Remediation of Irradiated Fuel Fragments Buried Offshore At Dounreay, Scotland, UK - 9204

J. Toole
WorleyParsons
35 St Ninian's Road, Stirling, Scotland, FK8 2HE

J. Cassidy
Fathoms Ltd, The Harbour, Fishmart, Wick, Scotland, KW1 5HA

ABSTRACT

The Dounreay nuclear site, located on the north coast of Scotland, was responsible for the accidental release of an unknown quantity of approximately sand-sized fragments of irradiated nuclear fuel during the 1960's and 1970's. In the last decade, major research programmes were carried out by UKAEA and contractors to detect and remove the particles from both local beaches and from the offshore zone, to characterize the particles and their environmental behaviour and to carry out a Best Practicable Environmental Option (BPEO) for the management of the contamination. Following 9 years of recovery of offshore particles by divers and four years of offshore mapping using an innovative tracked remotely operated vehicle (ROV), the project has now moved into a remediation phase. Independent assessments by an external advisory group show that of the order of 5000 particles, covering a range of ^{137}Cs activities and burial depths, currently remain in the offshore plume. Preliminary proving trials of a modified ROV were carried out in December 2007 and four particles were successfully detected and retrieved remotely for laboratory analysis and eventual disposal. An initial phase of offshore cleanup, to assess the performance of the modified retrieval system, was completed during August and September 2008 and 55 buried particles were retrieved to the Dounreay site for waste disposal. The Site is presently reviewing the performance of remote retrieval technology and the experience gained from these offshore remediation operations and will discuss future remediation efforts with its key stakeholders. This paper will describe the various offshore surveys carried out, from the early diving programmes in the late 1990s through the stages of development of remote particle detection technology and up to the present status of remote particle recovery trials offshore at Dounreay.

INTRODUCTION

The radioactive particles found in the local environment at Dounreay are fragments of irradiated nuclear fuel elements, which had been released accidentally into the environment from the Dounreay site in the late 1960s and early 1970s. UKAEA Dounreay has expended significant effort and costs in the surveying of the local environment in an effort to understand the extent of contamination of beaches and of the offshore sediments.

This paper focuses on the work carried out in the offshore environment. Four distinct types of gamma survey were undertaken offshore over the period 1997 to 2005 [1]:

- divers using handheld radiation probes (1997 to 2005),
- use of a towed plastic detector (1998 and 1999),

- static trials of a 3 inch x 3 inch low resolution sodium iodide (NaI) gamma detector (2003) and
- dynamic trials of a large 4 inch x 4 inch x 16 inch NaI detector fitted to a tracked Remotely Operated Vehicle (ROV) (2004 and 2005).

In addition to the gamma surveys, detailed studies have been undertaken of tidal flow, wave characteristics, sediment migration, seabed classification etc. The results of these surveys have helped in the understanding of particle migration and the possible present and future residency of the particles.

Since the use of divers was considered by the Site management to be a higher risk activity than the risk posed by the buried particles themselves, diving to locate and remove particles was stopped in 2005 and the development programme for a remote particle detection capability obtained management sanction. There was also a need to extend the particle searches beyond the 30 metre water depth limit of the dive team. Although the ROV system was not at this time capable of physically retrieving buried particles, the Site needed to obtain more knowledge about the extent of the offshore contamination, as required by the environmental regulator SEPA (Scottish Environment Protection Agency) and to inform the deliberations of the independent Dounreay Particles Advisory Group (DPAG).

Following laboratory and field testing of the large NaI detector and spectrum processing technology in 2004, a series of particle mapping surveys were carried out offshore at Dounreay mainly in the summer and autumn months in 2005, 2006 and 2007. These surveys helped to confirm the limited spread of the radioactive particles, being able to survey deeper waters than the divers, to cover more ground outside of the main particle plume and at approximately twice the coverage rate. In addition, a model was developed, based on processing of the gamma spectrum acquired above each detected particle, which provided the capability to successfully predict the radioactivity content (Cs-137) and burial depth *in-situ*, without the need to retrieve them during the particle mapping phases between 2005 and 2007.

In parallel, a Best Practicable Environmental Option (BPEO) was being carried out to determine the management option for dealing with the particle contamination issue. Information from the UKAEA research programme, the offshore surveys, the beach monitoring programme and the advice from DPAG was continuously being fed in to the BPEO process. The management option recommended, following extensive stakeholder consultation [2], was for targeted retrieval in areas offshore (the main plume) which contained the more hazardous higher-activity particles, coupled with continued monitoring and particle retrieval onshore (beach monitoring). On safety considerations, and subject to acceptable technical performance, offshore particle cleanup is intended to be carried out by remote means, using an ROV equipped with sediment/particle retrieval capability, rather than by using divers. This approach is consistent with the requirements of the Ionising Radiation Regulations 1999 to keep doses as low as reasonably achievable (ALARP principle).

A preliminary offshore trial of a modified ROV was carried out in December 2007 and four particles were successfully detected and retrieved remotely for laboratory analysis and eventual disposal. An initial phase of offshore cleanup, to assess the performance of the modified retrieval system, was completed in August and September 2008 and 55 buried particles were retrieved to the Dounreay site for waste disposal. The Site is presently reviewing the performance of this remote retrieval technology and the experience gained from these offshore remediation operations and will discuss future remediation efforts with its key stakeholders.

SURVEYS BY DIVERS

In the first year when divers were deployed, in 1997, they detected and retrieved 34 buried particles using a prototype handheld underwater probe, within a total surveyed area of 24,000 m^2. In the following year, 1998, using an improved handheld probe (Figure 1), they retrieved 88 particles. In 1999 most effort offshore was expended on testing and deployment of a towed array of a single plastic scintillator detector (see below) and only 15 particles were detected and retrieved by divers. From 2000 to 2005, more intensive surveys were carried out annually, including studies on repopulation rates of pre-defined circular areas. In these six years, a total of 747 particles were retrieved by the divers. The results of the repopulation studies and their significance are discussed by Crawford et al [3]. The pattern of finds obtained from diving campaigns was very informative and has been studied extensively by DPAG [4]. DPAG showed that particle densities peaking at about 200 per hectare close to the diffuser outfall, falling gradually eastwards to about 50 per hectare at 1.5 km east and reducing to about 20 per hectare at 5 to 8 km east. Particle densities fell more rapidly westwards. In addition, the Cs-137 activity levels in the particles retrieved strongly suggested that the more hazardous high-activity particles had not spread far from the diffuser outfall which was regarded as the source of the contamination given the spread pattern of the particles on the seabed and what was known about the on-site particle production and transfer routes. From the available information on particle weights and dimensions, a positive correlation between size, mass and activity was observed.

Figure 1. Diver surveying seabed using improved plastic scintillation detector at the end of an ergonomically designed crutch.

SURVEYS BY TOWED PLASTIC SCINTILLATION DETECTOR

The first towed survey was undertaken in 1998 using a single gamma detector attached to a frame capable of being towed over the seabed sediments by boat In 1999 two detectors were fitted for tows in deