute current conclusions or is regarded as desirable to improve the relevant knowledge base.

7.1.2 This independent report might, therefore, represent a scientific base on which political, societal, regulatory and management decisions can be taken in relation to future actions or inactions.

7.1.3 The Group's first Term of Reference, "*to provide impartial expert scientific advice on the current UKAEA research programme in respect of particles in the Dounreay local environment*", entailed compilation, sifting and assimilation of a large volume of extant information on the origins of particles, their routes of release to the environment and their behaviour in the marine and littoral environments. In so doing, important areas were identified in which information was non-existent, inadequate or needed further testing. Considerable progress has been made in a number of areas, not always as expeditiously as desirable, contributing to delays in publishing this report. This progress has been described in previous reports and in preceding chapters. However, cognisance of the gaps in knowledge that remain has been taken.

7.1.4 The second Term of Reference is "*to provide comprehensive reports on particles in the environment and any associated potential implications for the health of the public*". Shortly after DPAG's foundation, the Group recommended that a review of the potential health effects of particles be undertaken to update and elaborate upon that included in the SEPA report (1998a). SEPA commissioned relevant studies in 2001. The NRPB (now the HPA-RPD) has completed a comprehensive, detailed and thorough re-assessment, including a cautionary approach to rare circumstances. Chapter 3 summarises the key features of this reassessment.

7.1.5 In seeking to provide a report that is as definitive as present knowledge permits, it is now possible to set the Group's work in the context of public health, which the Group regards as the primary concern.

7.2 Nature of Particles

7.2.1 MTR and DFR particles are similar in size to grains of sand. MTR particles have a density similar to that of sand grains, but no measurement of the density of DFR particles has yet been achieved. The Group concluded that the behaviour (including transport) of particles in the marine environment would approximate to that of grains of sand of corresponding size and density.

7.2.2 A positive relationship was found between the mass of particles and their content of radioactivity. However, some particles deviated significantly, probably because of differences in the history of the fuel from which they originated.

7.2.3 Particles ranged from those of pure aluminium, containing effectively no radioactivity and, therefore, having no radiological implications for health, through those containing small quantities of fission products and actinides to those containing large quantities; the latter are of undoubted radiological concern. In the present state of knowledge and its context, the generic term 'particles' without qualification was no longer considered appropriate or sufficiently meaningful.

7.2.4 Having taken careful account of the authoritative re-assessment of health effects, summarised in Chapter 3, pragmatically and for ease of understanding, the Group subdivided the particles into three categories, *viz*. *significant*, *relevant* and *minor*, according to their potential to cause harm. The Group concluded that only particles containing 1 x 10^6 Bq ^{137}Cs (with associated fission products and actinides) or greater pose a realistic potential of causing harm for members of the public. These have been categorised as *significant* particles. Nevertheless, DPAG considers it prudent that particles having activities between 1 x 10^5 and 1 x 10^6 Bq ^{137}Cs should be monitored and removed. These have been categorised as *relevant* particles. Those having activities of less than 1 x 10^5 Bq ^{137}Cs have been categorised as *minor* particles. Drawing upon the Group's findings relating to the occurrence of particles, particularly in the littoral environment, but also in the marine environment, the potential exposures of the public to these groups have been assessed.

7.3 Occurrence of Particles in the Environment

7.3.1 It is well-established that many, perhaps several hundred thousand, of sand sized fragments (particles) primarily of MTR and DFR fuel were discharged into the marine environment at Dounreay.

7.3.2 These were generated during treatment of fuel elements and released during procedures and incidents on site, arguably as a consequence of practices and controls that were less than adequate.

7.3.3 The major discharges of particles to the environment, via the Low Active Liquid Waste Disposal System, the Effluent Tanks and the Diffuser, would be expected to have occurred primarily in the 1960's and 1970's. During this period, intensive campaigns of reprocessing of MTR and DFR fuel were undertaken. Milling, that generated most MTR particles, was in operation and non-standard fuels, such as the particularly difficult French Pegase fuel, which notably generated many particles and much contamination, was processed. Treatment of DFR fuel ceased in 1979.

7.3.4 Although particles in the environment were not identified until 1983, it seems most likely that many particles had been released, but not recognised in preceding decades.

7.3.5 Some of these particles have been found on the Dounreay Foreshore and, since 1984, on the beach at Sandside Bay where exposures of the general public, although improbable, could have occurred.

7.3.6 The Group considered the possibility of continuing sources of discharge for particles, especially the Shaft, but concluded that none was likely to be contributing significantly to the numbers remaining in the marine environment from previous historical discharges.

7.4 The Marine Environment

7.4.1 The Group considers that it has now achieved a workable coherent understanding of the distribution and behaviour of particles in the marine environment that this is consistent with the information available. Nevertheless, the considerable gaps in knowledge and uncertainties that remain are recognised and proposals are made for further work to confirm or refute its present conclusions.

7.4.2 A model developed by members of the Group implies that *significant* particles, generally of greater mass and less amenable to marine transport, have been buried to depths of 100 mm or more in sea-bed sediment, primarily in the area around the Diffuser. At these depths, they are much less likely to be disturbed and made available for transport by wave action, except perhaps under extreme sea conditions, such as major storms.

7.4.3 In contrast, *relevant* and *minor* particles of lesser mass are more amenable to marine transport out of the area of the Diffuser from which the majority of all particles emerged into the marine environment.

7.4.4 This interpretation is consistent with the pattern of particles so far established offshore. Particles are found primarily in a plume extending over 2 km in a northeasterly direction from the Diffuser in accordance with the predominant marine currents. The proportion of *significant* particles in the plume decreases fairly rapidly with distance from the Diffuser. A smaller number of *relevant* and *minor* particles are found west of the Diffuser towards Sandside Bay, transported there by near-shore currents.

7.4.5 Based primarily on surveys by divers, estimates of the number (and distribution) of particles remaining in or close to the known extent of the plume offshore from Dounreay have been made. Although subject to considerable uncertainty, the upper bound estimate for *significant* particles is 1500, for *relevant* particles is 1500 and for *minor* particles is 4300. Of the *significant* particles present in the local marine environment, it is estimated that about 92% are within 0.5 km of the Old Diffuser and of the *relevant* particles about 95% are within 1 km of the Old Diffuser. The Wallingford modelling suggests that, about 30 years following their release, approximately 50 % of larger (*significant*) particles and 40 % of smaller particles remain in the modelled area of their Inner Model. Applying these values to the estimated number of particles in the offshore plume, including those retrieved by divers, suggests that an upper bound of about 3000 *significant* particles, a similar number of *relevant* particles and about 10,000 *minor* particles were released into the marine environment. These numbers are substantially smaller than expected from even conservative estimates derived in Chapter 2. They are similar to those associated with a single event, whereas other events and practices were likely to have increased these numbers substantially. This potential discrepancy remains to be resolved. One explanation may lie in entrapment of particles in the Old Diffuser. Another may be deficiencies identified in the Wallingford Model.

7.4.6 There is evidence that particles fragment in the marine environment as a result of physical and chemical processes. Fragmentation of larger particles would obviously contribute to the number of smaller particles remaining. More importantly, in practice, fragmentation of *significant* particles seems likely to sustain the number of *relevant* and *minor* particles for several decades more.

7.4.7 Repopulation studies showed that the mean activity of particles found on resurvey was significantly less than that of the original finds. These studies indicate that high activity (*significant*) particles are not repopulating the seabed to a significant extent over a period of about 5 years either close to the Diffuser, where a relative abundance was found initially, nor more remotely where their initial proportion was much smaller.

7.4.8 This evidence suggests that *significant* particles will continue to remain primarily in the area of the Diffuser, even after a fairly major storm. They will be transported mainly to the nearby Dounreay Foreshore. It would be expected that *relevant* and *minor* particles will continue to reach the beach at Sandside Bay for decades to come while the possibility of a small number of *significant* particles arriving cannot be ruled out. *Minor* and possibly *relevant* particles may reach other beaches but, to date, only one *minor* particle has been found at Dunnet Bay.

7.5 Monitoring of the Littoral Environment

7.5.1 Monitoring of the littoral environment, particularly beaches, has been undertaken by UKAEA since site operations began. The equipment used initially comprised hand-held Geiger-Muller tubes having limited sensitivity and area of coverage. The original programme was concerned primarily with material deposited in inter-tidal areas. It was, therefore, probably serendipitous that a particle was detected on the beach at Sandside in 1984. Thereafter, the same survey equipment continued in use along the strandline until 1997, when Groundhog was introduced. As particles are distributed across the beach and not preferentially at the strandline, it is perhaps not surprising that no further particle was found at Sandside until 1997. It could be inferred, however, that a substantial number of high activity particles was unlikely to have been present, especially on the strandline.

7.5.2 After the introduction of Groundhog (single detector) in 1997, a second particle was found in that year.

7.5.3 In 1999, the vehicle-mounted version (Groundhog Mk 1) was first employed with much improved detection sensitivity and allowing greater coverage of the beach area in the available time. In 2003, Groundhog Mk 1 was replaced by an improved system known as Groundhog Evolution.

7.5.4 As described in Chapter 5, the Group has undertaken detailed theoretical evaluations of the performance of Groundhog Mk 1, taking into account additional information available since the preliminary assessment included in the Second (2003) Report. It has also evaluated the performance of Groundhog Evolution, while the development of software through SEPA enabled the efficient processing of monitoring datasets comprising in excess of 6 million data points. Essentially, the evaluations primarily assessed the ability of the systems to detect particles containing 10^5 Bq ^{137}Cs to 100 mm depth.

7.5.5 Although during beach surveys Groundhog Mk 1 has detected such particles to this depth and occasionally greater, the evaluations showed that the detection limit is affected significantly by variations in the natural background radiation likely to be encountered on some beaches. In adverse circumstances, the detection limit could be about 4 x 10^5 Bq ^{137}Cs. Consequently, the system was unlikely to comply with the detection criteria under all circumstances. Operation at a reduced speed of 0.8 ms^{-1} improved the performance. In contrast, the performance of Groundhog Evolution is substantially better than that of Groundhog Mk 1. At operating speeds of 1 to 1.2 ms^{-1}, the system complies with the evaluation criteria at most of the beaches being monitored, the possible exception to this being the beach at Crosskirk where a hand-held system is used. At Sandside Beach, in the best-case scenario, the detection limit may be as small as 1.4×10^4 Bq ^{137}Cs at a depth of 100 mm.

7.5.6 Extrapolation of the sand-pit trial of the systems largely confirmed the theoretical assessment.

7.5.7 For several years, DPAG and COMARE have pressed for an empirical evaluation of the monitoring systems on a beach to simulate as closely as possible the real situation. This was achieved only in April 2006, and was one of the major factors underlying the decision of the Group to delay publication of this report. The evaluation confirmed that Groundhog Evolution is capable of detecting *relevant* particles to a depth of at least 100 mm in sand and potentially to 200 mm while *significant* particles can be detected to depths of at least 300 mm. The Group considers that this performance should be improved such that *relevant* particles will be confidently detected at a depth of at least 200 mm. As discussed earlier, the beach is known to change level naturally by at least 300 mm. This depth is also a more realistic depth to which a small child might dig.

7.5.8 The Group has sought to establish any change in the rate of arrival of particles on the Dounreay Foreshore and on the beach at Sandside. However, it was not possible to reach any well-founded conclusions because of the potential impact on the Dounreay Foreshore population of the number of particles retrieved offshore by divers. At Sandside, the data were confounded by long periods when access to the beach was denied and by changes in monitoring systems. However, reconstruction of the particle abundances over the monitoring period since 1999 provides little evidence of any change.

7.5.9 Although DPAG has attempted to estimate the potential monthly abundance of *minor* particles on the beach at Sandside, substantial uncertainties exist because of the assumptions that are necessary in detection efficiency and the precise depth at which each particle was found. A mean monthly estimate of between 3 and 6 was derived of which 95% are likely to be *minor*.

7.6 Health Implications

7.6.1 The Group brought together these diverse aspects of particles in the environment to assess their potential implications for the health of the public.

The Dounreay Foreshore

7.6.2 *Significant* particles have been found so far only in the offshore environment (where direct contact by the public is extremely unlikely) and on the Foreshore at Dounreay, which is effectively inaccessible to the public.

7.6.3 The particle containing the greatest quantity of radioactivity (2×10^8 Bq ^{137}Cs), found in November 1991, could have had life-threatening consequences if it had been ingested. The majority of *significant* particles on the Foreshore contained 10 to 100 times less radioactivity. A smaller number of *relevant* and *minor* particles have also been found. The mean activity of all particles found annually during the last five years has been about 6.4×10^6 Bq ^{137}Cs.

7.6.4 The Dounreay Foreshore should be closed to the public until the Regulator decides that this is of no further practical value. Access should be available to local beaches unless future monitoring shows significant deterioration in the current situation.

The Beach at Sandside Bay

7.6.5 The most active particle found so far contains 3 x 10^5 Bq ^{137}Cs with associated radionuclides. For all particles, the average is 8.9 x 10^4 Bq ^{137}Cs. The assessment of health implications (Harrison *et al*. 2005), summarised in Chapter 3, indicates that for particles of this magnitude enduring health effects are highly unlikely. Even cautiously assuming long periods of contact with skin, any effects would be indiscernible or transient. Analogously, doses to the rectosigmoid would be orders of magnitude less than the threshold for acute damage and any localised damage to the lining of the gut should be repairable by natural regeneration. The committed effective dose following ingestion would be comparable with the annual dose due to natural background radiation.

Significant Particles

7.6.6 No *significant* particles have been found on the beach at Sandside Bay since monitoring began in the Spring of 1984 up to February 2006. It is important to note that none has been found since the Groundhog monitoring systems with the capability to monitor large areas of the beach were introduced in 1999.

Relevant Particles

7.6.7 Nine *relevant* particles have been found over the same area during this 22-year period. For ‘high rate’ users of the beach, such as bait diggers and dog walkers, the probability of direct skin contact with a *relevant* particle is about 1 in 80 million per year and of ingestion or inhalation about 1 in 1 million million per year (Wilkins *et a*l. 2006), as outlined in Chapter 6. For infrequent visitors, such as holidaymakers, the probabilities are even smaller, by about an order of magnitude or more.

7.6.8 The hazard associated with *relevant* particles is evidently extremely small. It is a combination of the very small probability of contact with a particle and the unlikelihood of the particle causing serious detriment to health.

Minor Particles

7.6.9 Up to 10 February, 2006, 50 *minor* particles containing less than 10^5 Bq ^{137}Cs have been detected and recovered. The range of activity is 8.2 x 10^3 to 9.7 x 10^4 Bq ^{137}Cs. As a consequence of the limits of detection of the systems used to monitor the beach, perhaps 10 to 50 times as many particles could have been present, but undetected for which allowance was made in the health assessment. For ‘high rate’ user groups, the probability of contact with skin is estimated as about 1 or 2 in 10 million and for ingestion or inhalation about 1 or 2 in ten thousand million. For members of the public making occasional use of the beach, the probabilities would be smaller by about a further factor of ten.

7.6.10 Particles containing these levels of radioactivity are still less likely to cause significant health effects. Even in highly improbable circumstances, estimated radiation doses to the skin and rectosigmoid would be much less than the threshold for deterministic (acute) effects and, if ingested, the committed effective dose would be a fraction of the annual dose due to natural background radiation.

Other Local Beaches

7.6.11 No *significant* or *relevant* or *minor* particles have been found to date in regular monitoring of the beaches at Thurso, Scrabster and Brims Ness, using Groundhog

Evolution. A similar absence at Crosskirk is less certain because less sensitive monitoring occurred.

7.6.12 The Group instigated a survey of the beach at Dunnet Bay, undertaken in 2005, during which a *minor* particle containing 8.9 x 10^3 Bq ^{137}Cs was found as well as stones containing natural radioactivity and a piece of plastic of pebble-like appearance contaminated with radiocaesium. There was no evidence of historic accumulation of particles on this previously unsurveyed beach and, in view of its larger area, the probability of contact, ingestion or inhalation would be much less than that at Sandside.

7.7 Intervention: Remediation and Amelioration

7.7.1 In considering what remediation or amelioration might be beneficially undertaken in practice, the Group took full account of the facts that *significant* particles have been found so far only on the Dounreay Foreshore and, of the beaches accessible to the public, *relevant* particles have been found only at Sandside Bay. *Minor* particles have been discovered regularly only at Sandside Bay. A single *minor* particle has been found at Dunnet Bay. No particles have so far been detected on the beaches at Thurso, Scrabster, Brims Ness and Crosskirk.

7.7.2 The extent to which these situations will persist is inevitably speculative. Although it has been possible to estimate the number of *significant* and *relevant* particles remaining in an offshore plume and their potential to reach publicly accessible beaches, substantial uncertainties inevitably remain. However, monitoring of Sandside Beach (and the Dounreay Foreshore) specifically for particles has been conducted during some 20 years (about 6 years using the vehicle mounted Groundhog systems) and particles released to the marine environment have been subjected to some 40 years of marine disturbance, including storms. To that extent, the accumulated evidence of littoral contamination might be considered to be reasonably representative. If that were so, and coupled with our earlier analysis of particle transport in the marine environment, a number of *relevant* particles might continue to reach the beach at Sandside together with *minor* particles. It is much less likely that *significant* particles would reach the beach, but this cannot be excluded. It seems probable that few, if any, *relevant* particles would reach other public accessible beaches, but some *minor* particles might do so.

7.7.3 Having considered various options for remediation or amelioration, the Group drew the following conclusions:

- Given the extremely small probability of contact with or ingestion or inhalation of a particle typical of those found so far on the beach at Sandside Bay, coupled with the additional unlikely circumstances that even transient observable health effects would be caused, prevention or restriction of access to the beach by members of the public would result in a loss of amenity that would be difficult to justify on health grounds. This conclusion is even firmer for other beaches, such as those at Thurso and Dunnet Bay, where the improbabilities are so great that their continued unrestricted use seems appropriate. In contrast, it would be prudent to deny public access to the Dounreay Foreshore for the foreseeable future.
- For similar reasons, the need for signs is questionable on the grounds of radiation protection, again the exception being the Dounreay Foreshore. In principle, if suitably worded, signs could enable an informed choice to be made by potential users of the beach.

- Stepwise excavation, monitoring and replacement of the entire beach at Sandside Bay would be unjustifiable given the small level of risk and the potentially substantial damage to the environment. Furthermore, it is anticipated that *relevant* and *minor* particles will continue to be deposited from the sea onto the beach for the foreseeable future, negating the purpose of such amelioration.

- Remediation of the seabed to 'pristine condition' by removal of all radioactive fragments is unrealistic and would entail a major operation, as outlined earlier. It would cause substantial environmental damage and considerable expense. Disturbance of the seabed could cause mobilisation and fragmentation of large particles before they could be retrieved, increasing the likelihood of particles reaching beaches to cause potential exposure of the public. A situation could be created that was much less well understood than that now pertaining. Arguably, however, a targeted operation to remove the most active fragments could provide some benefits with minimal detriment and disturbance to the environment. For example, a *significant* particle containing 10^6 Bq ^{137}Cs or more could ultimately fragment into at least 10 *relevant* particles more amenable to marine transport onto local beaches. Retrieval of *significant* particles from the marine environment could, in principle, reduce the future period during which *relevant* particles could be expected to arrive, for instance, at Sandside Bay. This is an issue which, so far, the Group has not had the opportunity to consider in any detail. The Group recommends thorough consideration of its potential benefits, such as reducing the long term need for monitoring of beaches, weighed against the costs (and potential risks, for example to divers) of work on the sea bed and the potential environmental detriment.

- The ultimate safeguard of public health, taking account of residual uncertainties or of unexpected events, is the monitoring of accessible beaches. In considering earlier the health implications, the Group concluded that, in practical terms, the requirement placed on SEPA by the Secretary of State would be fulfilled by the prompt detection and removal of particles of radiological significance to a depth of at least 200 mm on beaches. It has been demonstrated that Groundhog Evolution will detect *significant* particles to this depth. However, DPAG concludes that a more stringent requirement of reliably detecting *relevant* particles to this depth would provide further safeguards and would be realistically achievable. The Group, therefore, recommends that this is a requirement of the imminent re-tendering process for monitoring of beaches as well as the requirement of an analogous ability to detect, in real time, particles containing similar amounts of ^{60}Co. It is anticipated that SEPA will, in due course, reconsider the Technical Implementation Document and take into account the Group's conclusions about the areas of beaches to be monitored and the frequency of routine monitoring. It would seem prudent to continue such monitoring. This should also have the benefit of providing public reassurance, for the immediately foreseeable future, until such time as regulatory, political and societal judgements deem monitoring to be no longer necessary or of no practical value.

7.8 Recommendations

7.8.1 DPAG considers that UKAEA should mitigate the potential future release of particles into the marine environment by isolating the Old Diffuser Chamber.

7.8.2 The Group considers that Low Level Waste Pits should either be emptied or protected adequately from environmental impacts, including the possibility of breaching by exceptionally large waves.

7.8.3 Offshore contamination by particles should be characterised further in terms of their extent, numeric density and distribution.

7.8.4 A larger sample of the particles recovered should be characterised to determine their mass, density, shape, size, composition, chemical reactivity and radionuclide content to test assumptions made as to the behaviour of particles in the sea.

7.8.5 Further offshore monitoring should be undertaken. This will provide information on the continuing need for beach monitoring, both in terms of its extent and frequency.

7.8.6 UKAEA should undertake further work to determine the potential number of ^{60}Co particles in the environment.

7.8.7 The Group recommends that work be undertaken to establish a best estimate of the proportion of particles of similar characteristics to particle MTR113 that may have been released.

7.8.8 Beach and Foreshore monitoring systems deployed must be capable of detecting particles on any monitored area of activity of 10^6 Bq ^{137}Cs and ^{60}Co to a minimum depth of 300 mm. The capabilities of such systems should also allow particles with activities of 10^5 Bq ^{137}Cs and ^{60}Co or greater to be detected to a minimum depth of 200 mm and should strive to achieve a monitoring depth of 300 mm.

7.8.9 The Group considers that any new monitoring systems must be empirically validated and compared directly with their predecessor.

7.8.10 The Dounreay Foreshore should be closed to the public until the Regulator decides that this is of no further practical value. Access should be available to local beaches unless future monitoring shows significant deterioration in the current situation.

7.8.11 The beaches at Scrabster, Crosskirk, Brims Ness, and Thurso should be appropriately monitored at the current intervals. The beach at Sandside should be monitored comprehensively every two weeks. Melvich, Murkle, Peedie and Dunnet beaches should be monitored annually.

7.8.12 Monitoring of the Dounreay Foreshore and local beaches should continue until the Regulator decides that these procedures are of no further practical value.

7.8.13 In 1998, the then Secretary of State wrote to SEPA asking that "*SEPA ensure that there is sufficient monitoring in place to ensure that any particles finding their way to the beach at Sandside are promptly detected and removed*". This statement was presumably intended to be interpreted in practice, according to the degree of risk entailed. DPAG considers that the removal of literally 'any' particle is impractical and, in the case of *minor* particles, is unnecessary on the grounds of radiological protection of the public.

7.8.14 The extent of the contamination of the environment means that it is impractical to aim to return the environment to a pristine condition. Remediation options should aim to do more good than harm to the environment. DPAG recommends that serious consideration should be given to the targeted removal of significant particles in the marine environment providing that this causes only minimal disturbance.

7.9 Identification of further work

7.9.1 Due to the late availability of information as well as other gaps in knowledge identified within this report, the Group considers it appropriate that further work is undertaken on specific aspects.

7.9.2 Within about 12 months an evaluation should be completed of:

- Reports on the Old Diffuser and particle properties provided recently and others that might become available;
- Results of offshore monitoring during 2006/2007 using TROL and their relationship to the Wallingford model and fragmentation. Evaluation of TROL;
- Particle finds at Sandside in relation to beach height;
- Measurements of the density of particles;
- ‘On-beach’ evaluation of any new monitoring system;
- More comprehensive monitoring of the Dounreay Foreshore;
- Friability of particles;
- The effects of bioturbation on the retention and availability of particles in marine and beach sediments.

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GLOSSARY OF TERMS AND DEFINITIONS USED

Absorbed dose	The quantitiy of energy imparted by ionising radiation to unit mass of matter such as tissue. The unit of absorbed dose is the Gray (symbol Gy).
Actinide	A group of 15 elements from that of actinium (atomic number 89) to lawrencium (atomic number 103) inclusive. All are radioactive. The group includes uranium, plutonium, americium and curium.
Becquerel (Bq)	The standard international unit of measurement of radioactivity, equivalent to disintegration per second. MBq Megabecquerel; a unit of radioactivity equal to one million becquerels. GBq Gigabecquerel; a unit of radioactivity equal to one thousand million becquerels. TBq Terabecquerel; a unit of radioactivity equal to one million million becquerels.
Best Practicable Environmental Option (BPEO)	The BPEO is a set of procedures for managing waste and other environmental concerns. According to the Royal Commission on Environmental Pollution, BPEO "emphasises the protection and conservation of the environment across land, air and water. The BPEO procedure establishes for a given set of objectives, the option that provides the most benefits or the least damage to the environment, as a whole, at acceptable cost, in the long term as well as in the short term."
Cache	A potential source of particles currently held within sediment on the beach or on the sea bed offshore and from which particles can be released when the sediment is disturbed.
COMARE	Committee on Medical Aspects of Radiation in the Environment; an independent committee providing advice to Government which is sponsored by the Department of Health. COMARE was set up in 1985 in response to a recommendation in the report of the independent advisory committee chaired by Sir Douglas Black on the possible increased incidence of cancer in West Cumbria. Its terms of reference are to assess, and advise the Government on, health effects of natural and man-made radiation in the environment and to assess the adequacy of the available data and the need for further research.
Crustaceans	A large and diverse group of primary aquatic invertebrates with a rigid external skeleton, jointed appendages and evidence of body segmentation. Groups include the sessile filter feeding barnacles, crawling and walking forms such as the predatory and scavenging lobsters and crabs and swimming forms such as shrimps.
Demersal	A term generally applied to fish which spend the greater part of their time on or very near the bottom of the sea feeding on

	prey located on or coming down to the seabed. Many species are non-migratory or show limited or relatively slow migration movements. Examples include cod, haddock and plaice.
Deterministic effect	A radiation-induced health effect characterised by a severity that increases with dose above some critical threshold above which such effects are almost always observed. Examples of deterministic effects are nausea and radiation burns.
Dounreay Fast Reactor (DFR)	The first fast reactor operated at Dounreay 1959-1977. DFR mainly used enriched metallic uranium mixed with molybdenum fabricated into cylindrical pellets held within, but separated from, a niobium (^{93}Nb) cladding.
DFR Particle	An agglomeration, about the size of a grain of sand, containing radioactive elements generally associated with irradiated DFR fuel and its cladding. Typically ^{94}Nb may be identified along with ^{137}Cs and ^{90}Sr.
Differential GPS (DGPS)	A Global Positioning System (GPS) is a world-wide radio-navigation system formed from a constellation of 24 satellites and their ground stations. A GPS receiver calculates its location on the basis of the triangulation between three or more satellites, coupled with a forecast of their orbital characteristics. Differential GPS involves the use of two ground-based receivers. One monitors variations in the GPS signal and communicates those variations to the other receiver. Where communication is not possible, post-processing correction can be undertaken. Both these procedures improve the accuracy in positioning.
Diffuser	The diffuser is the point on the seabed where authorised discharges of low level liquid radioactive waste has been made since the 1950's. The so called "old diffusion chamber" was utilised fully from 1958 until 1992 and partially until 1997. This chamber has been replaced by a new separate diffuser system that is constructed to a modern design allowing better dispersion.
Dounreay Foreshore	In this report, the strip of land contiguous with the seaward boundary of the Dounreay site which is affected by normal tidal movement. In relation to references to the migration of radioactive particles from the offshore sediments to the Dounreay Foreshore. In broad terms, the western part of the Dounreay Foreshore consists of a sand and pebble beach and the eastern part of rocks. The two parts of the foreshore are separated by the deep-water of the cooling water intake for the DFR. The Dounreay Foreshore is owned by the Crown.
EDAX	Energy Dispersive X-ray Analysis, an investigative method, using scanning electron microscopy (SEM) techniques to determine the proportion of chemical elements present within the particles.

Effective dose	The quantity obtained by multiplying the equivalent dose to various tissues and organs by a tissue weighting factor and summing of the products. The individual tissue weighting factors take accont of the sensitivity of that organ or tissue to radiation. This provides a means of bringing doses from all radionuclides and exposure pathways on to a common basis.
Equivalent dose	A means of taking account of the differing effectiveness of different types of ionising radiation in causing harm to tissue. The equivalent dose is obtained by multiplying the absorbed dose by a radiation weighting factor.
Explosion in ILW Shaft 1977	A violent explosion occurred in the gas space at the top of the Shaft in the early hours of 10 May 1977. UKAEA concluded that the explosion was caused by a chemical reaction between sodium and potassium placed in the Shaft reacting with water to generate hydrogen. There is no evidence that criticality was the cause of the incident. Substantial damage was caused to structures at the top of the Shaft, including the concrete roof slab and steel adapter plates which had been blown off, with the steel top plate blown a distance of about 12 metres. Following the explosion, radioactive contamination, including debris, was detected both within and outside the Dounreay Site fence.
Exposure pathway	The means by which radiation of radionuclides in the environment deliver a radiation dose to people. A radiation dose can be delivered by a source that is outside the body *(external irradiation)* or from radionuclides that are inside the body *(internal irradiation)*. For external irradiation, exposure pathways are generally direct, since the person needs to be relatively close to the source to receive the dose. For internal irradiation, exposure pathways may be more complex because of the need for radionuclides to be transferred through various environmental media before being taken into the body. The grass – cow – milk – man pathway is a well-known example.
Fathoms Instrument Towed System (FITS)	A system which enables a radiation detector (or other) device to be towed through the water close to the seabed to provide a map of radioactivity in the seabed, with all output data being recorded on a computer aboard the survey vessel.
FEPA exclusion zone	An area of sea where restrictions on the collection and consumption of seafood are being enforced by the Food Standards Agency (FSA).
Fuel Cycle Area (FCA)	The Fuel Cycle Area at Dounreay; collectively, the plants undertaking nuclear fuel cycle operations, including the fabrication and reprocessing of specialist nuclear fuels, and the recovery of nuclear material.
Foreshore	The coastal zone between the highest reach of waves and Low Water Mark. It may be rocky or hold a sandy or pebble beach.

Fragments	Particles are more accurately described in the main as fragments of irradiated nuclear fuel. This terminology has been adopted by SEPA.
Food Standards Agency (FSA)	The Foods Standards Agency (FSA) function is to protect public health from risks which may arise in connection with the consumption of food and protect the interests of the consumers in relation to food.
Gamma ray	Gamma rays (often denoted by the Greek letter gamma γ) are an energetic form of electromagnetic radiation produced by radioactive decay.
Gamma ray spectrometry	The detection and separation of polyenergetic gamma ray sources by their energy, usually keV. The detection of individual gamma ray energies enables the sources of gamma rays to be identified. This requires a detector that has sufficiently good energy resolution to discriminate between individual sources.
Gastrointestinal tract	The gastrointestinal tract or digestive tract, also referred to as the GI tract or the alimentary canal or the gut, is the system of organs that takes in food, digests it to extract energy and nutrients, and expels the remaining waste.
Global positioning system	See Differential GPS.
Gray	The unit of absorbed dose. One Gray is one joule of energy deposited in one kilogram of matter.
Groundwater upwelling	Springs rising to the sea bed offshore.
Hot particle	A hot particle is a small, radioactive object, with significant content of radionuclides.
Intermediate Level Waste (ILW)	Classified by Government in Cm 2919 as wastes with radioactivity levels exceeding the upper boundaries for low level wastes, but which do not require heating to be taken into account in the design of storage or disposal facilities.
Internal radiation dose	A means of placing the possible effects of different radionuclides within the body on a common basis. Differences in factors such as radioactive half-life, mode of radioactive decay and biokinetic behaviour are taken into account. "Dose" is often used as a shorthand notation for *equivalent dose,* which provides an index of the risk of harm to a particular organ or tissue from exposure to various radiations regardless of their type or energy, and for *effective dose,* which takes account of the differences in risk between organs and so enables the equivalent doses to different organs in the body to be represented as a single number.
In vitro	Experiments carried out under conditions that imitate those found in living organisms.

In vivo	Experiments carried out using living organisms.
Irradiated fuel	Nuclear fuel that has been irradiated in a nuclear reactor.
Low level (radioactive) wastes (LLW)	Classified by Government in Cm 2919 as wastes containing radioactive materials other than those acceptable for disposal with ordinary refuse, but not exceeding 4 GBq per tonne of alpha or 12 GBq per tonne of beta/gamma activity.
Lumen	The interior of the lower large intestine.
Made ground	Ground built up by the deliberate tipping of soil, building rubble and other debris. Parts of the cliffs along the Dounreay site have been built up in this way and are now slowly eroding.
Material testing reactor (MTR)	Materials Test Reactor; a class of research reactor used throughout the world. Fuel from such reactors, including that operated at Dounreay between 1958 and 1968, has been reprocessed at Dounreay. MTR fuel consists of enriched uranium contained in an aluminium substrate.
Median	The median of a set of data, is the numerical value such that 50% of the observed values lie above (are greater than) and 50% of the observed values fall below (are smaller than) its value.
Molluscs	A large and very diverse group of aquatic and terrestrial invertebrates which appear unsegmented, frequently possess a large muscular foot and have one pair of gills. Many forms possess an obvious external shell which is secreted by and grows with the animal. Groups include the relatively sessile snail and slug-like forms which may be predatory or graze on plants, filter feeding forms which possess a hinged or bivalve shell surrounding the soft structures and much more active and predatory cephalopod groups such as squids and octopus which may or may not have an internal shell.
Monte Carlo	Monte Carlo methods are a general class of statistical methods which are based on the principle of simulation of random variables.
MTR (Materials Test Reactor)	A research reactor of a type widely used throughout the world to subject materials to radiation. Dounreay's MTR operated from 1958 to 1968.
MTR Particles	Small fragments of irradiated MTR fuels, typically about the size of a grain of sand. These are largely composed of aluminium with about 20% irradiated fuel and fission products.
NaI based detector	Sodium Iodide (NaI) crystal is a scintillating medium, which via a photomultiplier enables gamma photon interactions to be detected and energies to be discriminated when coupled to a multi-channel analyser.

Neutron activation	Neutron activation is the process in which neutron radiation induces radioactivity in materials, and occurs when nuclei capture free neutrons, becoming heavier and entering excited states. Such nuclei are frequently radioactive, sometimes with very short half-lives, so they and their decay products generally make the material radioactive.
Neutron fluence	The number of particles traversing a unit area in a certain point in space. Most frequently measured in neutrons per cm^2.
NRPB	The National Radiological Protection Board (NRPB) was created in 1970. The body with the function to conduct research, and to provide technical services in the field of protection against both ionising and non-ionising radiations. Since 1977, NRPB has been required, by government, to give advice on the acceptability to and the application in the UK of standards recommended by international or inter-governmental bodies. The NRPB became part of the Health Protection Agency (HPA-RPD) on 1 April 2005.
Offshore	The area below Low Water Mark.
Particles	Particles discussed in this report are fragments of irradiated nuclear fuel from MTR, DFR or PFR fuel processing carried out at Dounreay. Their density is reported by UKAEA to be 2.64 g/cm^3 and are typically 0.5 mm in diameter. Particles consist of aluminium (MTR), niobium (DFR) or steel (PFR) with uranium as the main minority component. Particles would be classified as intermediate level waste because of the amounts of fission products (mainly caesium and strontium) produced by their irradiation in a reactor. DFR and PFR particles also contain activation products (^{94}Nb (DFR) & ^{60}Co (PFR)).
Particle Population Studies	Investigational work using divers and remote survey instruments to provide information on the density and distribution of particles on the seabed.
Particle replenishment	The concept that additional particles are moving into an area (e.g. from the disturbance of a *cache*) to replace those lost by natural processes, or after the removal of particles found by divers. Studies of the extent to which this is taking place can be called *particle repopulation studies*.
Pelagic	A term generally applied to fish which spend the greater part of their time away from the bottom, frequently in mid or surface water. Many species feed on prey located in the water column. Some move down to the seabed to lay eggs. Many species are migratory covering large distances in relatively short periods of time and exhibit strong shoaling behaviour. Examples include herring and mackerel.
PFR	Prototype Fast Reactor; the second fast reactor operated at Dounreay 1974 – 1994.

Plastic scintillator detector	An organic scintillator which has been dissolved and polymerised to produce the equivalent of a solid solution.
Plume	A pattern of distribution of particles on the seabed.
Poisson distribution	The Poisson distribution is a mathematical model, which is used to describe the number of events observed in a given time or a given area. The Poisson distribution is defined in terms of a single rate parameter. Classically it is used to model the number of counts observed as a result of radioactive decay.
Precautionary principle	The Rio Declaration defines the precautionary principle as “where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation”. Precautionary action requires assessment of the costs and benefits of action, and transparency in decision making.
Radionuclide	An atom with an unstable nucleus that emits ionising radiation.
Rectosigmoid	The lower large intestine.
Re-population studies	Particle population studies in defined seabed areas where divers have removed all particles to investigate by further survey the rate at which the areas become re-populated with particles.
Running median	The running median is a sequence of medians of subsets of the data. Typically it is calculated sequentially (e.g. the median of observations 1 through 5, then the median of observations 2 through 6 and so on). This generates a smoothed sequence of values.
The Radioactive Waste Management Advisory Committee (RWMAC)	The independent advisory body that advises UK Government, including the devolved administrations for Scotland and Wales, on issues relating to the management of civil radioactive waste.
Saltation	Periodic resuspension and transport of large sediment particles in a bouncing manner.
Sandside	The coastal area of Reay, about three kilometres southwest of the Dounreay site; references in this report being to Sandside Bay and to Sandside beach. Sandside beach is privately owned and open to the public.
Sand waves	Large scale ripple-like structures on the seabed.
Scintillation counter	A device for detecting and counting ionizing radiation by exploiting the atomic or molecular excitation produced by a charged particle as it passes through matter.

Self attenuation	Absorbance or radiation by the material within which the radioactivity resides.
SEM	Scanning electron microscopy.
SEPA	The Scottish Environment Protection Agency (SEPA) was established on 1 April 1996 with duties, powers and responsibilities provided under the Environment Act 1995. It regulates discharges to fresh and tidal waters, emissions to the atmosphere, and disposal and transport of waste. SEPA also has specific duties with respect to radioactive substances and will assume a regulatory role for the more severely contaminated land sites. SEPA amalgamated the environmental duties of 64 predecessor bodies including Her Majesty's Industrial Pollution Inspectorate (HMIPI), the Hazardous Waste Inspectorate, the River Purification authorities, and the components of former Local Authorities handling waste regulation and other polluting activities. SEPA is the body responsible, *inter alia*, for granting authorisations to dispose of radioactive waste under the Radioactive Substances Act 1993.
Shaft	The shaft was excavated in 1956 to facilitate removal to the surface of earth and rubble from a 600 metres long tunnel, which was then under construction to house the site's liquid waste sea discharge pipeline. The Shaft is 65 metres deep with an additional 4.6 metre sump excavated at the base of the Shaft proper (to accommodate two submersible pumps used during construction). About 12 metres of the Shaft are above sea-level. The Shaft is 4.6 metres wide and is unlined except for the top 8 metres (where there is a wire mesh and shotconcrete cover to the rock). A link tunnel was constructed to connect the Shaft to the pipeline tunnel. The main depth of the Shaft and, consequently, its contents (waste and water) are in contact with the Dounreay Shore Formation bedrock and the groundwater system. At the surface, the Shaft is about 5 metres from the cliff face. By August 1957, UKAEA had decided to use the Shaft for disposal of radioactive waste. A reinforced concrete plug was emplaced in the connecting tunnel and pressure grouted to isolate the Shaft from both the pipeline tunnel and the sea. In 1959, the Scottish Office licensed the Shaft as a disposal facility for ILW and authorised disposals took place between 1959 and 1977.
SHIP investigations	Shaft Hydrogeological Isolation Programme.
Sievert	The sievert (symbol: Sv) is the SI derived unit of dose equivalent. It attempts to reflect the biological effects of radiation as opposed to the physical aspects, which are characterised by the absorbed dose, measured in grays.
Spectral stripping procedure	Detectors with relatively poor energy resolutions, require stripping when multiple gamma photon energies are being detected. For example, contributions to the ^{137}Cs 662 keV

	full energy peak may come from scattered gamma photons from higher energy gamma emitting radionuclides and primary gamma contributions from natural series radionuclides with energies close to 662keV. Previously recorded spectra from pure sources are required so that their influence on more complex multiple gamma spectra can be measured. The recorded spectrum is then stripped or “unpeeled” by starting with the largest anticipated energy.
Stochastic effect	A radiation induced health effect characterised by a severity that does not depend on dose and for which no lower threshold exists. The probability of such an effect being observed is proportional to the dose. An example of a stochastic effect if cancer.
Swarf	Swarf is the debris or waste resulting from metalworking operations and consists of shavings and chippings of metal.
UKAEA	The United Kingdom Atomic Energy Authority; a state owned organisation reporting to the Department of Trade and Industry responsible, *inter alia*, for decommissioning nuclear research facilities, including those at Dounreay itself, Harwell and Winfrith.

APPENDIX A DPAG MEMBERSHIP

Chair
Professor Keith Boddy, CBE, DSc, FRSE (from April 2003, member since inception)

Dr Campbell Gemmell (from May 2001 to March 2003)

Ms Julie Tooley (from April 2001 to May 2001)

Ms Tricia Henton (since inception to March 2001)

Members
Professor Tim Atkinson, FGS, C. Geol. (from April 2003)

Professor Keith Clayton, CBE (since inception)

Professor Alex Elliott, BA, PhD, DSc, FInstP, ARCP (from April 2003)

Professor Anthony Harris, PhD, F.G.S, C.Geol. FRSE, (from April 2003)

Dr Andrew Tyler, BSc, MSc (since inception)

Professor Marian Scott, BSc, C. Stat, FRSE (since inception)

Professor Lynda Warren, BSc, MSc, PhD, FRSA, (from April 2003)

Dr Bernard Wilkins, BA, DPhil (since inception)

Dr Nick Bailey (from inception to September 2001)

Dr Phil Gillibrand (from September 2002 to January 2004)

Technical Secretariat
Dr Paul Dale BSc, DPhil (from March 2002)

Mr Peter Orr (from inception to March 2002)

Administrative Support
Ms June Moore (from January 2005)

Ms Allyson Wilson (from June 2001)

Ms Jane Bremner (from inception to March 2002)

Observers
Scottish Environment Protection Agency

The Scottish Executive

The United Kingdom Atomic Energy Authority

APPENDIX B BIOGRAPHICAL DETAILS OF CURRENT MEMBERS

PROFESSOR KEITH BODDY CBE (Chairman)

Professor Boddy gained his PhD from the University of Glasgow and Doctorate of Science the from the University of Strathclyde. His was awarded an Honorary DSc De Montford University and is a Fellow of The Royal Society of Edinburgh; Fellow of Institute of Physics and an Honorary Fellow of: Institute of Physics and Engineering in Medicine; British Nuclear Medicine Society; British Institute of Radiology; Society for Radiological Protection; European Federation of Medical Physics.

He was formerly; a Lecturer/ Senior Lecturer Scottish Universities Research and Reactor Centre and Head of Health Physics and Nuclear Medicine Unit; Professor and Head of Regional Medical Physics Department and Regional Radiation Protection Adviser, Northern Regional Health Authority and Head of University Department of Medical Physics, Newcastle University.

He was a member of Committee Member of Radioactive Waste Management Advisory Committee (RWMAC); Committee on Medical Aspects of Radiation in the Environment (COMARE); Ionising Radiations Advisory Committee (IRAC).

Professor Boddy is also the former President of: Institute of Physics and Engineering in Medicine; Hospital Physicists Association; International Organisation for Medical Physics; International Union for Physics and Engineering in Medicine.

PROFESSOR TIM ATKINSON (Member)

Tim Atkinson is Professor of Environmental Geoscience at University College London and a Visiting Fellow at the School of Environmental Sciences, University of East Anglia. He directs UCL's Groundwater Tracing Unit and the Bloomsbury Environmental Isotope Facility. His research contributions have ranged across the disciplines of hydrology, hydrogeology, geomorphology, Quaternary geology, palaeo-climatology and geochemistry. He has a BSc and a PhD from the University of Bristol, is a Chartered Geologist and Fellow of the Geological Society of London, and a member of COMARE.

PROFESSOR KEITH CLAYTON CBE (Member)

Professor Clayton gained his first degree in geography at Sheffield, 1949. Following National Service, he was awarded MSc and PhD degrees in geomorphology. He was appointed Founding Dean, School of Environmental Sciences, University of East Anglia, 1967, and Dean again from 1987 to 1993. He served on COMARE, 1985-2001.

PROFESSOR ALEX ELLIOTT (Member)

Professor Elliott graduated with a B.A. with first class honours in Physics from the University of Stirling. He gained a Ph.D. in the Faculty of Medicine from the University of Glasgow and a D.Sc. in the Faculty of Science University of Glasgow.

He is currently the director of West of Scotland Health Boards Department of Clinical Physics and Bioengineering, Glasgow and a Professor of Clinical Physics, University of Glasgow, Glasgow. He is the Chairman, Clinical Services North Glasgow University Hospitals NHS Trust/Division and vice-Chairman, of the R&D Strategy Group and Deputy Lead Officer. He is the current Chairman of COMARE.

PROFESSOR ANTHONY HARRIS (Member)

Professor Harris graduated B.Sc. (1956) and Ph.D. (1959) at the University College of Wales, Aberystwyth. He is: a Fellow of the Royal Society of Edinburgh, Fellow of the Geological Society of London and Fellow of the Geological Society of America; Emeritus Professor of Geology, University of Liverpool; Distinguished Visiting Fellow, University of Cardiff and Research Associate, National Museum of Wales. He was formerly a Principal Geologist of the British Geological Survey, Edinburgh; Professorial Head of Department of Earth Sciences and Dean of the Faculty of Science, University of Liverpool; President of the Geological Society of London; a member of RWMAC and a non-executive Director of the British Geological Survey.

PROFESSOR MARIAN SCOTT (Member)

Professor Scott is currently a Professor of Environmental Statistics at the University of Glasgow. She is: the Head of Department of Statistics, University of Glasgow; past Chair of Royal Statistical Society, Environmental Statistics Section. Advisory editor, Wiley Statistics in Practice book series. Trustee of S.P.R.U.C.E. She is also a Fellow of the Royal Society of Edinburgh.

DOCTOR ANDREW TYLER (Member)

Dr Tyler is a Senior Lecturer in the School of Biological and Environmental Sciences at the University of Stirling. He specialises in the development of monitoring and remote sensing systems for the detection and impact assessment of environmental radioactivity, and the use of radionuclides as tracers for environmental processes. In 2003, Dr Tyler was invited to join UKAEA's, Beach Monitoring Steering Group (BMSG), to provide impartial advice on the next generation of beach monitoring equipment. He is also an editorial board member on the international journals *Water Air and Soil Pollution* and *Water Air and Soil Pollution Focus*.

PROFESSOR LYNDA WARREN (Member)

Lynda Warren is Emeritus Professor of Law at the University of Wales Aberystwyth. She has postgraduate qualifications in marine biology and marine law and policy and is a fellow of the Institute of Biology. She was a member of RWMAC and is a member of the Committee on Radioactive Waste Management (CoRWM). She is a Board Member of the Environment Agency and a non-executive Director of the British Geological Survey. She has recently been appointed as a member of the Royal Commission on Environmental Pollution. She undertakes consultancy work on nuclear law and policy for IDM (Integrated Decision Management) a consultancy specialising in the provision of strategic advice on nuclear matters.

DOCTOR BERNARD WILKINS (Member)

Dr Wilkins joined the National Radiological Protection Board (NRPB)[7] in 1973, having obtained his degree in chemistry at the University of York and completed his doctoral research in physical chemistry at the University of Sussex. He is currently leader of the Environmental Investigations Group. Since joining NRPB, he has undertaken a wide range of applied research dealing with radionuclides in the environment. For example, he was heavily involved in the response to the Chernobyl accident in 1986 and in 1998 led the NRPB's part in the response to the discovery of contaminated feral pigeons around Sellafield in Cumbria.

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[7] NRPB became part of the Health Protection Agency in April 2005.

Dr Wilkins has contributed to the work of the COMARE sub-group on Dounreay particles since the early 1990's. Following the discovery of such particles on the seabed, he contributed to the assessment commissioned by SEPA that was published in 1998. He coordinated the subsequent work commissioned by SEPA that has since been published as a series of reports on the Agency's website.

APPENDIX C RECOMMENDATIONS FROM DPAG'S SECOND INTERIM REPORT

C.1.1 DPAG considers that all parties involved in the issue of particles at Dounreay have made progress in developing greater comprehension of the particle issues. However, it is DPAG's opinion that greater progress could be and needs to be made in the following areas.

C.2 Characterisation of particles

C.2.1 Particles that are still contained in the non-active drains on the Dounreay site should be characterised to determine abundance together with physical and chemical constituents.

C.2.2 A representative sample of particles should undergo basic high-resolution gamma-ray spectrometry to determine their content of ^{137}Cs and ^{95}Nb. Further analysis should also be undertaken on a number of particles to determine the range of radionuclides contained within the particles. Routine characteristics to be determined should include mass.

C.2.3 There is a need to characterise adequately the possible corrosion of particles, which should include any aluminium and niobium associated with the particles.

C.3 Estimation of particle population

C.3.1 Building on the implications of existing reports, a further review of the historic practices at UKAEA Dounreay may indicate further potential sources of particles entering the marine environment. This review may be able to quantify the potential contribution from sources such as the Low Activity Drains (LAD) and non-active drainage systems, whilst being able to discount other potential sources.

C.3.2 With respect to the detection of particles in the historic, non-active drainage systems, DPAG recommends that UKAEA ensure that all current and historic drainage systems on the Dounreay site are or have been monitored to determine if they currently contain particles.

C.3.3 Information should be obtained on the possible contamination by particles of filters on the LAD to provide evidence of the potential extent of contamination.

C.3.4 DPAG considers that at this time the marine monitoring programme is insufficient to allow a reliable estimate of the particle population to be determined. DPAG awaits information from UKAEA on the progress it has been able to achieve in developing appropriate monitoring methodologies to determine extent and density of particles in the marine environment. DPAG would welcome information from UKAEA on any progress it has been able to make on the interpretation of the Fathom Instrument Towed System (FITS) data as recommended in the first DPAG report. DPAG has welcomed the particle re-population work which has been undertaken by UKAEA since 2000 to determine the rates at which particle movement may be occurring. DPAG would welcome the continuation of this work.

C.3.5 The particle finds at Cross Kirk and Brims Ness indicate that the density of particles at these areas is greater than that estimated close to the Diffuser in an earlier report by SEPA[8].

C.4 Adequate marine monitoring

C.4.1 DPAG notes that work is in progress on a number of our recommendations detailed in the first interim report concerning the ability to determine the population of particles present in the marine environment. Particularly DPAG note that work is developing the use of gamma spectroscopy in surveys offshore (to distinguish particles from naturally radioactive rocks and sand) and with reviewing the statistical processing used to recognise peaks in the Fathoms Instrument Towed System (FITS) data. This work should improve confidence in interpreting the number, distribution and movement of particles remaining in the marine environment. DPAG acknowledges the difficulty in developing an appropriate monitoring methodology and would welcome an update of any progress achieved in developing any suitable monitoring methodology since the last DPAG report.

C.4.2 DPAG would welcome a direct approach to search for potential offshore springs to determine whether they are capable of carrying particles and/or polluted water.

C.5 Modelling of particle movement

C.5.1 DPAG has been informed of work commissioned to determine the possible destination of particles discharged from UKAEA Dounreay. We would welcome further work to be commissioned into determining the potential of differing particle populations in the marine environment to be transferred beyond the FEPA area and the probability of particles being taken up by biota.

C.5.2 The disturbance of particles in and around the Diffuser, as a consequence of hosing and high pressure jetting in 1979, 1980 and 1983, and discharges through the Non-Active Drainage system deserve further consideration in relation to the distribution and transportation of particles.

C.6 Terrestrial monitoring programme

C.6.1 DPAG considers that the requirements stipulated by SEPA for the monitoring and detection of particles on local beaches should be reviewed to reflect particle activities that may pose a significant risk to health. DPAG understands that SEPA has commissioned further research work in this area and would encourage SEPA to ensure that this work is completed and reported timeously.

C.6.2 DPAG recommends that SEPA and/or UKAEA provide information on the typical depths of sand which are disturbed through the progression of a seasonal cycle.

C.6.3 Overall, our understanding of the offshore distribution has improved considerably, though some important issues remain unresolved and are the subject of continuing investigation. The re-population studies indicate a highly mobile surface layer with sand containing active particles of relatively small size. The regular repopulation of cleared areas shows that particles are able to move at least 27 m over a 4 month period of a summer season; thus, concepts of particle supply and dispersal which require smaller rates of movement need to be treated with considerable caution.

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8 Particle density estimated in 0-2 km from the Diffuser in 1998, (the estimate in 1998 was based on very limited sea bed surveys).

C.6.4 Particles are still being detected in the marine and coastal environments around UKAEA Dounreay. However, as pointed out earlier, UKAEA has not yet been able to develop an appropriate methodology to allow discrimination of particles in the marine environment from natural radioactivity. In the absence of suitable methodology for such detection, DPAG can only attempt to make approximate estimations of the extent or concentration of particles in the marine environment on which to base its preliminary recommendations.

C.6.5 UKAEA has continued to develop modelling of the marine circulatory patterns around Dounreay to determine the fate of any particles discharged from the site. DPAG welcomes this development and wishes for the models to be fully developed and peer reviewed, ensuring the validity of the model outputs. The development of appropriate marine monitoring would provide data to confirm calibration of the model. DPAG could then provide basic advice and recommendations on the extent and concentration of particles in the environment with greater confidence.

APPENDIX D CHRONOLOGY OF HISTORICAL PRACTICES AND EVENTS, AT UKAEA DOUNREAY

D.1 Introduction

D.1.1 This simplified chronology of historical practices and events, at UKAEA Dounreay, potentially involving the discharge of radioactive particles from the site, was produced originally as an aide-memoir for the Dounreay Particles Advisory Group (DPAG) of SEPA. Although a comprehensive summary has been attempted based on current knowledge, it cannot be exhaustive and will inevitably be incomplete.

D.1.2 In considering practices, their time-span has been identified as far as possible and a note provided of the route(s) for potential discharges.

D.1.3 This summary of events is an update of the review undertaken previously by RWMAC (RWMAC 1999), which was itself based on a UKAEA report (Simson 1997).

D.2 Practices

Treatment of MTR fuel (Higginson 2000)

D.2.1 Milling of MTR fuel in the D1204 Pond began in 1958, and stopped after Run 21 in July 1963. The operations were transferred to the DMTR Pond, recommencing there in January 1964 and ceasing, after Run 39, in 1969. The process resumed in the D1204 Pond in November 1969 and ended, after Run 49 in 1973.

D.2.2 There is evidence, including events listed below, that many more than 100,000 active particles, generated by milling, were discharged *via* the Low Activity Drain (LAD) and hence the Diffuser to the marine environment.

D.2.3 Particular reference was made to severe problems with radiation and contamination at the DMTR Pond during the breaking down of fuel elements from the French Pegase reactor. An identified cause was the production of irradiated uranium- aluminium swarf because the separation of the milling cutters required adjustment for these elements. In addition, the greater length of the separated Pegase fuel plates entailed cutting them in half in the DMTR Pond before transfer to D1204 for coiling and dissolution, adding to the number of particles generated during milling. As a consequence of the brittleness of this fuel, pieces frequently broke off during the coiling operation.

D.2.4 After 1973, a procedure involving “crushing and cropping operations” was adopted in the D1204 Pond, during which particles or ‘slivers’ continued to be created and discharged. This practice continued until Run 61 in 1996.

D.2.5 The unsophisticated system intended to catch inactive and active particles generated in these processes was inadequate. Consequently, particles entered the Pond water and accumulated sludge. During the 1960’s to mid-1980, the “filtration” system was evidently concerned primarily with maintaining water clarity rather than preventing particles being released into the LAD.

D.2.6 Indeed, it is reported that the ‘overflow facility’ of the D1204 Pond was used to remove ‘suspended fission product particles’ in 1973 and again during Run 54 (March – August 1979) to maintain clarity of the Pond water. An ion-exchange unit was introduced in Run 57 (July- October 1987), followed by an engineered Pond Clean-up Unit used in the final Runs 59, 60 and 61 from April 1992 to October 1996. It should also be noted that, although a ‘Stella Meta-filter’ had been introduced in May 1966 to improve clarity of the Pond water, the filter medium (a diatomaceous powder) and the particulate collected were periodically discharged, in the form of a slurry, and flushed down the LAD. In 1979, a new recirculatory filtration system was fitted that did not generate sludges. Filtration of Pond water was installed in 1984.

D.2.7 Replacement of the original LAD was completed in 1981 and the Diffuser in 1992.

D.2.8 This chronology suggests that the generation and discharge of MTR particles, albeit in smaller quantities, continued for, at least, some 15 years after milling ceased and, perhaps, longer depending upon the effectiveness of filtration introduced in 1984. Some particles were presumably discharged along the new LAD to the Old Diffuser but, if the filtration was effective, not to the New Diffuser.

Treatment of DFR fuel (Higginson 1999)

D.2.9 The treatment of DFR fuel using the leach dissolver began in February 1969. Fires occurred periodically. On 30 May 1972 a more substantial fire resulted in the release of $4x10^{11}$ Bq ^{137}Cs at the FCA stack. The dissolver was taken out of service in 1979.

D.2.10 No release of airborne particulate associated with the May 1972 incident was reported. UKAEA has stated *“At all times the gaseous discharge from the D1206 dissolver was initially supplied with a wet scrubber, but this was changed to a dry type in the early 1960’s. There was also installed a mercuric-nitrate scrubber to deal with ^{131}I and it is believed that there was a further wet scrubber in the low active cell and HEPA filtration. The ^{137}Cs was in the form of a vapour.”*

D.2.11 Operationally, DFR particles were discharged *via* the LAD system in a manner similar to that of MTR particles. Figure 2.3 illustrates that DFR particles were probably discharged to the LAD from the leach dissolver and decontamination of the Blanket Cave. The niobium content of the fuel was used as a marker. Although subject to considerable uncertainty, the “best estimate” of the amount of niobium discharged to sea was 200 g[9].

Transfer and disposal of swarf to the Shaft

D.2.12 Between July 1959 and September 1966, about 200 disposals to the Shaft of MTR swarf from the D1204 Pond were made together with a further 65 disposals from the DMTR Pond between January 1964 and March 1968. Routine disposals of swarf ceased towards the end of 1969, when a policy of returning swarf to the dissolver was adopted. DFR fuel residues were also disposed of in the Shaft.

9 Appendix 1 of Higginson 1999 quotes the mass of two particles and the percentage of niobium they contained. These limited data suggest that the mass of niobium in each particle was about 30-100 microgrammes. This would imply that about 1 million particles could have been discharged to sea, but only an unknown fraction may have contained fission products. There also appears to be large variations in the relative amounts of Nb-94 and Cs-137 among particles for which data are quoted. Despite these considerable uncertainties, it seems reasonable to assume that, like MTR, a large number of particles (perhaps in excess of 100,000) could have been released to the LAD.

D.2.13 There is evidence of particle contamination of roadways and verges along the transit routes. Such contamination was common at the Shaft Head and its surroundings as a result of the somewhat crude tipping of swarf into the Shaft. Some degree of airborne contamination, at least, to local surroundings including the beach and cliff tops would have been inevitable, especially in windy conditions. Recent surveys have shown no significant residual contamination off site.

The Diffusion Chamber

D.2.14 During normal operation, the Diffusion Chamber housed the intact Effluent Discharge pipework and its branches to the upstands through which discharges were made to the marine environment.

D.2.15 As indicated in the following section of Events, it became clear in 1981 that the pipework had failed earlier. Presumably, thereafter, mixing occurred within the Diffusion Chamber itself prior to discharge. Settling of particles in the Chamber and re-entrainment of some particles during the turbulence of subsequent discharges seems likely.

D.2.16 Although the New Diffuser became operational in 1992, the old discharge lines were purged monthly until 1998, with consequent potential for entrainment of some of the particles remaining in the Old Diffuser.

D.3 <u>Events</u>

Year: 1958

D.3.1 The generation of swarf from irradiated MTR fuel elements started on 9 July 1958 when the MTR Fuel Reprocessing Plant (DI204) log indicated that the first batch of active elements had been discharged into the pond where they were milled, sheared and coiled for loading into the dissolver. Later entries in the Dl204 log, during August, indicated that swarf was removed from the pond for transfer to the Shaft for disposal. The first of the entries suggests that the pond had been drained before the removal of the swarf.

D.3.2 Such practices could have led to some of the swarf in the pond being discharged by the LAD. Indeed, notes of the Dounreay Management Committee meeting, held on 21 August 1958, mentioned that levels of up to 80 mR per hour [0.8 millisievert per hour] had been detected on top of the duct carrying the LAD. These dose rates were attributed to the transfer of raffinates to the High Active Liquor Store (DI208) but it is also possible that they included discharges from the plant washout in D1204. Other incidents of high radiation levels up to 6 R per hour [60 mSv h^{-1}] had been reported over the drain line.

Year: 1963

D.3.3 An intense cleaning exercise on the D1204 pond started on 10 May. Particulate activity in the pond had been high and obstinate. On the night shift of 21 May 1963, the night shift supervisor at D 1204 noted that, after 90% of the swarf had been removed to the disposal flask and the pond had been emptied, a radiation reading of 11 R per hour [110 mSv h^{-1}] was found on the pond ejector. This indicated that swarf had been ejected into the LAD.

D.3.4 During drain surveys, high spots were noted on 25 May. By 12 June, they had progressively moved down the drainage system. On the 14 June 1963, a worker who was inspecting the effluent line at the radiation monitoring point north of the Dounreay Fast Reactor received a dose of 7 R [70 mSv] in an estimated exposure time of one minute. The comment was made "*I noticed sludge coming down the effluent line*". It is possible that in this incident the sludge could have been particulate matter, which may or may not have been connected with the incident at D1204 briefly described above.

D.3.5 Estimates of the activity in the material are put at 400 Ci [14.8 TBq] of which it was estimated that up to 17 Ci [0.6 TBq] were discharged after the pipeline was washed. If the activity discharged was in the form of swarf it could represent well over 100,000 particles.

D.3.6 Whether or not this is the case, it seems to demonstrate that it was not uncommon for sludges or particulate material of high specific activity to have entered the LAD system. It may well be possible that similar incidents occurred before 1963 and these could be revealed by further examination of the records of that period.

Year: 1964

D.3.7 Leakage of swarf was reported to have occurred from a hole in the cast iron Low Active Drain into the drain trench at a point close to D1204, shortly before 26 August 1964. Study of the records of the Shaft disposals has revealed that on 3 September 1964, one cubic foot of swarf with an estimated activity of 23.8 Ci [0.9 TBq], which had been recovered from the LAD duct outside D1204, had been discharged into the Shaft. As one review points out, "*The fact that this swarf had leaked through a hole corroded in the cast-iron pipe implies that an even greater quantity of swarf had been discharged from the pond into the LAD. Although the quantity of swarf could have been large, the amount of fuel associated with the swarf appears to have been small as the activity of recovered swarf suggests that it contained less than 1 gram of irradiated fuel*." However, three MTR particles found on the Dounreay Foreshore contained an average of about 0.5 mg of uranium. This suggests that the leaked material contained about 1000 particles and the discharge many more, possibly 100,000 or more. This event demonstrates again that significant quantities of highly active particulate material were often found to be in the discharges through the LAD.

D.3.8 Health Physics supervisors' logs showed that support was given for the removal of the swarf from the LAD trench and that radiation levels in the trench were in excess of 100 R per hour [1 Sv h^{-1}]. Anecdotal information suggests that, after the greater part of the swarf had been removed, the fire brigade was called to hose any remaining swarf down the drain trench. In theory, such water should have reached the low level liquid effluent tanks (DI2II). However, there are design features that are unlikely to have provided sufficient separation between the LAD trench and the now defunct Acid Drain trench to cope with large quantities of water from a fire hose. It seems highly probable that overflow would have resulted in direct discharge of swarf to sea via the acid drain trench.

D.3.9 If the swarf recovered contained about 1,000 particles, conjecturally, hosing of the swarf remaining in the LAD trench could have caused, at least several hundred thousand particles to pass into and be discharged via the Acid Drain Trench, which is nominally a Non-Active drain.

D.3.10 Recent checks on the old Acid Drain have failed to find any residual particles.

Year: 1965

D.3.11 In November 1965, de-mineralised water was being transferred from the Dounreay Fast Reactor (DFR) in order to top up the Dounreay Materials Test Reactor (DMTR) fuel pond during cleaning operations. A spillage occurred when the pipe was fractured by a lorry and contaminated water, possibly including some active particles, was siphoned from the DMTR pond onto the roadway near the DFR. It is reported that this was then washed down a storm drain by the site fire brigade, which could have led to the discharge of particles via this route.

D.3.12 It has been estimated that the discharge amounted to about 5 mCi (2×10^2 MBq), corresponding to a few hundred particles. However, its basis is unclear and may represent an underestimate.

D.3.13 With the exception noted below, recent investigations of the entire non-active drain system on the site have failed to identify any particles in this system.

Year: 1977

D.3.14 The explosion in the Shaft could, in principle, have been responsible for the distribution of the particles. However, the explosion occurred in the air space above the waste and it is most unlikely that any significant waste particulate material would have been disturbed. Some spots of contamination were sufficiently active to be explained by the presence of a particle, but at the time, no separation was carried out to confirm this. However, if the Shaft explosion were the source of the particles being found on the Foreshore over such a long period of time, the level of contamination following the explosion would need to have been substantially greater than that which was reported. Also, the recent work to provide the containing wall around the Shaft showed no evidence of residual particulate contamination in the rock and soil which forms the cliff edge.

Year: 1979

D.3.15 In July 1979, the pumping rate from the D1211 Effluent Tanks suddenly decreased, resulting in a discharge taking about 8 hours to occur rather than the customary period of about 2 hours.

D.3.16 Pumping pressures, reportedly of 3.4 to 10 bar, were applied to the discharge pipeline and the Diffusion Chamber (from the landward side), apparently without resultant improvement in flow.

D.3.17 In August 1979, divers reported that the upstands could not be located but the annual inspection by divers in that year revealed that "*something had swept the area and had broken off the upstand pipes flush with the seabed*". (A similar situation was found in 1983 when most of the pipes were again flush with the seabed). The upstands were repaired by placing stainless steel surrounds, weighted with concrete filled bags, around them.

D.3.18 In December 1979, pumping rates suddenly improved, returning to normal values (without any direct intervention). Within two months however the divers were again unable to locate the risers.

Year: 1980 (see Higginson 2000)

D.3.19 Increased resistance to flow through the discharge pipework, encountered from 1979 onwards, was attributed to mobile sand waves on the sea- bed covering the outfall location. In 1980, the sand was blasted clear of the Diffuser area. It seems likely that this procedure would have dispersed particles previously settled in the Diffuser and in neighbouring sand.

D.3.20 In August 1981, dye testing showed that, regardless of the discharge tube being used, dye emerged not only from all of the unblocked upstands but also along fissures in the rock. This indicated that the pipework in the Diffusion Chamber had failed.

Year: 1983

D.3.21 A number of the upstands from the old diffusion chamber, situated 25 metres below the sea- bed, had become blocked prior to 1983. In July of that year, they were cleaned by high- pressure water- jetting. Shortly after this operation, the first positively identified particle was found on the Dounreay Foreshore. There had been finds in 1979 and 1982 that could have been particles. Regular monitoring of the Foreshore was begun which revealed and continues to reveal, about one particle per month. Following the finding of ‘black tarry agglomerates during the monitoring of Sandside Beach the first fuel particle was found on this beach. It is not possible to say if this and subsequent findings of particles were the result of the high velocity clean out of the pipework, which may have retained particulate contamination from some of the incidents described above. Alternatively, this could have been merely a result of more intense surveying that identified particles already present on the Foreshore prior to the water jetting operation.

D.3.22 In the mid-1980’s, the site Director placed an embargo on any excavation or water jetting of the old upstands.

Recent finding in a Non-Active drain and an isolated Sentencing Tank

D.3.23 Following a recent survey of Non-Active drains, particles were recovered from a blocked section of a drain that runs under building D9814.The drain is an extension of the DMTR Pond complex D1251. These MTR particles may have been generated during the breakdown of fuel elements in the DMTR Pond, from mid 1964 to mid 1968. A tundish, provided to collect surplus water, was connected to this extension from this drain.

D.3.24 The drain has now been fully isolated and the nature of the blockage apparently suggests that it had not “*carried any flow for a considerable time*”. Nevertheless, it is considered reasonable to assume that releases to the sea occurred historically, probably *via* Outfall 01, but possibly others.

D.3.25 It is evidently not possible to estimate the number of particles discharged by this route nor when the last releases might have occurred. The importance of this realisation is that it is evidence strongly indicating that particles have been discharged previously through the Non-Active drainage system.

D.3.26 In the same general area, an isolated Sentencing Tank has been identified that potentially contains particles from the DMTR Pond. However, unlike the drain, particles would have been discharged *via* the LAD system.

APPENDIX E COULD THE DOUNREAY SHAFT BE A POSSIBLE SOURCE FOR THE MARINE PARTICLES?

E.1 Introduction

E.1.1 Spatial evidence from maps showing the position and shape of the sea-floor plume of particles strongly suggests an origin in the Old Diffuser and dispersal from there mainly to the eastnortheasterly, largely driven by tidal currents and storms from a general westerly direction.

E.1.2 However, improved hydrogeological knowledge of the site and awareness that quantities of radioactive swarf derived from fuel-reprocessing activities were disposed of in the Shaft while it was an authorised ILW disposal site, have prompted suggestions that the Shaft, too, may be an indirect, but ongoing source of particles found on the seabed.

E.1.3 One of the implications of this would be that, even following the proposed isolation of the Shaft during Site remediation, particles now in transit from Shaft to the seabed might continue to appear on the seabed for an unpredictable time into the future.

E.1.4 This section of the report assesses the likelihood of this possibility.

E.2 The geological setting of the Dounreay Shaft

E.2.1 As shown in Figures E.1 and E.2, the Dounreay Establishment, the coast and the Foreshore to the seaward of it, and the sea bed within the area of interest for the particle problem, are all underlain by rocks of the Middle Devonian, Dounreay Shore Formation. These are well-bedded sandstones, mudstones, calcareous siltstones and sparse thin limestones. The strata dip at ~ 10° to the northwest, striking approximately parallel to the general trend of the coast line between Sandside Bay and Crosskirk Bay.

E.2.2 Locally above the Dounreay Shore Formation to the east of the site is a siltstone/sandstone unit >50 m thick, the Crosskirk Bay Formation; below this is the Sandside Bay Formation which is divided at the Fresgoe Sandstone Unit into Upper and Lower members. The Upper Sandside Bay Member is predominantly siltstone, whereas sandstones predominate in the Lower Sandside Bay Member within which is included the Fresgoe Sandstone itself. Beneath the Sandside Bay Formation, the Bighouse Formation is also predominantly sandstone.

E.2.3 Two boreholes 1300m deep, named Nirex 1 and Nirex 2 (Figures E.1 and E.2) were drilled in the 1980's as part of an investigation into the potential of the Dounreay site for deep disposal of nuclear wastes. The base of the Bighouse Formation was encountered at different levels in the two holes, c. –370 m OD in Nirex 1 and c. –440 m in Nirex 2. Beneath the Bighouse Formation, the Nirex 1 borehole entered the Precambrian crystalline basement rocks of the Moine Supergroup, whereas the Nirex 2 penetrated a further series of mudstones, sandstones and conglomerates assigned to the Lower Devonian Luachair Formation. These continued down to c. –550 m OD at which level the basement rocks were penetrated.

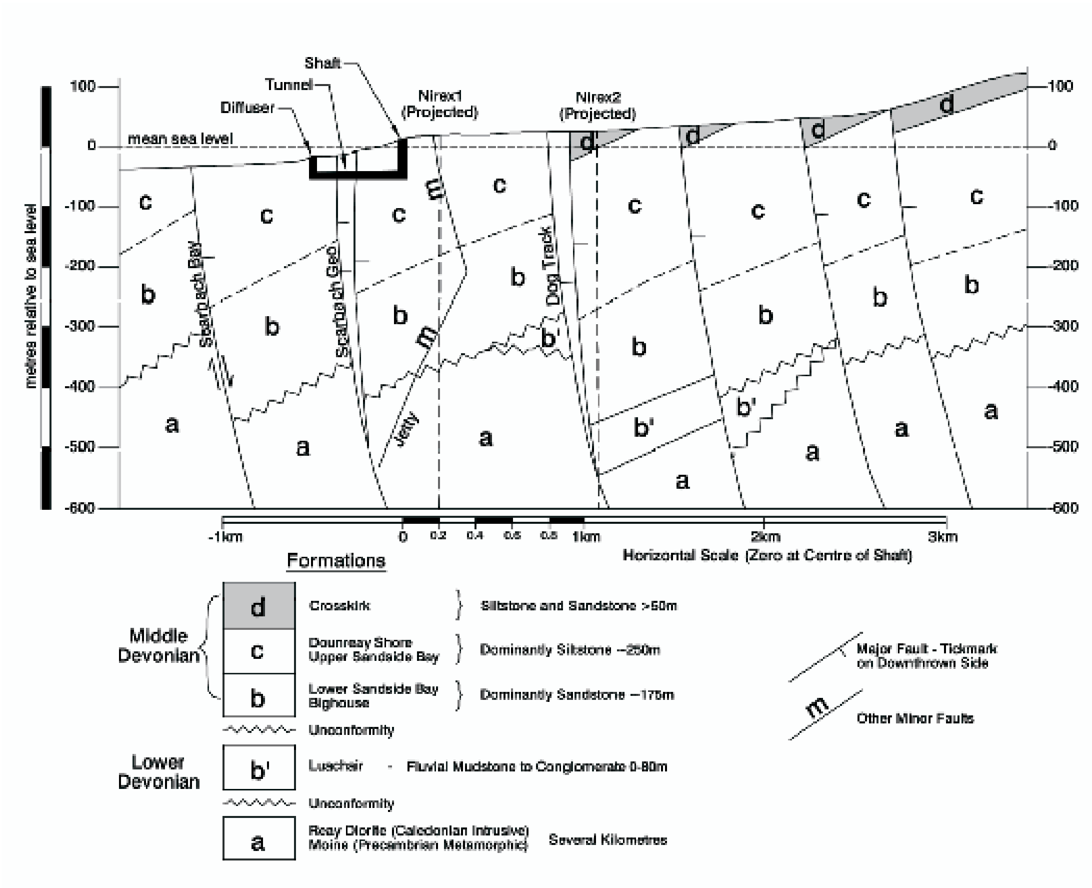

Figure E.1 Geological cross-section along line shown on Figure E.2. Nirex boreholes 1 and 2 (see Figure E.2 are projected)

E.2.4 Geological mapping at the surface has demonstrated the existence of a series of faults trending generally N-S and lying 150-700 m apart. These, together with other faults, are shown on Figures E.1 and E.2. The Shaft lies between the Scarbach Geo Fault and the Jetty Fault. The projected line of the Scarbach Geo Fault passes through the Tunnel at about 470 m from the base of the Shaft. The two Nirex boreholes lie on either side of the Dog Track Fault which is a single fault in the south, but divides into two branches northwards.

E.2.5 The level of the base of the Bighouse Formation is about 200 m deeper in the Nirex 2 borehole than would be expected from a simple projection of the dip of the strata from the level of the same rocks in Nirex 1. This is due to vertical displacement of c. 300m down to the E across the Dog Track Fault.

E.2.6 Figure E.1 is a schematic cross-section of the large-scale geological structure along the line shown on Figure E.2. The exact displacements along faults other than the Dog Track Fault are conjectural, although to some extent constrained by the patterns of outcrop along the coast. All are smaller than the 200m associated with the Dog Track Fault.

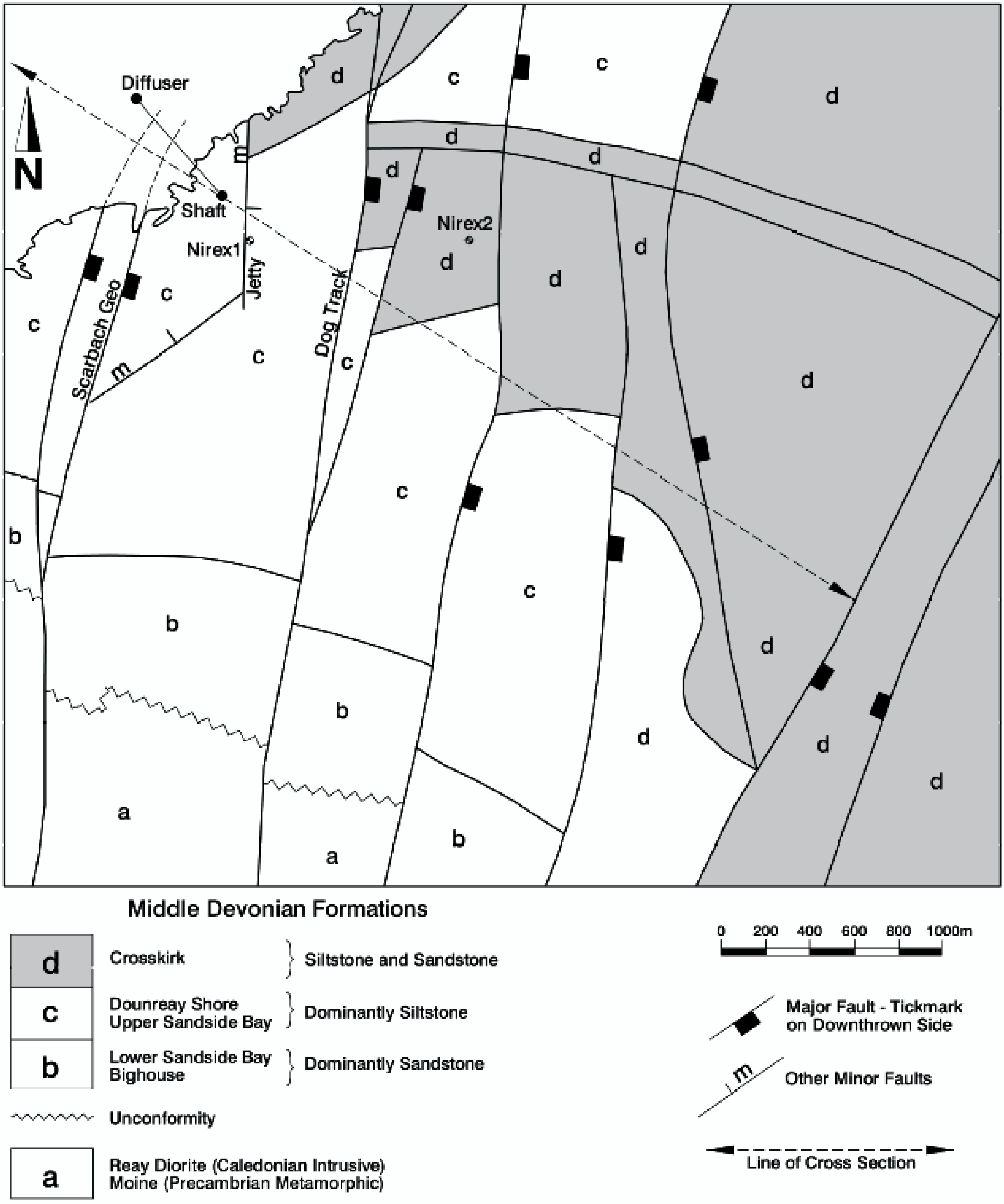

Figure E.2 **Solid geological map of the Dounreay area. (Note the position of the Nirex boreholes 1 and 2).**

E.2.7 Fig. E.1 also shows that the Shaft, Tunnel and Diffuser all lie at a shallow depth (down to –54 m OD) within the Dounreay Shore Formation, which, because of their shared siltstone-fine sandstone lithology, has been grouped in this Figure with the Upper Sandside Member. The base of this combined layer is stepped by faulting and is underlain by a stepped, but laterally continuous layer of sandstones, comprising the Lower Sandside Member, and Bighouse Formation. Below this, across unconformities, lie the conglomerates, sandstones and mudstones of the Luachair Formation and the fractured, crystalline Moine rocks.

E.2.8 At a much more local scale, outcrops of the Dounreay Shore Formation are cut by three sets of fractures aligned perpendicular to the strata. The two main sets are aligned approximately in the direction of dip and in the direction of strike (i.e. at 900 to the dip direction) and are known as the dip-set and strike-set respectively. A less prominent set of joints is aligned approximately N-S, parallel to the faults described in paragraph E.2.4. Examined at exposure, many minor faults are seen to be parallel to the N-S and strike-set and have displacements ranging down to a few millimetres.

E.2.9 All three sets of joints show differences in expression between sandstone and siltstone beds on the one hand, and mudstones on the other. These lithologies alternate, with the coarser grained rock predominant in zones up to about 20m thick, separated by zones in which mudstones predominate. Within the sandstone-siltstone zones, joints of all sets tend to be laterally persistent and to transect several beds vertically. On the foreshore these joints are often weathered and open for horizontal distances of tens of metres. By contrast, joints in mudstones are tightly closed and rarely penetrate from one layer to another.

E.2.10 Only a tiny sample of the total volume of the rock involved in the problems of understanding the detailed geology and hydrogeology of the Dounreay Establishment and its installations is available for direct inspection. Furthermore, although this is a three-dimensional problem, foreshore apart, the boreholes, Shaft and Tunnel are all one-dimensional sections and prone to the cut-effect and other limitations of one-dimensional evidence.

E.3 <u>The regional hydrogeological setting of the Dounreay Shaft</u>

E.3.1 The hydrogeology of the Dounreay area was first discussed in a report by the Institute of Geological Sciences (now the British Geological Survey) in 1987. Their report described the general geological structure, and the relative balance of rainfall, evaporation and stream flow in the area. It concluded that there is an annual surplus of rainfall over evaporation that is not fully accounted for by stream-flow. The surplus rainfall was, therefore, inferred to flow through the subsurface strata towards the coast, before finally discharging *via* seepage or springs to the sea. This model was supported by water-level data in several boreholes.

E.3.2 There are few springs or seepages of fresh water from the cliffs or beach along the Dounreay Foreshore. Therefore, any groundwater that does not contribute to streams must exit directly to the seabed. Observations made by divers support this hypothesis. Data on water salinity were obtained during a survey and search for radioactive particles within a rectangular area that straddles the line of the Tunnel and extends from c. 75 m to c. 400 m offshore of the Low Water Mark (Figure E.3). Readings from several patches of the seafloor showed salinity to be >5% lower than the usual salinity for seawater in this vicinity. These patches were concentrated around locations between 250 m and 400 m offshore on either side of the line of the Tunnel and appear to imply the presence of fresh water springs that are locally diluting the sea water close to the sea bed. At one location a salinity anomaly of c. 2% was associated with radioactive count rates that were well above background levels. Precise pinpointing of the supposed springs was hampered by the tidal currents which dispersed the fresh water. Hence it has not been established that the anomalies represent springs issuing from a definite fracture; they may be diffuse zones of freshwater seepage through the seabed. Nevertheless, the salinity anomalies strongly imply discharges of groundwater directly to the seabed. Were it not for other considerations, such discharges could imply the existence of a viable mechanism for the transport of particles by this route.

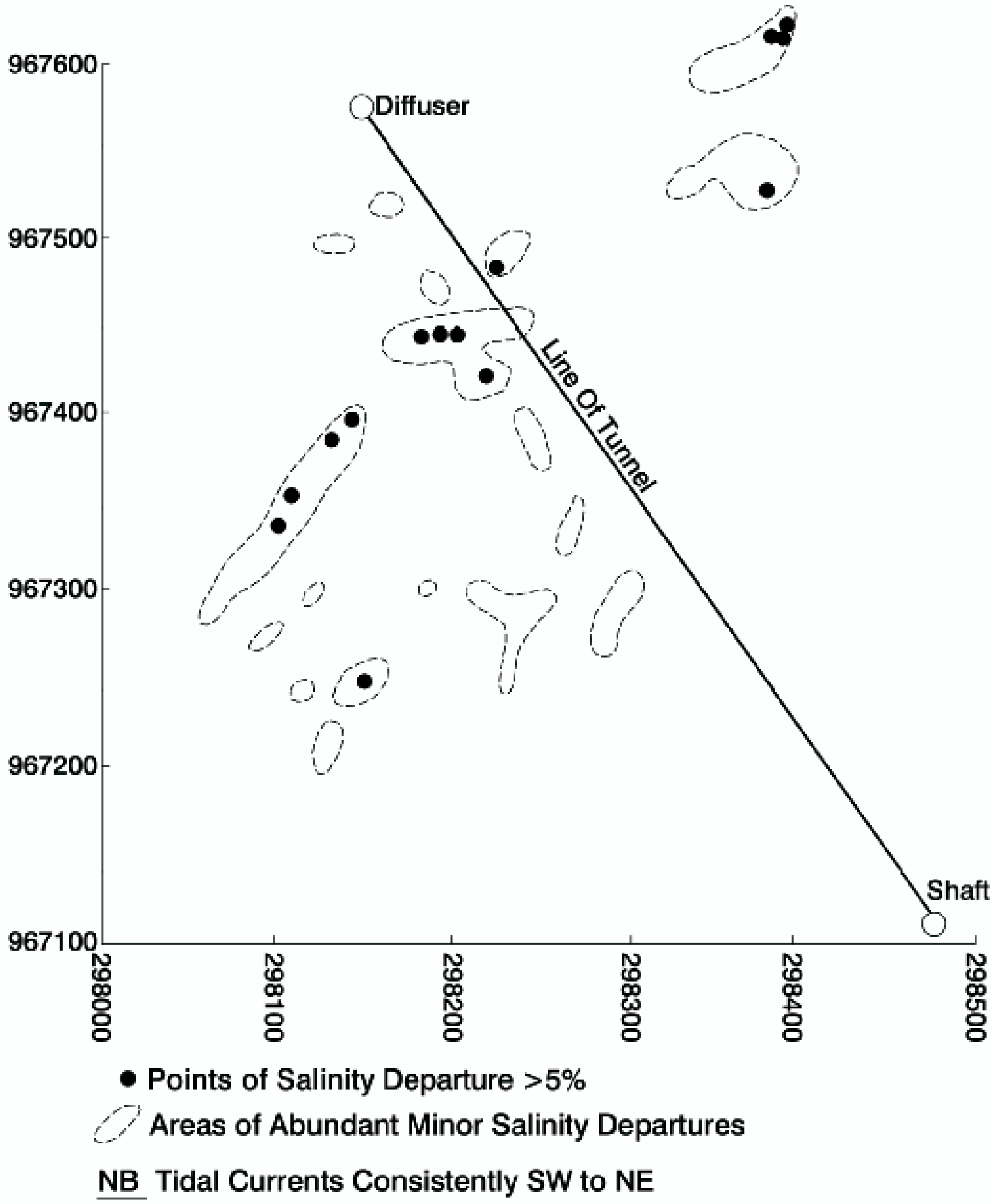

Figure E.3 Distribution of sea-water salinity anomalies in the vicinity of the Shaft/ Tunnel/Diffuser

E.3.3 Measurements of groundwater level (also termed hydraulic head) have been obtained from a number of boreholes drilled since the 1970's, in the two Nirex boreholes, and in a series of holes drilled for the Shaft Hydrogeological Isolation Programme (SHIP) (2000-2003). The permeability of the rock has been measured by means of hydraulic tests at different levels in all of these boreholes. Figure E.4 shows the depth distributions of hydraulic head and permeability (expressed as hydraulic conductivity for fresh water) in the Nirex boreholes. Permeability and head are both highest in the sandstones of the Lower Sandside Bay and Bighouse formations. Above these the Dounreay Shore Formation displays lower values of hydraulic head. Permeability is also high close to the surface. The upward vertical gradient in hydraulic head, and the much higher permeability of the Devonian sandstones compared with that of the Moine crystalline rocks beneath them, can be used to infer the broad pattern of regional ground-water flow shown in Figure E.5.

E.3.4 Figure E.5 shows a schematic cross section from high ground south of the Dounreay Establishment to the seabed in the NW. The permeable sandstones of the Lower Sandside Bay and Bighouse formations are recharged by rainfall at their outcrop in the south. Groundwater flowing seawards in these formations must cross the strata to discharge either onto the sea floor or into streams on land. The poorly jointed nature of the mudstones of the Upper Sandside Bay and Dounreay Shore formations (see E.2-9) reduces the cross-strata permeability, creating the steep hydraulic gradient seen across the Upper Sandside Bay Member in Figure E.4. Beneath the area of the Dounreay Establishment, the regional-scale hydrogeology produces two general directions of groundwater flow – broadly northwards towards the sea, and upwards from deeper to shallower formations.

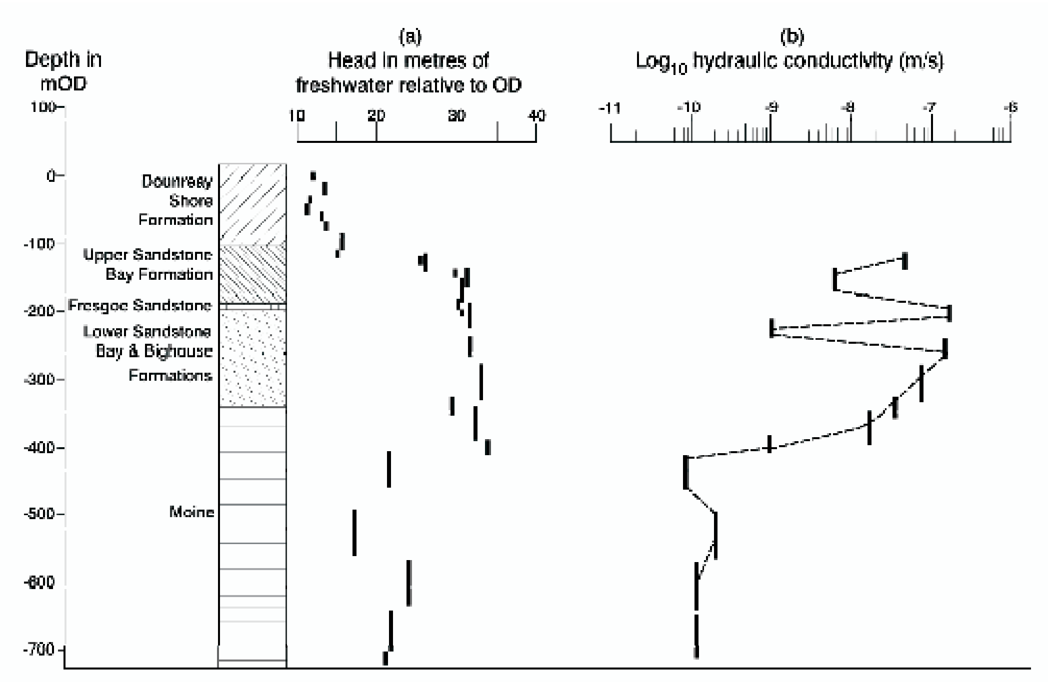

Figure E.4 **Depth distribution of hydraulic head (a) and permeability (hydraulic conductivity) (b) determined in the Nirex and SHIP boreholes in relation to solid geology (see column)**

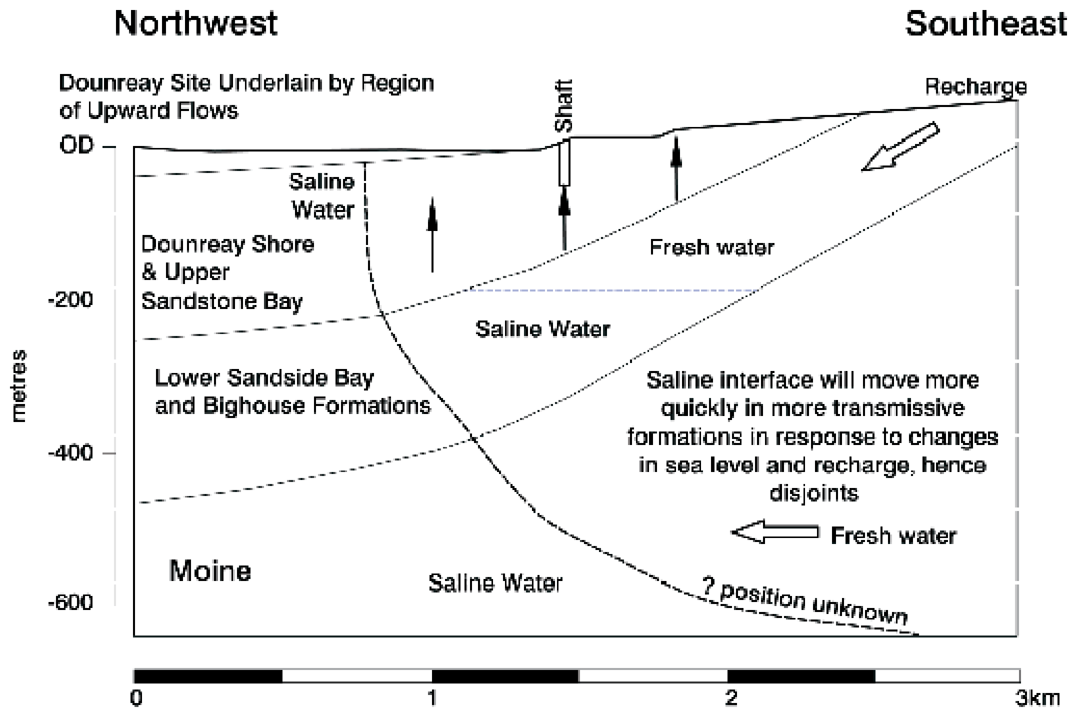

Figure E.5 **Schematic representation of inferred regional groundwater flow**

E.4 <u>Hydrogeological conditions locally around the Shaft and Tunnel</u>

E.4.1 Knowledge of hydrogeological conditions around the Shaft has greatly improved as a result of the SHIP investigations. Figure E.6, provided by UKAEA, summarises much of the current understanding of the detailed situation around the Shaft and the proximal part of the Tunnel.

E.4.2 The strata penetrated by the Shaft and Tunnel show distinct contrasting zones with respect to permeability. Figure E.6 shows that there are two permeable zones, respectively named the Upper Transmissive Zone (UTZ) and the Lower Transmissive Zone (LTZ). They are separated by a zone of lower permeability. As with the regional groundwater pattern, the local groundwater pattern has two directional components. There is a seaward movement of fresh groundwater, modified by a fluctuating flow imposed by tides in the sea. These flows tend to occur along the dip of the strata. The second component is the regionally imposed upward flow and discharge of fresh water to the seabed, which requires flow across the strata. These two components are indicated schematically by arrows in Figure E.6.

E.4.3 Due to their higher permeability, groundwater in the LTZ and UTZ is likely to be recharged at their outcrops by rainfall, and to flow down the stratal dip towards a zone of discharge to the sea bed. To reach the sea bed, the flow must rise against the strata in pathways that are likely to lie along faults and fractures. The areas of low salinity on the sea bed described above (E.3.2) are grouped around the line of the Scarbach Fault. It is likely that the salinity anomalies are due to fresh water rising along fractures associated with this fault. Due to the upward hydraulic gradient in the deeper strata, this rising groundwater is probably derived from the Dounreay area as a whole, and not merely from specific outcrops of formations.

E.4.4 The magnitude of each anomaly suggests that the volume flow rate must be in the order of litres or tens of litres of water per second, indicating that the whole zone of salinity anomalies may be discharging water derived from quite a large area of land to the south of the Establishment.

E.4.5 The presence of the Shaft and Tunnel cause a modification in their vicinity of the pattern just described. Water in the Tunnel is connected directly to the sea *via* the Diffuser and its level fluctuates by almost 5 m with the tides. This tidal influence is transmitted through the surrounding rock. Figure E.6 shows that the greatest fluctuations occur between –24 m OD and –44 m OD and that tidal oscillations are much smaller above and below these levels. The zone of largest tidal fluctuations corresponds to the zone of rock between the LTZ and the UTZ close to the Shaft. Fluctuations within the LTZ and UTZ are smaller and more uniform.

E.4.6 The average hydraulic heads have been recorded in boreholes in the vicinity of the Shaft. The lowest heads occur within the zone of greatest tidal fluctuation because of the proximity of the Tunnel, in which the average head is at sea level. Generally higher values of head occur above –24 m OD. Below –44 m OD heads are more than 7 m above OD. These two zones of high heads correspond to the UTZ and LTZ respectively.

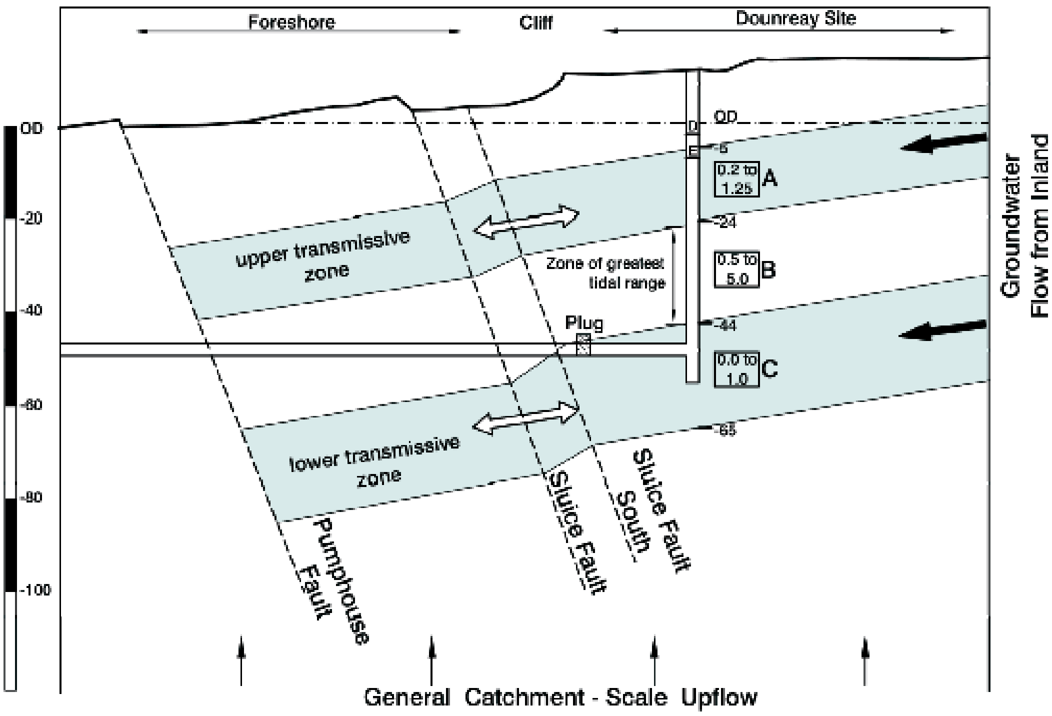

Figure E.6 Bedding-parallel permeable zones- the Upper and Lower Transmissive zones (UTZ and LTZ) – contrast with regional-scale upflow. These show minimal tidal range fluctuation and contrast with the tidal ranges detected in the intervening zone.

E.4.7 The distribution of heads determines the directions of groundwater flow within the UTZ and the LTZ, in the vicinity of the Shaft and Tunnel. Flow within the UTZ will be captured by the Tunnel. However, only the uppermost part of the LTZ is intersected by the Tunnel. It is possible that most of the flow in this zone passes down-dip to the northwest before rising to the sea bed *via* cross-stratal fractures or small faults. In other words the presence of the Tunnel causes a major local modification of the natural pattern of groundwater flow in the UTZ, but it is possible that its effect on that in the LTZ is much smaller. This possibility really depends on the permeability of whatever cross-stratal fractures may exist in the rock between the Tunnel floor and the top of the LTZ beneath it. If this rock is well fractured and hence readily permeable, ground water flow in the LTZ will probably be diverted and captured by the Tunnel. On the other hand, if there are few fractures in the critical zone of rock, then the low heads in the Tunnel may be effectively isolated from the LTZ by a barrier of low-permeability mudstones.

E.5 Discussion of the Shaft as a possible source for particles in the sea

E.5.1 We now turn to the hypothesis that particles have been transported from the Shaft to the seabed by groundwater flow. This is a complex issue, which has to be broken down into constituent parts for its overall viability to be assessed. For the hypothesis to be true, a series of conditions would have to be fulfilled at the Dounreay site. Most of these conditions relate to the situation beneath the ground, and beneath the sea bed. The main evidence comes from observations made in boreholes, and although such data are invaluable, they are also incomplete by their very nature (see E.2.10). Boreholes penetrate only along distinct lines and provide a tiny sample of the rock volume of interest. Much has to be inferred by interpolation and extrapolation from the observations made in them.

E.5.2 In the most general terms, the conditions that must be fulfilled for particle transport from Shaft to sea bed to be a reality are as follows:

i) There must be at least one pathway that is suitable for particle transport over the whole distance between Shaft and sea bed.

ii) The Shaft itself must act as an effective source of particles. In other words, circumstances within the Shaft must be such as to cause some particles to enter fractures in the surrounding rock in the lowest part of the Shaft system (see E.5.5), and thereby become available for transport.

E.5.3 Transport of sand-sized particles by groundwater in fractured rocks like those at Dounreay is generally highly unusual and has not been studied much. Considering the matter from first principles, for condition i) above to be met, a further series of conditions would have to be satisfied:

iii) There must be a flow of groundwater from relevant levels of the Shaft to the sea bed.

iv) At least a part of this flow must be via a continuously connected pathway through voids that are all large enough to permit the passage of particles of the appropriate size. At least one such pathway must persist throughout the whole distance between the base of the Shaft and the sea bed.

v) Water velocities along each and every part of such a pathway must be sufficient to move the particles under the conditions obtaining there, including those of steep upward gradients.

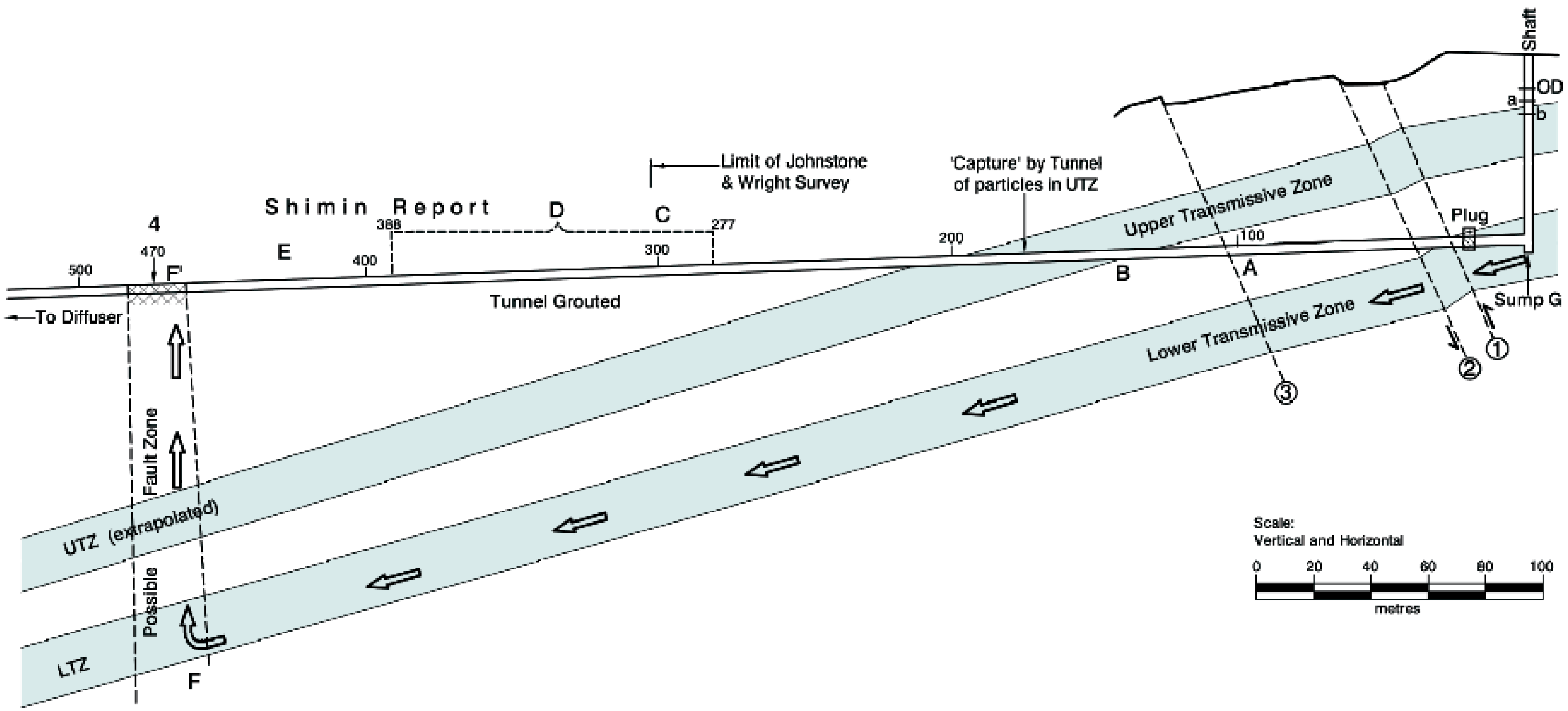

Figure E.7 Summary diagram (vertical and horizontal scales are equal) to show the relationship between groundwater flow and Shaft/Tunnel/Diffuser system and known geological features reported by observations contemporary with construction work. Note that the section is vertical and is in the plane containing the shaft/Tunnel/Diffuser

Notes to accompany Figure E.7

Notes on Shaft Content:

a) level of water in Shaft (fluctuates slightly)
b) level of surface of waste in Shaft

Notes on Geological Structures:

1 Sluice South Fault
2 Sluice Fault
3 Pumphouse Fault
4 Intersection of putative Scarbach Geo Fault with Tunnel/Sea Bed.

Notes on Geological conditions in Tunnel

Based on Johnstone & Wright (1956) and Shimin (1963). Both reports are based on observations made in the Tunnel during its construction.

A) Some water flowing on bedding planes (J&W);
B) Water flowing from small fissures on bedding planes (J&W);
C) Breakage and abundant close with flowing water; two open fissures 20cm and 10cm wide (J&W);
D) Zone 277m to 388m " very bad ground" and " extensive……. grouting required; quite wide fissures every metre or so ("few feet") in badly crushed rock—fissures filled with clay and sand and carrying abundant sea water---suspected more or less directly connected with sea" (S)
E) NW from ~ 388m (rock) conditions suddenly improved. No further grouting" "Inflow of sea water practically ceased" (S);
F) The sea floor to the SW and NE of this zone is locally the site of anomalously low salinity (Fig. E3), possibly caused by fresh-water springs issuing from the Scarbach Geo fault zone. (KC).

Attention is drawn to the potential connectivity of waste (particles) in the lowest part of the Shaft/Sump/Stub Tunnel part of the system (G) and the putative fault (F) by means of ground-water flow via the Lower Transmissive Zone (LTZ) (see discussion in text E5.6 to E5.13).

E.5.4 Groundwater flow around the Shaft was considered in sections E.2 and E.3. Figures E.5 and E.7 suggest that any water leaving the Shaft above the level of –44 m OD is likely to flow down the dip and be captured by the Tunnel. This is because the average hydraulic head in the Tunnel is at sea level, whereas heads in the rock are higher, so there is a net hydraulic gradient which water flow will follow towards the Tunnel.

E.5.5 Below –44 m OD the Shaft, Stub Tunnel and Sump (the lowest part of the Shaft, below the floor level of the Stub Tunnel) all lie within the LTZ. It is possible that groundwater within this zone flows down the dip before rising up fracture pathways across the strata. Some such pathways might be intersected by the tunnel, while others might reach the sea bed.

E.5.6 It is apparent that groundwater flow may exist between the lowest parts of the Shaft and the sea bed. It is therefore possible that condition iii) is fulfilled. However, this is not certain and it is also possible that the flow from the bottom part of the shaft rises upwards through short fracture pathways and is captured by the Tunnel.

E.5.7 Whilst water will flow through the narrowest of voids, particles require a continuity of void diameter larger than themselves if they are to pass. The relevant voids along which particles might be transported are all fracture openings of one type or another. Because of the 'cut effect', vertical borehole investigations, mainly give information about sub-horizontal fractures, as nearly vertical fractures present an easily-missed target for vertical drilling. On the other hand, the first 315 m of the very shallowly inclined Tunnel, which includes the whole of the UTZ, was inspected by geologists during its excavation. Their notes provide information along an approximately horizontal line and emphasise the role of sub-vertical fractures; again as result of 'cut effect'. In one section of the Tunnel, between 277 and 388 m from the Shaft, the Chief Engineer's published account describes the rock as being broken with many open upright fractures through which sea water plus sand and gravel entered the workings, and which had to be grouted to seal them. Elsewhere in the Tunnel the amount of water inflow was much less and was mostly *via* sub-vertical joints. Just two bedding plane fractures were recorded as showing obvious seepage. Their positions are marked on Figure E.7 and it may be noted that only one of these is in the UTZ, at its base.

E.5.8 Values of permeability determined from hydraulic tests can be used as the basis for calculation of the aperture of idealised, plane-sided fractures. These calculated hydraulic apertures are usually several times smaller than the apertures of the more open areas of real fractures, so they provide a minimum estimate for the aperture that a particle might follow during transport. Photographs taken in Dounreay boreholes show that observed apertures range from mere hairline cracks to openings as wide as 30 mm. Such a large range of apertures is best reconciled with the measured permeabilities of the same fractures if the fractures themselves possess channels – sinuous linear zones lying in the plane of the fractures with wider-than-average apertures that are separated by areas with lesser or zero apertures. Groundwater flow naturally concentrates along the channels and velocities are highest there. Therefore, channels are the most likely locus for particle transport. Detailed studies elsewhere have shown that channels are common features and may arise from a variety of causes.

E.5.9 A review of fractures and their suitability for particle transport was undertaken for UKAEA by Jacobs Gibb, and their report has been made available to DPAG. The report concludes that most of the permeability of the rock is due to sub-horizontal, bedding-parallel fractures that extend over hundreds of metres. They are spaced 1 - 5 m apart and have a channelled structure, with channels typically ~0.1 m wide and ~1 m apart. The apertures within the channels vary considerably, but may average about 1.5 mm, a value that would reconcile evidence from permeability tests with that from photographs. This is large enough for smaller Dounreay particles to pass, provided that there is an unbroken connectivity of apertures of this dimension.

E.5.10 An alternative view of the topographic form of the channels within the rock is that much of the permeability is due to intersecting sets of sub-vertical fractures. Although the recorded observations in the Tunnel support this, borehole investigations do not; all of the channel apertures seen in photographs are in horizontal fractures and none is associated with a vertical fracture. In part, this could be as a result of the cut effect.

E.5.11 Some bedding-parallel fractures probably have channel apertures wide enough for the smaller Dounreay particles to pass along them for quite long distances. The fractures show hydraulic continuity over hundreds of metres, and the estimates of fracture aperture are derived from the same hydraulic tests that demonstrate this; therefore it is possible that particles could be transported over similar distances, provided there is continuity of apertures of appropriate diameter. However, little is known of the apertures of bedding-normal, sub-vertical fractures in general. Although some large, open fissures were recorded in the Tunnel, these were a minority of the fractures observed, and there is no information on the apertures of these tighter, more common fractures.

E.5.12 Another critical requirement for particle transport through the rock is that water velocities should be large enough, not only to roll particles along bedding-parallel fractures, but also to lift them up vertical fractures. Calculations suggest that upward velocities of about 0.001 ms^{-1} are necessary in wide-aperture voids for particles with 40 μm diameter and about 0.5 ms^{-1} for 4 mm particles. These necessary velocities could be reduced by 10- or 20-fold if the larger particles were in channels only twice as wide as their own diameter, *i.e.* to a few centimetres per second. Groundwater velocities of centimetres per second are found in certain rocks, notably limestones, but have not been recorded in sandstones. Reported tracer tests in sandstones have demonstrated water velocities of a few millimetres per second, but there is no direct evidence from Dounreay regarding water velocities.

E.5.13 To summarise, it is conceivable that suitable conditions do exist for smaller particles to be transported through the rock mass from near the Shaft to either the Tunnel or the sea bed. However, all pathways that originate from the Shaft at levels above –43 m OD are likely to end in the Tunnel. Water velocities in the Tunnel are too low to move sediment along its floor. Therefore any particles that did reach the tunnel would remain trapped there and could not have escaped to form part of the marine particle population. As far as transport to the sea floor is concerned, the only conceivable source appears to be from the lowest part of the Shaft or the floor of the Stub Tunnel. Particles originating from here would have to be carried down the dip within the LTZ and then be lifted up faults or fractures to the sea bed. A vertical lift of about 100 m would be needed to reach the sea bed in the area of salinity anomalies described above (E.3.2). The velocities required even for large, significant or relevant particles could feasibly occur in a spring with a discharge of several litres per second fed by a channel persistently with 0.01 m^2 cross section – equivalent to a 1 cm wide fissure, and 1 m long across the direction of flow. The salinity anomalies would require discharges of this order, and these fissure dimensions are reasonable. Therefore, transport of large, *significant* or *relevant* particles from the LTZ to the sea floor cannot be ruled out. However, the evidence from boreholes regarding average channel apertures suggests that particles larger than ~1 mm are likely to be filtered out by bottlenecks and irregularities in bedding-parallel fractures. This consideration appears to make transport of the largest particles from the Shaft to the sea bed quite unlikely, although for the smaller ones (<1 mm) the possibility is feasible.

E.5.14 For a phenomenon to be conceivably possible is not the same as saying that it is likely to exist. Unfortunately the information at Dounreay is too limited for anything other than a qualitative assessment to be made of whether the necessary conditions which have been identified for particle transport are likely or unlikely. For particles with diameters larger than 1 mm, they seem unlikely, because groundwater velocities may be too slow to sustain transport and bottlenecks in bedding-parallel fractures would probably trap any large particles that reached them. For smaller particles, the likelihood of transport to the sea depends upon whether or not flow in the LTZ near the base of the Shaft is directed into the Tunnel or not. The observation that most of the seepage from the Tunnel walls was from vertical fractures militates in favour of flow being captured from the LTZ. However, the high heads in the LTZ militate against this, as the proximity of the sea-level head in the Tunnel would be expected to lower heads if pathways large enough to admit particles exist, as it does in the overlying zone of maximum tidal fluctuations. The possibility cannot be ruled out that a path to the sea such as the hypothetical one shown in Figure E.7 exists. If it does, particles smaller than 1 mm are much more likely to be carried along it, than are larger particles.

E.5.15 Returning to the general conditions identified in E.5.2, the second condition is that particles should be able to leave the Shaft and enter fractures in the surrounding rock. The numbers of particles involved are quite large. If we assume ~6000 radioactive particles present in the marine environment, and a ratio of radioactive particles to non-active particles in the original swarf of ~1:400, around 2.4 million particles should have left the Shaft and passed along fractures to the sea bed. This implies one particle every 7 minutes over a 30-year period, or over 200 particles per day, which seems an improbably high rate. Consideration of possible combinations of different ranges of mass among marine particles (from 1 to 20 mg) with the fraction of radioactive particles and the estimated numbers in the plume suggests that between 2 and 20 kg of swarf should have been transported to the sea bed over 30 years if the Shaft were the main source of the marine plume. Transport on this scale would require the swarf to remain as loose particles in the lower part of the Shaft, despite compaction of the wastes and corrosion of the ferrous metals present. (Evidence for a corrosive environment towards iron and steel is provided by the shaft explosion in 1977, which was due to hydrogen. This could have been produced either directly by slow corrosion of iron or, more probably, by corrosion in a reducing environment etching through the stainless steel containers in which sodium metal was disposed into the Shaft. Sodium reacts violently and explosively with water to produce hydrogen.) Movement of particles from the Shaft into the surrounding rock would require high water velocities among the loose particles, which also seems unlikely given the very large cross-sectional area of the Shaft and Stub Tunnel, and the small tidal ranges recorded within boreholes in the LTZ.

E.5.16 If the Shaft were the sole source of marine particles, very large numbers of particles would have had to have migrated into the surrounding rock. This seems very unlikely on the grounds that very high water velocities would have had to be maintained in a large open void containing loose particulate material over a 30 year period, during which the overlying wastes are known to have been compacted and corroded. It would also imply that the fractures in the rock around the Shaft would be likely to contain large numbers of particles, in train along pathways to the sea floor. No metal particles were found during the drilling of the SHIP, which also militates against the hypothesis.

E.6 <u>Conclusions</u>

E.6.1 For the Shaft to be the main or sole source of the particles in the marine environment would require two independent conditions to be met, both of them assessed above as unlikely. First, particles would have had to have left the Shaft and entered the surrounding rock at a rate of about 200 per day. Only one in about 400 of these would be radioactive. Second large particles would have had to be transported to the sea bed along pathways that have been assessed as being probably too narrow. While neither of these conditions is impossible in themselves, their occurrence in combination is far less likely than the probability of only one of them occurring. This combination renders it very unlikely that the Shaft is a source of the large (>1 mm) particles in the marine environment.

E.6.2 There remains the question of whether the Shaft might be contributing smaller particles to the marine environment. This would require much the same combination of conditions in the Shaft itself as for large particles. Filtering out of large particles could be envisaged to occur within the bedding-plane fractures of the LTZ. This possibility is much less improbable than the transport of large particles. Apart from the necessity of moving particles out of the Shaft itself, the main argument against it is that groundwater flow from the LTZ may be directed into the Tunnel and not down-dip towards the sea at all. Overall, it appears unlikely that the Shaft could be a source of smaller particles, but considerably less unlikely than for the larger particles.

E.6.3 It should be noted that a Shaft source that delivered only smaller particles to the sea bed would seem to be at odds with our current understanding of the dynamic behaviour of particles within the sea-bed plume. It appears from study of the particle finds, and the particles themselves, that the plume has been maintained by the presence of a cache of buried high activity particles which contain over 80% of the total radioactivity, but account for less than 15% of the total numbers. These high activity particles are mostly physically large, so are very unlikely to have come from the Shaft. When released by storm disturbance of the sea-bed sediments, they may break up to form smaller, low-activity particles, which are relatively rapidly dispersed from the area by tidal currents. Consideration of the Shaft as a possible contributor to this behaviour suggests that it is unlikely to be supplying the large, high activity particles which have maintained the plume over 30 years, although it is less improbable that it could contribute to the numbers of small, low -activity particles. Thus, if the Shaft is a source of particles at all, it is most unlikely that it plays any major part in the maintenance and longevity of the particle contamination of the sea floor off the coast of northern Scotland.

E.6.4 It is the intention of UKAEA to isolate the Shaft hydraulically from the surrounding rock by means of a grout and piling curtain. When this operation has been successfully completed, it should impede any potential particle migration from the Shaft to the sea bed thereafter. Only if there were a store of radioactive particles in transit would it be feasible for there to be a continuing supply to the sea bed once isolation of the Shaft had been achieved. The fact that no particles were found in any of the open fractures penetrated by the SHIP boreholes suggests that such a store must be small, if it exists at all. It is unlikely that a small store could maintain a flux of particles to the sea bed for very long after the Shaft had been isolated.

E.7 Summary of Conclusions

E.7.1 Though the hydrogeological situation at Dounreay involves many imponderables, the following conclusions have been drawn by assessing the available evidence and its implications.

- It is unlikely that particles could have migrated from the Shaft into the surrounding rock over a 30 year period, in sufficient numbers to form and sustain the sea bed population.
- Transport of larger (e.g. >1 mm) particles through the rock over distances of several hundred metres is unlikely.
- The necessary combination of two improbable processes makes it very unlikely that the Shaft is or has been a source of the large particles on the sea bed.
- The transport of smaller (e.g. <1 mm) particles is less improbable, but it is unlikely that the Shaft is contributing small particles to the sea bed, since this also would require the combination of two improbable processes. However, it is less improbable for small than for large particles.
- It follows from these considerations and from the dynamic behaviour of particles within the plume that it is very unlikely that particles from the

Shaft have played any significant role in the maintenance and longevity of the contamination by radioactive particles of the sea bed off northern Scotland.

E.8 Acknowledgement

E.8.1 The maps and diagrams accompanying this section of the Appendix are based on information and data made available from the UKAEA archives.

APPENDIX F THE PROBABILITY OF ENCOUNTERING A FUEL PARTICLE WHILE ON THE BEACH AT SANDSIDE BAY

F.1.1 This appendix draws extensively on material developed by HPA-RPD and published by SEPA (Smith and Bedwell 2005a; Smith *et al*. 2005).

F.2 Part A

F.2.1 The HPA-RPD study used published habit data to identify various groups of people who use the beach for different purposes and who, as a result, could come into direct contact with a fuel particle. These groups were then separated into sub-groups of "typical" and "high-rate" users. Thus, for example, people who took walks on the beach were divided into occasional users and those who used it more frequently such as dog-walkers. The habit data used by HPA-RPD are summarised in Table F.1. In common with the HPA-RPD study, this appendix focuses on high-rate users, since it is these sub-groups that will have the greatest chance of coming into close contact with fuel particles. The probabilities derived by HPA-RPD were based on monitoring data produced using the Groundhog Evolution system.

F.2.2 DPAG has designated particles containing 10^5 - 10^6 Bq ^{137}Cs as *relevant* and those containing more than 10^6 Bq as *significant*. It was important, therefore, to estimate specifically the probabilities of coming into contact with particles of 10^5 Bq ^{137}Cs or greater (although it should be remembered that so far no significant particles have been found on the beach at Sandside Bay). The estimates made by DPAG of the numbers of particles containing $>10^5$ Bq ^{137}Cs were very similar to the values derived by HPA-RPD (Chapter 5). Consequently, for relevant particles DPAG has used the estimates of probabilities and chance derived by HPA-RPD.

F.2.3 HPA-RPD considered the probability of contact with fuel particles in four activity ranges, and their results are reproduced in Table F.2. These data represent the total probabilities, taking all of the appropriate routes into account. HPA-RPD has, however, evaluated each of these routes individually as a function of the ^{137}Cs activity of the particle. The detailed data are given in Part B of this appendix. Probabilities are given on an annual basis and in terms of single visits. The text in this appendix focuses on annual values.

F.2.4 Table F.3 summarises the breakdown of probabilities by potential exposure route for each of the sub-groups considered. The values given relate to all particles found on the beach at Sandside Bay. From this table, estimated probabilities of a fuel particle getting trapped on clothing or in shoes were comparable or, in some cases, slightly greater than the values for direct skin contact. However, initial trapping of a fuel particle on clothes or in shoes would not inevitably result subsequently in direct physical contact of the particle with the skin. The probability of skin contact following trapping in shoes or clothing could therefore be much lower than the values given in Table F.3, although no confirmatory information is available. Overall, therefore, for all of the sub-groups except consumers of molluscs, HPA-RPD considered that direct contact with the skin was the most important individual pathway. Estimates of overall probabilities did, however, assume that trapping in shoes or clothing would give rise to skin contact. Consequently, the overall estimates given in Table F.2 and F.3 should be regarded as cautious.

Table F.1 Assumptions made about annual occupancies at Sandside beach

Age Group	Occupancy rates (h y^{-1})	
	High rate	Distribution
Adult Bait Diggers	330[b]	470-39[b]
Adult Leisure	300	410-24
Child Leisure	85	125-2
Infant Leisure	13.5	30-2

Notes

a The distributions are lognormal in all cases. The upper and lower bounds given represent the 97.5th and 2.5th percentiles respectively

b These values apply jointly to angling and bait digging. To apply to bait digging only, a scaling factor is applied.

F.2.5 Taking all of the potential routes of exposure together, the sub-group most likely to come into contact with relevant particles was that comprising adults who used the beach for leisure purposes at high rates (Table F.2). However, the probability was only 1.2 x 10^{-8} y^{-1}. In terms of chance, this corresponds to about 1 in 80 million per year. To take the converse approach, this implies that over the year there is roughly a 99.999999% chance of not coming into contact with a relevant particle while on the beach at Sandside Bay.

F.2.6 For direct contact with the skin only, bait diggers were the most important sub-group. The chance of a member of this sub-group having a relevant particle in direct contact with the skin was 1 in about 100 million per year (Part B, Table F.9). The chances of bait diggers or leisure users of any age group ingesting a particle of > 10^5 Bq ^{137}Cs were around 1 in 1 million million per year (Table F.6). The corresponding chances of inhaling a particle of this activity were lower still (Table F.4). The chances of particles becoming trapped in the ear and the eye were considered in a separate report (Smith *et al*. 2005). The chance of a particle of any activity becoming trapped in the eye was about 1 in 1 million million per year, the value for becoming trapped in the ear being lower still. The corresponding chances for relevant particles would be much lower than the values for all particles.

F.2.7 The HPA-RPD assessment indicated that the total estimated probabilities of encountering a fuel particle of any activity were dominated by what DPAG has termed *minor* particles. For example, HPA-RPD estimated that the chance of a member of the adult leisure group coming into contact with a particle of any activity was about 1 in about 2 million per year. This compared with the value of 1 in about 80 million per year for relevant particles only. For minor particles only, the HPA-RPD data in Table F.9 correspond to a chance of direct skin contact of about 1 or 2 in 10 million per year. The values for ingestion or inhalation would be about 1 in ten thousand million per year (from Tables F.6 and F.4 respectively). Both DPAG and HPA-RPD have noted that there are considerable uncertainties in the estimated numbers of minor particles present in the beach, and have used different approaches to scope the problem (see main text, Chapter 5).

Table F.2 HPA-RPD estimates of annual probabilities of encountering a fuel particle on Sandside Beach for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Annual probability of encountering a fuel particle on Sandside Beach (y^{-1})
< 20 kBq	Adult Bait Digger	$2.6\ 10^{-7}$
	Adult Leisure	$3.6\ 10^{-7}$
	Adult Winkle Consumer	$5.5\ 10^{-9}$
	Child Leisure	$1.2\ 10^{-7}$
	Child Winkle Consumer	$3.9\ 10^{-9}$
	Infant Leisure	$1.5\ 10^{-8}$
20 kBq - 50 kBq	Adult Bait Digger	$6.7\ 10^{-8}$
	Adult Leisure	$9.3\ 10^{-8}$
	Adult Winkle Consumer	$1.4\ 10^{-9}$
	Child Leisure	$3.2\ 10^{-8}$
	Child Winkle Consumer	$9.9\ 10^{-10}$
	Infant Leisure	$3.8\ 10^{-9}$
50 kBq - 100 kBq	Adult Bait Digger	$5.2\ 10^{-8}$
	Adult Leisure	$7.2\ 10^{-8}$
	Adult Winkle Consumer	$1.1\ 10^{-9}$
	Child Leisure	$2.4\ 10^{-8}$
	Child Winkle Consumer	$7.6\ 10^{-10}$
	Infant Leisure	$2.9\ 10^{-9}$
> 100 kBq	Adult Bait Digger	$8.9\ 10^{-9}$
	Adult Leisure	$1.2\ 10^{-8}$
	Adult Winkle Consumer	$1.9\ 10^{-10}$
	Child Leisure	$4.2\ 10^{-9}$
	Child Winkle Consumer	$1.3\ 10^{-10}$
	Infant Leisure	$5.0\ 10^{-10}$
Total	Adult Bait Digger	$3.9\ 10^{-7}$
	Adult Leisure	$5.4\ 10^{-7}$
	Adult Winkle Consumer	$8.2\ 10^{-9}$
	Child Leisure	$1.9\ 10^{-7}$
	Child Winkle Consumer	$5.8\ 10^{-9}$
	Infant Leisure	$2.2\ 10^{-8}$

Table F.3 HPA-RPD estimates of probabilities of encountering a fuel particle of any activity on Sandside Beach for the 'high rate' sub-group of each potentially exposed group

Exposure pathway		Adult Bait Digger	Adult Winkle consumer	Child Winkle consumer	Adult Leisure	Child Leisure	Infant Leisure
Direct contact on skin	Annual	$3.7\ 10^{-7}$	-	-	$1.9\ 10^{-7}$	$9.4\ 10^{-8}$	$8.4\ 10^{-9}$
	Per Beach Visit	$1.7\ 10^{-8}$	-	-	$1.1\ 10^{-9}$	$1.4\ 10^{-9}$	$6.2\ 10^{-10}$
Under a fingernail	Annual	$9.8\ 10^{-10}$	-	-	$1.4\ 10^{-8}$	$1.4\ 10^{-9}$	$4.9\ 10^{-11}$
	Per Beach Visit	$4.6\ 10^{-11}$	-	-	$4.6\ 10^{-11}$	$1.6\ 10^{-11}$	$3.6\ 10^{-12}$
Inhalation	Annual	$3.4\ 10^{-12}$	-	-	$1.7\ 10^{-11}$	$7.0\ 10^{-13}$	$4.0\ 10^{-14}$
	Per Beach Visit	$1.6\ 10^{-13}$	-	-	$5.7\ 10^{-14}$	$8.2\ 10^{-15}$	$2.9\ 10^{-15}$
Inadvertent Ingestion	Annual	$1.8\ 10^{-11}$	-	-	$1.3\ 10^{-10}$	$7.2\ 10^{-11}$	$5.8\ 10^{-11}$
	Per Beach Visit	$8.5\ 10^{-13}$	-	-	$4.3\ 10^{-13}$	$8.3\ 10^{-13}$	$4.3\ 10^{-12}$
Ingestion of winkles	Annual	**-**	$8.2\ 10^{-9}$	$5.8\ 10^{-9}$	-	-	-
On clothing[10]	*Annual*	$3.9\ 10^{-9}$	-	-	$5.4\ 10^{-8}$	$9.0\ 10^{-9}$	$6.8\ 10^{-10}$
	Per Beach Visit	$1.8\ 10^{-10}$	-	-	$1.8\ 10^{-10}$	$1.1\ 10^{-10}$	$5.0\ 10^{-11}$
In shoes[10]	*Annual*	$2.0\ 10^{-8}$	-	-	$2.8\ 10^{-7}$	$8.2\ 10^{-8}$	$1.3\ 10^{-8}$
	Per Beach Visit	$9.5\ 10^{-10}$	-	-	$9.5\ 10^{-10}$	$9.5\ 10^{-10}$	$9.5\ 10^{-10}$
Total[10]	Annual	$3.9\ 10^{-7}$	$8.2\ 10^{-9}$	$5.8\ 10^{-9}$	$5.4\ 10^{-7}$	$1.9\ 10^{-7}$	$2.2\ 10^{-8}$
	Per beach visit	$1.8\ 10^{-8}$	-	-	$2.3\ 10^{-9}$	$2.5\ 10^{-9}$	$1.6\ 10^{-9}$

F.3 Part B - Detailed data on the probability of encountering particles of differing ^{137}Cs activity as a function of the potential route of exposure.

F.3.1 Probabilities are given in terms of both annual values and on a per visit basis. These data have been taken directly from material produced by HPA-RPD and published by SEPA (Smith and Bedwell, 2005a). The data have therefore been derived using estimates of the numbers of fuel particles per unit area of beach derived by HPA-RPD. For relevant particles, these values are in good agreement with those derived by DPAG.

F.3.2 For completeness, the possibility of sand being taken from the beach for use in a child's sand pit were also considered by HPA-RPD. The probabilities of a particle being in the sand and of a child coming into close contact with it have been derived. The data are included here. From Table F.19, the chance of a child coming into close contact with a *significant* particle via this route was about 1 in 10 million.

10 The other exposure pathways relate to direct physical contact with a fuel particle. These exposure pathways do not imply direct physical contact but are simply used to determine the probability of a fuel particle getting trapped on clothes or in shoes. The probability of direct physical contact with a fuel particle following initial trapping on clothing or in shoes is expected to be significantly lower than the values given here. However, in the absence of data on this, the probabilities for these exposure pathways have been conservatively added to the probabilities for the direct exposure pathways to give the total.

F.3.3 Probabilities of skin contact are given for both “cold” and “warm” conditions. “Cold” conditions reflect those parts of the year when visitors to the beach would be warmly dressed and when they would be confined to activities such as walking and ball games. “Warm” conditions reflect periods when activities such as sunbathing and swimming might be carried out, and when children dig and play in wet sand.

Table F.4 Annual probabilities of inhaling a fuel particle on Sandside beach for the ‘high rate’ subgroup of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Annual Probability of inhaling a fuel particle (y^{-1})
< 20 kBq	Adult (bait digger)	$2.31\ 10^{-12}$
	Adult (leisure)	$1.15\ 10^{-11}$
	Child (leisure)	$4.70\ 10^{-13}$
	Infant (leisure)	$2.66\ 10^{-14}$
20 kBq - 50 kBq	Adult (bait digger)	$5.89\ 10^{-13}$
	Adult (leisure)	$2.94\ 10^{-12}$
	Child (leisure)	$1.20\ 10^{-13}$
	Infant (leisure)	$6.78\ 10^{-15}$
50 kBq - 100 kBq	Adult (bait digger)	$4.54\ 10^{-13}$
	Adult (leisure)	$2.27\ 10^{-12}$
	Child (leisure)	$9.24\ 10^{-14}$
	Infant (leisure)	$5.23\ 10^{-15}$
> 100 kBq	Adult (bait digger)	$7.81\ 10^{-14}$
	Adult (leisure)	$3.90\ 10^{-13}$
	Child (leisure)	$1.59\ 10^{-14}$
	Infant (leisure)	$9.00\ 10^{-16}$
Total	Adult (bait digger)	$3.44\ 10^{-12}$
	Adult (leisure)	$1.72\ 10^{-11}$
	Child (leisure)	$7.00\ 10^{-13}$
	Infant (leisure)	$3.96\ 10^{-14}$

Table F.5 Probabilities of inhaling a fuel particle on Sandside Beach per beach visit for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Probability of inhaling a fuel particle per beach visit
< 20 kBq	Adult (bait digger)	$1.07\ 10^{-13}$
	Adult (leisure)	$3.84\ 10^{-14}$
	Child (leisure)	$5.52\ 10^{-15}$
	Infant (leisure)	$1.97\ 10^{-15}$
20 kBq - 50 kBq	Adult (bait digger)	$2.74\ 10^{-14}$
	Adult (leisure)	$9.80\ 10^{-15}$
	Child (leisure)	$1.41\ 10^{-15}$
	Infant (leisure)	$5.02\ 10^{-16}$
50 kBq - 100 kBq	Adult (bait digger)	$2.11\ 10^{-14}$
	Adult (leisure)	$7.56\ 10^{-15}$
	Child (leisure)	$1.09\ 10^{-15}$
	Infant (leisure)	$3.88\ 10^{-16}$
> 100 kBq	Adult (bait digger)	$3.63\ 10^{-15}$
	Adult (leisure)	$1.30\ 10^{-15}$
	Child (leisure)	$1.87\ 10^{-16}$
	Infant (leisure)	$6.67\ 10^{-17}$
Total	Adult (bait digger)	$1.60\ 10^{-13}$
	Adult (leisure)	$5.73\ 10^{-14}$
	Child (leisure)	$8.24\ 10^{-15}$
	Infant (leisure)	$2.94\ 10^{-15}$

Table F.6 Annual probabilities of inadvertently ingesting a fuel particle on Sandside Beach for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Annual Probability of inadvertently ingesting a fuel particle (y^{-1})
< 20 kBq	Adult (bait digger)	$1.23\ 10^{-11}$
	Adult (leisure)	$8.57\ 10^{-11}$
	Child (leisure)	$4.86\ 10^{-11}$
	Infant (leisure)	$3.86\ 10^{-11}$
20 kBq - 50 kBq	Adult (bait digger)	$3.13\ 10^{-12}$
	Adult (leisure)	$2.19\ 10^{-11}$
	Child (leisure)	$1.24\ 10^{-11}$
	Infant (leisure)	$9.84\ 10^{-12}$
50 kBq - 100 kBq	Adult (bait digger)	$2.42\ 10^{-12}$
	Adult (leisure)	$1.69\ 10^{-11}$
	Child (leisure)	$9.56\ 10^{-12}$
	Infant (leisure)	$7.59\ 10^{-12}$
> 100 kBq	Adult (bait digger)	$4.16\ 10^{-13}$
	Adult (leisure)	$2.90\ 10^{-12}$
	Child (leisure)	$1.64\ 10^{-12}$
	Infant (leisure)	$1.31\ 10^{-12}$
Total	Adult (bait digger)	$1.83\ 10^{-11}$
	Adult (leisure)	$1.28\ 10^{-10}$
	Child (leisure)	$7.24\ 10^{-11}$
	Infant (leisure)	$5.75\ 10^{-11}$

Table F.7 Probabilities of inadvertently ingesting a fuel particle on Sandside Beach per beach visit for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Probability of inadvertently ingesting a fuel particle per beach visit
< 20 kBq	Adult (bait digger)	$5.72\ 10^{-13}$
	Adult (leisure)	$2.86\ 10^{-13}$
	Child (leisure)	$5.72\ 10^{-13}$
	Infant (leisure)	$2.86\ 10^{-12}$
20 kBq - 50 kBq	Adult (bait digger)	$1.46\ 10^{-13}$
	Adult (leisure)	$7.29\ 10^{-14}$
	Child (leisure)	$1.46\ 10^{-13}$
	Infant (leisure)	$7.29\ 10^{-13}$
50 kBq - 100 kBq	Adult (bait digger)	$1.13\ 10^{-13}$
	Adult (leisure)	$5.63\ 10^{-14}$
	Child (leisure)	$1.13\ 10^{-13}$
	Infant (leisure)	$5.63\ 10^{-13}$
> 100 kBq	Adult (bait digger)	$1.94\ 10^{-14}$
	Adult (leisure)	$9.68\ 10^{-15}$
	Child (leisure)	$1.94\ 10^{-14}$
	Infant (leisure)	$9.68\ 10^{-14}$
Total	Adult (bait digger)	$8.52\ 10^{-13}$
	Adult (leisure)	$4.26\ 10^{-13}$
	Child (leisure)	$8.52\ 10^{-13}$
	Infant (leisure)	$4.26\ 10^{-12}$

Table F.8 Annual probabilities of ingesting a fuel particle in winkles for the 'high rate' sub-group of winkle consumers for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Annual probability of ingesting a fuel particle (y^{-1})
< 20 kBq	Adult (leisure)	$5.52\ 10^{-09}$
	Child (leisure)	$3.87\ 10^{-09}$
20 kBq - 50 kBq	Adult (leisure)	$1.41\ 10^{-09}$
	Child (leisure)	$9.86\ 10^{-10}$
50 kBq - 100 kBq	Adult (leisure)	$1.09\ 10^{-09}$
	Child (leisure)	$7.61\ 10^{-10}$
> 100 kBq	Adult (leisure)	$1.87\ 10^{-10}$
	Child (leisure)	$1.31\ 10^{-10}$
Total	Adult (leisure)	$8.23\ 10^{-09}$
	Child (leisure)	$5.76\ 10^{-09}$

Table F.9 Annual probabilities of direct skin contact with a fuel particle on Sandside Beach for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Annual probability of contact with a fuel particle in sand on skin (y^{-1})
< 20 kBq	Adult (bait digger)	$2.46\ 10^{-07}$
	Adult (leisure)	$1.28\ 10^{-07}$
	Child (leisure)	$6.31\ 10^{-08}$
	Infant (leisure)	$5.64\ 10^{-09}$
20 kBq - 50 kBq	Adult (bait digger)	$6.27\ 10^{-08}$
	Adult (leisure)	$3.26\ 10^{-08}$
	Child (leisure)	$1.61\ 10^{-08}$
	Infant (leisure)	$1.44\ 10^{-09}$
50 kBq - 100 kBq	Adult (bait digger)	$4.84\ 10^{-08}$
	Adult (leisure)	$2.52\ 10^{-08}$
	Child (leisure)	$1.24\ 10^{-08}$
	Infant (leisure)	$1.11\ 10^{-09}$
> 100 kBq	Adult (bait digger)	$8.32\ 10^{-09}$
	Adult (leisure)	$4.33\ 10^{-09}$
	Child (leisure)	$2.14\ 10^{-09}$
	Infant (leisure)	$1.91\ 10^{-10}$
Total	Adult (bait digger)	$3.66\ 10^{-07}$
	Adult (leisure)	$1.91\ 10^{-07}$
	Child (leisure)	$9.41\ 10^{-08}$
	Infant (leisure)	$8.41\ 10^{-09}$

Table F.10 Probabilities of direct skin contact with a fuel particle on Sandside Beach for a beach visit under 'cold conditions' for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	**Exposed Group**	**Probability of contact with a fuel particle per beach visit**
< 20 kBq	Adult (bait digger)	$1.14\ 10^{-08}$
	Adult (leisure)	$3.18\ 10^{-10}$
	Child (leisure)	$1.91\ 10^{-10}$
	Infant (leisure)	$1.11\ 10^{-11}$
20 kBq - 50 kBq	Adult (bait digger)	$2.92\ 10^{-09}$
	Adult (leisure)	$8.10\ 10^{-11}$
	Child (leisure)	$4.86\ 10^{-11}$
	Infant (leisure)	$2.84\ 10^{-12}$
50 kBq - 100 kBq	Adult (bait digger)	$2.25\ 10^{-09}$
	Adult (leisure)	$6.25\ 10^{-11}$
	Child (leisure)	$3.75\ 10^{-11}$
	Infant (leisure)	$2.19\ 10^{-12}$
> 100 kBq	Adult (bait digger)	$3.87\ 10^{-10}$
	Adult (leisure)	$1.08\ 10^{-11}$
	Child (leisure)	$6.45\ 10^{-12}$
	Infant (leisure)	$3.76\ 10^{-13}$
Total	Adult (bait digger)	$1.70\ 10^{-08}$
	Adult (leisure)	$4.74\ 10^{-10}$
	Child (leisure)	$2.84\ 10^{-10}$
	Infant (leisure)	$1.66\ 10^{-11}$

Table F.11 Probabilities of direct skin contact with a fuel particle on Sandside Beach for a beach visit under 'warm conditions' for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Probability of contact with a fuel particle per beach visit
< 20 kBq	Adult (bait digger)	$1.14\ 10^{-08}$
	Adult (leisure)	$7.52\ 10^{-10}$
	Child (leisure)	$9.26\ 10^{-10}$
	Infant (leisure)	$4.18\ 10^{-10}$
20 kBq - 50 kBq	Adult (bait digger)	$2.92\ 10^{-09}$
	Adult (leisure)	$1.92\ 10^{-10}$
	Child (leisure)	$2.36\ 10^{-10}$
	Infant (leisure)	$1.07\ 10^{-10}$
50 kBq - 100 kBq	Adult (bait digger)	$2.25\ 10^{-09}$
	Adult (leisure)	$1.48\ 10^{-10}$
	Child (leisure)	$1.82\ 10^{-10}$
	Infant (leisure)	$8.22\ 10^{-11}$
> 100 kBq	Adult (bait digger)	$3.87\ 10^{-10}$
	Adult (leisure)	$2.55\ 10^{-11}$
	Child (leisure)	$3.14\ 10^{-11}$
	Infant (leisure)	$1.41\ 10^{-11}$
Total	Adult (bait digger)	$1.70\ 10^{-08}$
	Adult (leisure)	$1.12\ 10^{-09}$
	Child (leisure)	$1.38\ 10^{-09}$
	Infant (leisure)	$6.23\ 10^{-10}$

Table F.12 Annual probabilities of trapping a fuel particle under a fingernail for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Annual probability of trapping a fuel particle under a fingernail (y^{-1})
< 20 kBq	Adult (bait digger)	$6.55\ 10^{-10}$
	Adult (leisure)	$9.14\ 10^{-09}$
	Child (leisure)	$9.18\ 10^{-10}$
	Infant (leisure)	$3.26\ 10^{-11}$
20 kBq - 50 kBq	Adult (bait digger)	$1.67\ 10^{-10}$
	Adult (leisure)	$2.33\ 10^{-09}$
	Child (leisure)	$2.34\ 10^{-10}$
	Infant (leisure)	$8.31\ 10^{-12}$
50 kBq - 100 kBq	Adult (bait digger)	$1.29\ 10^{-10}$
	Adult (leisure)	$1.80\ 10^{-09}$
	Child (leisure)	$1.81\ 10^{-10}$
	Infant (leisure)	$6.41\ 10^{-12}$
> 100 kBq	Adult (bait digger)	$2.22\ 10^{-11}$
	Adult (leisure)	$3.10\ 10^{-10}$
	Child (leisure)	$3.11\ 10^{-11}$
	Infant (leisure)	$1.10\ 10^{-12}$
Total	Adult (bait digger)	$9.77\ 10^{-10}$
	Adult (leisure)	$1.36\ 10^{-08}$
	Child (leisure)	$1.37\ 10^{-09}$
	Infant (leisure)	$4.86\ 10^{-11}$

Table F.13 Probabilities per beach visit of trapping a fuel particle under a fingernail for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Probability of trapping a fuel particle under a fingernail per beach visit
< 20 kBq	Adult (bait digger)	$3.05\ 10^{-11}$
	Adult (leisure)	$3.05\ 10^{-11}$
	Child (leisure)	$1.08\ 10^{-11}$
	Infant (leisure)	$2.41\ 10^{-12}$
20 kBq - 50 kBq	Adult (bait digger)	$7.78\ 10^{-12}$
	Adult (leisure)	$7.78\ 10^{-12}$
	Child (leisure)	$2.75\ 10^{-12}$
	Infant (leisure)	$6.16\ 10^{-13}$
50 kBq - 100 kBq	Adult (bait digger)	$6.00\ 10^{-12}$
	Adult (leisure)	$6.00\ 10^{-12}$
	Child (leisure)	$2.13\ 10^{-12}$
	Infant (leisure)	$4.75\ 10^{-13}$
> 100 kBq	Adult (bait digger)	$1.03\ 10^{-12}$
	Adult (leisure)	$1.03\ 10^{-12}$
	Child (leisure)	$3.66\ 10^{-13}$
	Infant (leisure)	$8.17\ 10^{-14}$
Total	Adult (bait digger)	$4.55\ 10^{-11}$
	Adult (leisure)	$4.55\ 10^{-11}$
	Child (leisure)	$1.61\ 10^{-11}$
	Infant (leisure)	$3.60\ 10^{-12}$

Table F.14 Annual probabilities of a fuel particle adhering to clothing for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Annual Probability of a fuel particle adhering to clothing (y^{-1})
< 20 kBq	Adult (bait digger)	$2.59\ 10^{-09}$
	Adult (leisure)	$3.62\ 10^{-08}$
	Child (leisure)	$6.05\ 10^{-09}$
	Infant (leisure)	$4.54\ 10^{-10}$
20 kBq - 50 kBq	Adult (bait digger)	$6.62\ 10^{-10}$
	Adult (leisure)	$9.23\ 10^{-09}$
	Child (leisure)	$1.54\ 10^{-09}$
	Infant (leisure)	$1.16\ 10^{-10}$
50 kBq - 100 kBq	Adult (bait digger)	$5.11\ 10^{-10}$
	Adult (leisure)	$7.13\ 10^{-09}$
	Child (leisure)	$1.19\ 10^{-09}$
	Infant (leisure)	$8.94\ 10^{-11}$
> 100 kBq	Adult (bait digger)	$8.78\ 10^{-11}$
	Adult (leisure)	$1.23\ 10^{-09}$
	Child (leisure)	$2.05\ 10^{-10}$
	Infant (leisure)	$1.54\ 10^{-11}$
Total	Adult (bait digger)	$3.87\ 10^{-09}$
	Adult (leisure)	$5.40\ 10^{-08}$
	Child (leisure)	$9.02\ 10^{-09}$
	Infant (leisure)	$6.78\ 10^{-10}$

Table F.15 Probabilities per beach visit of a fuel particle adhering to clothing for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	**Exposed Group**	**Probability of a fuel particle adhering to clothing per beach visit**
< 20 kBq	Adult (bait digger)	$1.21\ 10^{-10}$
	Adult (leisure)	$1.21\ 10^{-10}$
	Child (leisure)	$7.11\ 10^{-11}$
	Infant (leisure)	$3.37\ 10^{-11}$
20 kBq - 50 kBq	Adult (bait digger)	$3.08\ 10^{-11}$
	Adult (leisure)	$3.08\ 10^{-11}$
	Child (leisure)	$1.81\ 10^{-11}$
	Infant (leisure)	$8.59\ 10^{-12}$
50 kBq – 100 kBq	Adult (bait digger)	$2.38\ 10^{-11}$
	Adult (leisure)	$2.38\ 10^{-11}$
	Child (leisure)	$1.40\ 10^{-11}$
	Infant (leisure)	$6.63\ 10^{-12}$
> 100 kBq	Adult (bait digger)	$4.09\ 10^{-12}$
	Adult (leisure)	$4.09\ 10^{-12}$
	Child (leisure)	$2.41\ 10^{-12}$
	Infant (leisure)	$1.14\ 10^{-12}$
Total	Adult (bait digger)	$1.80\ 10^{-10}$
	Adult (leisure)	$1.80\ 10^{-10}$
	Child (leisure)	$1.06\ 10^{-10}$
	Infant (leisure)	$5.02\ 10^{-11}$

Table F.16 Annual probabilities of a fuel particle becoming trapped in a shoe for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Annual probability of encountering a fuel particle in a shoe (y^{-1})
< 20 kBq	Adult (bait digger)	$1.37\ 10^{-08}$
	Adult (leisure)	$1.91\ 10^{-07}$
	Child (leisure)	$5.40\ 10^{-08}$
	Infant (leisure)	$8.57\ 10^{-09}$
20 kBq - 50 kBq	Adult (bait digger)	$3.48\ 10^{-09}$
	Adult (leisure)	$4.86\ 10^{-08}$
	Child (leisure)	$1.38\ 10^{-08}$
	Infant (leisure)	$2.19\ 10^{-09}$
50 kBq - 100 kBq	Adult (bait digger)	$2.69\ 10^{-09}$
	Adult (leisure)	$3.75\ 10^{-08}$
	Child (leisure)	$1.06\ 10^{-08}$
	Infant (leisure)	$1.69\ 10^{-09}$
> 100 kBq	Adult (bait digger)	$4.62\ 10^{-10}$
	Adult (leisure)	$6.45\ 10^{-09}$
	Child (leisure)	$1.83\ 10^{-09}$
	Infant (leisure)	$2.90\ 10^{-10}$
Total	Adult (bait digger)	$2.04\ 10^{-08}$
	Adult (leisure)	$2.84\ 10^{-07}$
	Child (leisure)	$8.05\ 10^{-08}$
	Infant (leisure)	$1.28\ 10^{-08}$

Table F.17 Probabilities per beach visit of a fuel particle becoming trapped in a shoe for the 'high rate' sub-group of each potentially exposed group for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Exposed Group	Probability of encountering a fuel particle in a shoe per beach visit
< 20 kBq	Adult (bait digger)	$6.35\ 10^{-10}$
	Adult (leisure)	$6.35\ 10^{-10}$
	Child (leisure)	$6.35\ 10^{-10}$
	Infant (leisure)	$6.35\ 10^{-10}$
20 kBq - 50 kBq	Adult (bait digger)	$1.62\ 10^{-10}$
	Adult (leisure)	$1.62\ 10^{-10}$
	Child (leisure)	$1.62\ 10^{-10}$
	Infant (leisure)	$1.62\ 10^{-10}$
50 kBq - 100 kBq	Adult (bait digger)	$1.25\ 10^{-10}$
	Adult (leisure)	$1.25\ 10^{-10}$
	Child (leisure)	$1.25\ 10^{-10}$
	Infant (leisure)	$1.25\ 10^{-10}$
> 100 kBq	Adult (bait digger)	$2.15\ 10^{-11}$
	Adult (leisure)	$2.15\ 10^{-11}$
	Child (leisure)	$2.15\ 10^{-11}$
	Infant (leisure)	$2.15\ 10^{-11}$
Total	Adult (bait digger)	$9.47\ 10^{-10}$
	Adult (leisure)	$9.47\ 10^{-10}$
	Child (leisure)	$9.47\ 10^{-10}$
	Infant (leisure)	$9.47\ 10^{-10}$

Table F.18 Probability of a sandpit filled using sand from Sandside Beach containing a fuel particle for different ^{137}Cs activity ranges

Particle activity range (^{137}Cs activity)	Probability of a sandpit containing a fuel particle
< 20 kBq	$1.02\ 10^{-05}$
20 kBq - 50 kBq	$2.59\ 10^{-06}$
50 kBq - 100 kBq	$2.00\ 10^{-06}$
> 100 kBq	$3.44\ 10^{-07}$
Total	$1.52\ 10^{-05}$

Table F.19 Annual probability of an infant encountering a fuel particle in a sandpit filled using sand from Sandside Beach for different ^{137}Cs activity ranges

Exposure Pathway	Particle activity range (^{137}Cs activity)	Annual probability of an infant encountering a fuel particle in a sandpit (y^{-1})
Direct skin contact with a fuel fragment	< 20 kBq	$4.45\ 10^{-07}$
	20 kBq - 50 kBq	$1.13\ 10^{-07}$
	50 kBq - 100 kBq	$8.75\ 10^{-08}$
	> 100 kBq	$1.51\ 10^{-08}$
	Total	$6.63\ 10^{-07}$
Ingesting a fuel fragment	< 20 kBq	$1.59\ 10^{-10}$
	20 kBq - 50 kBq	$4.05\ 10^{-11}$
	50 kBq - 100 kBq	$3.13\ 10^{-11}$
	> 100 kBq	$5.38\ 10^{-12}$
	Total	$2.37\ 10^{-10}$
Inhaling a fuel fragment	< 20 kBq	$9.84\ 10^{-14}$
	20 kBq - 50 kBq	$2.51\ 10^{-14}$
	50 kBq - 100 kBq	$1.94\ 10^{-14}$
	> 100 kBq	$3.33\ 10^{-15}$
	Total	$1.47\ 10^{-13}$

APPENDIX G ANALYSIS OF LOG(10) ACTIVITY AND MASS FOR THE PARTICLE FINDS

G.1.1 The two boxplots (Figures G.1 and G.2) below show the distribution of log (mass) and log (activity) by location of find. Foreshore and offshore particles have approximately the same range of mass, while the 4 particles at Sandside seem lighter, although their masses do overlap with the other locations. Offshore particles are on average more active, with the Sandside particles less active than the Foreshore particles.

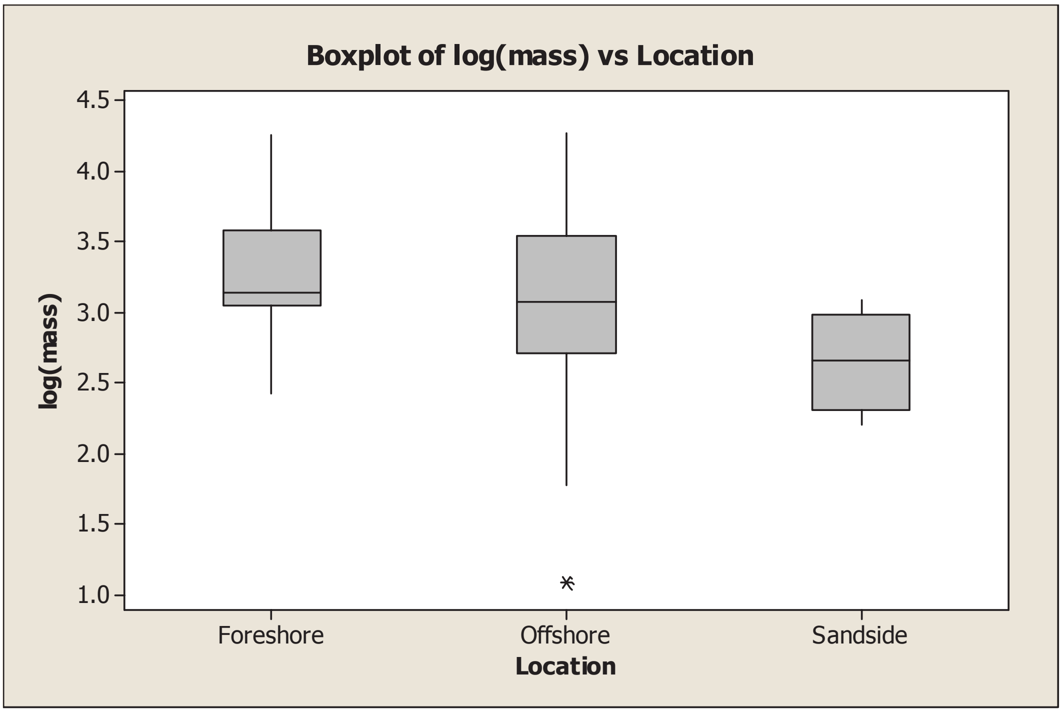

Figure G.1 Distribution of log (mass) by location

G.1.2 The log mass and log activity relationship seems broadly linear in Figure G.3. There are very few Sandside particles, so it is difficult to characterise them fully, and the Foreshore particles seem to be rather varied, while the offshore particles seem more coherent as a group. There are some outliers apparent, but difficult to class them as a subgroup and so treat them differently. In the Sandside mass range there clearly are similar particles (same mass), but with higher activities found on both Foreshore and offshore.

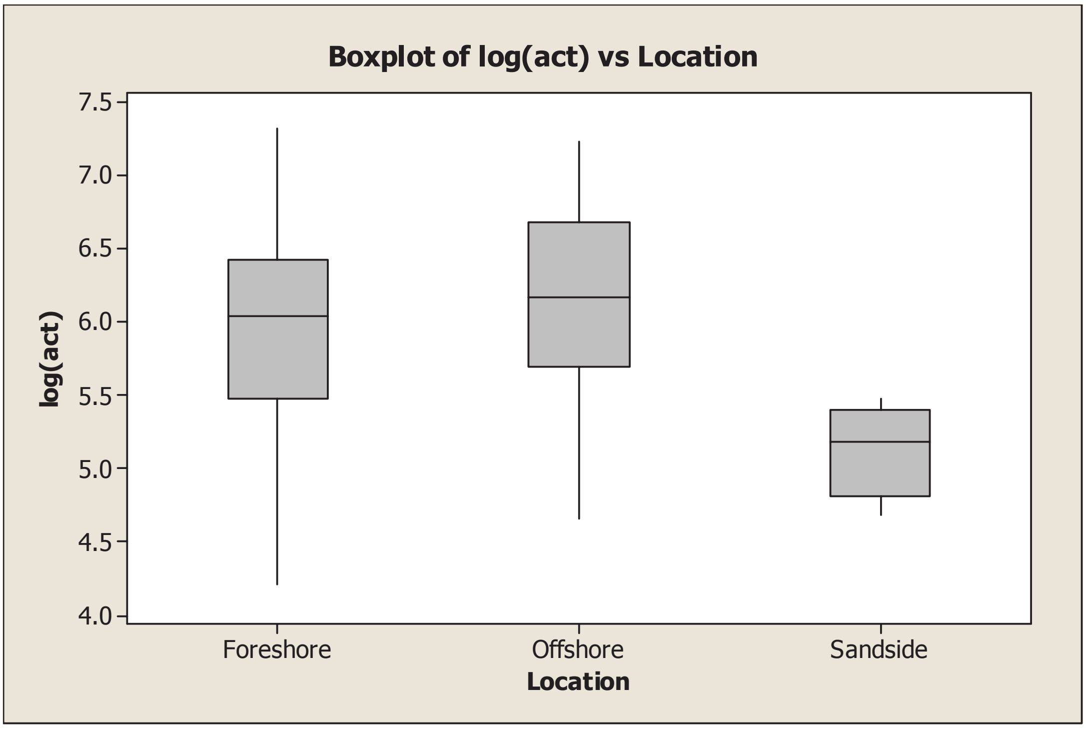

Figure G.2 Relationships between mass and activity

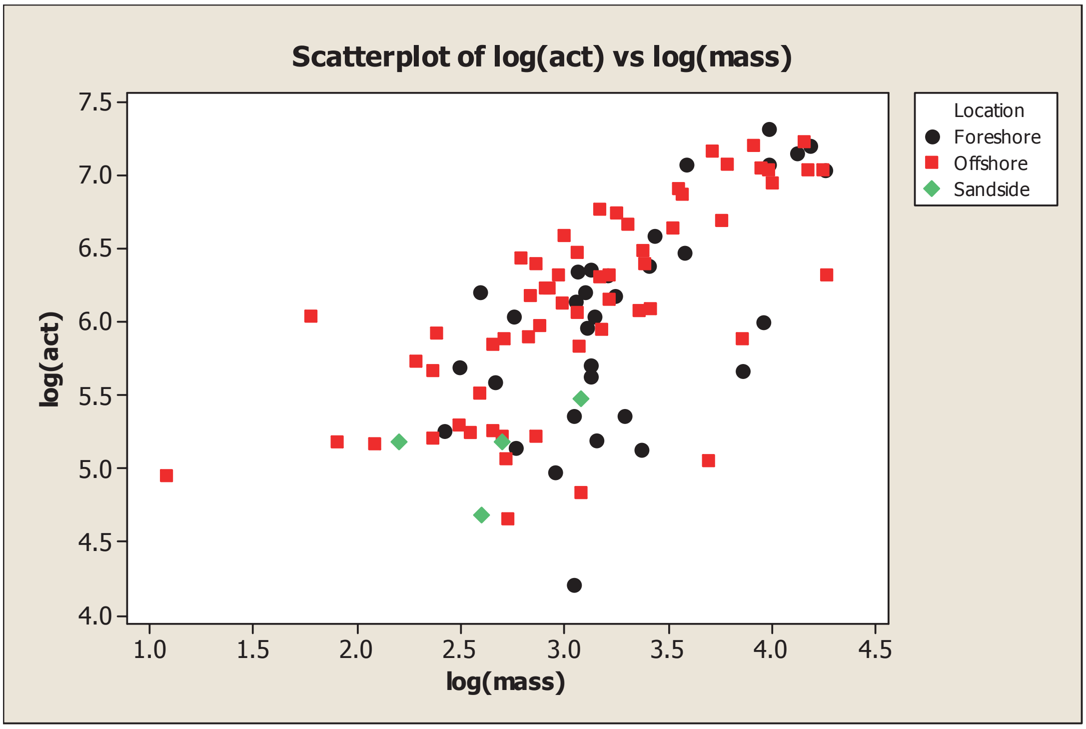

Figure G.3 Scatterplot of activity versus mass

G.1.3 Assuming a linear relationship between log activity and log mass, we can investigate the linear relationship for each of the three particle types/locations. The lines (shown below in Fig G.4) are the best fitting straight lines fit to each particle location separately and hence are non-parallel.

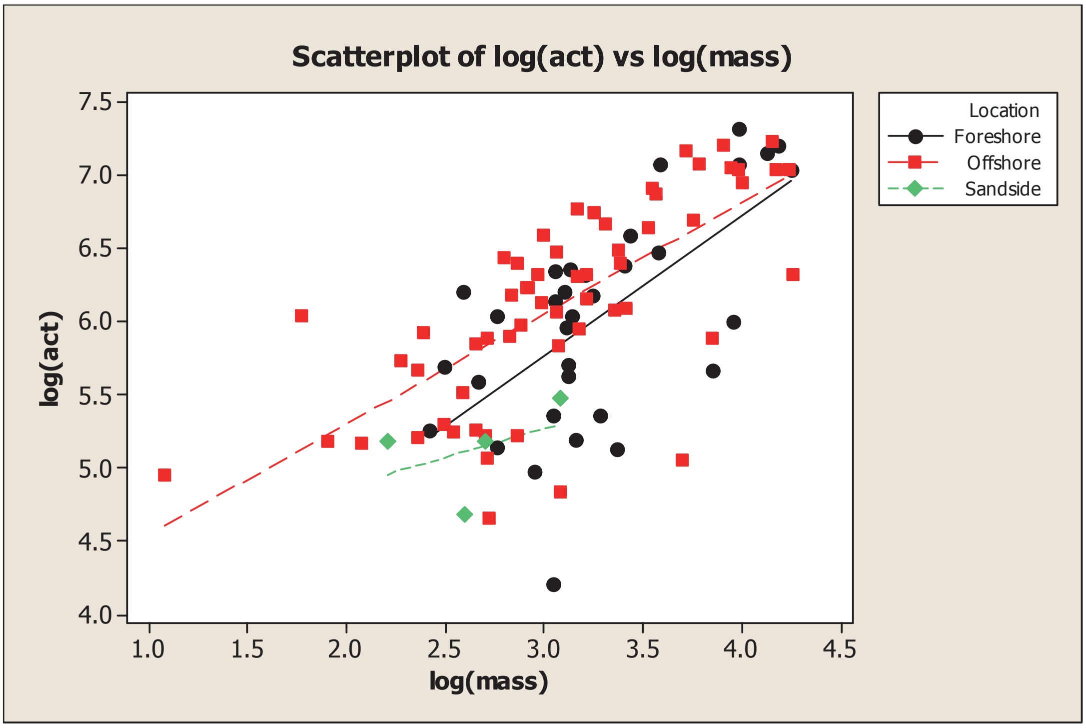

Figure G.4 Scatterplot and regression lines for each location

G.1.4 It is clear that the offshore particles have a wider mass range than Foreshore or Sandside, but this is due to one particle in particular which has low mass. Again, in the mass range of those few Sandside particles studied, there are clearly similar mass particles of higher activity found on both Foreshore and offshore. A linear model including mass and location can be fitted to the data, based on parallel regression lines (the model of different slopes can be rejected).

Table G.1 Analysis of Variance for log(act), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
log(mass)	1	22.0035	20.6713	20.6713	77.14	0.000
Location	2	2.4196	2.4196	1.2098	4.51	0.013
Error	93	24.9219	24.9219	0.2680		
Total	6	49.3450				

S = 0.517666 R-Sq = 49.49% R-Sq(adj) = 47.87%

Term	Coef	SE Coef	T	P
Constant	3.3592	0.2892	11.62	0.000
log(mass)	0.79920	0.09100	8.78	0.000
Location	0.0525	0.1103	0.48	0.635
Foreshore				
Offshore	0.2939	0.1020	2.88	0.005

G.1.5 The parallel line model is appropriate for the observed data (if we consider particles of the same mass, then offshore particles tend to have higher activity, Sandside lower activity relative to Foreshore).

G.1.6 Removing the Sandside particles (4), then the parallel-line analysis for Foreshore and offshore is shown below in Figure F.5 showing the fitted parallel line model.

Table G.2 Analysis of Variance for log(act), using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
log(mass)	1	19.643	20.676	20.676	75.67	0.000
Location	1	1.223	1.223	1.223	4.47	0.037
Error	90	24.591	24.591	0.273		
Total	92	45.456				

S = 0.522714 R-Sq = 45.90% R-Sq(adj) = 44.70%

Term	Coef	SE Coef	T	P
Constant	3.5167	0.2998	11.73	0.000
log(mass)	0.80413	0.09244	8.70	0.000
Location Foreshore	-0.12116	0.05728	-2.12	0.037

G.1.7 It is worth noting that only 44% of the variation in activity is explained by mass. This is discussed further in Chapter 4.

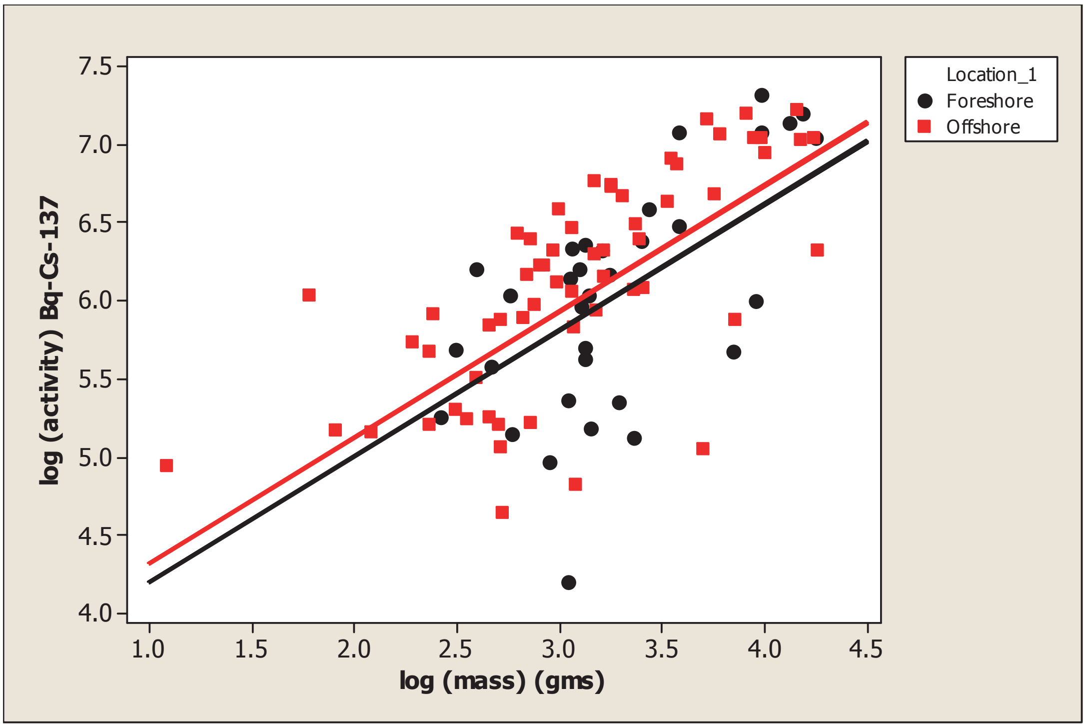

Figure G.5 Parallel-line model for Foreshore and offshore.

G.2 Discrimination

G.2.1 Also, it is of interest to see how well these primary variables can define the location groups, how distinguishable are the particle characteristics at the three locations? The technique used here is discrimination and overall, this shows that the particles found are quite well mixed in terms of their physical characteristics. Overall, the groups are not very coherent (best case is 50% discrimination).

Table G.3 Discriminant Analysis: Location *versus* log(act), log(mass)

Predictors: log(act), log(mass)			
Group	Foreshore	Offshore	Sandside
Count	33	60	4
Summary of Classification with Cross-validation			
		True Group	
Put into Group	Foreshore	Offshore	Sandside
Foreshore	10	13	1
Offshore	15	33	0
Sandside	8	14	3
Total N	33	60	4
N correct	10	33	3
Proportion	0.303	0.550	0.750
N = 97	N Correct = 46	Proportion Correct = 0.474	

Table G.4 Discriminant Analysis: Location *versus* log(act), log(mass)

Predictors: log(act), log(mass), Bq / gm, Volume (cc), Density			
Group	Foreshore	Offshore	Sandside
Count	33	58	4
Summary of Classification with Cross-validation			
		True Group	
Put into Group	Foreshore	Offshore	Sandside
Foreshore	13	16	1
Offshore	14	27	0
Sandside	6	15	3
Total N	33	58	4
N correct	13	27	3
Proportion	0.394	0.550	0.750
N = 95	N Correct = 43	Proportion Correct = 0.453	

G.3 Sandside analysis

G.3.1 Using the discrimination approach to classify the Sandside particles, based only on their mass and activity, the first three would be predicted as belonging to the foreshore population, the last particle to the offshore population.

Table G.5 Classification of Particles

Observation	Pred Group	From Group	Distance	Probability
1	Foreshore			
		Foreshore	1.513	0.551
		Offshore	1.920	0.449
2	Foreshore			
		Foreshore	0.687	0.600
		Offshore	1.501	0.400
3	Foreshore			
		Foreshore	3.705	0.629
		Offshore	4.758	0.371
4	Offshore			
		Foreshore	3.276	0.398
		Offshore	2.451	0.602

G.4 Conclusions

G.4.1 Lower mass particles are likely to have lower activity and to be more amenable to distant transport, higher mass particles are likely to be more active, less amenable to transport away from diffuser.

G.4.2 There is a positive relationship between activity and mass as predicted, however there is also considerable scatter in the results. There is also a statistically significant difference between the Foreshore and offshore particles (particle activity is related to mass (common slope)), but Foreshore particles are on average less active for the same mass, so does this suggest that lower activity particles are more likely to be transported (as being of lower mass)? Foreshore particles have slightly lower activities and Sandside particles are lower still, but if we believe that this is a mass-related transport phenomenon then Foreshore particles are heavier on average than the offshore particles. From the various plots and regression, it is clear that for a given mass range, the predicted activity is known with substantial uncertainty.

G.4.3 So, for example, using the mass of the 4 Sandside particles, assuming that they belong to either the Foreshore or offshore population, and the regression models, it is possible to predict activity based on their mass. The results are uncertain (the prediction intervals are wide) since the statistical regression models explain only approximately half of the variation; thus there must be other (perhaps unmeasured) factors to explain the residual variation. It would also be useful to have more of the Sandside particles characterised. Nonetheless, the results indicate that more active, smaller mass particles do exist in the environment and so could potentially be transported to Sandside.

G.4.4 Predicted activities based on Foreshore mass/activity model for Sandside particles using their measured mass gives:

Table G.6 Predicted Activities for Sandside Particles (using foreshore mass/activity)

ID	predicted log(activity)	95% Prediction interval for log activity
974151	5.478	(4.252, 6.703)
992005	5.841	(4.638, 7.045)
03/096	5.385	(4.151, 6.619)
03/017	5.004	(3.720, 6.288)

and using the offshore regression model, the predicted values for Sandside particles using their measured mass gives:

Table G.7 Predicted Activities for Sandside Particles (using measured mass)

ID	predicted log(activity)	95% prediction interval for log activity
974151	5.8274	(4.8353, 6.8196)
992005	6.1146	(5.1256, 7.1036)
03/096	5.7542	(4.7604, 6.7481)
03/017	5.4537	(4.4489, 6.4585)

G.4.5 Using the activity mass relationship derived for the offshore and Foreshore particles, the Sandside particles could have had activities that are likely to lie between 6.3×10^4 and 1.3×10^7 Bq ^{137}Cs (based on the 95% prediction intervals).

APPENDIX H SUPPORTING INFORMATION FOR CHAPTER 5

H.1 Technical implementation documents specified by SEPA

H.1.1 The data provided in the following tables have been reproduced from material supplied by SEPA and the use of terms such as "> 10^5 Bq ^{137}Cs" implies that the minimum detection limit should be no greater than this value.

Table H.1 Frequency and extent of beach monitoring for particle of irradiated fuel. (February, 1999) (Sites, frequencies and levels to be reviewed 12 months from the date of issue)

Beach	Extent of monitoring	Grid references (GRs)	Frequency of monitoring	Detection criteria
Sandside Bay	All sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	295700, 966280 & 296690, 965780	Monthly	> 10^7 Bq of ^{137}Cs at 100 mm depth
Sandside Bay	All sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	295700, 966280 & 296690, 965780	Twice per year	> 10^5 Bq of ^{137}Cs at 100 mm depth
Thurso Bay	All sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	311360, 968960 & 312070, 968850	Twice per year	> 10^7 Bq of ^{137}Cs at 100 mm depth
Thurso Bay	All sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	311360, 968960 & 312070, 968850	Once per year**	> 10^5 Bq of ^{137}Cs at 100 mm depth
Scrabster Bay	All sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	310040, 970180 & 310605, 969170	Twice per year	> 10^7 Bq of ^{137}Cs at 100 mm depth
Scrabster Bay	All sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	310040, 970180 & 310605, 969170	Once per year**	> 10^5 Bq of ^{137}Cs at 100 mm depth
Crosskirk Bay	All accessible sandy areas from MHWS to MLWS between GRs in column 3	302860, 969900 & 302970, 970250	Twice per year	> 10^5 Bq of ^{137}Cs at 100 mm depth
Brims Ness	All accessible sandy areas from MHWS to MLWS between GRs in column 3	304250, 971270 & 304410, 971030	Twice per year**	> 10^5 Bq of ^{137}Cs at 100 mm depth

*Low water means as reasonably practicable to low water springs, but at least to neap low water.
**Or equivalent coverage by several visits.

Table H.2 Frequency and extent of beach monitoring for particles of irradiated fuel. (September 2001).

Beach	Extent of monitoring	Grid references (GRs)	Frequency of monitoring	Detection criteria
Sandside Bay	All of the sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	295700, 966280 & 296690, 965780	Monthly	> 10^5 Bq of ^{137}Cs at 100 mm depth
Sandside Bay	Accessible sandy areas which do not permit vehicle access including north beach, harbour, sandy areas below Fresgoe House, bands of sand northeast of the beach below the public lavatories and the sandy areas north of Isauld Burn .	295700, 966280 & 296690, 965780	Monthly	> 10^5 Bq of ^{137}Cs at 100 mm depth
Sandside Bay	Strandline that can be accessed by vehicle between GR's in column 3	295700, 966280 & 296690, 965780	Fortnightly	> 10^5 Bq of ^{137}Cs at 100 mm depth
Thurso Bay	All sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	311360, 968960 & 312070, 968850	Three times per year	> 10^5 Bq of ^{137}Cs at 100 mm depth
Scrabster Bay	All sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	310040, 970180 & 310605, 969170	Three times per year	> 10^5 Bq of ^{137}Cs at 100 mm depth
Crosskirk Bay	All accessible sandy areas from MHWS to MLWS between GRs in column 3	302860, 969900 & 302970, 970250	Twice per year	> 10^5 Bq of ^{137}Cs at 100 mm depth
Brims Ness	All accessible sandy areas from MHWS to MLWS between GRs in column 3	304250, 971270 & 304410, 971030	Twice per year	> 10^5 Bq of ^{137}Cs at 100 mm depth

*Low water means as reasonably practicable to low water springs, but at least to neap low water.

H.1.2 The Groundhog Mk 1 system was replaced in May 2002 by the Groundhog Evolution system. Following preliminary calculations of the detection capability of the Evolution system, the TID was revised on October 2003 and summarised in Table H.3. Instead of requiring detection limits, the new TID requires the system to maintain a mean operating velocity of 1 ms^{-1} and no account shall be taken of any measurement when the equipment is operating in excess of 1.2 ms^{-1}. In addition, the requirement of monitoring Dunnet Beach was added. The supporting documentation also indicated that UKAEA should strive to achieve better detection sensitivities, *i.e.* 3 x 10^4 Bq and 7.5 x 10^2 Bq ^{137}Cs particles at 30 cm and 5 cm depth respectively. The frequency and extent of coverage in the revised TID is summarised in Table H.3.

Table H.3 Frequency and extent of beach monitoring of irradiated fuel (October 2003)

Beach	Extent of monitoring	Grid references (GRs)	Frequency of monitoring
Sandside Bay	All of the sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	295700, 966280 & 296690, 965780	Monthly
Sandside Bay	Accessible sandy areas which do not permit vehicle access including north beach, harbour, sandy areas below Fresgoe House, bands of sand northeast of the beach below the public lavatories and the sandy areas north of Isauld Burn .	295700, 966280 & 296690, 965780	Monthly
Sandside Bay	Strandline that can be accessed by vehicle between GR's in column 3	295700, 966280 & 296690, 965780	Fortnightly
Thurso Bay	All sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	311360, 968960 & 312070, 968850	Three times per year
Scrabster Bay	All sandy areas that can be accessed by a vehicle from MHWS to low water* between GRs in column 3	310040, 970180 & 310605, 969170	Three times per year
Crosskirk Bay	All accessible sandy areas from MHWS to low water* between GRs in column 3	302860, 969900 & 302970, 970250	Six times per year
Brims Ness	All accessible sandy areas from MHWS to low water* between GRs in column 3	304250, 971270 & 304410, 971030	Six times per year
Dounreay East Foreshore	All accessible sandy areas from MHWS to low water* between GRs in column 3	298190, 967029 & 298340, 967095.	Fortnightly except during the period 1 May to 31 August.
Dounreay West Foreshore	All accessible sandy areas from MHWS to low water* between GRs in column 3	298190, 967029 & 298340, 967095.	Fortnightly except during the period 1 May to 31 August.
Melvich Beach	All accessible sandy areas from MHWS to low water* between GRs in column 3	288246, 965662 & 289109, 965028.	Once during 2004
Dunnet Beach	All accessible sandy areas from MHWS to low water* between GRs in column 3	320336, 968460 & 321440, 970870.	Once during 2004

H.2 Groundhog Mk 1

H.2.1 Groundhog Mk 1 was operated by AEA Technology (later renamed RWE NUKEM) until May 2002 and utilised four independently operated 76 mm diameter sodium

Iodide (Tl doped) scintillation detectors (NaI(Tl)). The detectors were operated at about 200 mm above the surface of the beach and spaced 500mm apart and supported from the front of a four-wheel drive Unimog, which was occasionally substituted by a Land Rover. The speed of the vehicle was to be maintained at 1 ms^{-1}. Following a detailed internal review, the vehicle velocity was reduced to 0.8 ms^{-1} from June 2001 (UKAEA 2001).

H.2.2 For each detector, rate meters collected counts within three windows, the first within the ^{137}Cs window, around the 662 keV full energy peak (C). The second window, beyond the ^{137}Cs window, represents the natural contribution to the gamma ray environment (N). The third is below the ^{137}Cs window and is not utilised in the particle detection procedure. The integration time for each count is one second.

H.2.3 A data logger also recorded positional data from a Differential Global Positioning System (DGPS). The data logger also sounded an alarm when both the following criteria were met:

1. $C/N > 1.8$
2. $C \geq 30$ cps

H.2.4 The statistical noise associated with the relatively low count rate in the C and N windows resulted in a significant number of false alarms being triggered based only on the C/N ratio. The second trigger was therefore introduced to reduce the number of false alarms.

H.3 DPAG review of Groundhog Mk 1 detection capability

H.3.1 The review is reproduced from the 2nd Interim Report (DPAG 2003).

H.3.2 A derivation of the detection limit of the Groundhog Mk 1 system was based on:

- Background count data for an individual detector (above ^{137}Cs window) from the Groundhog system supplied by RWE NUKEM.
- Detector response characteristics derived from the validated RWE NUKEM Monte Carlo model (MCBend) simulations and published in the NRPB Report (NRPB, 2003), assuming the vehicle travels at 1 ms^{-1}.
- Both alarm triggering criteria.
- ^{137}Cs window background contribution calculated from a constant C/N = 0.6087 (calculated from values previously supplied by UKAEA).

H.3.3 The technical details on the calculation undertaken by DPAG are provided in Appendix B of DPAG's 2nd Interim report (DPAG 2003). The key findings are summarised here. A vehicle speed of 1 ms^{-1} is assumed as this represents the mean velocity prior to June 2001 and approximately the upper 95th percentile of the vehicle velocity distribution for June 2002 (example from UKAEA 2002).

H.3.4 DPAG's calculations are based on the Poisson probability of detecting a particle with the activity of 10^5 Bq. For the mean background (N = 19 and C = 12) situation, the probability of detecting a particle at a radial distance of 250 mm and depth of 100 mm is between 0.013 and 0.522 for the worst- and best-case scenarios respectively (Table H.4).

Table H.4 Probability of detecting a 10^5 Bq particle with Detector 1 only for mean background conditions for Detector 1

a. Worst Case Scenario Off Axis Distance (mm)				b. Best Case Scenario Off Axis Distance (mm)			
Depth (mm)	**0**	**100**	**250**	**Depth (mm)**	**0**	**100**	**250**
0	1.000	1.000	1.000	**0**	1.000	1.000	1.000
50	0.984	0.978	0.522	**50**	1.000	1.000	1.000
100	0.157	0.116	0.013	**100**	0.969	0.944	0.522
200	0.000	0.000	0.000	**200**	0.001	0.000	0.000

H.3.5 From Poisson statistics, the minimum detection limits (95% level of confidence of detection; i.e. the activity of particle required to be detected with a 95% level of confidence) of the system under the mean background conditions are given in Table H.5. Again, these values are similar to those quoted in the NRPB report.

Table H.5 Minimum Detection Limits (10^3 Bq) at 95% level of confidence level for mean background conditions for Detector 1.

a. Worst Case Scenario Off Axis Distance (mm)				b. Best Case Scenario Off Axis Distance (mm)			
Depth (mm)	**0**	**100**	**250**	**Depth (mm)**	**0**	**100**	**250**
0	35.9	38.4	52.4	**0**	17.9	19.2	26.2
50	86.8	89.2	137.5	**5**	43.4	44.6	68.8
100	183.3	194.1	275.0	**10**	91.7	97.1	137.5
200	767.4	1031.3	1650.0	**20**	383.7	515.6	825.0

Heterogeneity in background

H.3.6 The heterogeneity in the background should also be considered and in what follows, the upper and lower 95 percentiles of the background are used to estimate the 95% detection capability of the Groundhog system for the Sandside Beach environment in the first instance. In addition, it is understood that the natural background levels on Thurso and Scrabster beaches may be generally higher than at Sandside Bay. It is therefore important to try and evaluate what happens to the detection capability when the background changes.

H.3.7 The resulting probabilities of detection for the high background situation are provided in Table H.6. In this case, the findings show that the probability of detecting a 10^5 Bq particle at 100 mm depth is as low as 0.001 (worst case) and reaches 0.41 (best case) decreasing with increasing radial distance to 250 mm where the detection probabilities are zero and 0.02 respectively.

Table H.6 Probability of detecting a 10^5 Bq particle with Detector 1 only for the upper 95 percentile of the background counts (High Background).

a. Worst Case Scenario Off Axis Distance (mm)				b. Best Case Scenario Off Axis Distance (mm)			
Depth (mm)	**0**	**100**	**250**	**Depth (mm)**	**0**	**100**	**250**
0	1.000	1.000	0.999	**0**	1.00	1.00	1.00
50	0.517	0.465	0.023	**50**	1.00	1.00	0.90
100	0.001	0.001	0.000	**100**	0.41	0.31	0.02
200	0.000	0.000	0.000	**200**	0.00	0.00	0.00

H.3.8 The resulting minimum detection limits for this situation are provided in Table H.7, demonstrating that the detection limits at 100 mm depth and 250 mm from the detector decrease to 4.17 x 10^5 Bq (worst case) and 2.08 x 10^5 Bq (best case).

H.3.9 The results for the high background environment are similar to those presented by the NRPB through their work, *i.e.* 3.1 x 10^5 Bq for the worst-case and 1.5 x 10^5 Bq for the best-case scenario. Differences in the absolute values may be a function of the assumptions made of the ratio of the within window count relative to the above window background and that only one of the four detectors has been characterised. Nevertheless, the results show the importance influence of the higher natural background on the systems' detection limits. This is not only important in consideration of beach heterogeneity but also of detection limits on other beaches with higher natural backgrounds (*i.e.* Thurso and possibly Scrabster beaches).

Table H.7. Minimum Detection (10^3 Bq) Limits at 95% level of confidence level for the upper 95 percentile of the background counts (High Background).

a. Worst Case Scenario Off Axis Distance (mm)				b. Best Case Scenario Off Axis Distance (mm)			
Depth (mm)	**0**	**100**	**250**	**Depth (mm)**	**0**	**100**	**250**
0	54.3	58.1	79.4	**0**	27.2	29.1	39.7
50	131.6	135.1	208.3	**50**	65.8	67.6	104.2
100	277.8	294.1	416.7	**100**	138.9	147.1	208.3
200	1162.8	1562.5	2500.0	**200**	581.4	781.3	1250.0

H.3.10 In the low background situation, Table H.8 shows the detection probability is decreased relative to the mean background case. The probability of detecting a 10^5 Bq particle at 10 mm depth is 0.04 (worst case) and reaches 0.94 (best case) and decreases with increasing radial distance. Table H.9 shows the lower minimum detection limits, which are marginally worse than the mean background situation.

Table H.8 Probability of detecting a 10^5 Bq particle with Detector 1 only for the lower 95 percentile of the background counts (Low Background).

a. Worst Case Scenario Off Axis Distance (mm)				b. Best Case Scenario Off Axis Distance (mm)			
Depth (mm)	**0**	**100**	**250**	**Depth (mm)**	**0**	**100**	**250**
0	1.000	1.000	1.000	**0**	1.000	1.000	1.000
50	0.967	0.955	0.310	**50**	1.000	1.000	1.000
100	0.041	0.024	0.001	**100**	0.938	0.891	0.310
200	0.000	0.000	0.000	**200**	0.000	0.000	0.000

Table H.9 Minimum Detection (10^3 Bq) Limits at 95% level of confidence level for the lower 95 percentile of the background counts (Low Background).

a. Worst Case Scenario Off Axis Distance (mm)				b. Best Case Scenario Off Axis Distance (mm)			
Depth (mm)	**0**	**100**	**250**	**Depth (mm)**	**0**	**100**	**250**
0	38.0	40.7	55.6	**0**	19.0	20.3	27.8
50	92.1	94.6	145.8	**50**	46.1	47.3	72.9
100	194.4	205.9	291.7	**100**	97.2	102.9	145.8
200	814.0	1093.8	1750.0	**200**	407.0	546.9	875.0

H.3.11 In the worst -case scenario only, the detection probability is higher than the single observation case stated, as the same detector has a second opportunity of seeing the particle as the count acquisition starts at the particle and moves away. Consequently, the detection probability in the worst-case scenario for the mean background, at 100 mm depth and 250 mm from the detector, is approximately 0.0262.

Multiple Detector Array

H.3.12 Preliminary calculations suggest that, given the rigid detection trigger criteria, this variation in performance results in only slightly different detection probabilities and detection limits.

H.3.13 Given that there are two detectors potentially observing a particle the overall detection limit must be a function of the two detection probabilities. Taking the detection probabilities for two detectors, assuming they have identical characteristics to detector 1, for a particle at 250 mm distance and 100 mm depth the detection probability for the mean background situation and the worst-case scenario will be 0.0262 and for the best-case 0.772. Taking into consideration, in the worst-case scenario only, a single detector has a second chance of viewing the particle, the worst-case scenario probability increases to 0.0517 for the mean background situation, but remains significantly lower for the high and low background situations.

H.3.14 However, the detectors are said to be free running and consequently may be in or out of synchronisation. It is therefore difficult to fully characterise the detection capability, as there appears to be no systematic control on detector acquisition time synchronisation. A worst-case situation should therefore be assumed.

H.4 Variation in Groundhog Mk 1 detection capability with monitoring velocity

H.4.1 The following graphs illustrated the variation in detection capability with monitoring velocity. The data are based on a subset (about 10%) of the Groundhog Mk 1 monitoring data from Sandside on the July 2001.

H.5 Summary of Groundhog Evolution system and detection criteria

H.5.1 The new ‘Groundhog Evolution’ system incorporates 5 larger volume (7.6 cm x 40 cm) detectors mounted to provide a contiguous lateral cover of 2 m, representing 6.7 times increase in detector volume over the old Groundhog system.

H.5.2 It is intended that the system will be replicated and mounted or two lighter vehicles, with a nominal detector height of 200 mm above the sediment surface. This should enable more of the beach environment to be surveyed and the combined system approach, if run at 1 ms^{-1}, should allow the beaches to be monitored at double the rate of the previous Mk 1 system.

H.5.3 As with the Mk 1 system, the counts from the detectors are recorded in a below ^{137}Cs window, a ^{137}Cs window and an above ^{137}Cs window. Detection criteria will be set on the basis of a gross gamma count exceeding a certain threshold and a within ^{137}Cs window exceeding a certain threshold. The thresholds will incorporate a running average and constants to provide an appropriate confidence level of detection.

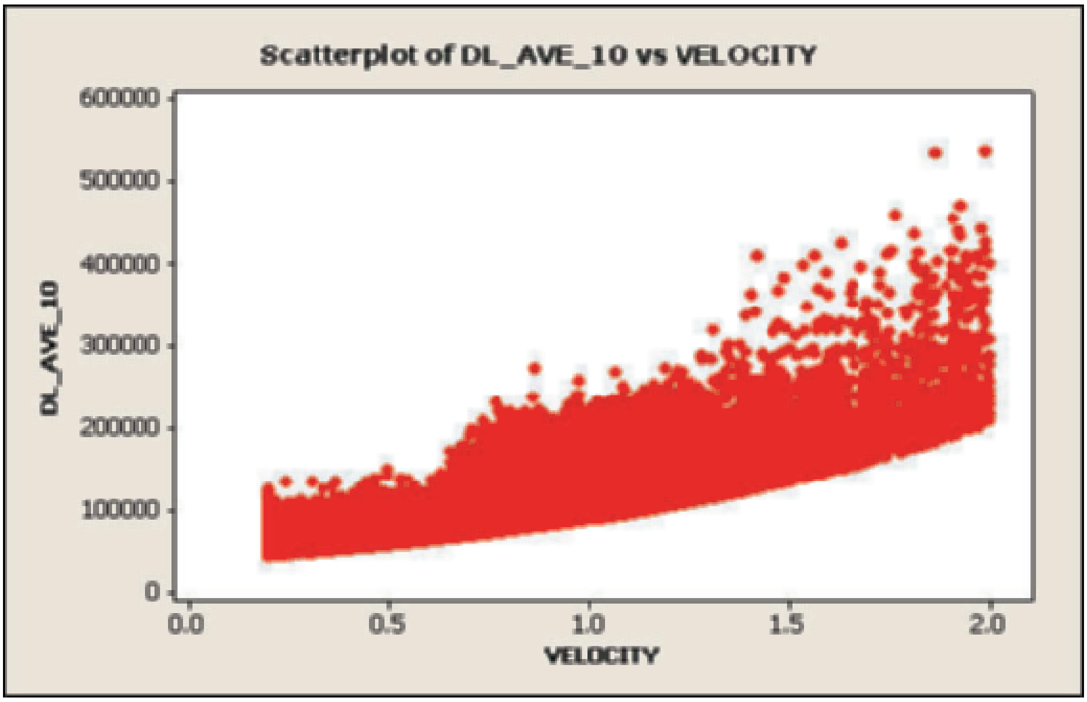

Figure H.1 Change in Groundhog Mk 1 Detection Limits with monitoring velocity

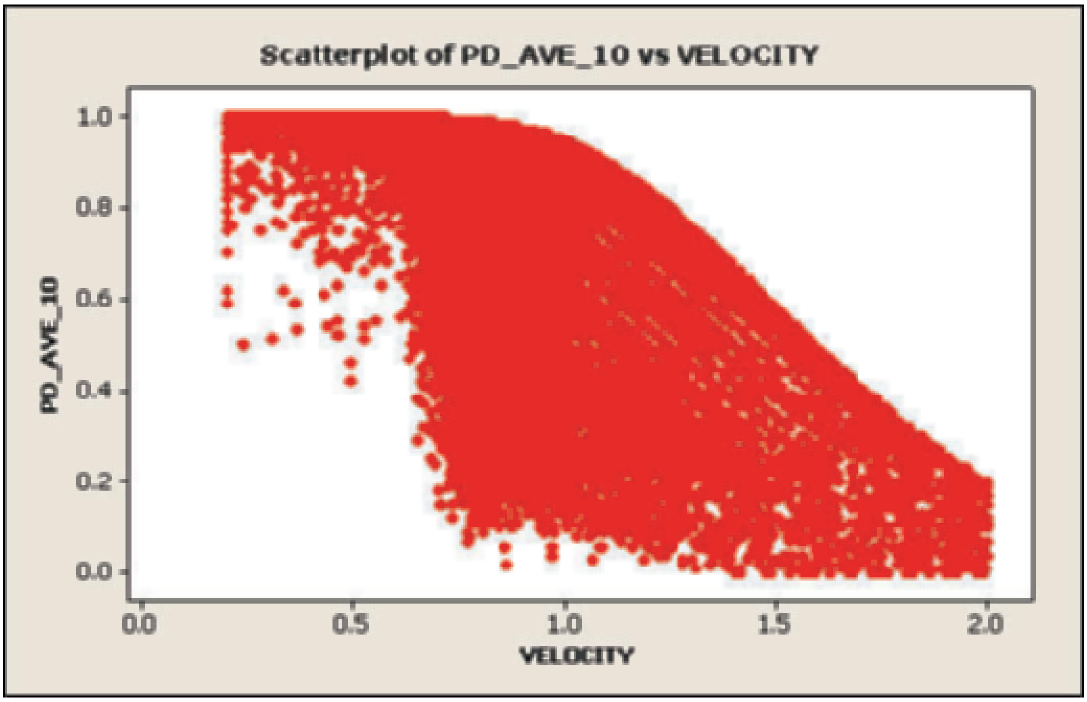

Figure H.2 Change in Groundhog Mk 1 Probability of Detection with monitoring velocity

H.5.4 In addition to a gross background alarm and various permutations thereof, the detection capability is primarily determined by two triggers detailed in confidential reports.

H.6 <u>Variation in Groundhog Evolution detection capability with monitoring velocity</u>

H.6.1 The following graphs (H.3 to H.6) illustrate the detection capability of Groundhog Evolution, based on data from Scrabster, June 2003.

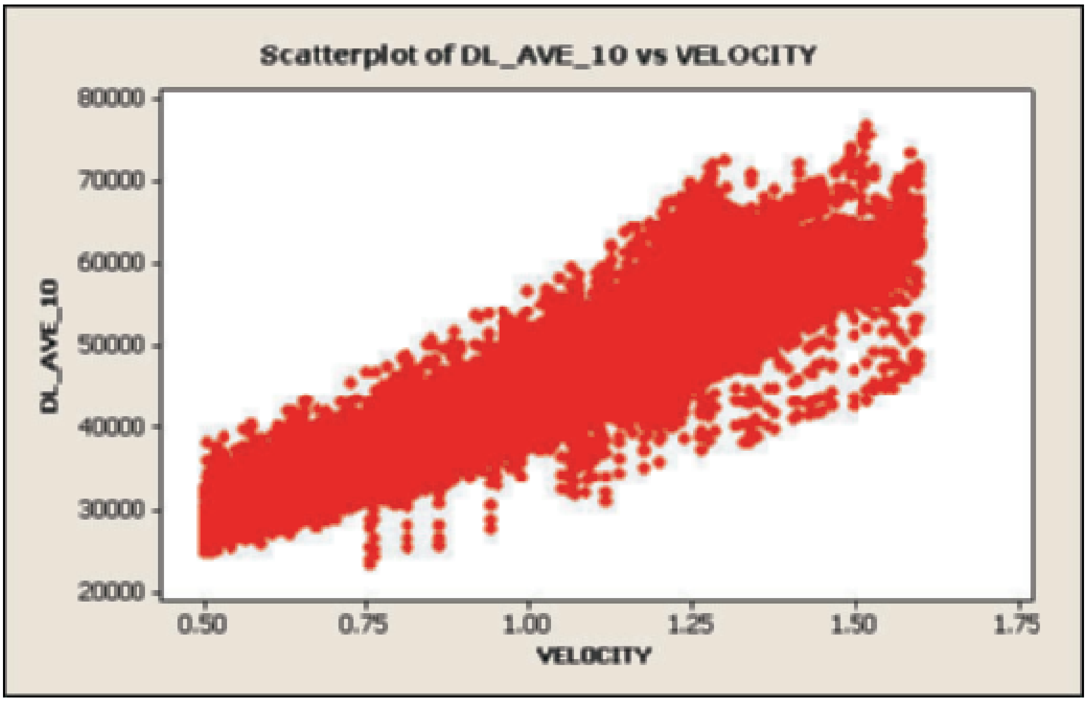

Figure H.3 Change in Groundhog Evolution Detection Limits at 100 mm depth with monitoring velocity

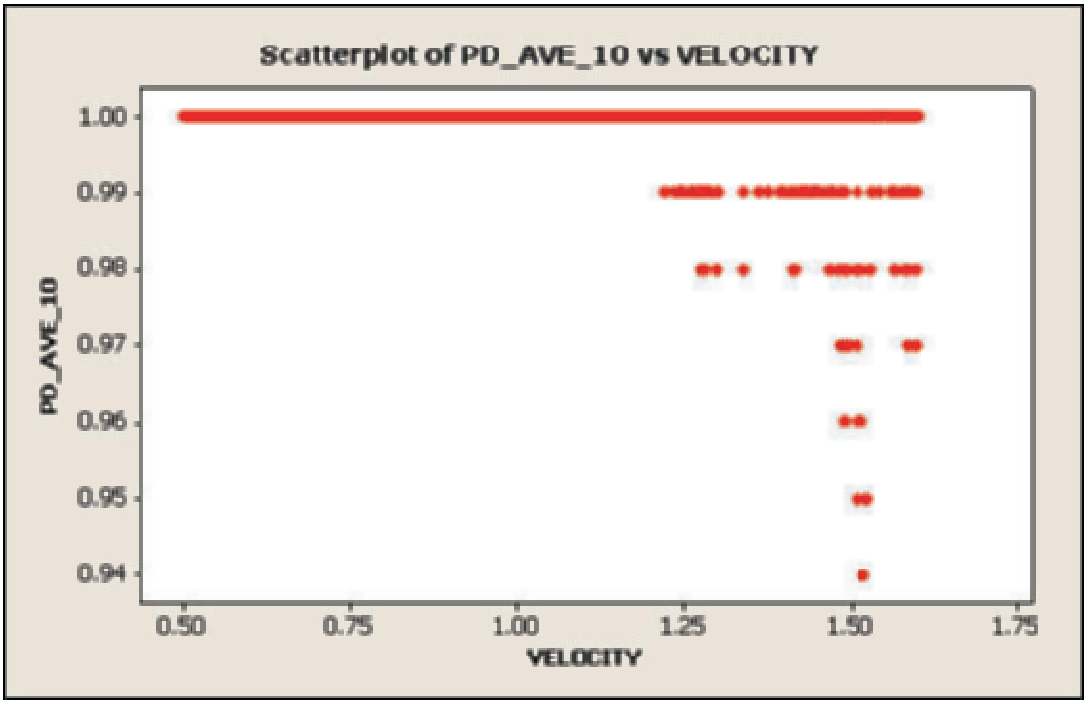

Figure H.4 Change in Groundhog Evolution Probability of Detection for 10^5 Bq ^{137}Cs at 100 mm depth with monitoring velocity

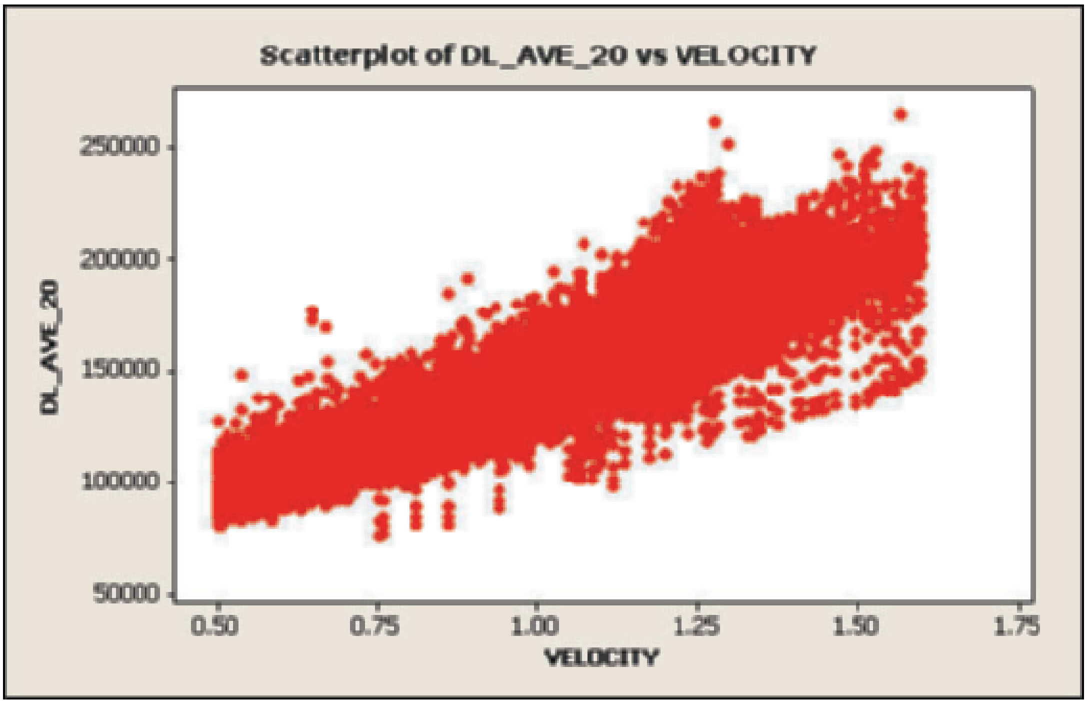

Figure H.5 Change in Groundhog Evolution Detection Limits at 200 mm depth with monitoring velocity

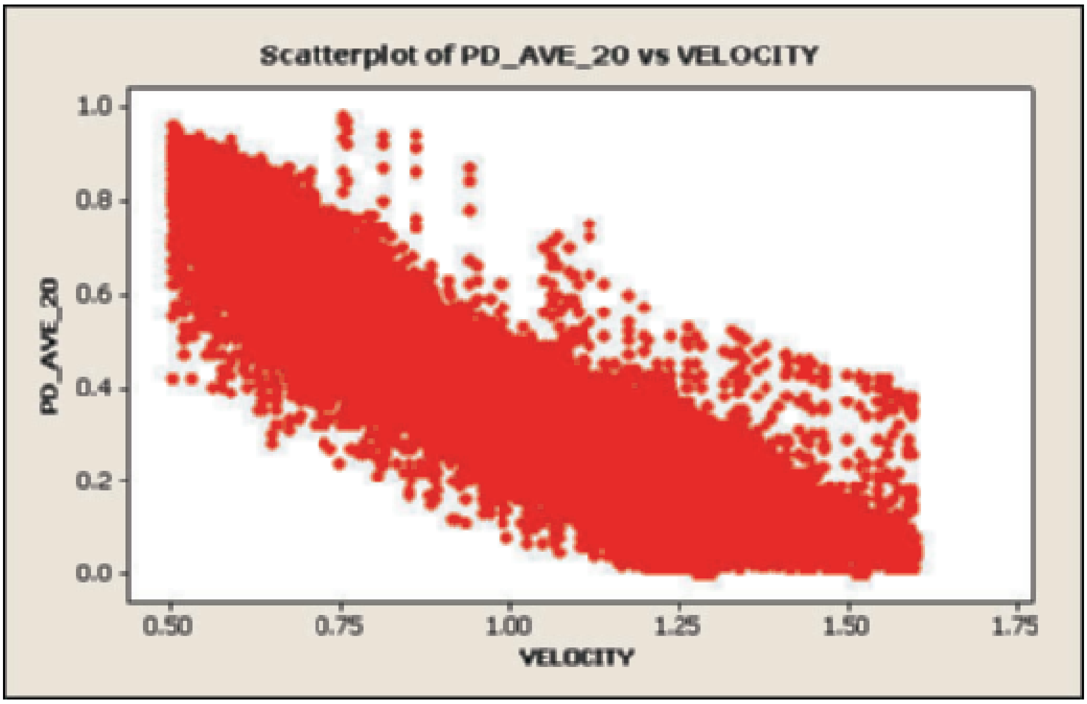

Figure H.6 **Change in Groundhog Evolution Probability of Detection for 10^5 Bq ^{137}Cs at 200 mm depth with monitoring velocity**

H.6.2 The graphs show that Evolution detects 10^5 Bq particles reliably at 100 mm depth. However, at 200 mm depth, the detection capability is highly dependent on monitoring velocity.

H.7 Detection Capability on other Caithness Beaches

Detection Capabilities at Scrabster

H.7.1 The background characteristics are generally more uniform on Scrabster although slightly higher than observed at Sandside. Table H.10 summarises the results for Scrabster. Given the similar monitoring speed characteristics as observed at Sandside, the higher natural background has led to a slight deterioration in detection capability.

Table H.10 **The mean probability of detection and detection limits for Groundhog Evolution across Scrabster Beach is based on monitoring data recorded in June 2003. Figures given are estimated from the SEPA commissioned software. Mean vehicle speed = 1.2 ± 0.2 ms^{-1}. n = 148,311.**

	Mean Probability of detecting 10^5 Bq *Mean across the detector array and best- and worst-case scenarios*			**Mean Detection Limits (Bq)** *Mean across the detector array and best- and worst- case scenarios*			**Detection limit range from best to worst case (Bq)**
Depth (mm)	**Mean**	**1 σ**	**Range**	**Mean**	**1 σ**	**Range**	
0	1	0	1-1	2.1×10^4	0.27×10^4	$1.0 - 3.1 \times 10^4$	$0.73 - 4.3 \times 10^4$
50	1	0	1 - 1	3.0×10^4	0.44×10^4	$1.4 - 4.8 \times 10^4$	$0.97 - 6.7 \times 10^4$
100	1	0.0006	0.94 - 1	5.0×10^4	0.73×10^4	$2.3 - 7.7 \times 10^4$	$1.6 - 11.3 \times 10^4$
200	0.26	0.16	0.003-0.98	16×10^4	2.4×10^4	$7.6 - 26 \times 10^4$	$5.4 - 38 \times 10^4$

Detection Capabilities at Thurso

H.7.2 The detection capabilities at Thurso are similar to that of Sandside and Scrabster, although there area a few areas where in the worst-case scenario, the detection limits marginally exceed the 10^5 level at 100 mm depth and the mean probability of detection reaches as low as around 0.7. The results are summarised in Table H.11.

Table H.11 The mean probability of detection and detection limits for Groundhog Evolution across Thurso Beach, based on monitoring data recorded in May 2003. Figures given are estimated from the SEPA-commissioned software. Mean vehicle speed = 1.23 ± 0.16 ms^{-1}. n = 229,669.

Depth (mm)	**Mean Probability of detecting 10^5 Bq** *Mean across the detector array and best- and worst-case scenarios*			**Mean Detection Limits (Bq)** *Mean across the detector array and best- and worst-case scenarios*			**Detection limit range from best- to worst- case (Bq)**
	Mean	**1 σ**	**Range**	**Mean**	**1 σ**	**Range**	
0	1	0	1 - 1	1.99 $x10^4$	0.2 $x10^4$	1.1 - 3.7 $x10^4$	0.78 - 5.2 $x10^4$
50	1	0	1 - 1	2.9 $x10^4$	0.3 $x10^4$	1.5 - 5.5 $x10^4$	1.0 - 8.1 $x10^4$
100	1	0.0008	0.77 - 1	4.8 $x10^4$	0.55 $x10^4$	2.4 - 9.3 $x10^4$	1.7 - 13.6 $x10^4$
200	0.28	0.13	0 - 0.97	15.7 $x10^4$	1.9 $x10^4$	7.7 - 30 $x10^4$	5.6 - 43 $x10^4$

Crosskirk and Brims Ness

H.7.3 The mean results indicate that the hand held system is broadly meeting the 10^5 Bq detection requirement. However, examination of the areas mapped indicate that the separation between monitoring transects often exceeds 50 cm and the probability of detecting a particle at the mid points will be much lower than indicated in Appendix Table H.12 and H.13 from Crosskirk and Brims Ness respectively. It is therefore unlikely that these beaches are being monitored effectively through this approach. The higher background at Crosskirk has a measurable influence in the detection capabilities with worst-case detection limits at 100 mm depth exceeding 2 x 10^5 Bq.

Table H.12 The mean probability of detection and detection limits for Groundhog Evolution at Crosskirk , based on monitoring data recorded in June 2003. Figures given are estimated from the SEPA commissioned software. Mean vehicle speed = 1.04 ± 0.2 ms^{-1}. n = 609

Depth (mm)	**Mean Probability of detecting 10^5 Bq** *Mean across the detector array and best- and worst-case scenarios*			**Mean Detection Limits (Bq)** *Mean across the detector array and best- and worst-case scenarios*			**Detection limit range from best- to worst-case (Bq)**
	Mean	**1 σ**	**Range**	**Mean**	**1 σ**	**Range**	
0	1	0	1 - 1	3.4 $x10^4$	0.55 $x10^4$	2.2 - 5.6 $x10^4$	1.6 - 7.9^+ $x10^4$
50	0.999	0.011	0.86 - 1	4.9 $x10^4$	0.9 $x10^4$	3 - 8.4 $x10^4$	2.1 - 12.4^+ $x10^4$
100	0.88	0.13	0.41 - 1	8.2 $x10^4$	1.5 $x10^4$	5 -14 $x10^4$	3.5 - 21^+ $x10^4$
200	0.008	0.02	0 - 0.16	26.2 $x10^4$	4.8 $x10^4$	16 - 45 $x10^4$	11 - 65^+ $x10^4$

Table H.13 The mean probability of detection and detection limits for Groundhog Evolution at Brims Ness, based on monitoring data recorded in June 2003) Evolution probability of detection for sand-pit bench trial validation (DPAG). Figures given are estimated from the SEPA commissioned software. Mean vehicle speed = 1.17 ± 0.25 ms^{-1}. n = 2151

Depth (mm)	**Mean Probability of detecting 10^5 Bq** *Mean across the detector array and best- and worst-case scenarios*			**Mean Detection Limits (Bq)** *Mean across the detector array and best- and worst- case scenarios*			**Detection limit range from best- to worst-case (Bq)**
	Mean	**1 σ**	**Range**	**Mean**	**1 σ**	**Range**	
0 mm	1	0	1 - 1	2.5 x10^4	0.44 x10^4	1.4 - 4 x10^4	1.0 - 5.6$^+$ x10^4
50 mm	1	0	1 - 1	3.7 x10^4	0.7 x10^4	1.9 - 6 x10^4	1.3 - 8.7$^+$ x10^4
100 mm	0.986	0.035	0.677 - 1	6.1 x10^4	1.2 x10^4	3 - 10 x10^4	2.2 - 14.8$^+$ x10^4
200 mm	0.035	0.15	0 - 0.795	19.6 x10^4	4 x10^4	9.8 - 37 x10^4	7.1 - 53$^+$ x10^4

H.8 Uncertainties on detection probability for UKAEA Sandpit trials

Table H.14 The number of individual observations required for given detection probabilities and Uncertainties

Detection probability	**Uncertainty**				
	5%	**10%**	**15%**	**20%**	**25%**
0.9	44	11	5	3	2
0.8	100	25	11	6	4
0.7	171	43	19	11	7
0.6	267	67	30	17	11
0.5	400	100	44	25	16
0.4	600	150	67	38	24
0.3	933	233	104	58	37
0.2	1600	400	178	100	64

APPENDIX I ALL PARTICLES DETECTED AND RECOVERED TO END OF FEBRUARY 2006

I.1.1 This appendix provides details of all particles that that have been detected and recovered from the coastal area around Dounreay. The information has been derived from http://www.ukaea.org.uk/sites/dounreay_part_part_finds.html with the kind permission of UKAEA.

I.2 Dounreay Foreshore Particle Finds

Field Ref	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
	A	04-Nov-83	Dounreay Foreshore [opp fm house]	298435	967070	20	5.60E+07			
	84000	06-Jan-84	East of castle	298350	967000		2.00E+07			
	84046	21-Jan-84	Castle	298320	966960		3.40E+06			
	84048	21-Jan-84	West foreshore	298380	967090		6.70E+01			
	84049	21-Jan-84	West foreshore	298400	967090		6.66E+05			
	84050	21-Jan-84	West foreshore beach	298380	967020		2.00E+06			
	84051	21-Jan-84	West foreshore	298420	967090		2.59E+06			
	84056	21-Jan-84	West foreshore	298410	967060		4.44E+06			
8408B	??	28-Jan-84	West of D1123	298500	967250		2.40E+06			
8410B	3	28-Jan-84	Beach area opp DMTR	298920	967600		5.55E+07			
8409B	950972	28-Jan-84	East foreshore	298550	967260		7.03E+06			
	84096	25-Feb-84	Nr Castle	298300	966970	25	2.66E+06			
	84170	17-Mar-84	Nr castle	298305	966950	23	5.92E+06			
	84171	17-Mar-84	West bank of stream	298300	966950	13	7.40E+05			
	84172	17-Mar-84	West of stream	298250	966940	5	3.66E+05			
	84173	17-Mar-84	West of stream by castle	298250	966950	46	1.26E+07			
	84267	12-May-84	Sand east of stream	298300	966980	23	2.04E+06			
	84315	26-May-84	Shingle nr DFR inlet	298510	967260	30	9.25E+07			
	84591	22-Sep-84	West foreshore	298300	966970	3	8.14E+06			
	84693	10-Nov-84	West foreshore beach	298340	966980	15	1.11E+06			
	84712	17-Nov-84	Shingle near DFR inlet	298510	967260	20	1.11E+07			
	84734	01-Dec-84	Shingle east foreshore	298690	967380	15	7.40E+05			

Field Ref	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
	84775	15-Dec-84	Beach west foreshore	298360	967000	20	7.40E+05			
	84776	15-Dec-84	Beach west foreshore	298390	967025	8	7.40E+05			
	84777	15-Dec-84	West Foreshore	298410	967030	1	nd	1.50E+04		
	84788	22-Dec-84	Sand west f'shore	298390	967040		1.48E+06			
	84789	22-Dec-84	Sand west f'shore	298400	967050		1.48E+06			
	85004	05-Jan-85	West foreshore	298370	966980	20	7.40E+05			
	85076	26-Jan-85	West foreshore	298420	967130	6	9.25E+06			
	85148	09-Mar-85	West foreshore	298390	967060	10	3.70E+06			
	85177	23-Mar-85	West foreshore	298370	966990	15	1.04E+06			
	85178	23-Mar-85	West foreshore	298190	966990	8	2.96E+06			
	85231	04-May-85	East of PFR outlet	298450	967200		nd	7.40E+03		
	85344	15-Jun-85	West foreshore	298520	967250	10	4.63E+06			
	85458	10-Aug-85	East foreshore	298700	967380	30	2.22E+07			
	85759	23-Nov-85	West foreshore	298370	967010	1	8.51E+05			
	85760	23-Nov-85	West foreshore	298500	967220	1	3.03E+06			
	85784	07-Dec-85	West foreshore	298370	967030	1	6.29E+05			
	86001	04-Jan-86	West foreshore	298480	967250	5	1.11E+07			
	86002	04-Jan-86	West foreshore	298330	967110	10	3.70E+06			
	86034	18-Jan-86	West foreshore	298370	966980	3	1.55E+06			
	86035	18-Jan-86	West foreshore	298380	967030	23	8.51E+06			
	86036	18-Jan-86	West foreshore	298380	967020	23	4.81E+06			
	86037	18-Jan-86	West Foreshore	298380	967000	8	nd	8.50E+06		
	86075	01-Feb-86	West foreshore	298410	967050	15	3.48E+06			
	86076	01-Feb-86	East foreshore	298730	967380	23	6.29E+06			
	86111	15-Feb-86	East foreshore	298720	967380	3	1.74E+06			
	86112	15-Feb-86	East foreshore	298750	967420	30	8.88E+06			
	86179	15-Mar-86	West foreshore	298380	967020	5	5.18E+05			
	86180	15-Mar-86	West foreshore	298420	967070	5	4.44E+04			
	86181	15-Mar-86	West foreshore	298520	967250	15	1.07E+06			
	86227	05-Apr-86	West foreshore	298420	967070	3	3.03E+06			

Field Ref	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
	86228	05-Apr-86	West foreshore	298530	967230	13	3.33E+06			
	86753	28-Jun-86	East foreshore	298630	967470	15	3.70E+06			
	861267	22-Nov-86	West foreshore	298380	967020	10	4.44E+05			
	861310	06-Dec-86	West foreshore	298380	967070	25	7.40E+05			
	870015	10-Jan-87	West foreshore	298410	967070	0	1.00E+06			
	870130	21-Feb-87	West foreshore	298410	967090	15	5.50E+06			
	870228	04-Apr-87	West foreshore	298330	966970	8	2.00E+05			
	870281	25-Apr-87	West foreshore	298380	967050	46	4.50E+07			
	870330	09-May-87	East foreshore	298690	967390	10	1.30E+07			
	870375	23-May-87	East foreshore	298960	967580	3	6.00E+05			
	870697	15-Aug-87	West foreshore	298750	967350	0	4.00E+04			
	870977	07-Nov-87	West foreshore	298350	966990	15	1.20E+06			
	870978	07-Nov-87	East foreshore	298740	967370	3	3.40E+06			
	871085	05-Dec-87	East foreshore	298740	967370	23	2.30E+07			
	880061	27-Jan-88	East foreshore	298700	967370	23	3.10E+06			
	880062	27-Jan-88	East forehore	298700	967390	3	1.00E+07			
	880120	23-Feb-88	West foreshore	298350	967080	4	3.20E+06			
	880169	24-Mar-88	West foreshore	298530	967260	8	3.10E+06			
	880170	24-Mar-88	West foreshore	298535	967270	15	7.80E+05			
	880545	30-Jul-88	West forshore	298542	967264	1	1.30E+07			
	880546	30-Jul-88	East forshore	298630	967398	1	2.00E+07			
	880597	13-Aug-88	East foreshore	298670	967345	1	3.10E+06			
	880686	27-Aug-88	East foreshore	298705	967395	10	2.50E+06			
	881055	09-Nov-88	West forshore (sluice)	298520	967190	3	4.30E+05			
	881261	21-Dec-88	Dounreay beach	298320	966950	8	2.60E+05			
	890028	09-Jan-89	West foreshore	298520	967270	23	4.90E+07			
	890091	25-Jan-89	West foreshore	298420	967080	15	2.40E+06			
	890093	25-Jan-89	East foreshore	298650	967450	3	3.20E+06			
	890140	07-Feb-89	West foreshore	298380	967020	1	2.80E+06			
	890346	03-Apr-89	East foreshore	298720	967370	10	6.20E+06			

Field Ref	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
	890446	19-Apr-89	West foreshore	298410	967080	10	9.60E+06			
	890503	03-May-89	West foreshore	298330	966980	0	4.50E+06			
	890543	10-May-89	West foreshore	298420	967080	3	5.50E+06			
	890549	11-May-89	West foreshore	298390	967090	5	4.25E+06			
	890566	16-May-89	West foreshore	298380	967040	8	1.00E+05			
	890579	19-May-89	West foreshore	298400	967030	8	4.00E+05			
	891071	12-Sep-89	East foreshore	298720	967390	8	1.30E+07			
	891130	27-Sep-89	West foreshore	298390	967050	8	2.30E+06			
	891131	27-Sep-89	East foreshore	298720	967380	8	9.50E+06			
	891372	21-Nov-89	East foreshore	298790	967450	5	3.40E+06			
	900003	06-Jan-90	West foreshore	298190	966980	5	2.70E+05			
	900004	06-Jan-90	West foreshore	298380	967050	3	2.80E+06			
	900051	15-Jan-90	West foreshore	298250	966990	10	4.60E+05			
	900052	15-Jan-90	West foreshore	298250	967000	13	2.60E+06			
	900104	06-Feb-90	West foreshore	298350	967070	5	4.00E+06			
	900133	12-Feb-90	West foreshore	298290	966990	8	1.70E+06			
	900254	13-Mar-90	West foreshore	298420	967120	13	1.60E+06			
	900405	23-Apr-90	East foreshore	298740	967450	30	7.00E+06			
	901196	14-Aug-90	East foreshore	298850	967440	8	1.20E+06			
	901515	08-Oct-90	West foreshore	298370	967020	5	2.10E+05			
	901516	08-Oct-90	West foreshore	298380	967050	30	1.20E+06			
	910163	30-Jan-91	East foreshore	298900	967600	15	1.10E+06			
	910164	30-Jan-91	East foreshore	298880	967590	8	4.00E+06			
	910165	30-Jan-91	East foreshore	298870	967580	15	4.00E+06			
	910166	30-Jan-91	East foreshore	298850	967560	10	3.70E+06			
	910241	11-Feb-91	East foreshore	298860	967580	5	3.00E+06			
	910522	09-Apr-91	East foreshore	298710	967470	38	5.00E+06			
	910643	06-May-91	West foreshore	298375	967040	8	3.00E+06			
	910985	22-Jul-91	East foreshore	298720	967450	8	5.00E+05			
	911077	12-Aug-91	East foreshore	298720	967390	25	1.10E+07			

Field Ref	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
	911541	25-Nov-91	West foreshore	298370	967010	20	5.00E+05			
	911542	25-Nov-91	West foreshore	298400	967080	15	6.00E+06			
	911550	26-Nov-91	East foreshore	298720	967400	15	1.80E+07			
	911551	26-Nov-91	East foreshore	298770	967430	30	2.00E+08			
	920834	16-Jun-92	West foreshore	298380	967020	4	1.00E+04			
	920890	30-Jun-92	West foreshore	298280	966980		1.00E+04			
	921026	11-Aug-92	West foreshore	298430	967070		9.00E+03			
	921088	25-Aug-92	West foreshore	298450	967130		1.60E+05			
	930178	19-Feb-93	West foreshore	298310	966970	15	3.00E+06			
	930284	19-Feb-93	West foreshore	298340	966990	8	1.00E+05			
	930271	04-Mar-93	West foreshore	298380	967060	25	1.00E+06			
	930304	18-Mar-93	West foreshore	298380	967020	5	nd	8.00E+05		
	930335	31-Mar-93	West foreshore	298410	967050	8	5.00E+05			
	930417	16-Apr-93	East foreshore	298780	967480	10	5.00E+06			
	930421	16-Apr-93	East foreshore	298870	967570	15	1.00E+06			
	930456	28-Apr-93	West foreshore	298450	967160	20	1.00E+06			
	930457	29-Apr-93	East foreshore	298830	967550	15	3.00E+06			
	930509	10-May-93	West foreshore	298390	967070	5	4.00E+06			
	930517	11-May-93	East foreshore	298710	967410	5	6.00E+06			
	930518	11-May-93	East foreshore	298820	967450	13	5.00E+06			
	930637	22-Jun-93	East foreshore	298720	967420	20	6.00E+06			
	940122	20-Jan-94	West Foreshore	298380	967080	8	2.00E+06			
	940241	15-Feb-94	West Foreshore	298280	966980	5	1.70E+06			
	940242	15-Feb-94	West foreshore	298390	967070	10	1.10E+06			
	940310	03-Mar-94	West Forshore	298380	967030	4	3.60E+05			
	940459	07-Apr-94	West foreshore	298305	966970	2	2.00E+06			

Field Ref	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
	940568	12-May-94	West foreshore	298380	967010	5	5.00E+06			
	941123	01-Oct-94	Adjacent to Shaft	298489	967135	nm	7.70E+05			MTR
	941300	27-Oct-94	East foreshore	298830	967480	10	1.00E+07			
	941306	31-Oct-94	~20m from castle gate	298380	967000	3	7.50E+06			
	941497	07-Dec-94	West of mill laide	298270	966940	3	8.00E+06			
	941498	08-Dec-94	West of HA shaft oppY45	298470	967120	20	4.40E+05			
	941499	08-Dec-94	Between Ypnts 39 & 40	298440	967050	8	1.70E+05			
	941508	14-Dec-94	Opp Y pt 45	298470	967120	15	6.20E+06			
	941510	15-Dec-94	SWPH beteen Ypt 3&4	298540	967280	1	4.90E+05			
	950056	14-Jan-95	Nr DFR SWPH	298540	967280	15	1.10E+06			MTR
	950210	06-Mar-95	Shingle below HA shaft	298440	967100	8	1.10E+07			MTR
	950265	25-Mar-95	West of mill laide	298320	966980	10	3.00E+06			MTR
	950266	25-Mar-95	West foreshore	298340	966995	10	1.00E+06			MTR
	950267	25-Mar-95	West foreshore	298330	966960	8	5.00E+05			MTR
	950440	11-May-95	West of mill laid	298270	966950	5	9.20E+05			MTR
	951344	07-Oct-95	East foreshore	298880	967600	45	1.20E+07			MTR
	951451	26-Oct-95	East Forshore	298770	967480	2	1.10E+06			MTR
	951535	08-Nov-95	East Foreshore	298770	967480	8	2.30E+06			MTR
	951633	22-Nov-95	East forshore	298720	967470	5	1.20E+07			MTR
	951835	21-Dec-95	West Foreshore	298380	967090	10	2.10E+07			MTR
	960300	29-Feb-96	North of castle	298290	966960	5	1.32E+06			
	960939	18-Apr-96	Grid No 2 N84 E45	298345	966984	15	1.57E+06			MTR
	961049	25-Apr-96	East Foreshore	298720	967445	15	4.62E+06			
	961466	25-May-96	West beach	298380	967030	4	3.13E+05			
	961541	07-Jun-96	East Foreshore G25 E75 N38	298675	967438	0	1.41E+07			MTR
	961544	10-Jun-96	West F'shore G2 10E 60N	298310	966960	8	1.45E+05			MTR
	961545	10-Jun-96	West F'shore G2 10E 60N	298310	966960	8	1.80E+03			
	961555	11-Jun-96	West F'shore G5 46E 02N	298346	967002	1	1.80E+05			MTR
	961581	13-Jun-96	EAST Clifftop G33 E13 N95	299013	967595	2	5.98E+03			
	961620	23-Jun-96	Grid 25 96E 0N	298696	967400	10	1.60E+06			MTR

Field Ref	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
	961759	01-Jul-96	outside fence nr HA shaft	298469	967132	5	1.38E+05			MTR
	962175	15-Aug-96	East Foreshore	298830	967450	6	7.50E+04			
	962227	19-Aug-96	16m North of outer castle fence	298259	966952	40	9.40E+04			MTR
	962228	19-Aug-96	34m North of outer castle fence	298245	966963	60	3.87E+06			MTR
	962232	22-Aug-96	4m North of baseline on East edge of trench 4	298345	966985	70	2.17E+06			MTR
	962271	28-Aug-96	Sand Survey Strip 17	298381	967018	60	4.93E+05			MTR
	962272	29-Aug-96	East Foreshore	298710	967390	10	4.24E+06			
	962276	29-Aug-96	Steep Cliffs Survey	298945	967566	5	4.80E+04			DFR
	962725	23-Oct-96	West Foreshore	298372	967038	3	1.22E+06			
	970001	31-Dec-96	West Foreshore(W of burn)	298270	966950	10	2.39E+06			MTR
	970980	25-Mar-97	Shingle below MHWS seawater pump house	298498	967247	5	4.70E+05			MTR
	971239	08-Apr-97	Strand line west foreshore	298372	967033		2.30E+05			MTR
	971240	08-Apr-97	Strand line west foreshore	298372	967033		1.40E+03			No Conc
	971241	08-Apr-97	Strand line west foreshore	298372	967033		1.50E+03			MTR
	972051	07-Jun-97	West Foreshore (west of burn)	298190	966980	15	1.60E+07			MTR
	972505	15-Jul-97	West F'shore nr SW pump house	298453	967225	10	3.10E+05			MTR
	973065	15-Sep-97	East foreshore	298603	967362	15	1.50E+06			MTR
	973183	24-Sep-97	Shingle west of SW pumphouse	298460	967166	10	4.30E+05			MTR
	973325	07-Oct-97	Shingle below DFR spillway	298487	967230	6	2.10E+06			MTR
	973924	14-Nov-97	beach west of DFR pump house	298507	967250	8	1.90E+05			DFR
	980768	10-Feb-98	Stony Beach West SW PHouse	298515	967245	5	2.26E+05			MTR
	980892	16-Feb-98	Stony Beach West SW PHouse	298489	967217	60	1.55E+05			MTR
	980893	16-Feb-98	Stony Beach West SW PHouse	298495	967233	120	1.34E+05			MTR
	982394	21-May-98	East Foreshore (Shingle below)	298748	967372	2	1.59E+04			MTR
	983905	25-Nov-98	West foreshore	298329	966991	5	7.30E+05			
	984054	23-Dec-98	West Foreshore	298371	967012		1.60E+06			
	990036	07-Jan-99	West Foreshore	298377	967006	2	5.52E+06			
	990103	17-Jan-99	West Foreshore	298386	967027	10	7.30E+06			
	990136	19-Jan-99	West Foreshore (nc98390 67012)	298390	967036	1	3.60E+05			
	990163	27-Jan-99	East forshore (NC98876 67469)	298850	967440	2	7.30E+05			

Field Ref	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
	990266	14-Feb-99	West Foreshore	298326	966984	15	1.00E+06			
	990337	18-Feb-99	West Foreshore shigle nr Pump House	298495	967249	22	4.90E+05			
	990679	15-Apr-99	Sandy area west foreshore	298344	967029	8	1.50E+06			
	991450	01-Jul-99	East foreshore	298786	967382	1	1.40E+07			
	991414	13-Jul-99	DFR Spillway (A3/1)	298480	967163	100	1.30E+06			
	992363	05-Oct-99	C2 area outside DFR west gate	298489	967146		3.80E+03			
	992647	10-Dec-99	West foreshore	298420	967050	5	4.60E+06			
DF/00/01	OOO59	14-Jan-00	West foreshore	298420	967060	5	5.14E+06			
DF/00/02	OO254	10-Feb-00	West foreshore	298283	966954	12	5.89E+06			
DF/00/03	OO454	09-Mar-00	West Foreshore	298390	967080	5	7.59E+06			
DF/00/04	OO795	05-Apr-00	West Foreshore	298380	967022	2	6.38E+06			
DF/00/005	L80PART/ 00/171	04-Oct-00	West Foreshore	298349	967034	2	1.40E+06			MTR
DF/00/006	00/173	04-Dec-00	Foreshore (beside Castle)	298330	966938	1	1.07E+06			MTR
DF/01/001	01/001	11-Jan-01	West Foreshore	298346	967015	2	3.85E+05			MTR
DF/01/002	01/003	20-Mar-01	West Foreshore	298371	967037	2	7.76E+06			
DF/01/003	01/118	30-Jul-01	F'shore of Perimeter fence	298467	967124	3	6.85E+04			
DF/02/001	02/003	21-Mar-02	West Foreshore	298341	967015	2	3.00E+06			
DF/02/002	02/004	04-Apr-02	West Foreshore	298374	967010	1.5	9.10E+05			MTR
DF/02/003	02/006	02-May-02	West foreshore	298308	966950	2	1.00E+06			
DF/02/004	02/240	02-Aug-02	West foreshore	298324	966950	2	7.40E+05			
DF/02/005	02/339	02-Sep-02	West foreshore	298390	967052	2	8.10E+05			
DF/03/001	03/001	08-Jan-03	West Foreshore	298360	967030	5	1.70E+06			
DF/03/002	03/002	20-Feb-03	West Foreshore	298295	966961	5	3.20E+06			
DF/03/003	03/104	27-Nov-03	West Foreshore	298290	966969	10	2.20E+06			
DF/04/001	04/108	16-Aug-04	West Foreshore	298380	967010	5	5.30E+05			
DF/04/002	04/125	14-Oct-04	West Foreshore	298371	967020	15	1.80E+05			
DF/04/003	04/126	28-Oct-04	West Foreshore	298309	966973	10	3.40E+05			
DF/04/004	04/132	10-Nov-04	West Foreshore	298343	966988	10	3.20E+05			
DF/04/005	04/133	10-Nov-04	West Foreshore	298263	966974	15	5.20E+04			

Field Ref	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
	04/134						9.10E+03			
	04/135						5.30E+04			
DF/04/006	04/136	09-Dec-04	West Foreshore	298337	966994	15	8.20E+04			
DF/04/007	04/137	09-Dec-04	West Foreshore*	298359	967064	5	2.00E+05			
DF/04/008	04/138	09-Dec-04	West Foreshore	298269	966977	5	8.00E+05			
DF/04/009	04/145	21-Dec-04	West Foreshore*	298352	967065	5	5.50E+05			
DF/05/001	05/001	06-Jan-05	West Foreshore	298356	967004	5	4.30E+04			
DF/05/002	05/002	07-Jan-05	West Foreshore*	298363	967051	5	1.90E+05			
DF/05/003	05/003	07-Jan-05	West Foreshore*	298376	967046	10	9.60E+05			
DF/05/004	05/005	01-Feb-05	West Foreshore	298341	967018	10	9.60E+05			
DF/05/005	05/009	17-Feb-05	West Foreshore	298353	967048	10	1.60E+06			
DF/05/006	05/008	17-Feb-05	West Foreshore	298343	967013	15	5.90E+06			
DF/05/007	05/010	17-Feb-05	West Foreshore	298251	966959	5	2.30E+05			

I.3 Sandside Beach Particle Finds

EFSN	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
	84235	28/04/84	Inter tidal area to east of Reay burn	296230	965360	1	2.00E+05			
	971921	28/05/97	Sandside Beach	296588	965346	0	1.50E+04			MTR
	974151	24/11/97	Sandside beach	296680	965450	5	1.50E+05			MTR
	991452	29/07/99	Sandside edge of river top of beach	296067	965319	5	9.30E+04			MTR
	991655	17/08/99	Sandside, West side of beach (top)	295985	965345	5	6.10E+04			MTR
	991951	10/09/99	Sandside beach edge of river	296055	965498	2	1.81E+05			DFR
	992005	23/09/99	Sandside beach (intertidal area W of Reay burn)	295945	965520	10	3.00E+05			MTR
	992691	20/12/99	East side Sandside beach	296581	965443	2	6.50E+04			MTR
SSBCH/00/001	000288	17/02/00	Sandside beach	296638	965505	2	7.57E+04			MTR
SSBCH/00/002	000389	02/03/00	Sandside Beach	296234	965382	1	4.63E+04			MTR
SSBCH/00/003	000878	14/04/00	Sandside beach [intertidal area east of Reay Burn	296610	965503	2	6.25E+04			MTR
SSBCH/00/004	00/004	17/07/00	Sandside, West side of beach	296002	965437	8	1.20E+05			MTR
SSBCH/00/005	00/074	16/08/00	Sandside mid way Reay & Isauld	296733	965450	1	4.00E+04			MTR
SSBCH/00/006	00/172	03/11/00	Sandside, Above MHWS at centre of beach	296270	965296	10	4.80E+04			MTR
SSBCH/01/001	01/002	16/02/01	Sandside, Central Section	296369	965345	2.5	1.00E+05			

EFSN	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
SSBCH/01/002	01/095	12/06/01	Sandside West side of beach	295890	965439	8	6.16E+04			
SSBCH/01/003	01/106	26/06/01	Sandside East side of beach	296462	965439	13	5.70E+04			
SSBCH/02/001	02/001	11/03/02	Sandside Middle of beach	296487	965358	10	9.10E+04			
SSBCH/02/002	02/002	15/03/02	Sandside West side of beach	295837	965448	15	1.10E+05		1.00E+02	DFR
SSBCH/02/003	02/005	16/04/02	Sandside, West side	296679	965524	10	6.40E+04		9.80E+01	
SSBCH/02/004	02/410	29/11/02	Sandside, West side almost on exposed rock	295824	965555	13	8.90E+04			
SSBCH/02/005	02/411	23/12/02	Sandside, East side	296531	965407	in cms of water	3.90E+04			
SSBCH/03/001	03/003	26/02/03	Sandside	296553	965405	7	1.30E+04			
SSBCH/03/002	03/004	27/02/03	Sandside	296736	965447	18	6.50E+04			DFR
	03/005						5.80E+02			MTR
SSBCH/03/003	03/006	27/02/03	Sandside	296725	965435	13	8.20E+04		9.80E+01	DFR
	03/007						9.30E+02			DFR
SSBCH/03/004	03/008	03/03/03	Sandside	295859	965447	4	1.90E+04			
SSBCH/03/005	03/009	13/03/03	Sandside	296422	965372	4	8.40E+03			
SSBCH/03/006	03/010	18/03/03	Sandside	295984	965364	0	2.70E+04			
SSBCH/03/007	03/011	20/03/03	Sandside	296697	965454	2	1.30E+04			
SSBCH/03/008	03/012	27/03/03	Sandside	296539	965462	7.5	4.10E+04			
SSBCH/03/009	03/013	28/03/03	Sandside	296265	965383	17	6.10E+04			
SSBCH/03/010	03/014	28/03/03	Sandside	296479	965419	20	6.40E+04			
SSBCH/03/011	03/015	02/04/03	Sandside strandline survey almost at MHWS	296291	965305	9	5.70E+04			

EFSN	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
SSBCH/03/012	03/016	08/04/03	Sandside, West side of beach	295904	965428	9	1.30E+04			
SSBCH/03/013	03/017	10/04/03	Sandside	296458	965405	4	1.50E+05			MTR
SSBCH/03/014	03/018	10/04/03	Sandside	296631	965410	5	1.60E+04			
SSBCH/03/015	03/019	11/04/03	Sandside	296705	965508	13	3.80E+04			
SSBCH/03/016	03/020	11/04/03	Sandside	296663	965473	10	2.30E+04			
SSBCH/03/017	03/034	12/05/03	Sandside	296588	965487	5	1.30E+04			
SSBCH/03/018	03/035	12/05/03	Sandside	296723	965557	9	1.80E+04			
SSBCH/03/019	03/094	09/07/03	Sandside	296706	965498	10	2.70E+04			
SSBCH/03/020	03/095	15/07/03	Sandside, West side of beach	295866	965511	4	2.00E+04			
SSBCH/03/021	03/096	18/07/03	Sandside, West side of beach	295906	965480	9	4.80E+04			MTR
SSBCH/03/022	03/101	14/11/03	Sandside	296591	965356	5	2.50E+04			
SSBCH/03/023	03/102	14/11/03	Sandside	296437	965328	10	7.70E+04			MTR
SSBCH/03/024	03/103	21/11/03	Sandside	296329	965355	4	2.80E+05			
SSBCH/04/001	04/001	21/01/04	Sandside East side of beach	296594	965450	4	5.80E+04			
	04/002						4.20E+03			
SSBCH/04/002	04/014	19/02/04	Sandside East side of beach	296617	965453	10	4.40E+04			
SSBCH/04/003	04/015	01/03/04	East side of Sandside Beach	296717	965497	5	1.40E+04			
SSBCH/04/004	04/019	18/03/04	East side of Sandside Beach	296464	965395	10	9.70E+04			
SSBCH/04/005	04/034	28/04/04	Sandside, West side of beach	296091	965484	4	7.30E+04			
SSBCH/05/001	05/011	19/02/05	Sandside, Mid-section of beach	296317	965351	5	1.50E+04			

EFSN	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
SSBCH/05/002	05/012	21/02/05	Sandside, Mid-section of beach	296399	965382	15	4.70E+04			
SSBCH/05/003	05/013	21/02/05	Sandside, Mid-section of beach	296206	965391	7	1.10E+04			
SSBCH/05/004	05/018	16/03/05	Sandside West side of beach	295905	965517	5	2.90E+04		3.20E+02	DFR?
SSBCH/05/004	05/158	09/09/05	Sandside Eastern Side	296507	965390	10	1.90E+04		4.90E+01	

I.4 Offshore Particle Finds

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/97/001/1	11-Jun-97	972131		298137	967585	nr	6.05E+03	6.05E+03		3.20E+02	DFR
DIVE/97/006/A	08-Aug-97	972709		298076	967513	0	2.50E+06	2.50E+06			MTR
DIVE/97/006/B	09-Aug-97	972710		298086	967471	0	2.00E+05	2.00E+05			MTR
DIVE/97/006/C	10-Aug-97	972711		298105	967459	10	1.10E+05	1.10E+05			MTR
DIVE/97/006/D	10-Aug-97	972712		298118	967469	10	7.00E+05	7.00E+05			MTR
DIVE/97/006/E	12-Aug-97	972721		298106	967425	75	1.10E+07	1.10E+07			MTR
DIVE/97/004/F	13-Aug-97	972726		297996	967342	50	2.10E+06	2.10E+06			MTR
DIVE/97/004/G	13-Aug-97	972727		298001	967334	25	4.20E+04	4.20E+04			MTR
DIVE/97/004/H	13-Aug-97	972728		298005	967328	0	5.20E+04	5.20E+04			MTR
DIVE/97/004/I	13-Aug-97	972729		298009	967325	35	5.10E+05	5.10E+05			MTR
DIVE/97/006/J	14-Aug-97	972756		298125	967419	25	3.00E+05	3.00E+05			MTR
DIVE/97/006/K	14-Aug-97	972757		298125	967424	0	7.70E+05	7.70E+05			MTR
DIVE/97/006/L	14-Aug-97	972765		298139	967439	5	5.50E+06	5.50E+06			MTR
DIVE/97/008/M	15-Aug-97	972766		298200	967524	5	5.60E+05	5.60E+05			MTR
DIVE/97/008/N	15-Aug-97	972767		298205	967524	5	1.30E+05	1.30E+05			MTR
DIVE/97/008/0	15-Aug-97	972768		298201	967531	0	3.10E+05	3.10E+05			MTR
DIVE/97/004/P	16-Aug-97	972769		298029	967348	25	9.50E+05	9.50E+05			MTR
DIVE/97/006/Q	17-Aug-97	972770		298156	967429	0	3.70E+04	3.70E+04			MTR
DIVE/97/014/R	17-Aug-97	972771		298654	967741	5	2.30E+05	2.30E+05			DFR
DIVE/97/010/S	19-Aug-97	972799		298351	967576	5	1.00E+05	1.00E+05			MTR
DIVE/97/010/T	19-Aug-97	972800		298349	967568	0	3.20E+04	3.20E+04			MTR
DIVE/97/005/U	20-Aug-97	972819		298305	967253	10	1.60E+07	1.60E+07			MTR
DIVE/97/005/V	02-Sep-97	972941		298311	967266	30	4.46E+04	4.46E+04			MTR
DIVE/97/005/W	02-Sep-97	972942		298280	967254	30	2.70E+06	2.70E+06			MTR
DIVE/97/005/X	02-Sep-97	972943		298267	967246	5	3.90E+06	3.90E+06			MTR
DIVE/97/005/Y	02-Sep-97	972944		298255	967238	5	2.50E+06	2.50E+06			MTR
DIVE/97/005/Z	02-Sep-97	972945		298254	967225	0	4.90E+06	4.90E+06			MTR
DIVE/97/012/2A	03-Sep-97	972949		298482	967670	0	5.80E+05	5.80E+05			DFR
DIVE/97/012/2B	03-Sep-97	972950		298482	967644	5	1.70E+06	1.70E+06			MTR

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/97/012/2C	03-Sep-97	972951		298457	967621	50	1.60E+04	1.60E+04			
DIVE/97/012/2D	03-Sep-97	972952		298469	967617	5	2.00E+05	2.00E+05			MTR
DIVE/97/012/2E	03-Sep-97	972958		298487	967641	5	1.70E+07	1.70E+07			MTR
DIVE/97/012/2F	03-Sep-97	972953		298463	967623	30	3.20E+05	3.20E+05			MTR
DIVE/97/009/2G	04-Sep-97	972959		298304	967512	50	7.50E+06	7.50E+06			MTR
DIVE/97/013/2H	11-Sep-97	973104		298518	967770	0	6.90E+04	6.90E+04			DFR
DIVE/98/001/01	29-Aug-98	983158	3	298382	967421	30	1.13E+05	1.13E+05			MTR
DIVE/98/001/02	29-Aug-98	983160	3	298378	967413	13	1.80E+05	1.80E+05			MTR
DIVE/98/001/03	29-Aug-98	983162	3	298382	967414	6	7.28E+04	7.28E+04			MTR
DIVE/98/002/04	02-Sep-98	983174	3	298632	967806	60	1.72E+06	1.72E+06			MTR
DIVE/98/002/05	02-Sep-98	983176	3	298618	967802	15	1.51E+05	1.51E+05			MTR
DIVE/98/002/06	02-Sep-98	983178	3	298629	967795	15	6.18E+05	6.18E+05			MTR
DIVE/98/002/07	02-Sep-98	983180	3	298610	967773	5	6.75E+04	6.79E+04		7.83E+01	DFR
		983181					4.21E+02				
DIVE/98/002/08	02-Sep-98	983183	3	298592	967790	10	1.96E+05	2.47E+05			DFR
		983184					5.09E+04				
DIVE/98/004/09	05-Sep-98	983186	3	298346	967558	40	1.18E+05	1.18E+05			MTR
		983187					1.16E+02				
DIVE/98/004/10	05-Sep-98	983189	3	298360	967566	25	6.01E+04	6.01E+04		1.55E+02	DFR
DIVE/98/003/11	05-Sep-98	983208	3	298230	967476	25	4.04E+05	4.04E+05			MTR
DIVE/98/005/12	06-Sep-98	983210	3	298848	968174	15	3.96E+04	3.96E+04			MTR
DIVE/98/005/13	06-Sep-98	983212	3	298847	968190	10	7.78E+02	5.97E+03			
		983213					5.80E+02				
		983214					3.91E+03				Activity too low
		983215					2.44E+02				
		983216					4.60E+02				
DIVE/98/005/14	06-Sep-98	983219	3	298847	968190	10	1.24E+04	1.24E+04			Activity too low
DIVE/98/005/15	06-Sep-98	983221	3	298847	968190	10	1.04E+04	1.92E+04			Activity too low
		983222					8.77E+03				
DIVE/98/005/16	06-Sep-98	983269	3	298847	968190	10	6.08E+04	6.08E+04			DFR

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/98/005/17	06-Sep-98	983271	3	298855	968165	4	5.27E+03	5.27E+03			Activity too low
DIVE/98/005/18	06-Sep-98	983273	3	298854	968171	1	2.53E+03	4.71E+04			
		983274					4.15E+04				MTR
		983275					1.19E+03				
		983276					5.15E+02				
		983277					9.76E+02				
		983278					3.84E+02				
DIVE/98/005/19	06-Sep-98	983280	3	298853	968175	35	1.16E+05	1.16E+05			MTR
DIVE/98/005/20	06-Sep-98	983282	3	298854	968190	<5	4.06E+04	4.06E+04			DFR
DIVE/98/007/21	09-Sep-98	983382	1	298090	967464	20	1.34E+06	1.34E+06			MTR
DIVE/98/008/22	18-Sep-98	983384	4	298625	968138	15	7.73E+04	7.73E+04			MTR
DIVE/98/008/23	19-Sep-98	983386	4	298600	968130	70	4.39E+06	4.39E+06			MTR
DIVE/98/015/24	21-Sep-98	983388	1	298113	967258	35	1.44E+06	1.44E+06			MTR
DIVE/98/015/25	21-Sep-98	983390	1	298100	967265	5	6.77E+04	6.77E+04			MTR
DIVE/98/015/26	21-Sep-98	983392	1	298100	967293	20	1.78E+05	1.78E+05			MTR
DIVE/98/015/27	21-Sep-98	983394	1	298109	967289	10	9.38E+03	9.38E+03			MTR
DIVE/98/015/28	21-Sep-98	983396	1	298106	967285	15	5.45E+05	5.45E+05			MTR
DIVE/98/015/29	21-Sep-98	983398	1	298107	967280	30	4.82E+04	5.59E+04		5.06E+01	DFR
		983399					7.72E+03				
DIVE/98/015/30	21-Sep-98	983401	1	298115	967282	7	2.87E+04	2.87E+04			MTR
DIVE/98/015/31	21-Sep-98	983403	1	298121	967284	5	1.64E+05	1.64E+05			MTR
DIVE/98/015/32	21-Sep-98	983405	1	298133	967292	5	3.26E+05	3.26E+05			MTR
DIVE/98/015/33	21-Sep-98	983524	1	298128	967285	22.5	1.45E+05	1.45E+05			MTR
DIVE/98/016/34	22-Sep-98	983526	5	298286	967286	5	1.20E+05	1.20E+05			MTR
DIVE/98/016/35	22-Sep-98	983528	5	298296	967295	20	2.09E+05	2.09E+05			MTR
DIVE/98/016/36	22-Sep-98	983530	5	298296	967279	25	8.28E+05	8.28E+05			MTR
DIVE/98/016/37	22-Sep-98	983532	5	298303	967290	5	1.95E+05	1.95E+05			MTR
DIVE/98/016/38	22-Sep-98	983534	5	298310	967288	30	5.23E+05	5.23E+05			MTR
DIVE/98/018/39	23-Sep-98	983536	5	298521	967502	20	1.75E+05	1.75E+05			MTR
DIVE/98/019/40	24-Sep-98	983538	5	298800	967680	1	8.84E+04	8.84E+04			MTR
DIVE/98/020/41	24-Sep-98	983540	3	298433	967766	8	1.75E+06	1.75E+06			DFR
DIVE/98/021/43	25-Sep-98	983794	4	298614	968170	0	1.49E+06	1.49E+06			MTR
DIVE/98/022/44	25-Sep-98	983796	5	298202	967203	5	1.66E+05	1.66E+05			MTR
DIVE/98/025/45	27-Sep-98	983798	1	298112	967450	25	5.45E+06	5.45E+06			MTR

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/98/025/46	27-Sep-98	983800	1	298100	967442	15	7.86E+05	1.40E+06			MTR
		983801					6.00E+05				
		983802					1.43E+04				
DIVE/98/025/47	27-Sep-98	983804	1	298095	967436	1	6.78E+05	6.78E+05			MTR
DIVE/98/025/48	27-Sep-98	983806	1	298100	967435	75+	1.42E+06	1.42E+06			MTR
DIVE/98/026/49	28-Sep-98	984051	3/4(a)	298266	967747	60	1.11E+07	1.11E+07			MTR
DIVE/98/026/50	28-Sep-98	983809	3/4	298260	967751	5	9.83E+04	9.83E+04		1.92E+02	DFR
DIVE/98/026/51	28-Sep-98	983811	3/4	298253	967755	40	4.66E+06	4.66E+06			MTR
DIVE/98/026/52	28-Sep-98	983813	3/4	298248	967758	10	<1.30E+02	<1.30E+02	2.37E+04		SS
DIVE/98/026/53	28-Sep-98	983815	3/4	298244	967753	0	2.20E+04	2.20E+04		5.46E+01	DFR
DIVE/98/026/54	28-Sep-98	990025	3/4(a)	298270	967762	25.3	8.86E+06	8.86E+06			MTR
DIVE/98/026/55	28-Sep-98	990026	3/4(a)	298273	967760	30	1.09E+07	1.09E+07			MTR
DIVE/98/026/56	29-Sep-98	983819	3/4	298254	967740	0	5.02E+04	5.02E+04			DFR
DIVE/98/026/57	29-Sep-98	983821	3/4	298256	967731	7.5	6.42E+03	6.42E+03			U only seen
DIVE/98/026/58	29-Sep-98	990027	3/4	298252	967740	30	2.11E+06	2.1E+06			MTR
DIVE/98/026/59	29-Sep-98	990047	3/4	298251	967736	35	1.13E+05	1.13E+05		7.77E+01	DFR
DIVE/98/026/60	29-Sep-98	983825	3/4	298252	967731	0	2.86E+03	2.86E+03			MTR
DIVE/98/026/61	29-Sep-98	984052	3/4	298256	967746	5	4.99E+04	4.99E+04		2.65E+01	DFR
DIVE/98/026/62	29-Sep-98	983828	3/4	298255	967744	60	3.11E+06	3.11E+06			MTR
DIVE/98/026/63	29-Sep-98	983830	3/4	298256	967737	5	1.95E+04	1.95E+04			DFR
DIVE/98/026/64	29-Sep-98	990048	3/4(a)	298259	967740	20	1.26E+07	1.78E+07			MTR
		984053					5.24E+06				
DIVE/98/026/65	29-Sep-98	983833	3/4	298260	967737	20	1.79E+04	1.79E+04		4.36E+01	DFR
DIVE/98/026/66	29-Sep-98	990049	3/4(a)	298262	967748	45	1.18E+07	1.18E+07			MTR
DIVE/98/026/67	29-Sep-98	983836	3/4	298260	967740	7.5	9.38E+04	9.38E+04		7.90E+01	DFR
DIVE/98/026/68	29-Sep-98	983838	3/4	298270	967732	0	2.83E+04	2.83E+04			MTR
DIVE/98/026/69	29-Sep-98	983840	3/4	298270	967741	100	2.99E+06	2.99E+06			MTR
DIVE/98/026/70	29-Sep-98	983842	3/4	298270	967747	50	8.81E+05	8.81E+05			MTR
DIVE/98/026/71	29-Sep-98	983844	3/4	298270	967736	5	1.53E+04	1.53E+04		6.85E+01	DFR
DIVE/98/026/72	29-Sep-98	983969	3/4	298279	967739	0.5	1.87E+03	1.87E+03			DFR

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/98/026/73	29-Sep-98	983970	3/4	298276	967748	1	3.25E+05	3.25E+05			DFR
DIVE/98/026/74	29-Sep-98	983848	3/4	298284	967735	45	1.15E+06	1.15E+06			MTR
DIVE/98/027/75	01-Oct-98	990089	1	297614	967329	3	6.29E+02	6.29E+02			
DIVE/98/028/76	01-Oct-98	990090	1	297050	967092	5	2.37E+04	2.37E+04			DFR
DIVE/98/029/77	03-Oct-98	990091	1	297523	967253	30	1.61E+05	1.61E+05			MTR
DIVE/98/031/78	05-Oct-98	983853	1	296430	966510	7	2.46E+04	2.46E+04			DFR
DIVE/98/031/79	05-Oct-98	984040	1	296441	966519	12	8.50E+03	8.50E+03			DFR
DIVE/98/031/80	05-Oct-98	983856	1	296460	966530	2.5	8.55E+04	8.55E+04			too small
DIVE/98/033/81	06-Oct-98	984041	4(a)	298167	967646	100	1.10E+07	1.10E+07			MTR
DIVE/98/033/82	06-Oct-98	983859/a 983859/b	3	298198	967674	50	1.22E+06	1.22E+06			MTR
DIVE/98/034/83	07-Oct-98	984042	4	298077	967598	7.5	1.25E+05	1.25E+05		5.67E+01	DFR
DIVE/98/034/84	07-Oct-98	990105 990106	1	298068	967546	30	4.80E+04 3.24E+05	3.72E+05			 MTR
DIVE/98/034/85	07-Oct-98	983863	1	298056	967546	35	2.31E+05	2.31E+05		9.76E+01	Niob only no U
DIVE/98/034/86	07-Oct-98	983865	1	298054	967584	40	7.60E+05	7.60E+05			MTR
DIVE/98/037/87	08-Oct-98	990107	3	298722	968024	0	1.21E+04	1.21E+04		1.82E+01	DFR
DIVE/98/036/88	08-Oct-98	990120	4	298495	967974	0	2.00E+06	2.00E+06			MTR
DIVE/98/036/89	08-Oct-98	990122	4	298495	967975	30	8.10E+06	8.10E+06			MTR
DIVE/99/038/90	27-May-99	991682	2	296420	966425	5	2.16E+04	2.16E+04			
DIVE/99/047/92	01-Jun-99	991683	1	298027	967563	0	9.04E+03	9.04E+03			
DIVE/99/047/97	01-Jun-99	991684	1	297942	967521	30	2.80E+04	2.80E+04			
DIVE/99/048/98	02-Jun-99	991685	1	296405	966637	0	2.28E+04	2.28E+04			
DIVE/99/050/99	04-Jun-99	991686	1	297619	967339	0	3.53E+04	3.53E+04			
DIVE/99/051/104	04-Jun-99	991687	1	297543	967360	7.5	2.87E+04	2.87E+04			
DIVE/99/058/110	12-Jun-99	991688	3/4	298382	967890	40	1.45E+07	1.45E+07			
DIVE/99/067/113	18-Jun-99	991689	4	297538	967390	0	1.73E+05	1.73E+05			
DIVE/99/077/114	26-Aug-99	991776	2	296177	965638	0	1.20E+04	1.20E+04			
DIVE/99/077/115	31-Aug-99	992440	E. of Site	299114	968600	30	2.34E+06	2.34E+06			
DIVE/99/077/116	31-Aug-99	992442	E. of Site	299120	968612	15	2.50E+05	2.50E+05			
DIVE/99/078/119	04-Sep-99	992444	E. of Site	299266	968737	50	1.34E+07	1.34E+07			
DIVE/99/080/121	05-Sep-99	992446	E. of Site	298980	967766	4	5.79E+04	5.79E+04			
DIVE/99/084/123	23-Sep-99	000155	E of Site	298694	968450	3	2.47E+06	2.47E+06			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/99/084/124	23-Sep-99	000157	E of Site	299446	969323	3	4.60E+04	4.60E+04			
DIVE/00/008/01	28-Jul-00	00/005	Re-pop 3	298095	967461	10	6.79E+04	6.79E+04		1.66E+02	
DIVE/00/009/01	28-Jul-00	00/009	Re-pop 3	298102	967454	20	1.18E+06	1.18E+06			
DIVE/00/009/02	28-Jul-00	00/006	Re-pop 3	298103	967443	15	1.84E+05	1.84E+05			
DIVE/00/010/01	28-Jul-00	00/014	Re-pop 3	298112	967439	10	2.46E+04	2.46E+04			
DIVE/00/010/01a	28-Jul-00	00/015	Re-pop 3	298112	967439	nr	1.72E+03	1.72E+03			
DIVE/00/010/02	28-Jul-00	00/007	Re-pop 3	298125	967437	20	2.54E+03	7.46E+05			
		00/008					7.43E+05				
DIVE/00/011/01	28-Jul-00	00/017	Re-pop 3	298101	967436	2	3.29E+04	3.29E+04			
DIVE/00/011/02	28-Jul-00	00/016	Re-pop 3	298122	967433	11	1.70E+06	1.70E+06			
DIVE/00/013/01	29-Jul-00	00/011	Re-pop 3	298099	967414	40	1.67E+06	1.67E+06			
DIVE/00/014/01	29-Jul-00	00/010	Re-pop 3	298088	967430	40	4.88E+05	4.88E+05			
DIVE/00/015/01	29-Jul-00	00/013	Re-pop 3	298099	967434	5	3.75E+05	3.75E+05			
DIVE/00/015/02	29-Jul-00	00/012	Re-pop 3	298081	967430	25	1.02E+05	1.02E+05			
DIVE/00/015/03	29-Jul-00	00/025	Re-pop 3	298084	967429	5	4.64E+06	5.60E+06			
		00/026					9.10E+05				
		00/027					5.44E+04				
DIVE/00/025/01	08-Aug-00	00/019	Re-pop 3	298078	967436	17.5	3.50E+05	3.50E+05			
DIVE/00/025/02	08-Aug-00	00/020	Re-pop 3	298070	967436	20	1.59E+06	1.59E+06			
DIVE/00/027/01	08-Aug-00	00/021	Re-pop 2	297664	967419	30	4.90E+04	8.00E+04			
		00/022					3.10E+04				
DIVE/00/028/01	08-Aug-00	00/018	Re-pop 2	297664	967428	8	7.21E+04	7.21E+04			
DIVE/00/028/02	08-Aug-00	00/023	Re-pop 2	297673	967419	10	1.28E+04	1.28E+04			
DIVE/00/029/01	08-Aug-00	00/024	Re-pop 2	297634	967410	5	1.53E+04	1.53E+04			
DIVE/00/032/01	09-Aug-00	00/030	Re-pop 2	297664	967430	5	3.89E+04	3.89E+04			
DIVE/00/032/02	09-Aug-00	00/028	Re-pop 2	297661	967430	5	1.16E+04	1.16E+04			
DIVE/00/033/01	09-Aug-00	00/029	Re-pop 6	298907	968238	10	4.79E+04	4.79E+04			
DIVE/00/034/01	11-Aug-00	00/031	Re-pop 6	298874	968230	10	1.70E+04	2.21E+04			
		00/032					4.70E+03				
		00/033					4.10E+02				
DIVE/00/035/01	11-Aug-00	00/034	Re-pop 6	298886	968246	5	5.20E+03	5.20E+03			
DIVE/00/036/01	12-Aug-00	00/038	Re-pop 6	298880	968262	35	1.70E+05	1.71E+05			
		00/039					4.20E+02				
		00/040					<120				
		00/041					2.70E+02				
		00/042					<120				

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
		00/043					<120				
DIVE/00/037/01	12-Aug-00	00/046	Re-pop 6	298886	968255	10	2.43E+04	2.43E+04		1.20E+02	
DIVE/00/038/01	12-Aug-00	00/044	Re-pop 6	298885	968261	5	2.00E+04	2.00E+04			
DIVE/00/038/02	12-Aug-00	00/047	Re-pop 6	298897	968256	30	8.24E+04	8.24E+04			
DIVE/00/039/01	12-Aug-00	00/045	Re-pop 6	298894	968256	5	7.10E+03	7.10E+03		5.67E+02	
DIVE/00/039/02	12-Aug-00	00/048	Re-pop 6	298901	968264	5	3.57E+04	3.57E+04			
DIVE/00/039/03	12-Aug-00	00/035	Re-pop 6	298908	968258	5	2.70E+02	4.47E+03			
		00/036					4.20E+03				
DIVE/00/040/01	12-Aug-00	00/037	Re-pop 6	298908	968260	10	1.50E+04	1.50E+04			
DIVE/00/041/01	13-Aug-00	00/052	Re-pop 6	298907	968259	10	4.70E+03	4.70E+03			
DIVE/00/042/01	13-Aug-00	00/049	Re-pop 6	298900	968246	70	3.90E+05	1.16E+06			
		00/050					7.70E+05				
		00/051					2.90E+03				
DIVE/00/043/01	13-Aug-00	00/053	Re-pop 6	298909	968246	35	2.70E+04	1.62E+05			
		00/054					5.90E+04			8.70E+01	
		00/055					7.60E+04			1.10E+02	
DIVE/00/043/02	13-Aug-00	00/056	Re-pop 6	298916	968246	35	3.43E+06	3.43E+06			
DIVE/00/046/01	14-Aug-00	00/057	Re-pop 5	298637	967934	5	6.60E+05	6.60E+05			
DIVE/00/047/01	14-Aug-00	00/059	Re-pop 5	298652	967945	8	1.09E+06	1.09E+06			
DIVE/00/048/01	14-Aug-00	00/058	Re-pop 5	298660	967956	11	3.00E+04	3.00E+04			
DIVE/00/049/01	15-Aug-00	00/060	Re-pop 5	298666	967966	10	8.88E+04	8.88E+04		8.00E+02	DFR
DIVE/00/050/01	15-Aug-00	00/061	Re-pop 5	298652	967968	15	4.09E+02	2.39E+03		5.80E+03	Nb only min U
		00/062					1.98E+03				
DIVE/00/051/01	15-Aug-00	00/063	Re-pop 5	298670	967977	5	9.40E+03	9.79E+03			
		00/064					3.90E+02				
DIVE/00/051/02	15-Aug-00	00/065	Re-pop 5	298670	967969	10	1.65E+04	1.65E+04			
DIVE/00/052/01	15-Aug-00	00/067	Re-pop 5	298669	967987	20	5.80E+02	7.09E+04			
		00/068					3.70E+02				
		00/069					4.90E+02				
		00/070					3.00E+03				
		00/071					3.80E+02				
		00/072					1.00E+03				

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
		00/073					6.51E+04				
DIVE/00/052/02	15-Aug-00	00/066	Re-pop 5	298672	967970	10	2.10E+04	2.10E+04			
DIVE/00/053/01	16-Aug-00	00/077	Re-pop 5	298672	967982	22	4.10E+04	4.10E+04			
DIVE/00/053/02	16-Aug-00	00/075	Re-pop 5	298671	967970	30	3.29E+06	3.29E+06			
DIVE/00/054/01	16-Aug-00	00/078	Re-pop 5	298673	967964	10	1.30E+04	1.30E+04			
DIVE/00/054/02	16-Aug-00	00/079	Re-pop 5	298671	967958	5	8.45E+03	9.45E+03			
		00/080					1.00E+03				
DIVE/00/056/01	16-Aug-00	00/076	Re-pop 5	298679	967937	10	7.95E+05	7.95E+05			
DIVE/00/056/02	16-Aug-00	00/081	Re-pop 5	298680	967936	7.5	1.90E+04	1.90E+04			
DIVE/00/057/01	16-Aug-00	00/082	Re-pop 5	298672	967949	5	3.00E+05	3.04E+05		4.00E+02	
		00/083					2.00E+03				
		00/084					1.40E+03				
		00/085					8.40E+02				
DIVE/00/057/02	16-Aug-00	00/086	Re-pop 5	298677	967934	5	4.10E+05	4.10E+05			
DIVE/00/057/03	16-Aug-00	00/087	Re-pop 5	298677	967935	5	7.05E+04	1.63E+05			
		00/088					8.07E+04				
		00/089					2.59E+03				
		00/090					9.16E+03				
DIVE/00/058/01	17-Aug-00	00/091	Re-pop 5	298667	967950	7.5	2.40E+05	2.40E+05			
DIVE/00/059/01	17-Aug-00	00/092	Re-pop 4	298196	967712	13	4.90E+04	1.77E+05			
		00/093					3.20E+04				
		00/094					7.10E+04				
		00/095					1.45E+04				
		00/096					6.65E+03				
		00/097					3.94E+03				
DIVE/00/060/01	17-Aug-00	00/098	Re-pop 4	298198	967717	20	1.76E+05	1.76E+05		1.90E+02	
DIVE/00/060/02	17-Aug-00	00/099	Re-pop 4	298194	967700	45	7.72E+05	7.72E+05			
DIVE/00/062/01	18-Aug-00	00/101	Re-pop 4	298207	967714	50	3.23E+06	3.23E+06			
DIVE/00/063/01	18-Aug-00	00/109	Re-pop 4	298210	967715	17.5	4.45E+06	4.45E+06			
DIVE/00/063/02	18-Aug-00	00/100	Re-pop 4	298207	967702	10	1.06E+05	1.06E+05			
DIVE/00/063/03	18-Aug-00	00/102	Re-pop 4	298208	967710	10	8.00E+04	9.28E+04			
		00/103					1.28E+04				
DIVE/00/063/04	18-Aug-00	00/107	Re-pop 4	298208	967704	5	8.00E+03	8.00E+03			
DIVE/00/063/05	18-Aug-00	00/108	Re-pop 4	298204	967715	5	2.20E+05	2.20E+05			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/00/064/01	18-Aug-00	00/104	Re-pop 4	298195	967690	5	2.10E+04	2.10E+04			
DIVE/00/064/02	18-Aug-00	00/105	Re-pop 4	298191	967686	20	3.80E+06	3.80E+06			
DIVE/00/064/03	18-Aug-00	00/106	Re-pop 4	298205	967715	5	1.90E+05	1.90E+05		1.40E+02	
DIVE/00/065/01	19-Aug-00	00/111	Re-pop 4	298218	967715	10	2.20E+05	2.23E+05		9.00E+01	
		00/112					2.70E+03				
DIVE/00/066/01	19-Aug-00	00/113	Re-pop 4	298223	967701	17	6.30E+04	6.30E+04			
DIVE/00/066/02	19-Aug-00	00/110	Re-pop 4	298224	967706	50	4.47E+06	4.47E+06			
DIVE/00/067/01	19-Aug-00	00/114	Re-pop 4	298214	967694	50	1.50E+06	1.50E+06			
DIVE/00/069/01	20-Aug-00	00/115	Re-pop 4	298221	967688	5	8.40E+03	8.40E+03			
DIVE/00/069/02	20-Aug-00	00/116	Re-pop 4	298225	967684	5	7.30E+03	7.30E+03			
DIVE/00/069/03	20-Aug-00	00/117	Re-pop 4	298229	967682	5	7.10E+03	7.10E+03			
DIVE/00/069/04	20-Aug-00	00/118	Re-pop 4	298218	967683	10	5.42E+04	5.42E+04			
DIVE/00/069/05	20-Aug-00	00/119	Re-pop 4	298216	967672	20	3.76E+06	3.76E+06			
DIVE/00/071/02	21-Aug-00	00/121	Re-pop 4	298212	967666	5	5.47E+04	5.47E+04			MTR
DIVE00/071/03	21-Aug-00	00/126	Re-pop 4	298206	967685	55	5.80E+06	5.80E+06			
DIVE/00/072/01	21-Aug-00	00/122	Re-pop 4	298204	967665	50	1.10E+06	1.10E+06			
		00/123					1.20E+03				
DIVE/00/074/01	21-Aug-00	00/124	Re-pop 4	298195	967680	5	1.04E+04	1.04E+04			
DIVE/00/074/02	21-Aug-00	00/125	Re-pop 4	298194	967686	5	1.60E+05	1.60E+05			
DIVE/00/074/03	21-Aug-00	00/127	Re-pop 4	298189	967673	40	4.40E+06	4.40E+06			
DIVE/00/076/01	22-Aug-00	00/139	Re-pop 4	298193	967683	50	4.40E+06	4.40E+06			
DIVE/00/076/02	22-Aug-00	00/140	Re-pop 4	298188	967690	40	3.90E+06	3.90E+06			
DIVE/00/077/01	22-Aug-00	00/141	Re-pop 4	298175	967675	32	1.00E+06	1.00E+06			
DIVE/00/077/02	22-Aug-00	00/128	Re-pop 4	298187	967690	30	3.47E+05	4.20E+05		3.20E+02	
		00/129					6.79E+02				
		00/130					1.18E+04				
		00/131					3.41E+02				
		00/132					5.78E+04				
		00/133					2.40E+03				
DIVE/00/078/01	22-Aug-00	00/142	Re-pop 4	298171	967682	30	4.60E+06	4.60E+06			
DIVE/00/078/02	22-Aug-00	00/143	Re-pop 4	298180	967688	45	4.30E+06	4.30E+06			
		00/144					1.80E+03				
		00/145					<1.10E+02				
DIVE/00/079/01	22-Aug-00	00/134	Re-pop 4	298185	967694	15	1.00E+05	3.50E+05		1.30E+02	

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
		00/135					2.50E+05			3.80E+02	
DIVE/00/080/01	22-Aug-00	00/136	Re-pop 4	298163	967705	5	1.30E+04	1.30E+04		4.20E+02	
DIVE/00/080/02	22-Aug-00	00/137	Re-pop 4	298182	967699	40	1.30E+04	2.83E+05			
		00/138					2.70E+05			1.40E+02	
DIVE/00/081/01	23-Aug-00	00/146	Re-pop 4	298188	967700	20	3.10E+04	3.10E+04		2.70E+02	
DIVE/00/081/02	23-Aug-00	00/147	Re-pop 4	298198	967697	25	1.00E+05	1.00E+05			
DIVE/00/083/01	25-Aug-00	00/150	Re-pop 7	299048	968660	22	<1.90E+02	<1.90E+02	1.30E+04		
DIVE/00/087/01	26-Aug-00	00/149	Re-pop 7	299042	968615	10	1.20E+05	1.20E+05			
DIVE/00/092/01	26-Aug-00	00/148	Re-pop 7	299042	968675	40	1.50E+05	1.50E+05			
DIVE/00/094/01	28-Aug-00	00/151	Re-pop 7	299041	968682	5	4.25E+04	4.27E+04			
		00/152					2.30E+02				
DIVE/00/100/01	29-Aug-00	00/153	Re-pop 7	299063	968657	30	3.40E+05	3.40E+05			
DIVE/00/101/01	29-Aug-00	00/154	Re-pop 7	299064	968656	10	1.90E+05	1.90E+05			
DIVE/00/103/01	30-Aug-00	00/160	GW5	298637	967749	10	1.48E+04	1.48E+04			
DIVE/00/104/01	30-Aug-00	00/161	GW5	298634	967741	7.5	6.60E+03	6.60E+03			
DIVE/00/104/02	30-Aug-00	00/162	GW5	298634	967741	30	6.05E+04	6.05E+04			
DIVE/00/105/01	30-Aug-00	00/164	GW5	298626	967737	15	5.67E+05	5.67E+05			
DIVE/00/105/02	30-Aug-00	00/157	GW5	298623	967752	5	1.10E+05	1.10E+05			
DIVE/00/106/01	31-Aug-00	00/158	GW5	298624	967752	5	6.37E+03	6.37E+03			
DIVE/00/106/02	31-Aug-00	00/159	GW5	298614	967756	10	5.09E+03	5.09E+03			
DIVE/00/108/01	31-Aug-00	00/165	GW5	298622	967769	40	6.89E+05	6.89E+05			
DIVE/00/109/01	31-Aug-00	00/163	GW5	298635	967776	25	5.77E+04	5.77E+04			
DIVE/00/110/01	01-Sep-00	00/155	GW5	298645	967775	15	6.94E+04	6.94E+04			
DIVE/00/110/02	01-Sep-00	00/156	GW5	298654	967787	20	8.71E+04	8.71E+04			
DIVE/00/112/01	01-Sep-00	00/166	GW5	298650	967744	5	8.00E+03	8.00E+03		1.50E+02	

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/00/121/01	05-Sep-00	00/167	GW3	298274	967258	15	2.10E+06	2.10E+06			MTR
DIVE/00/122/01	05-Sep-00	00/168	GW3	298261	967255	25	4.62E+05	4.62E+05			
DIVE/00/126/01	13-Sep-00	00/169	GW4	298340	967511	5	1.06E+06	1.06E+06			
DIVE/00/127/01	13-Sep-00	00/170	GW4	298347	967534	10	3.88E+05	3.88E+05			
DIVE/01/005/01	11-Apr-01	01/004	Re-pop 2	297645	967397	3	1.90E+04	1.90E+04			
DIVE/01/006/01	11-Apr-01	01/005	Re-pop 2	297650	967403	10	2.50E+04	2.50E+04			
DIVE/01/007/01	12-Apr-01	01/006	Re-pop 2	297653	967407	3	9.30E+03	9.30E+03			
DIVE/01/009/01	12-Apr-01	01/007	Re-pop 2	297658	967404	4	3.50E+04	4.60E+04			
		01/008					1.10E+04				
DIVE/01/018/01	21-Apr-01	01/009	Re-pop 1	296433	966444	0	7.50E+03	3.65E+04			
		01/010					2.90E+04				
DIVE/01/028/01	23-Apr-01	01/011	Re-pop 7	299032	968686	10	3.20E+05	3.20E+05			
DIVE/01/030/01	23-Apr-01	01/012	Re-pop 7	299039	968673	15	5.00E+04	5.00E+04			
DIVE/01/037/01	25-Apr-01	01/013	Re-pop 7	299054	968666	0	4.40E+04	4.40E+04			
DIVE/01/041/01	26-Apr-01	01/014	Re-pop 6	298880	968253	5	1.90E+04	1.90E+04			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/01/044/01	26-Apr-01	01/015	Re-pop 6	298918	968268	5	1.60E+04	1.73E+04			
		01/016					1.30E+03				
DIVE/01/047/01	27-Apr-01	01/017	Re-pop 5	298681	967992	0	7.60E+03	7.60E+03			
DIVE/01/048/01	27-Apr-01	01/018	Re-pop 5	298677	967962	20	6.70E+04	6.70E+04			
DIVE/01/049/01	28-Apr-01	01/019	Re-pop 5	298680	967957	0	5.10E+03	5.10E+03			
DIVE/01/049/02	28-Apr-01	01/020	Re-pop 5	298676	967950	0	1.10E+04	1.10E+04			
DIVE/01/052/01	28-Apr-01	01/021	Re-pop 5	298648	967955	0	2.10E+04	2.10E+04			
DIVE/01/052/02	28-Apr-01	01/022	Re-pop 5	298662	967962	15	1.20E+04	1.20E+04			
DIVE/01/055/01	30-Apr-01	01/023	Re-pop 5	298663	967975	0	3.40E+03	3.40E+03			
DIVE/01/058/01	01-May-01	01/024	Re-pop 3	298080	967463	0	3.90E+05	3.90E+05			
DIVE/01/060/01	01-May-01	01/025	Re-pop 3	298113	967468	25	8.50E+05	8.50E+05			
DIVE/01/060/02	01-May-01	01/026	Re-pop 3	298101	967461	0	2.50E+04	2.50E+04			
DIVE/01/061/01	01-May-01	01/027	Re-pop 3	298116	967459	20	1.50E+05	1.50E+05			
DIVE/01/062/01	01-May-01	01/028	Re-pop 3	298116	967439	30	6.20E+05	6.20E+05			
DIVE/01/062/02	01-May-01	01/029	Re-pop 3	298111	967429	25	2.00E+05	2.00E+05			
DIVE/01/063/01	05-May-01	01/030	Re-pop 3	298109	967430	20	1.40E+05	1.40E+05			
DIVE/01/063/02	05-May-01	01/031	Re-pop 3	298103	967437	10	1.40E+04	1.40E+04		1.30E+02	
DIVE/01/067/01	06-May-01	01/036	outside 4	298222	967692	40	3.00E+06	3.00E+06			
DIVE/01/068/01	06-May-01	01/032	Re-pop 4	298222	967700	10	1.90E+05	1.90E+05		1.20E+02	
DIVE/01/069/01	06-May-01	01/033	Re-pop 4	298222	967717	0	7.00E+03	7.00E+03			
DIVE/01/069/02	06-May-01	01/034	Re-pop 4	298218	967719	0	1.60E+04	1.60E+04		2.70E+02	DFR
DIVE/01/069/03	06-May-01	01/035	Re-pop 4	298211	967730	0	3.00E+04	3.00E+04			
DIVE/01/074/01	08-May-01	01/037	Re-pop 4	298197	967708	0	7.80E+04	7.80E+04			
DIVE/01/075/01	08-May-01	01/041	Re-pop 4	298182	967711	0	1.40E+04	1.40E+04			
DIVE/01/075/02	08-May-01	01/038	Re-pop 4	298183	967705	0	1.80E+04	1.80E+04			
DIVE/01/076/01	08-May-01	01/042	Re-pop 4	298177	967702	0	6.60E+03	6.60E+03			
DIVE/01/076/02	08-May-01	01/039	Re-pop 4	298191	967691	20	1.90E+05	2.02E+05			
		01/040					1.20E+04				
DIVE/01/084/01	12-May-01	01/053	Line A	298179	967227	0	1.98E+06	1.98E+06			
DIVE/01/085/01	12-May-01	01/054	Line A	298154	967176	7.5	1.40E+06	1.40E+06			
DIVE/01/086/01	12-May-01	01/055	Line B	298142	967234	22	1.48E+07	1.48E+07			MTR
DIVE/01/086/02	12-May-01	01/043	Line B	298140	967242	<10	4.51E+04	4.51E+04			
DIVE/01/086/03	12-May-01	01/044	Line B	298141	967244	35	1.83E+05	1.83E+05			
DIVE/01/087/01	13-May-01	01/045	Line B	298178	967299	10	1.21E+05	1.21E+05			
DIVE/01/088/01	13-May-01	01/046	Line B	298222	967313	17.5	1.58E+05	1.58E+05			
DIVE/01/089/01	13-May-01	01/050	Line C	298353	967531	12	1.70E+06	1.70E+06			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/01/089/02	13-May-01	01/052	Line C	298395	967546	10	4.60E+05	4.60E+05			
DIVE/01/090/01	14-May-01	01/047	Line C	298081	967258	17.5	3.45E+05	3.45E+05			
DIVE/01/090/02	14-May-01	01/048	Line C	298101	967277	0	7.34E+04	7.34E+04			
DIVE/01/091/01	14-May-01	01/049	Line C	298126	967302	0	9.13E+04	9.13E+04			
DIVE/01/092/01	14-May-01	01/051	Line C	298217	967385	20	2.46E+06	2.46E+06			
DIVE/01/096/01	15-May-01	01/061	Line C	298316	967530	35	1.10E+06	1.10E+06			MTR
DIVE/01/096/02	15-May-01	01/062	Line C	298347	967559	10	1.60E+06	1.60E+06			
DIVE/01/097/01	15-May-01	01/056	Line C	298352	967558	0	1.00E+05	1.00E+05			
DIVE/01/097/02	15-May-01	01/057	Line C	298340	967550	10	2.00E+05	2.00E+05			
DIVE/01/097/03	15-May-01	01/058	Line C	298340	967544	10	2.30E+05	2.30E+05			
DIVE/01/097/04	15-May-01	01/059	Line C	298334	967538	7.5	3.40E+05	3.40E+05			
DIVE/01/100/01	16-May-01	01/060	Line E	298181	967522	0	2.40E+05	2.40E+05			
DIVE/01/102/01	17-May-01	01/063	Line E	298328	967590	12.5	8.40E+05	8.40E+05			
DIVE/01/103/01	17-May-01	01/064	Line E/C	298375	967583	10	6.80E+04	6.80E+04			
DIVE/01/103/02	17-May-01	01/065	Line (n)E	298385	967629	0	1.10E+05	1.10E+05			
DIVE/01/104/01	22-May-01	01/066	Line D	298098	967329	20	1.40E+06	1.40E+06			
DIVE/01/105/01	22-May-01	01/067	Line D	298145	967398	10	5.90E+06	5.90E+06			MTR
DIVE/01/105/02	22-May-01	01/068	Line D	298129	967382	7.5	4.70E+05	4.70E+05			MTR
DIVE/01/106/01	22-May-01	01/069	Line D	298162	967405	<5	2.40E+06	2.40E+06			
DIVE/01/107/01	22-May-01	01/070	Line D	298165	967424	30	6.60E+06	6.60E+06			
DIVE/01/107/02	22-May-01	01/071	Line D	298181	967444	25	2.00E+06	2.00E+06			
DIVE/01/107/03	22-May-01	01/072	Line D	298178	967441	5	6.10E+04	6.10E+04			
DIVE/01/108/01	23-May-01	01/073	Line D	298162	967432	<5	8.80E+04	9.29E+04			
		01/074					4.90E+03				
DIVE/01/108/02	23-May-01	01/079	Line D	298175	967439	10	2.10E+06	2.10E+06			MTR
DIVE/01/108/03	23-May-01	01/080	Line D	298175	967437	10	5.20E+06	5.20E+06			
DIVE/01/108/04	23-May-01	01/081	Line D	298163	967434	20	9.50E+05	9.50E+05			
DIVE/01/108/05	23-May-01	01/076	Line D	298168	967435	0	7.20E+03	7.20E+03			
DIVE/01/109/01	23-May-01	01/077	Line D	298166	967436	5	1.70E+05	1.70E+05			
DIVE/01/109/02	23-May-01	01/078	Line D	298184	967448	0	1.30E+04	1.30E+04			
DIVE/01/109/03	23-May-01	01/082	Line D	298194	967454	25	3.00E+06	3.00E+06			
DIVE/01/110/01	23-May-01	01/075	Line D	298208	967462	0	1.30E+04	1.30E+04			
DIVE/01/110/02	23-May-01	01/086	Line D	298221	967485	10	1.50E+06	1.50E+06			
DIVE/01/112/01	24-May-01	01/085	Line X	298191	967465	0	9.10E+04	9.10E+04			
DIVE/01/113/01	24-May-01	01/084	Line X	298220	967420	15	1.30E+05	1.30E+05			
DIVE/01/114/01	24-May-01	01/083	Line X	298239	967389	<5	3.10E+04	3.10E+04			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/01/114/02	24-May-01	01/087	Line X	298251	967374	0	5.80E+05	5.82E+05			
		01/088					2.00E+03				
DIVE/01/116/01	27-May-01	01/089	Line X	298295	967270	15	4.40E+06	4.40E+06			
DIVE/01/117/01	27-May-01	01/090	Line W	298198	967269	20	1.30E+06	1.30E+06			
DIVE/01/119/01	28-May-01	01/091	Line W	298192	967294	10	2.70E+05	2.70E+05			
DIVE/01/120/01	28-May-01	01/092	Line W	298131	967371	0	5.40E+03	5.40E+03			
DIVE/01/120/02	28-May-01	01/093	Line W	298138	967351	10	1.90E+05	1.90E+05		2.20E+02	DFR
DIVE/01/120/03	28-May-01	01/094	Line W	298135	967370	15	8.90E+04	8.90E+04			MTR
DIVE/01/135/01	16-Jun-01	01/096	Re-pop 4	298212	967714	0	5.10E+02	6.30E+03			
		01/097					2.06E+03				
		01/098					3.80E+02				
		01/099					1.30E+03				
		01/100					2.05E+03				
DIVE/01/137/01	18-Jun-01	01/101	Re-pop 4	298172	967712	0	1.41E+04	1.41E+04			
DIVE/01/138/01	18-Jun-01	01/102	Re-pop 4	298190	967702	0	1.00E+04	1.09E+04			
		01/103					8.70E+02				
DIVE/01/141/01	19-Jun-01	01/104	Line Z	298382	967530	30	4.62E+05	4.62E+05			
DIVE/01/143/01	10-May-01	01/105	Offline E	298233	967373	35	1.10E+08	1.10E+08			
DIVE/01/156/01	19-Aug-01	01/108	Re-pop 2	297653	967434	<5	1.34E+04	1.34E+04			
DIVE/01/161/01	21-Aug-01	01/109	Re-pop 2	297631	967401	0	1.90E+03	3.00E+03			
		01/110					1.10E+03				
DIVE/01/164/01	24-Aug-01	01/111	Clay D	298194	967542	20	1.35E+05	1.35E+05			
DIVE/01/164/02	24-Aug-01	01/112	Clay D	298206	967455	30	3.30E+04	3.30E+04		1.60E+02	DFR
DIVE/01/168/01	25-Aug-01	01/113	Re-pop 7	299048	968695	0	4.40E+04	4.40E+04			
DIVE/01/177/01	28-Aug-01	01/115	Re-pop 7	299061	968645	0	2.00E+04	2.00E+04			
DIVE/01/180/01	29-Aug-01	01/116	Re-pop 7	299040	968652	0	1.80E+03	1.80E+03			
DIVE/01/190/01	01-Sep-01	01/117	Re-pop 6	298898	968233	5	1.20E+04	1.20E+04			
DIVE/01/194/01	18-Sep-01	01/119	Re-pop 5	298656	967946	0	5.22E+03	7.74E+03			
		01/120					2.52E+03				
DIVE/01/195/01	18-Sep-01	01/121	5(outside)	298637	967952	10	1.16E+05	1.16E+05			
DIVE/01/195/02	18-Sep-01	01/122	Re-pop 5	298657	967969	0	6.41E+03	6.41E+03			
DIVE/01/196/01	18-Sep-01	01/123	Re-pop 5	298650	967963	0	1.37E+04	1.37E+04			
DIVE/01/196/02	18-Sep-01	01/124	Re-pop 5	298638	967961	10	1.02E+05	1.02E+05			
DIVE/01/198/01	18-Sep-01	01/125	Re-pop 5	298678	967952	13	1.26E+05	1.26E+05			
DIVE/01/199/01	19-Sep-01	01/127	5 Outside	298688	967954	0	3.42E+05	3.43E+05			
		01/128					6.83E+02				

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/01/200/01	19-Sep-01	01/126	Re-pop 5	298674	967965	15	1.26E+05	1.26E+05			
DIVE/01/205/01	24-Sep-01	01/129	Re-pop 4	298192	967713	35	1.30E+05	1.30E+05			
DIVE/01/207/01	24-Sep-01	01/130	Re-pop 4	298182	967706	0	7.20E+03	7.20E+03		2.60E+02	Nb but no U
DIVE/01/213/01	25-Sep-01	01/131	Re-pop 4	298199	967705	35	3.50E+04	3.58E+04			
		01/132					7.80E+02				
DIVE/01/214/01	25-Sep-01	01/133	Re-pop 4	298215	967713	0	4.80E+02	4.80E+02		1.90E+02	DFR
DIVE/01/215/01	25-Sep-01	01/134	Re-pop 4	298207	967717	0	2.60E+03	2.60E+03			
DIVE/01/215/02	25-Sep-01	01/135	Re-pop 4	298199	967712	5	1.50E+04	1.50E+04			
DIVE/01/216/01	26-Sep-01	01/136	Re-pop 4	298210	967722	0	5.30E+03	5.30E+03			
DIVE/01/217/01	26-Sep-01	01/137	Re-pop 4	298197	967711	0	3.20E+03	3.85E+03			
		01/138					6.50E+02				
DIVE/01/223/01	27-Sep-01	01/139	Re-pop 3	298102	967466	0	5.20E+04	5.20E+04			
DIVE/01/227/01	28-Sep-01	01/140	Re-pop 3	298080	967440	0	4.00E+05	4.00E+05			
DIVE/01/229/01	30-Sep-01	01/141	Line V	298100	967274	0	6.30E+03	6.30E+03			
DIVE/01/230/01	30-Sep-01	01/143	Line V	298100	967269	40	2.50E+06	2.50E+06			
DIVE/01/230/02	30-Sep-01	01/142	Line V	298088	967288	15	9.50E+04	9.50E+04			
DIVE/01/231/01	30-Sep-01	01/144	Line V	298070	967325	5	1.50E+05	1.50E+05			
DIVE/01/232/01	01-Oct-01	01/146	Line V	298142	967207	45	3.60E+05	3.60E+05			
DIVE/01/232/02	01-Oct-01	01/145	Line V	298146	967197	15	5.40E+04	5.40E+04			
DIVE/02/019/01	17-May-02	02/007	Re-pop 2	297633	967412	<5	3.50E+03	3.50E+03			
DIVE/02/025/01	18-May-02	02/008	Re-pop 2	297664	967432	11	2.10E+04	2.10E+04			
DIVE/02/025/02	18-May-02	02/009	Re-pop 2	297667	967434	<5	2.90E+04	2.90E+04			
DIVE/02/032/01	19-May-02	02/011	Re-pop 2Outer	297674	967377	30	2.10E+04	2.10E+04			
DIVE/02/033/01	19-May-02	02/010	Re-pop 2Outer	297669	967378	7.5	2.60E+04	2.60E+04			
DIVE/02/034/01	20-May-02	02/012	Re-pop 2Outer	297658	967386	12.5	1.80E+05	1.80E+05			
DIVE/02/035/01	20-May-02	02/013	Re-pop 2Outer	297658	967368	<5	8.60E+03	8.60E+03			
DIVE/02/035/02	20-May-02	02/014	Re-pop 2Outer	297650	967365	7.5	5.20E+04	5.20E+04			
DIVE/02/035/03	20-May-02	02/015	Re-pop 2Outer	297650	967376	7.5	1.80E+04	1.80E+04			
DIVE/02/036/01	20-May-02	02/016	Re-pop 2Outer	297645	967368	15	1.10E+04	1.10E+04			
DIVE/02/041/01	21-May-02	02/017	Re-pop 2Outer	297614	967400	<5	<1.2E+02	<1.2E+02	9.30E+02		

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/042/01	21-May-02	02/018	Re-pop 2Outer	297610	967401	15	7.40E+03	2.14E+04			
		02/019					1.40E+04				
DIVE/02/043/01	21-May-02	02/020	Re-pop 2Outer	297597	967407	<5	5.10E+04	5.10E+04			
DIVE/02/045/01	22-May-02	02/021	Re-pop 2Outer	297615	967421	12.5	4.50E+04	4.50E+04			
DIVE/02/046/01	22-May-02	02/022	Re-pop 2Outer	297608	967425	10	1.20E+04	1.20E+04			
DIVE/02/066/01	26-May-02	02/023	Re-pop 3	298086	967469	<10	5.20E+05	5.20E+05			
DIVE/02/068/01	26-May-02	02/024	Re-pop 3	298102	967471	<5	2.50E+04	2.50E+04			
DIVE/02/069/01	27-May-02	02/025	Re-pop 3	298099	967453	<5	1.80E+04	1.80E+04			
DIVE/02/070/01	27-May-02	02/026	Re-pop 3	298119	967441	15	2.90E+04	2.90E+04			
DIVE/02/072/01	27-May-02	02/027	Re-pop 3	298096	967443	45	7.90E+06	7.90E+06			
DIVE/02/073/01	27-May-02	02/028	Re-pop 3	298094	967435	25	4.20E+05	6.80E+05			
		02/029					2.60E+05				
DIVE/02/074/01	28-May-02	02/030	Re-pop 3	298082	967428	40	1.40E+06	1.40E+06			
DIVE/02/076/01	29-May-02	02/031	Re-pop 3Outer	298109	967409	17	9.60E+04	9.60E+04			
DIVE/02/076/02	29-May-02	02/032	Re-pop 3Outer	298107	967414	15	5.10E+05	5.10E+05			
DIVE/02/076/03	29-May-02	02/033	Re-pop 3Outer	298111	967413	20	4.10E+05	4.10E+05			
DIVE/02/077/01	29-May-02	02/037	Re-pop 3Outer	298114	967409	50+	3.20E+06	3.20E+06			
DIVE/02/077/02	29-May-02	02/034	Re-pop 3Outer	298112	967419	30	1.00E+06	1.00E+06			
DIVE/02/078/01	29-May-02	02/038	Re-pop 3Outer	298121	967412	35	6.90E+06	6.90E+06			
DIVE/02/080/01	29-May-02	02/035	Re-pop 3Outer	298130	967441	<5	1.20E+05	1.20E+05			
DIVE/02/080/02	29-May-02	02/036	Re-pop 3Outer	298136	967440	<5	1.10E+04	1.10E+04			
DIVE/02/082/01	30-May-02	02/040	Re-pop 3Outer	298142	967472	40	2.80E+06	2.80E+06			
DIVE/02/082/02	30-May-02	02/039	Re-pop 3Outer	298138	967478	50+	1.00E+06	1.00E+06			
DIVE/02/088/01	01-Jun-02	02/041	Re-pop 3Outer	298070	967440	<5	4.50E+04	4.50E+04		1.10E+02	

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/088/02	01-Jun-02	02/042	Re-pop 3Outer	298068	967438	<5	2.10E+05	2.10E+05			
DIVE/02/088/03	01-Jun-02	02/043	Re-pop 3Outer	298060	967438	<5	3.80E+04	3.80E+04			
DIVE/02/089/01	01-Jun-02	02/044	Re-pop 3Outer	298074	967434	12.5	4.90E+05	4.90E+05			
DIVE/02/090/01	01-Jun-02	02/045	Re-pop 3Outer	298096	967417	<5	7.10E+04	7.10E+04			
DIVE/02/095/01	02-Jun-02	02/046	Re-pop 7	299057	968653	15	3.40E+04	3.40E+04			
DIVE/02/101/01	04-Jun-02	02/047	Re-pop 6	298913	968239	<5	2.50E+05	2.50E+05			
DIVE/02/105/01	04-Jun-02	02/048	Re-pop 6	298887	968249	<5	4.80E+03	4.80E+03		3.40E+01	
DIVE/02/106/01	04-Jun-02	02/049	Re-pop 6	298903	968246	50	2.60E+06	2.60E+06			
DIVE/02/106/02	05-Jun-02	02/053	Re-pop 6	298886	968257	10	4.60E+04	4.60E+04			
DIVE/02/107/01	05-Jun-02	02/050	Re-pop 6	298881	968254	<5	3.50E+04	3.50E+04		6.00E+01	
DIVE/02/109/01	05-Jun-02	02/051	Re-pop 6	298872	968272	7.5	1.60E+05	1.60E+05			
DIVE/02/109/02	05-Jun-02	02/052	Re-pop 6	298883	968273	10	2.70E+04	2.70E+04			
DIVE/02/111/01	06-Jun-02	02/054	Re-pop 6	298896	968282	<5	1.40E+05	1.40E+05			
DIVE/02/112/01	06-Jun-02	02/055	Re-pop 6	298905	968280	<5	1.20E+04	1.20E+04			
DIVE/02/113/01	06-Jun-02	02/056	Re-pop 6	298904	968264	<5	1.60E+04	1.60E+04			
DIVE/02/113/02	06-Jun-02	02/057	Re-pop 6	298906	968264	10	1.60E+04	1.60E+04		5.00E+01	
DIVE/02/114/01	06-Jun-02	02/058	Re-pop 6	298905	968260	<5	<6.4E+01	<6.4E+01	2.90E+03		
DIVE/02/116/01	07-Jun-02	02/059	Re-pop 6	298912	968245	<5	1.70E+04	1.70E+04			
DIVE/02/119/01	08-Jun-02	02/060	Re-pop 5	298661	967992	<5	7.70E+04	7.70E+04			
DIVE/02/120/01	08-Jun-02	02/061	Re-pop 5	298644	967997	5	1.70E+04	1.70E+04		7.80E+01	
DIVE/02/122/01	10-Jun-02	02/064	Re-pop 5	298637	967958	10	3.10E+05	3.10E+05			
DIVE/02/123/01	10-Jun-02	02/062	Re-pop 5	298662	967965	<5	2.10E+04	2.10E+04			
DIVE/02/125/01	10-Jun-02	02/063	Re-pop 5	298671	967965	<5	2.00E+04	2.00E+04			
DIVE/02/126/01	11-Jun-02	02/065	Re-pop 5	298691	967969	<5	7.00E+03	7.00E+03			
DIVE/02/128/01	11-Jun-02	02/066	Repop 5Outer	298689	968004	<5	<1.4E2	<1.4E2	3.50E+03		
DIVE/02/129/01	11-Jun-02	02/067	Repop 5Outer	298696	967991	<5	5.20E+03	5.20E+03			
DIVE/02/131/01	12-Jun-02	02/068	Repop 5Outer	298704	967980	5	2.40E+05	2.40E+05			
DIVE/02/132/01	12-Jun-02	02/069	Repop 5Outer	298694	967964	<5	1.60E+04	1.60E+04			
DIVE/02/132/02	12-Jun-02	02/070	Repop 5Outer	298703	967961	5	3.50E+05	3.50E+05			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/133/01	12-Jun-02	02/071	Repop 5Outer	298703	967961	<5	1.30E+03	1.30E+03			
DIVE/02/133/02	12-Jun-02	02/072	Repop 5Outer	298703	967952	10	4.90E+04	4.90E+04			
DIVE/02/134/01	12-Jun-02	02/073	Repop 5Outer	298697	967947	5	5.70E+04	5.70E+04			
DIVE/02/134/02	12-Jun-02	02/074	Repop 5Outer	298700	967943	<5	2.80E+04	2.80E+04		1.80E+02	
DIVE/02/135/01	13-Jun-02	02/078	Repop 5Outer	298688	967948	20	6.70E+05	6.70E+05			
DIVE/02/135/02	13-Jun-02	02/079	Repop 5Outer	298691	967940	<5	1.20E+04	1.20E+04		5.50E+01	
DIVE/02/136/01	13-Jun-02	02/075	Repop 5Outer	298679	967938	35	5.10E+04	1.55E+06			
		02/076					1.50E+06				
		02/077					<1.2E+02				
DIVE/02/137/01	13-Jun-02	02/080	Repop 5Outer	298675	967942	<5	9.00E+04	9.00E+04			
DIVE/02/137/02	13-Jun-02	02/081	Repop 5Outer	298676	967932	<5	1.90E+05	1.90E+05		3.60E+02	
DIVE/02/138/01	13-Jun-02	02/082	Repop 5Outer	298669	967931	20	1.00E+05	1.11E+05			
		02/083					6.40E+03				
		02/084					4.50E+03				
DIVE/02/138/02	13-Jun-02	02/085	Repop 5Outer	298668	967924	<5	1.50E+03	1.50E+03			
DIVE/02/139/01	14-Jun-02	02/086	Repop 5Outer	298661	967928	<5	7.70E+04	7.70E+04			
DIVE/02/140/01	14-Jun-02	02/087	Repop 5Outer	298659	967930	30	2.80E+06	2.80E+06			
DIVE/02/141/01	14-Jun-02	02/088	Repop 5Outer	298652	967937	15	7.20E+04	7.60E+04		1.90E+02	
		02/089					4.00E+03				
DIVE/02/141/02	14-Jun-02	02/090	Repop 5Outer	298647	967943	10	1.40E+04	1.40E+04			
DIVE/02/142/01	14-Jun-02	02/091	Repop 5Outer	298637	967942	<5	7.90E+04	7.90E+04			
DIVE/02/143/01	14-Jun-02	02/092	Repop 5Outer	298630	967938	15	1.20E+05	1.20E+05			
DIVE/02/144/01	15-Jun-02	02/093	Repop 5Outer	298627	967957	10	5.70E+04	5.70E+04		1.70E+02	
DIVE/02/146/01	15-Jun-02	02/094	Repop 5Outer	298618	967970	20	1.20E+06	1.20E+06			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/147/01	15-Jun-02	02/095	Repop 5Outer	298672	967972	<5	8.90E+03	8.90E+03			
DIVE/02/149/01	16-Jun-02	02/096	Repop 5Outer	298624	967990	10	7.20E+05	7.20E+05			
DIVE/02/150/01	16-Jun-02	02/097	Repop 5Outer	298624	968009	10	9.20E+04	9.20E+04			
DIVE/02/153/01	16-Jun-02	02/098	Repop 5Outer	298650	968002	<5	2.30E+03	2.30E+03			
DIVE/02/154/01	20-Jun-02	02/099	Repop 5Outer	298657	968008	<5	3.30E+03	3.30E+03			
DIVE/02/154/02	20-Jun-02	02/100	Repop 5Outer	298658	968008	<5	2.80E+04	2.80E+04			
DIVE/02/156/01	20-Jun-02	02/101	Repop 5Outer	298679	968005	<5	1.50E+04	1.60E+04			
		02/102					4.90E+02				
		02/103					5.50E+02				
DIVE/02/165/01	24-Jun-02	02/104	Brims	305310	971330	10	1.30E+04	1.30E+04			
DIVE/02/165/02	24-Jun-02	02/105	Brims	305320	971320	<5	1.20E+04	1.20E+04			
DIVE/02/166/01	24-Jun-02	02/106	Brims	305320	971335	<5	2.00E+04	2.00E+04			
DIVE/02/171/01	01-Jul-02	02/107	Brims	305323	971307	12.5	2.00E+04	2.27E+04			
		02/108					2.20E+03				
		02/109					4.90E+02				
DIVE/02/173/01	01-Jul-02	02/110	Brims	305307	971317	10	2.40E+02	5.42E+04			
		02/111					5.40E+04				
DIVE/02/178/01	05-Jul-02	02/112	C'Kirk	302641	970688	10	9.50E+04	9.50E+04			
DIVE/02/181/01	05-Jul-02	02/113	C'Kirk	302631	970677	<5	2.90E+04	2.90E+04			
DIVE/02/182/01	05-Jul-02	02/114	C'Kirk	302620	970680	<5	1.00E+04	1.00E+04			
DIVE/02/196/01	09-Jul-02	02/115	C'Kirk	302633	970703	<5	4.40E+03	4.40E+03			
DIVE/02/207/01	12-Jul-02	02/116	Repop 4	298193	967711	<5	1.60E+03	1.60E+03			
DIVE/02/208/01	12-Jul-02	02/117	Repop 4	298195	967704	15	1.50E+05	1.50E+05			
DIVE/02/209/01	12-Jul-02	02/118	Repop 4	298200	967721	<5	2.50E+03	2.50E+03			
DIVE/02/210/01	12-Jul-02	02/119	Repop 4	298212	967718	5	9.50E+03	9.50E+03		8.60E+01	
DIVE/02/210/02	12-Jul-02	02/120	Repop 4	298217	967714	<5	7.50E+03	7.50E+03			
DIVE/02/211/01	13-Jul-02	02/121	Repop 4	298224	967712	<5	3.20E+03	3.20E+03		4.30E+02	
DIVE/02/212/01	13-Jul-02	02/122	Repop 4	298205	967705	<5	6.20E+03	6.20E+03			
DIVE/02/212/02	13-Jul-02	02/123	Repop 4	298214	967699	10	1.10E+05	1.15E+05			
		02/124					4.60E+03				
DIVE/02/213/01	13-Jul-02	02/125	Repop 4	298216	967690	<5	5.50E+04	5.50E+04			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/215/01	14-Jul-02	02/126	Repop 4	298192	967684	<5	5.40E+03	5.40E+03			
DIVE/02/216/01	14-Jul-02	02/127	Repop 4	298189	967684	<5	3.50E+03	3.50E+03			
DIVE/02/216/02	14-Jul-02	02/128	Repop 4	298185	967687	40	1.50E+06	1.50E+06			
DIVE/02/217/01	14-Jul-02	02/129	Repop 4	298188	967686	<5	1.50E+03	1.50E+03			
DIVE/02/217/02	14-Jul-02	02/130	Repop 4	298185	967687	<5	<1.3e2	<1.3e2	2.50E+03		
DIVE/02/221/01	15-Jul-02	02/133	Repop 4 Outer	298234	967710	30	3.30E+06	3.31E+06			
		02/134					6.90E+03				
		02/135					2.40E+03				
DIVE/02/223/01	15-Jul-02	02/132	Repop 4 Outer	298246	967704	45	8.70E+05	8.70E+05			
DIVE/02/223/02	15-Jul-02	02/136	Repop 4 Outer	298225	967701	20	8.20E+03	8.20E+03		6.00E+02	
DIVE/02/224/01	15-Jul-02	02/131	Repop 4 Outer	298230	967693	40	3.10E+06	3.10E+06			
DIVE/02/225/01	16-Jul-02	02/140	Repop 4 Outer	298234	967682	40	3.20E+06	3.20E+06			
DIVE/02/226/01	16-Jul-02	02/138	Repop 4 Outer	298227	967688	50+	1.10E+07	1.10E+07			
DIVE/02/227/01	16-Jul-02	02/141	Repop 4 Outer	298233	967686	10	5.10E+05	5.10E+05			
DIVE/02/228/01	16-Jul-02	02/139	Repop 4 Outer	298228	967686	50	3.10E+06	3.10E+06			
DIVE/02/228/02	16-Jul-02	02/137	Repop 4 Outer	298222	967683	35	5.60E+06	5.60E+06			
DIVE/02/229/01	17-Jul-02	02/153	Repop 4 Outer	298222	967683	55	1.30E+06	1.30E+06			
DIVE/02/230/01	17-Jul-02	02/146	Repop 4 Outer	298221	967683	47.5	3.00E+06	3.03E+06			
		02/147					6.80E+03				
		02/148					4.70E+03				
		02/149					5.60E+03				
		02/150					4.70E+03				
		02/151					4.60E+03				
		02/152					1.50E+03				
DIVE/02/230/02	17-Jul-02	02/154	Repop 4 Outer	298220	967676	<5	2.00E+04	2.00E+04			
DIVE/02/230/03	17-Jul-02	02/155	Repop 4 Outer	298216	967677	7.5	1.80E+05	1.80E+05			
DIVE/02/232/01	17-Jul-02	02/144	Repop 4 Outer	298216	967674	40	2.40E+07	2.40E+07			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
		02/145					1.90E+03				
DIVE/02/232/02	17-Jul-02	02/142	Repop 4 Outer	298216	967667	50	8.90E+06	8.90E+06			
		02/143					7.90E+02				
DIVE/02/233/01	18-Jul-02	02/162	Repop 4 Outer	298211	967676	35	5.20E+06	5.20E+06			
DIVE/02/234/01	18-Jul-02	02/163	Repop 4 Outer	298214	967668	30	1.70E+06	1.70E+06			
DIVE/02/234/02	18-Jul-02	02/159	Repop 4 Outer	298215	967667	<5	3.10E+04	3.58E+04			
		02/160					4.80E+03				
DIVE/02/234/03	18-Jul-02	02/164	Repop 4 Outer	298216	967661	50	7.20E+05	7.88E+05			
		02/165					6.80E+04				
DIVE/02/234/04	18-Jul-02	02/158	Repop 4 Outer	298212	967661	25	2.30E+05	2.30E+05			
DIVE/02/235/01	18-Jul-02	02/156	Repop 4 Outer	298210	967663	50	8.50E+06	8.50E+06			
DIVE/02/235/02	18-Jul-02	02/157	Repop 4 Outer	298207	967668	5	1.10E+05	1.10E+05		1.40E+02	
DIVE/02/236/01	18-Jul-02	02/161	Repop 4 Outer	298200	967675	35	1.40E+05	1.40E+05		1.60E+02	
DIVE/02/237/01	19-Jul-02	02/166	Repop 4 Outer	298197	967665	40	3.70E+06	3.70E+06			
DIVE/02/238/01	19-Jul-02	02/170	Repop 4 Outer	298192	967667	7.5	2.40E+04	3.25E+04			
		02/171					5.20E+03				
		02/172					3.30E+03				
DIVE/02/238/02	19-Jul-02	02/173	Repop 4 Outer	298177	967660	<5	9.20E+03	3.77E+04			
		02/174					2.20E+04				
		02/175					6.50E+03				
DIVE/02/239/01	19-Jul-02	02/176	Repop 4 Outer	298184	967664	<5	3.50E+03	3.50E+03			
DIVE/02/239/02	19-Jul-02	02/167	Repop 4 Outer	298183	967664	40	2.60E+06	2.60E+06			
DIVE/02/240/01	19-Jul-02	02/168	Repop 4 Outer	298184	967669	40	4.50E+06	4.50E+06			
DIVE/02/240/02	19-Jul-02	02/169	Repop 4 Outer	298174	967668	45	4.70E+06	4.70E+06			
DIVE/02/241/01	20-Jul-02	02/177	Repop 4 Outer	298178	967680	35	2.40E+06	2.40E+06			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/242/01	20-Jul-02	02/181	Repop 4 Outer	298169	967673	35	7.10E+06	7.10E+06			
DIVE/02/242/02	20-Jul-02	02/178	Repop 4 Outer	298162	967669	30	2.40E+05	2.40E+05		1.60E+02	
DIVE/02/243/01	20-Jul-02	02/179	Repop 4 Outer	298164	967674	25	5.40E+04	5.40E+04			
DIVE/02/243/02	20-Jul-02	02/180	Repop 4 Outer	298166	967677	<5	2.40E+03	2.40E+03			
DIVE/02/243/03	20-Jul-02	02/184	Repop 4 Outer	298166	967681	45	1.20E+06	1.20E+06			
DIVE/02/244/01	20-Jul-02	02/182	Repop 4 Outer	298160	967684	40	1.10E+07	1.10E+07			
DIVE/02/244/02	20-Jul-02	02/183	Repop 4 Outer	298161	967684	25	2.90E+05	2.90E+05			
DIVE/02/245/01	23-Jul-02	02/186	Repop 4 Outer	298162	967693	50	1.30E+07	1.30E+07			
DIVE/02/246/01	23-Jul-02	02/187	Repop 4 Outer	298162	967693	30	1.50E+06	1.50E+06			
DIVE/02/246/02	23-Jul-02	02/194	Repop 4 Outer	298161	967691	10	7.50E+04	7.50E+04			
DIVE/02/246/03	23-Jul-02	02/192	Repop 4 Outer	298158	967691	20	1.10E+04	2.09E+04			
		02/193					9.90E+03				
DIVE/02/247/01	23-Jul-02	02/190	Repop 4 Outer	298157	967695	5	9.90E+04	9.90E+04		4.60E+02	
DIVE/02/247/02	23-Jul-02	02/191	Repop 4 Outer	298157	967697	10	3.30E+04	3.30E+04		6.20E+01	
DIVE/02/248/01	23-Jul-02	02/185	Repop 4 Outer	298164	967698	25	3.50E+06	3.50E+06			
DIVE/02/248/02	23-Jul-02	02/188	Repop 4 Outer	298167	967702	<5	9.50E+04	9.50E+04			
DIVE/02/248/03	23-Jul-02	02/189	Repop 4 Outer	298159	967702	15	2.20E+05	2.20E+05			
DIVE/02/249/01	25-Jul-02	02/198	Repop 4 Outer	298152	967709	30	1.50E+05	1.50E+05		2.40E+02	
DIVE/02/251/01	25-Jul-02	02/199	Repop 4 Outer	298163	967714	10	3.60E+04	3.60E+04			
DIVE/02/251/02	25-Jul-02	02/200	Repop 4 Outer	298171	967712	<5	9.70E+04	9.70E+04		5.80E+01	
DIVE/02/251/03	25-Jul-02	02/196	Repop 4 Outer	298169	967715	30	4.30E+06	4.30E+06			
DIVE/02/252/01	25-Jul-02	02/195	Repop 4 Outer	298159	967722	30	3.20E+06	3.20E+06			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/252/02	25-Jul-02	02/197	Repop 4 Outer	298165	967722	15	1.90E+06	1.90E+06			
DIVE/02/255/01	27-Jul-02	02/202	Repop 4 Outer	298171	967735	25	2.00E+05	2.00E+05			
DIVE/02/257/01	27-Jul-02	02/203	Repop 4 Outer	298173	967749	20	3.10E+04	3.10E+04			
DIVE/02/257/02	27-Jul-02	02/201	Repop 4 Outer	298177	967748	7.5	1.10E+04	1.10E+04			
DIVE/02/259/01	28-Jul-02	02/209	Repop 4 Outer	298179	967750	40	2.20E+06	2.20E+06			
DIVE/02/260/01	28-Jul-02	02/213	Repop 4 Outer	298188	967745	10	1.60E+04	1.60E+04			
DIVE/02/260/02	28-Jul-02	02/210	Repop 4 Outer	298188	967749	<5	1.70E+04	1.70E+04			
DIVE/02/260/03	28-Jul-02	02/211	Repop 4 Outer	298188	967751	5	7.20E+04	7.20E+04			
DIVE/02/261/01	28-Jul-02	02/204	Repop 4 Outer	298201	967752	25	1.60E+06	1.60E+06			
		02/205					<1.2e2				
		02/206					5.50E+02				
		02/207					6.70E+02				
		02/208					4.30E+02				
DIVE/02/262/01	28-Jul-02	02/214	Repop 4 Outer	298202	967745	25	2.00E+05	2.00E+05			
DIVE/02/262/02	28-Jul-02	02/215	Repop 4 Outer	298202	967743	<5	3.00E+05	3.00E+05			
DIVE/02/263/01	28-Jul-02	02/212	Repop 4 Outer	298209	967748	<5	3.90E+04	3.90E+04		9.70E+01	
DIVE/02/264/01	29-Jul-02	02/216	Repop 4 Outer	298207	967748	15	5.10E+04	5.10E+04			
DIVE/02/265/01	29-Jul-02	02/217	Repop 4 Outer	298205	967737	30	5.80E+06	5.80E+06			
DIVE/02/265/02	29-Jul-02	02/218	Repop 4 Outer	298211	967752	5	3.70E+04	3.70E+04		2.40E+02	
DIVE/02/266/01	29-Jul-02	02/219	Repop 4 Outer	298208	967735	35	8.00E+05	8.00E+05			
DIVE/02/267/01	29-Jul-02	02/220	Repop 4 Outer	298217	967738	<5	1.10E+03	1.10E+03			
DIVE/02/268/01	29-Jul-02	02/221	Repop 4 Outer	298220	967728	<5	1.10E+04	1.10E+04			
DIVE/02/268/02	29-Jul-02	02/222	Repop 4 Outer	298220	967725	7.5	6.30E+03	2.18E+04			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
		02/223					7.60E+03				
		02/224					7.90E+03				
DIVE/02/269/01	30-Jul-02	02/225	Repop 4 Outer	298234	967736	15	3.20E+06	3.20E+06			
DIVE/02/269/02	30-Jul-02	02/226	Repop 4 Outer	298236	967737	15	2.80E+06	2.80E+06			
DIVE/02/270/01	30-Jul-02	02/227	Repop 4 Outer	298224	967727	40	2.00E+06	2.00E+06			
DIVE/02/270/02	30-Jul-02	02/228	Repop 4 Outer	298224	967727	45	8.50E+06	8.50E+06			
DIVE/02/270/03	30-Jul-02	02/229	Repop 4 Outer	298238	967728	<5	2.40E+04	2.40E+04		7.50E+01	
DIVE/02/271/01	30-Jul-02	02/230	Repop 4 Outer	298230	967721	40	3.20E+05	3.20E+05			
DIVE/02/271/02	30-Jul-02	02/231	Repop 4 Outer	298242	967721	30	3.60E+06	3.60E+06			
DIVE/02/273/01	31-Jul-02	02/232	Repop 8	298182	967438	35	9.70E+06	9.70E+06			
DIVE/02/273/02	31-Jul-02	02/233	Repop 8	298181	967434	45	9.90E+06	9.90E+06			
DIVE/02/274/01	31-Jul-02	02/234	Repop 8	298180	967440	10	2.10E+04	2.10E+04			
DIVE/02/275/01	31-Jul-02	02/235	Repop 8	298183	967446	45	3.70E+06	3.70E+06			
DIVE/02/276/01	01-Aug-02	02/236	Repop 8	298189	967451	7.5	2.50E+05	2.50E+05			
DIVE/02/277/01	01-Aug-02	02/237	Repop 8	298174	967454	30	1.10E+06	1.10E+06			
DIVE/02/277/02	01-Aug-02	02/238	Repop 8	298164	967460	<5	2.20E+05	2.20E+05			
DIVE/02/278/01	01-Aug-02	02/239	Repop 8	298181	967469	7.5	4.20E+05	4.20E+05		4.40E+02	
DIVE/02/282/01	02-Aug-02	02/241	Repop 8	298202	967446	20	4.70E+04	4.70E+04			
DIVE/02/282/02	02-Aug-02	02/242	Repop 8	298196	967444	<5	6.90E+03	6.90E+03			
DIVE/02/284/01	06-Aug-02	02/243	Inshore 1	298118	967275	5	7.00E+04	7.00E+04			
DIVE/02/284/02	06-Aug-02	02/244	Inshore 1	298128	967274	25	1.40E+06	1.40E+06			
DIVE/02/286/01	06-Aug-02	02/246	Inshore 1	298116	967256	7.5	1.80E+06	1.80E+06			
DIVE/02/286/02	06-Aug-02	02/247	Inshore 1	298117	967253	20	4.20E+05	4.20E+05			
DIVE/02/287/01	06-Aug-02	02/245	Inshore 1	298148	967223	15	1.30E+06	1.30E+06			
DIVE/02/288/01	07-Aug-02	02/248	Inshore 2	298266	967344	7.5	2.70E+04	2.70E+04			
DIVE/02/288/02	07-Aug-02	02/249	Inshore 2	298297	967293	5	2.20E+06	2.20E+06			
DIVE/02/288/03	07-Aug-02	02/250	Inshore 2	298294	967292	5	3.50E+06	3.50E+06			
DIVE/02/289/01	07-Aug-02	02/251	Inshore 2	298287	967296	35	9.80E+06	9.80E+06			
DIVE/02/289/02	07-Aug-02	02/252	Inshore 2	298286	967294	20	7.00E+04	7.00E+04			
DIVE/02/290/01	07-Aug-02	02/253	Inshore 2	298286	967307	<5	3.00E+05	3.00E+05			
DIVE/02/291/01	07-Aug-02	02/254	Inshore 2	298288	967312	<5	1.60E+05	1.60E+05			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/292/01	08-Aug-02	02/255	Inshore 6	298390	967400	7.5	2.60E+05	2.60E+05			
DIVE/02/299/01	09-Aug-02	02/256	Repop 9(East)	298137	967582	5	2.00E+04	2.00E+04			
DIVE/02/300/01	10-Aug-02	02/259	Inshore 3	298660	967560	10	1.40E+05	1.40E+05			
DIVE/02/301/01	10-Aug-02	02/260	Inshore 3	298655	967565	35	5.40E+05	5.40E+05			
DIVE/02/302/01	10-Aug-02	02/261	Inshore 3	298650	967570	20	3.10E+05	3.10E+05			
DIVE/02/302/02	10-Aug-02	02/257	Inshore 3	298657	967583	10	7.70E+05	7.70E+05			
DIVE/02/302/03	10-Aug-02	02/262	Inshore 3	298665	967586	7.5	4.00E+05	4.00E+05			
DIVE/02/303/01	10-Aug-02	02/258	Inshore 3	298660	967587	40	1.70E+06	1.70E+06			
DIVE/02/305/01	11-Aug-02	02/264	Inshore 4/5	298745	967691	10	1.90E+05	1.90E+05			
DIVE/02/305/02	11-Aug-02	02/263	Inshore 4/5	298735	967671	10	3.50E+06	3.50E+06			
DIVE/02/305/03	11-Aug-02	02/265	Inshore 4/5	298750	967686	5	7.60E+04	7.60E+04			
DIVE/02/306/01	11-Aug-02	02/266	Inshore 4/5	298708	967605	<5	2.40E+03	2.40E+03			
DIVE/02/306/02	11-Aug-02	02/267	Inshore 4/5	298706	967612	20	3.40E+04	3.40E+04			
DIVE/02/309/01	12-Aug-02	02/268	Repop 9(South)	298134	967537	<5	8.30E+04	8.30E+04			
DIVE/02/310/01	12-Aug-02	02/270	Repop 9(South)	298138	967515	15	2.20E+04	2.20E+04			
DIVE/02/310/02	12-Aug-02	02/269	Repop 9(South)	298140	967502	10	9.40E+04	9.40E+04			
DIVE/02/316/01	14-Aug-02	02/274	Repop 9(West)	298068	967507	10	4.00E+05	4.00E+05			
DIVE/02/317/01	14-Aug-02	02/273	Repop 9(West)	298088	967517	20	2.70E+06	2.70E+06			
DIVE/02/318/01	14-Aug-02	02/271	Repop 9(West)	298056	967533	<5	9.30E+05	9.30E+05			
DIVE/02/318/02	14-Aug-02	02/272	Repop 9(West)	298065	967543	10	2.00E+06	2.00E+06			
DIVE/02/318/03	14-Aug-02	02/275	Repop 9(West)	298048	967545	<5	1.60E+04	1.60E+04			
DIVE/02/319/01	15-Aug-02	02/280	Repop 9(C1)	298138	967624	37.5	5.50E+06	5.50E+06			
		02/281					4.80E+02				
DIVE/02/320/01	15-Aug-02	02/279	Repop 9(C1)	298132	967629	50+	6.80E+06	6.80E+06			
DIVE/02/321/01	15-Aug-02	02/276	Repop 9(C1)	298137	967629	35	8.70E+05	8.70E+05			
DIVE/02/321/02	15-Aug-02	02/282	Repop 9(C1)	298138	967633	5	2.30E+04	2.30E+04			
DIVE/02/322/01	15-Aug-02	02/277	Repop 9(C1)	298138	967636	50	6.90E+06	6.90E+06			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
		02/278					2.80E+03				
DIVE/02/323/01	16-Aug-02	02/283	Repop 9(C1)	298143	967640	55	4.00E+06	4.00E+06			
DIVE/02/323/02	16-Aug-02	02/284	Repop 9(C1)	298145	967636	10	3.30E+04	3.30E+04		4.60E+02	
DIVE/02/324/01	16-Aug-02	02/285	Repop 9(C1)	298147	967635	50	6.60E+06	6.60E+06			
DIVE/02/324/02	16-Aug-02	02/286	Repop 9(C1)	298148	967634	60	3.90E+07	3.90E+07			
DIVE/02/325/01	16-Aug-02	02/287	Repop 9(C1)	298146	967632	42.5	7.20E+06	7.20E+06			
DIVE/02/325/02	16-Aug-02	02/288	Repop 9(C1)	298149	967633	50	7.50E+06	7.50E+06			
DIVE/02/325/03	16-Aug-02	02/289	Repop 9(C1)	298148	967636	<5	1.20E+06	1.20E+06		1.50E+03	
DIVE/02/326/01	16-Aug-02	02/290	Repop 9(C1)	298145	967623	50	2.90E+06	2.90E+06			
DIVE/02/327/01	17-Aug-02	02/291	Repop 9(C1)	298145	967625	<5	2.50E+04	2.50E+04			
DIVE/02/327/02	17-Aug-02	02/292	Repop 9(C1)	298151	967636	30	1.60E+06	1.60E+06			
DIVE/02/328/01	17-Aug-02	02/293	Repop 9(C1)	298151	967633	50	4.10E+06	4.10E+06			
DIVE/02/328/02	17-Aug-02	02/294	Repop 9(C1)	298148	967630	<5	7.90E+05	8.80E+05		3.90E+02	
		02/295					9.00E+04				
DIVE/02/328/03	17-Aug-02	02/296	Repop 9(C1)	298155	967640	10	1.90E+05	1.90E+05			
DIVE/02/329/01	17-Aug-02	02/297	Repop 9(C1)	298148	967629	40	2.60E+06	2.60E+06			
DIVE/02/329/02	17-Aug-02	02/298	Repop 9(C1)	298148	967629	70	3.80E+06	3.80E+06			
DIVE/02/330/01	17-Aug-02	02/299	Repop 9(C1)	298151	967628	55	9.90E+06	9.90E+06			
DIVE/02/331/01	18-Aug-02	02/300	Repop 9(C1)	298165	967636	5	8.20E+04	8.20E+04			
DIVE/02/331/02	18-Aug-02	02/301	Repop 9(C1)	298161	967630	80	4.10E+06	4.10E+06			
DIVE/02/332/01	18-Aug-02	02/302	Repop 9(C1)	298153	967623	5	2.60E+04	2.60E+04			
DIVE/02/333/01	18-Aug-02	02/303	Repop 9(C1)	298160	967616	30	4.60E+05	4.60E+05			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/333/02	18-Aug-02	02/304	Repop 9(C1)	298160	967615	7.5	2.20E+05	2.20E+05		5.70E+02	
DIVE/02/333/03	18-Aug-02	02/305	Repop 9(C1)	298163	967610	<5	2.90E+05	2.90E+05			
DIVE/02/334/01	18-Aug-02	02/306	Repop 9(C1)	298147	967620	55	2.60E+06	2.60E+06			
DIVE/02/335/01	22-Aug-02	02/307	Repop 9(C1)	298150	967598	10	3.10E+05	3.10E+05			
DIVE/02/336/01	22-Aug-02	02/308	Repop 9(C1)	298145	967606	60	3.90E+06	3.90E+06			
DIVE/02/336/02	22-Aug-02	02/309	Repop 9(C1)	298145	967598	<5	1.70E+04	1.70E+04			
DIVE/02/337/01	22-Aug-02	02/310	Repop 9(C1)	298143	967602	47.5	5.80E+05	5.80E+05		1.70E+02	
DIVE/02/337/02	22-Aug-02	02/311	Repop 9(C1)	298142	967607	60	8.60E+06	8.60E+06			
DIVE/02/339/01	23-Aug-02	02/312	Repop 9(C1)	298132	967592	30	3.00E+05	3.00E+05			
DIVE/02/340/01	23-Aug-02	02/313	Repop 9(C1)	298128	967598	55	5.10E+06	5.10E+06			
DIVE/02/341/01	23-Aug-02	02/314	Repop 9(C1)	298132	967608	60	2.30E+07	2.30E+07			
DIVE/02/341/02	23-Aug-02	02/315	Repop 9(C1)	298133	967608	50	5.90E+06	5.90E+06			
DIVE/02/342/01	23-Aug-02	02/316	Repop 9(C1)	298117	967602	65	5.50E+07	5.50E+07			
DIVE/02/343/01	24-Aug-02	02/317	Repop 9(C1)	298126	967613	40	3.00E+04	3.00E+04			
DIVE/02/344/01	24-Aug-02	02/318	Repop 9(C1)	298126	967613	60	7.30E+06	7.30E+06			
DIVE/02/344/02	24-Aug-02	02/319	Repop 9(C1)	298119	967616	7.5	9.80E+03	1.26E+04			
DIVE/02/344/03	24-Aug-02	02/320 02/321	Repop 9(C1)	298116	967616	7.5	2.80E+03 2.00E+04	2.00E+04		1.00E+02	
DIVE/02/345/01	24-Aug-02	02/322	Repop 9(C1)	298122	967622	10	1.90E+04	1.90E+04			
DIVE/02/346/01	24-Aug-02	02/323	Repop 9(C1)	298123	967623	55	3.50E+06	3.50E+06			
DIVE/02/347/01	26-Aug-02	02/324	Repop 9(C1)	298116	967631	60	2.00E+07	2.00E+07			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/348/01	26-Aug-02	02/327	Repop 9(C1)	298130	967622	<5	6.00E+03	6.00E+03			
DIVE/02/348/02	26-Aug-02	02/328	Repop 9(C1)	298134	967622	7.5	1.90E+03	2.59E+04			
		02/329					2.40E+04				
DIVE/02/349/01	26-Aug-02	02/326	Repop 9(C1)	298135	967622	55	3.80E+06	3.80E+06			
DIVE/02/350/01	26-Aug-02	02/330	Repop 9(C2)	298103	967612	7.5	4.40E+03	1.11E+05			
		02/331					5.80E+04				
		02/332					4.90E+04				
DIVE/02/350/02	26-Aug-02	02/325	Repop 9(C2)	298099	967611	15	3.20E+06	3.20E+06			
DIVE/02/351/01	26-Aug-02	02/333	Repop 9(C2)	298100	967608	35	4.30E+05	4.30E+05		2.80E+02	
DIVE/02/354/01	28-Aug-02	02/336	Repop 9(C2)	298089	967607	30	2.30E+05	5.60E+05		1.40E+02	
		02/337					3.30E+05				
DIVE/02/354/02	28-Aug-02	02/334	Repop 9(C2)	298090	967602	40	5.90E+06	5.90E+06			
DIVE/02/355/01	28-Aug-02	02/338	Repop 9(C2)	298087	967598	5	5.30E+04	5.30E+04			
DIVE/02/356/01	03-Sep-02	02/340	Repop 9(C2)	298071	967607	25	6.70E+05	6.70E+05			
DIVE/02/357/01	03-Sep-02	02/341	Repop 9(C2)	298070	967620	35	8.30E+05	8.30E+05			
DIVE/02/358/01	03-Sep-02	02/342	Repop 9(C2)	298067	967627	<5	4.40E+03	4.40E+03		1.60E+02	
DIVE/02/359/01	03-Sep-02	02/343	Repop 9(C2)	298077	967625	50	1.50E+05	1.50E+05			
DIVE/02/360/01	04-Sep-02	02/344	Repop 9(C2)	298063	967636	15	2.30E+04	2.30E+04		9.30E+01	
DIVE/02/361/01	04-Sep-02	02/345	Repop 9(C2)	298071	967639	30	7.80E+05	7.80E+05		4.10E+02	
DIVE/02/361/02	04-Sep-02	02/346	Repop 9(C2)	298075	967632	55	4.10E+06	4.10E+06			
DIVE/02/361/03	04-Sep-02	02/347	Repop 9(C2)	298073	967643	10	3.70E+04	3.70E+04			
DIVE/02/362/01	04-Sep-02	02/348	Repop 9(C2)	298079	967646	10	4.20E+04	4.20E+04			
DIVE/02/363/01	04-Sep-02	02/349	Repop 9(C2)	298085	967634	5	2.70E+04	2.70E+04			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/364/01	05-Sep-02	02/350	Repop 9(C2)	298093	967636	10	6.90E+04	6.90E+04		3.10E+02	
DIVE/02/365/01	05-Sep-02	02/351	Repop 9(C2)	298101	967634	40	3.20E+06	3.20E+06			
DIVE/02/367/01	05-Sep-02	02/352	Repop 9(C2)	298099	967631	40	1.80E+06	1.80E+06			
DIVE/02/368/01	06-Sep-02	02/353	Repop 9(C2)	298099	967628	25	5.30E+06	5.30E+06			
DIVE/02/368/02	06-Sep-02	02/357	Repop 9(C2)	298103	967621	10	1.90E+05	1.90E+05		3.00E+02	
DIVE/02/369/01	06-Sep-02	02/354	Repop 9(C2)	298092	967625	65	3.40E+06	3.40E+06			
DIVE/02/370/01	06-Sep-02	02/355	Repop 9(C2)	298100	967624	35	1.80E+06	1.80E+06			
DIVE/02/370/02	06-Sep-02	02/356	Repop 9(C2)	298096	967622	50	1.00E+07	1.00E+07			
DIVE/02/371/01	06-Sep-02	02/358	Repop 9(C2)	298100	967620	7.5	1.60E+04	1.60E+04			
DIVE/02/371/02	06-Sep-02	02/359	Repop 9(C2)	298091	967623	<5	5.90E+03	5.90E+03			
DIVE/02/375/01	07-Sep-02	02/360	GWU2-2002	298209	967406	25	3.70E+05	3.70E+05			
DIVE/02/376/01	09-Sep-02	02/361	GWU2-2002	298211	967405	15	2.20E+06	2.20E+06			
DIVE/02/377/01	09-Sep-02	02/362	GWU2-2002	298222	967408	5	1.10E+05	3.10E+05			
		02/363					2.00E+05				
DIVE/02/377/02	09-Sep-02	02/364	GWU2-2002	298207	967403	7.5	1.80E+05	1.80E+05			
DIVE/02/377/03	09-Sep-02	02/365	GWU2-2002	298208	967402	7.5	3.00E+04	3.00E+04			
DIVE/02/378/01	09-Sep-02	02/366	GWU2-2002	298217	967400	10	4.10E+05	4.10E+05			
DIVE/02/379/01	09-Sep-02	02/367	GWU2-2002	298223	967392	10	3.50E+05	3.50E+05			
DIVE/02/379/02	09-Sep-02	02/368	GWU2-2002	298208	967389	<5	1.40E+04	1.40E+04			
DIVE/02/387/01	12-Sep-02	02/369	GWU2-2002	298183	967410	<5	4.10E+04	4.10E+04			
DIVE/02/388/01	12-Sep-02	02/404	S of Repop 8 (Active Core)	298174	967413	20	3.40E+04	3.40E+04			
DIVE/02/389/01	12-Sep-02	02/370	S of Repop 8	298155	967419	15	3.30E+06	3.30E+06			
DIVE/02/390/01	12-Sep-02	02/402	S of Repop 8	298152	967413	35	4.80E+05	4.80E+05			
DIVE/02/391/01	13-Sep-02	02/371	SW of repop 4	298161	967665	35	3.90E+06	3.90E+06			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/392/01	13-Sep-02	02/372	SW of repop 4	298190	967638	<5	4.50E+04	1.99E+05			
		02/373					5.90E+03				
		02/374					3.20E+04				
		02/375					2.60E+04				
		02/376					2.50E+03				
		02/377					7.40E+04				
		02/378					1.00E+04				
		02/379					3.90E+03				
DIVE/02/393/01	13-Sep-02	02/380	SW of repop 4	298207	967646	<5	6.40E+03	6.40E+03			
DIVE/02/396/01	14-Sep-02	02/381	SW of repop 4	298176	967636	<5	1.00E+04	1.00E+04		2.10E+02	
DIVE/02/397/01	14-Sep-02	02/403	SW of repop 4 Active Core)	298163	967645	40	5.00E+06	5.00E+06			
DIVE/02/398/01	14-Sep-02	02/401	SW of repop 4	298157	967653	15	3.00E+05	3.00E+05			
DIVE/02/399/01	15-Sep-02	02/383	GWU 2.2002	298207	967393	20	1.20E+05	1.20E+05			
DIVE/02/400/01	15-Sep-02	02/382	GWU 2.2002	298200	967387	45	2.50E+06	2.50E+06			
DIVE/02/406/01	18-Sep-02	02/384	Repop 4 (2)	298208	967706	5	2.20E+04	2.20E+04			
DIVE/02/411/01	23-Sep-02	02/385	Repop 4 (2)	298184	967716	<5	2.90E+03	2.90E+03			
DIVE/02/413/01	24-Sep-02	02/386	Repop 8 (2)	298193	967468	35	2.80E+05	3.42E+05			
		02/387					6.20E+04				
DIVE/02/417/01	25-Sep-02	02/388	Repop 8 (2)	298175	967448	45	8.70E+05	8.70E+05			
DIVE/02/421/01	29-Sep-02	02/389	Grid K22	298654	967842	7.5	6.60E+04	6.60E+04			
DIVE/02/422/01	29-Sep-02	02/390	Grid K22	298665	967837	5	2.10E+05	2.10E+05			
DIVE/02/422/02	29-Sep-02	02/391	Grid K22	298666	967833	<5	8.40E+03	8.40E+03			
DIVE/02/423/01	29-Sep-02	02/392	Grid K22	298649	967834	5	2.20E+05	2.20E+05		1.00E+02	DFR
DIVE/02/424/01	29-Sep-02	02/393	Grid K22	298634	967827	<5	2.50E+04	2.50E+04			
DIVE/02/425/01	30-Sep-02	02/394	Grid K22	298630	967831	10	1.80E+04	1.80E+04			
DIVE/02/426/01	30-Sep-02	02/399	Grid K22	298630	967831	40	6.40E+06	6.40E+06			
DIVE/02/426/02	30-Sep-02	02/400	Grid K22	298631	967837	35	1.00E+07	1.00E+07			
DIVE/02/426/03	30-Sep-02	02/395	Grid K22	298632	967842	<5	1.00E+04	1.00E+04			
DIVE/02/427/01	30-Sep-02	02/396	Grid K22	298638	967842	10	8.60E+03	8.60E+03			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/02/428/01	30-Sep-02	02/397	Grid K22	298641	967861	7.5	8.10E+04	8.10E+04			
DIVE/02/428/02	30-Sep-02	02/398	Grid K22	298644	967852	10	8.40E+04	8.40E+04			
DIVE/03/002/01	24-Apr-03	03/021	Repop 8	298193	967433	10	8.50E+05	8.50E+05			
DIVE/03/005/01	25-Apr-03	03/022	Repop 8	298180	967443	<10	3.80E+04	3.80E+04			
DIVE/03/006/01	25-Apr-03	03/023	Repop 8	298173	967442	15	5.40E+04	7.20E+04			
		03/024					1.80E+04				
DIVE/03/006/02	25-Apr-03	03/025	Repop 8	298173	967440	10	3.70E+04	3.70E+04			
DIVE/03/008/01	25-Apr-03	03/026	Repop 8	298176	967451	<5	1.00E+05	1.00E+05			
DIVE/03/008/02	25-Apr-03	03/027	Repop 8	298165	967450	20	6.50E+04	6.50E+04			
DIVE/03/011/01	26-Apr-03	03/074	Repop 8	298203	967470	40	1.30E+06	1.30E+06			
DIVE/03/015/01	27-Apr-03	03/080	Repop 9E	298136	967560	30	2.80E+07	2.80E+07			
DIVE/03/018/01	28-Apr-03	03/028	Repop 9C1	298154	967604	7.5	1.80E+04	3.20E+04			
		03/029					1.40E+04				
DIVE/03/018/02	28-Apr-03	03/030	Repop 9C1	298145	967612	5	1.80E+04	2.01E+04			
		03/031					2.10E+03				
DIVE/03/018/03	28-Apr-03	03/032	Repop 9C1	298146	967610	7.5	2.00E+03	2.00E+03			
DIVE/03/020/01	28-Apr-03	03/033	Repop 9C1	298133	967612	7.5	2.90E+03	2.90E+03			
DIVE/03/023/01	15-May-03	03/036	Repop 9C1	298134	967624	9	1.20E+04	1.92E+04			
		03/037					2.70E+03				
		03/038					3.90E+03				
		03/039					5.90E+02				
DIVE/03/028/01	16-May-03	03/040	Repop 9C2	298102	967606	5	8.70E+04	8.70E+04			
DIVE/03/029/01	16-May-03	03/041	Repop 9C2	298084	967595	10	9.60E+03	9.60E+03			
DIVE/03/032/01	17-May-03	03/042	Repop 9C2	298067	967606	5	1.80E+04	1.80E+04			
DIVE/03/033/01	17-May-03	03/043	Repop 9C2	298057	967623	30	1.80E+05	1.80E+05			
DIVE/03/035/01	17-May-03	03/075	Repop 9C2	298060	967641	50	4.70E+06	4.70E+06			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/03/036/01	18-May-03	03/044	Repop 9C2	298063	967639	10	4.80E+04	4.80E+04		1.80E+02	
DIVE/03/037/01	18-May-03	03/045	Repop 9C2	298075	967635	5	3.40E+04	3.40E+04			
DIVE/03/039/01	18-May-03	03/046	Repop 9C2	298098	967640	5	6.20E+03	8.30E+03			
		03/047					2.10E+03				
DIVE/03/040/01	18-May-03	03/048	Repop 9C2	298095	967637	10	1.60E+04	2.21E+04			
		03/049					1.00E+03				
		03/050					5.00E+03				
		03/051					1.30E+02				
		03/052					<1.1e2				
DIVE/03/050/01	21-May-03	03/053	Repop 6	298897	968284	<5	3.50E+03	7.60E+03			
		03/054					4.10E+03				
DIVE/03/053/01	22-May-03	03/055	Repop 6	298893	968253	7.5	1.40E+04	1.55E+04			
		03/056					1.50E+03				
DIVE/03/054/01	22-May-03	03/057	Repop 6	298892	968254	5	2.80E+04	2.80E+04		1.70E+02	
DIVE/03/059/01	23-May-03	03/058	Repop 4 Outer	298156	967695	7.5	8.70E+03	8.70E+03		6.10E+02	
DIVE/03/060/01	23-May-03	03/059	Repop 4 Outer	298150	967704	5	3.60E+03	8.50E+03			
		03/060					4.90E+03			2.10E+02	
DIVE/03/061/01	23-May-03	03/061	Repop 4 Outer	298154	967716	10	4.50E+04	4.50E+04			
DIVE/03/062/01	24-May-03	03/063	Repop 4 Outer	298161	967729	5	9.90E+03	9.90E+03		8.30E+01	
DIVE/03/063/01	24-May-03	03/064	Repop 4 Outer	298182	967733	20	8.50E+05	8.50E+05		1.70E+02	
DIVE/03/064/01	24-May-03	03/062	Repop 4 Outer	298187	967751	5	1.96E+04	1.96E+04			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/03/067/01	25-May-03	03/065	Repop 4 Outer	298216	967741	50	2.10E+05	2.10E+05			
DIVE/03/073/01	26-May-03	03/066	Repop 4 Outer	298215	967678	5	<1.2e2	<1.2e2		1.30E+03	
DIVE/03/075/01	26-May-03	03/067	Repop 4 Outer	298197	967674	13	2.80E+04	2.80E+04			
DIVE/03/076/01	26-May-03	03/068	Repop 4 Outer	298177	967658	5	3.90E+05	3.90E+05			
DIVE/03/077/01	27-May-03	03/069	Repop 4 Outer (Outside)	298171	967661	5	7.90E+04	7.90E+04		1.20E+02	DFR
DIVE/03/078/01	27-May-03	03/070	Repop 4 Outer	298166	967672	10	2.00E+04	2.00E+04			
DIVE/03/078/02	27-May-03	03/071	Repop 4 Outer	298161	967672	15	9.10E+03	9.10E+03			
DIVE/03/079/01	27-May-03	03/072	Repop 9W	298051	967528	5	2.13E+05	2.13E+05			
DIVE/03/080/01	27-May-03	03/073	Repop 9W	298070	967535	5	1.60E+05	1.60E+05			MTR
DIVE/03/082/01	28-May-03	03/076	Repop 9W	298082	967506	15	1.50E+05	1.50E+05			MTR
DIVE/03/083/01	28-May-03	03/077	Repop 9W	298084	967503	15	1.40E+05	1.40E+05			
DIVE/03/083/02	28-May-03	03/078	Repop 9W	298092	967506	15	2.20E+05	2.20E+05			
DIVE/03/085/01	29-May-03	03/079	Repop 9E	298131	967560	30	1.60E+04	1.60E+04			
DIVE/03/087/01	30-May-03	03/081	Repop 9E	298137	967590	5	1.30E+04	1.30E+04			
DIVE/03/092/01	31-May-03	03/082	Sandside	296363	965851	7.5	5.20E+03	5.20E+03			
DIVE/03/093/01	31-May-03	03/083	Sandside	296377	965835	10	6.10E+03	6.10E+03			
DIVE/03/094/01	31-May-03	03/084	Sandside	296369	965825	5	1.80E+04	1.80E+04			
DIVE/03/098/01	02-Jun-03	03/085	Repop 5	298662	967948	5	2.70E+03	2.70E+03		4.90E+01	
DIVE/03/100/01	02-Jun-03	03/086	Repop 5	298664	967968	20	3.80E+05	3.80E+05			
DIVE/03/101/01	02-Jun-03	03/087	Repop 5	298680	967988	5	2.00E+03	2.00E+03			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/03/103/01	03-Jun-03	03/088	Repop 5	298644	967957	5	6.90E+04	6.90E+04			
DIVE/03/104/01	03-Jun-03	03/089	Repop 5	298643	967973	5	3.20E+03	2.02E+04			
		03/090					1.70E+04				
DIVE/03/105/01	03-Jun-03	03/091	Repop 5	298661	967985	10	1.50E+04	1.85E+04			
		03/092					3.50E+03				
DIVE/03/113/01	05-Jun-03	03/093	Cell C6	297036	967058	5	6.50E+03	6.50E+03			
03/03/SAM01	15-Sep-03	03/100	NE of Diffuser	298137	967701	10	4.40E+05	4.40E+05			
DIVE/04/007/01	24-Apr-04	04/022	Repop 6	298876	968248	0	8.50E+03	8.50E+03			
DIVE/04/010/01	24-Apr-04	04/023	Repop 6	298908	968248	0	7.10E+04	7.10E+04			
DIVE/04/011/01	25-Apr-04	04/024	Repop 6	298885	968248	0	6.20E+03	6.20E+03			
DIVE/04/012/01	25-Apr-04	04/025	Repop 6	298888	968240	5	2.40E+04	2.40E+04			
DIVE/04/013/01	25-Apr-04	04/026	Repop 6	298894	968240	5	1.00E+04	1.00E+04		6.40E+01	
DIVE/04/013/02	25-Apr-04	04/027	Repop 6	298896	968246	5	2.00E+03	2.00E+03			
DIVE/04/015/01	25-Apr-04	04/028	Repop 6	298899	968243	50	2.90E+06	2.90E+06			
DIVE/04/016/01	26-Apr-04	04/029	Repop 6	298907	968237	5	9.30E+03	9.30E+03			
DIVE/04/021/01	27-Apr-04	04/030	Repop 10	298020	967656	5	1.80E+03	1.80E+03		1.10E+02	
DIVE/04/022/01	27-Apr-04	04/031	Repop 10	298015	967645	10	3.10E+04	3.10E+04			
DIVE/04/023/01	27-Apr-04	04/032	Repop 10	298015	967656	7.5	8.20E+03	8.20E+03			
DIVE/04/024/01	27-Apr-04	04/033	Repop 10	298003	967658	10	2.10E+04	2.10E+04			
DIVE/04/025/01	28-Apr-04	04/035	Repop 10	298005	967664	0	8.40E+03	8.40E+03			
DIVE/04/026/01	01-May-04	04/037	Repop 9C1	298140	967610	5	8.20E+04	8.64E+04			
		04/038					6.90E+02				
		04/039					6.20E+02				
		04/040					3.10E+03				
DIVE/04/029/01	01-May-04	04/036	Repop 9C1	298129	967602	5	1.10E+04	1.10E+04			
DIVE/04/032/01	07-May-04	04/048	Repop 9C1	298128	967620	70+	4.40E+06	4.40E+06			
DIVE/04/036/01	08-May-04	04/041	Repop 9C1	298132	967631	7.5	4.80E+04	4.80E+04			
DIVE/04/039/01	08-May-04	04/042	Repop 9C1	298150	967639	50	1.60E+05	1.60E+05			
DIVE/04/040/01	09-May-04	04/043	Repop 9C1 (just outside)	298155	967643	10	1.30E+05	1.30E+05			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/04/040/02	09-May-04	04/044	Repop 9C1	298156	967641	<5	5.10E+02	5.10E+02			
DIVE/04/042/01	09-May-04	04/045	Repop 9C1	298166	967622	10	1.60E+04	1.60E+04		7.00E+01	
		04/046					<2.0E2				
DIVE/04/042/02	09-May-04	04/047	Repop 9C1	298155	967615	0	1.80E+03	1.80E+03			
DIVE/04/044/01	09-May-04	04/049	Repop 9C1	298142	967615	2.5	1.90E+03	1.90E+03			
DIVE/04/046/01	10-May-04	04/050	Repop 10	298036	967684	0	4.20E+04	4.20E+04			
DIVE/04/049/01	10-May-04	04/051	Repop 10	298019	967688	30	1.50E+05	1.50E+05			
DIVE/04/050/01	10-May-04	04/052	Repop 10	298017	967684	5	1.60E+04	1.60E+04		1.20E+02	
DIVE/04/053/01	11-May-04	04/053	Repop 10	298011	967684	0	2.40E+03	2.40E+03			
DIVE/04/055/01	11-May-04	04/054	Repop 11	298983	968462	10	1.30E+04	1.30E+04			
DIVE/04/057/01	12-May-04	04/057	Repop 11	298982	968445	0	1.40E+04	1.53E+04			
		04/058					1.30E+03				
DIVE/04/05901	12-May-04	04/059	Repop 11	298963	968453	0	3.50E+04	3.50E+04			
DIVE/04/060/01	12-May-04	04/055	Repop 11	298959	968450	40	2.50E+06	2.51E+06			
		04/056					8.70E+03				
DIVE/04/063/01	14-May-04	04/060	Repop 11	298968	968463	10	6.50E+04	6.50E+04			
DIVE/04/067/01	16-May-04	04/061	Repop 11	298997	968482	10	3.50E+03	3.50E+03			
DIVE/04/069/01	26-May-04	04/062	Repop 11	298987	968492	15	2.30E+05	2.30E+05			
DIVE/04/070/01	26-May-04	04/063	Repop 11	298976	968489	10	1.30E+04	1.30E+04			
DIVE/04/073/01	26-May-04	04/064	Repop 11	298967	968477	0	2.50E+04	4.73E+04		5.80E+01	
		04/065					8.50E+03				
		04/066					9.00E+03				
		04/068					2.80E+03				
		04/069					2.00E+03				
DIVE/04/077/01	27-May-04	04/067	Repop 12	299544	969106	15	7.00E+04	7.00E+04			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/04/082/01	28-May-04	04/086	Repop 12	299523	969115	10	<1.13E+02	<1.13E+02	3.13E+03		
DIVE/04/083/01	28-May-04	04/070	Repop 12	299528	969125	10	2.20E+04	5.39E+04			
		04/071					8.00E+03				
		04/072					5.00E+03				
		04/073					1.10E+04				
		04/074					4.00E+03				
		04/075					3.90E+03				
DIVE/04/086/01	28-May-04	04/076	Repop 12	299520	969144	0	2.70E+02	4.83E+02			
		04/077					9.30E+01				
		04/078					1.20E+02				
DIVE/04/087/01	29-May-04	04/079	Repop 12	299532	969152	20	3.90E+04	3.90E+04			
DIVE/04/088/01	29-May-04	04/080	Repop 12	299536	969154	35	1.50E+05	1.50E+05			
DIVE/04/089/01	29-May-04	04/081	Repop 12	299538	969147	8	2.50E+04	2.50E+04			
DIVE/04/094/01	30-May-04	04/082	Repop 12	299546	969122	0	1.20E+03	1.20E+03			
DIVE/04/098/01	31-May-04	04/083	Inshore Area 2004/01	298788	967852	7.5	3.50E+04	3.50E+04			
DIVE/04/098/02	31-May-04	04/084	Inshore Area 2004/01	298790	967850	50	4.80E+05	4.82E+05			
		04/085					1.50E+03				
DIVE/04/099/01	01-Jun-04	04/087	Inshore Area 2004/02	298537	967532	50 est	1.10E+06	1.10E+06			
DIVE/04/100/01	01-Jun-04	04/088	Inshore Area 2004/02	298548	967527	50	1.60E+06	1.60E+06			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/04/101/01	01-Jun-04	04/089	Inshore Area 2004/02	298494	967504	50	1.20E+07	1.20E+07			
DIVE/04/102/01	01-Jun-04	04/090	Inshore Area 2004/02	298493	967485	15	3.60E+04	3.60E+04			
DIVE/04/113/01	06-Jun-04	04/093	Repop 8	298192	967422	0	3.00E+05	3.00E+05			
DIVE/04/115/01	06-Jun-04	04/091	Repop 8	298168	967447	10	5.00E+04	5.00E+04			
DIVE/04/116/01	06-Jun-04	04/092	Repop 8	298171	967449	10	1.40E+06	1.40E+06			
DIVE/04/117/01	08-Jun-04	04/095	Repop 8	298170	967455	7.5	3.20E+04	3.20E+04		3.40E+01	
DIVE/04/117/02	08-Jun-04	04/096	Repop 8	298181	967459	10	1.40E+04	1.40E+04			
DIVE/04/118/01	08-Jun-04	04/097	Repop 8	298183	967459	5	1.80E+04	1.80E+04			
DIVE/04/119/01	08-Jun-04	04/098	Repop 8	298189	967463	20	7.00E+03	1.47E+05			
		04/099					1.40E+05				
DIVE/04/121/01	08-Jun-04	04/100	Repop 8	298205	967469	10	3.40E+04	3.40E+04		2.10E+01	
DIVE/04/122/01	09-Jun-04	04/101	Repop 8	298212	967470	12	1.60E+04	1.60E+04			
DIVE/04/122/02	09-Jun-04	04/102	Repop 8	298207	967460	5	2.40E+05	2.40E+05			
DIVE/04/123/01	09-Jun-04	04/103	Repop 8	298202	967441	10	1.60E+05	1.60E+05			
ROV/04/07/01	07-Sep-04	04/115	ROV Trial 1	298300	967752	50	2.00E+05	2.00E+05			
ROV/04/08/01	07-Sep-04	04/112	ROV Trial 2	298306	967751	>50-90	4.70E+06	4.70E+06			
ROV/04/09/01	07-Sep-04	04/114	ROV Trial 4	298312	967744	55	1.80E+06	1.80E+06			
ROV/04/10/01	08-Sep-04	04/113	ROV Trial 7	298317	967732	45-50	2.30E+06	2.30E+06			
ROV/04/10/02	08-Sep-04	04/117	ROV Trial 9	298308	967728	37-42	3.30E+06	3.30E+06			
ROV/04/11/01	08-Sep-04	04/118	ROV Trial 11	298305	967720	28-33	3.40E+06	3.40E+06			
ROV/04/12/01	08-Sep-04	04/122	ROV Trial 5	298316	967746	25-35	2.30E+06	2.30E+06			
ROV/04/12/02	08-Sep-04	04/116	ROV Trial 8	298316	967728	40-45	2.80E+05	2.80E+05			
ROV/04/14/01	09-Sep-04	04/119	ROV Trial 10	298304	967727	15-20	5.00E+05	5.00E+05			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
ROV/04/15/01	09-Sep-04	04/120	ROV Trial 12	298295	967721	10-15	6.60E+05	7.40E+05		3.90E+02	
		04/121					8.00E+04				
ROV/04/15/02	09-Sep-04	04/123	ROV Trial 3	298309	967745	35-42	2.30E+06	2.30E+06			
ROV/04/16/01	10-Sep-04	04/124	ROV Trial 6	298317	967741	20-25	2.70E+05	2.70E+05			
DIVE/05/001/01	16-Mar-05	L80PART/ 05/019	Repop 8	298209	967432	<5	5.10E+04	5.10E+04			
DIVE/05/002/01	16-Mar-05	L80PART/ 05/020	Repop 8	298198	967438	0	1.00E+05	1.04E+05			
		L80PART/ 05/021					4.00E+03				
DIVE/05/003/01	18-Mar-05	L80PART/ 05/022	Repop 8	298194	967424	10	5.15E+05	5.15E+05	<2.66E+0 1		
DIVE/05/004/01	18-Mar-05	L80PART/ 05/023	Repop 8	298183	967429	0	2.30E+04	2.30E+04		1.40E+02	
DIVE/05/006/01	18-Mar-05	L80PART/ 05/024	Repop 8	298167	967430	15	1.30E+05	1.30E+05			
DIVE/05/006/02	18-Mar-05	L80PART/ 05/025	Repop 8	298167	967440	10	5.60E+04	5.60E+04			
DIVE/05/008/01	19-Mar-05	L80PART/ 05/026	Repop 8	298172	967452	10	6.90E+04	6.90E+04			
DIVE05/009/01	19-Mar-05	L80PART/ 05/027	Repop 8	298170	967459	15	3.60E+02	1.09E+05			
		L80PART/ 05/028					1.70E+03				
		L80PART/ 05/029					3.30E+04				MTR
		L80PART/ 05/030					2.00E+04				
		L80PART/ 05/031					1.50E+04				
		L80PART/ 05/032					2.70E+04				

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
		L80PART/ 05/033					5.90E+03				
		L80PART/ 05/034					1.10E+03				
		L80PART/ 05/035					4.80E+03				
		L80PART/ 05/036					4.20E+02				
DIVE/05/011/01	20-Mar-05	L80PART/ 05/039	Repop 8	298193	967469	0	4.80E+04	4.80E+04			
DIVE/05/012/01	20-Mar-05	L80PART/ 05/037	Repop 8	298197	967462	30	5.50E+05	5.50E+05			
DIVE/05/012/02	20-Mar-05	L80PART/ 05/038	Repop 8	298205	967462	15	5.70E+04	5.70E+04			
DIVE/05/013/01	20-Mar-05	L80PART/ 05/040	Repop 8	298210	967459	0	1.40E+05	1.40E+05			
DIVE/05/014/01	20-Mar-05	L80PART/ 05/041	Repop 8	298206	967455	25	7.30E+04	7.30E+04			
DIVE/05/018/01	21-Mar-05	L80PART/ 05/042	Repop 3	298104	967472	10	4.30E+05	4.30E+05			
DIVE/05/019/01	21-Mar-05	L80PART/ 05/043	Repop 3	298112	967462	5	7.90E+04	7.90E+04			
DIVE/05/020/01	21-Mar-05	L80PART/ 05/044	Repop 3	298119	967452	0	9.00E+04	9.00E+04			
DIVE/05/020/02	21-Mar-05	L80PART/ 05/045	Repop 3	298103	967447	25	1.30E+05	1.30E+05			
DIVE/05/021/01	22-Mar-05	L80PART/ 05/046	Repop 3	298121	967440	10	1.80E+05	1.80E+05			
DIVE/05/022/01	22-Mar-05	L80PART/ 05/047	Repop 3 (2 m outside)	298106	967425	5	1.50E+05	1.50E+05			
DIVE/05/023/01	22-Mar-05	L80PART/ 05/048	Repop 3	298095	967429	5	<1.1E+02	<1.1E+02	2.60E+03		
DIVE/05/024/01	22-Mar-05	L80PART/ 05/049	Repop 3	298093	967447	0	2.40E+03	2.40E+03		6.90E+01	
DIVE/05/025/01	23-Mar-05	L80PART/ 05/051	Repop 3	298074	967445	10	2.50E+04	2.50E+04			
DIVE/05/026/01	23-Mar-05	L80PART/ 05/052	Repop 3	298077	967452	30	2.10E+05	2.10E+05			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/05/026/02	23-Mar-05	L80PART/ 05/050	Repop 3	298081	967453	10	1.10E+06	1.10E+06			
DIVE/05/027/01	23-Mar-05	L80PART/ 05/053	Repop 3	298088	967455	30	5.20E+05	5.20E+05			
DIVE/05/027/02	23-Mar-05	L80PART/ 05/054	Repop 3	298090	967464	10	6.90E+05	6.90E+05			
DIVE/05/029/01	24-Mar-05	L80PART/ 05/058	Repop 4	298189	967721	0	2.70E+03	2.70E+03			
DIVE/05/030/01	24-Mar-05	L80PART/ 05/057	Repop 4	298175	967722	0	2.40E+04	2.40E+04			
DIVE/05/031/01	24-Mar-05	L80PART/ 05/059	Repop 4	298179	967718	5	6.00E+03	6.00E+03		5.30E+01	
DIVE/05/031/02	24-Mar-05	L80PART/ 05/060	Repop 4	298194	967706	5	3.00E+03	3.00E+03			
DIVE/05/031/03	24-Mar-05	L80PART/ 05/056	Repop 4	298175	967718	0	3.30E+02	3.30E+02			
DIVE/05/032/01	24-Mar-05	L80PART/ 05/061	Repop 4	298177	967702	0	2.50E+03	2.50E+03			
DIVE/05/034/01	25-Mar-05	L80PART/ 05/063	Repop 4	298197	967699	20	6.40E+04	6.40E+04			
DIVE/05/035/01	25-Mar-05	L80PART/ 05/064	Repop 4	298194	967681	12	8.10E+05	8.10E+05			
DIVE/05/036/01	25-Mar-05	L80PART/ 05/062	Repop 4	298205	967720	15	2.10E+04	2.10E+04		5.10E+01	
DIVE/05/038/01	26-Mar-05	L80PART/ 05/080	Repop 4	298207	967687	5	1.00E+05	1.00E+05			
DIVE/05/044/01	28-Mar-05	L80PART/ 05/081	Repop 6	298913	968263	0	4.10E+03	4.10E+03			
DIVE/05/048/01	31-Mar-05	L80PART/ 05/082	Repop 6	298878	968276	5	4.40E+04	4.40E+04		4.40E+01	
DIVE/05/048/02	31-Mar-05	L80PART/ 05/085	Repop 6	298879	968276	0	4.40E+04	4.40E+04			
DIVE/05/050/01	31-Mar-05	L80PART/ 05/087	Repop 6	298872	968265	10	2.60E+04	2.60E+04			
DIVE/05/050/02	31-Mar-05	L80PART/ 05/083	Repop 6	298869	968262	0	4.40E+04	4.59E+04		6.30E+01	
		L80PART/ 05/084					1.90E+03				

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
DIVE/05/051/01	31-Mar-05	L80PART/ 05/086	Repop 6	298875	968253	0	7.00E+02	7.00E+02			
DIVE/05/053/01	01-Apr-05	L80PART/ 05/088	Repop 6	298893	968231	30	2.30E+04	2.30E+04			
DIVE/05/056/01	01-Apr-05	L80PART/ 05/089	Repop 12	299535	969110	5	3.60E+03	3.60E+03			
DIVE/05/056/02	01-Apr-05	L80PART/ 05/090	Repop 12	299535	969117	15	9.20E+03	9.20E+03			
DIVE/05/059/01	02-Apr-05	L80PART/ 05/091	Repop 12	299529	969121	15	4.70E+03	3.78E+04			
		L80PART/ 05/092					3.10E+03				
		L80PART/ 05/093					3.00E+04				
DIVE/05/063/01	02-Apr-05	L80PART/ 05/094	Repop 12	299524	969147	0	3.50E+06	3.50E+06			
DIVE/05/064/01	03-Apr-05	L80PART/ 05/095	Repop 12	299526	969147	0	2.80E+04	2.80E+04			
DIVE/05/067/01	03-Apr-05	L80PART/ 05/096	Repop 12	299548	969145	15	8.10E+04	8.10E+04			
DIVE/05/068/01	03-Apr-05	L80PART/ 05/097	Repop 12	299550	969137	5	2.70E+04	2.70E+04			
DIVE/05/070/01	04-Apr-05	L80PART/ 05/098	Repop 12	299554	969120	5	1.90E+04	1.90E+04			
ROV/05/020/01	16-Aug-05	L80PART/ 05/117	ROV Validation Area	298287	967824	10	1.70E+06	1.70E+06			
ROV/05/024/01	17-Aug-05	L80PART/ 05/118	ROV Validation Area	298287	967843	5	9.40E+03	4.14E+04			
		L80PART/ 05/119	ROV Validation Area				3.20E+04				
ROV/05/026/01	17-Aug-05	L80PART/ 05/120	ROV Validation Area	298281	967830	35	2.10E+04	6.00E+04			

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
		L80PART/ 05/121	ROV Validation Area				2.50E+04				
		L80PART/ 05/122	ROV Validation Area				1.40E+04				
ROV/05/027/01	17-Aug-05	L80PART/ 05/123	ROV Validation Area	298281	967825	10	8.50E+03	8.50E+03			
ROV/05/029/01	18-Aug-05	L80PART/ 05/124	ROV Validation Area	298286	967803	19	4.30E+03	4.30E+03			
ROV/05/029/02	18-Aug-05	L80PART/ 05/125	ROV Validation Area	298276	967795	9	3.50E+04	3.50E+04			
ROV/05/029/03	18-Aug-05	L80PART/ 05/126	ROV Validation Area	298277	967794	2.5	2.30E+02	1.03E+03			
		L80PART/ 05/127	ROV Validation Area				5.90E+02	5.90E+02			
		L80PART/ 05/128	ROV Validation Area				2.10E+02	2.10E+02			
ROV/05/030/01	18-Aug-05	L80PART/ 05/129	ROV Validation Area	298273	967779	5	1.10E+04	1.10E+04			
ROV/05/031/01	18-Aug-05	L80PART/ 05/130	ROV Validation Area	298253	967777	18	2.00E+05	2.00E+05		1.80E+02	
ROV/05/032/01	18-Aug-05	L80PART/ 05/131	ROV Validation Area	298249	967779	30	9.90E+04	1.00E+05			
		L80PART/ 05/132	ROV Validation Area				1.20E+03				

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
ROV/05/033/01	19-Aug-05	L80PART/ 05/133	ROV Validation Area	298320	967844	25	1.30E+06	1.30E+06			
ROV/05/033/02	19-Aug-05	L80PART/ 05/134	ROV Validation Area	298307	967838	5-10	1.50E+06	1.50E+06			
ROV/05/034/01	19-Aug-05	L80PART/ 05/135	ROV Validation Area	298302	967829	5	6.00E+02	6.00E+02			
ROV/05/034/02	19-Aug-05	L80PART/ 05/136	ROV Validation Area	298300	967830	7.5	8.50E+04	8.50E+04			
ROV/05/034/03	19-Aug-05	L80PART/ 05/137	ROV Validation Area	298297	967825	10	2.50E+05	2.50E+05			
ROV/05/035/01	19-Aug-05	L80PART/ 05/138	ROV Validation Area	298294	967839	30	1.90E+04	1.94E+04		3.10E+02	
		L80PART/ 05/139	ROV Validation Area				1.90E+02				
		L80PART/ 05/140	ROV Validation Area				1.40E+02				
		L80PART/ 05/141	ROV Validation Area				5.80E+01				
ROV/05/035/02	19-Aug-05	L80PART/ 05/142	ROV Validation Area	298298	967845	50	4.70E+06	4.70E+06			
ROV/05/036/01	19-Aug-05	L80PART/ 05/143	ROV Validation Area	298300	967847	35	1.40E+07	1.40E+07			
ROV/05/036/02	19-Aug-05	L80PART/ 05/144	ROV Validation Area	298305	967848	5	1.10E+05	1.10E+05		1.70E+02	

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
ROV/05/036/03	19-Aug-05	L80PART/ 05/145	ROV Validation Area	298283	967826	5	7.70E+04	7.70E+04			
ROV/05/037/01	20-Aug-05	L80PART/ 05/146	ROV Validation Area	298280	967824	35	6.10E+06	6.10E+06			
ROV/05/037/02	20-Aug-05	L80PART/ 05/147	ROV Validation Area	298279	967824	10	1.10E+05	1.10E+05		1.50E+02	
ROV/05/038/01	20-Aug-05	L80PART/ 05/148	ROV Validation Area	298281	967808	5	3.60E+05	3.60E+05			
ROV/05/038/02	20-Aug-05	L80PART/ 05/149	ROV Validation Area	298271	967811	7.5	1.10E+05	1.10E+05			
ROV/05/038/03	20-Aug-05	L80PART/ 05/150	ROV Validation Area	298274	967801	30	5.00E+05	5.00E+05		1.90E+02	
ROV/05/038/04	20-Aug-05	L80PART/ 05/151	ROV Validation Area	298273	967798	15	1.50E+06	1.50E+06			
ROV/05/039/01	20-Aug-05	L80PART/ 05/152	ROV Validation Area	298265	967797	7.5	3.60E+05	3.60E+05		3.60E+02	
ROV/05/039/02	20-Aug-05	L80PART/ 05/153	ROV Validation Area	298263	967799	5	2.90E+04	2.90E+04			
ROV/05/039/03	20-Aug-05	L80PART/ 05/154	ROV Validation Area	298253	967784	5	1.00E+05	1.00E+05		2.00E+02	
ROV/05/039/04	20-Aug-05	L80PART/ 05/155	ROV Validation Area	298264	967788	7.5	2.70E+06	2.70E+06			
ROV/05/040/01	21-Aug-05	L80PART/ 05/156	ROV Validation Area	298270	967785	5	34000	3.40E+04		8.40E+01	

Offshore Particle Reference	Date	LSN No.	Location	Easting	Northing	Depth cm	^{137}Cs	^{137}Cs	^{60}Co	^{94}Nb	EDAX Result
ROV/05/040/02	21-Aug-05	L80PART/ 05/157	ROV Validation Area	298266	967777	0	2400	2.40E+03			

I.5 Dunnet Beach Particle Finds

EFSN	LSN	Date	Location	Easting	Northing	Depth (cm)	^{137}Cs	^{60}Co	^{94}Nb	Type
DB/05/001	05/065-/079	16/03/05	Dunnet Beach	321283	968943	7	8.90E+03			

Erskine Court,
Castle Business Park,
Stirling,
FK9 4TR

www.sepa.org.uk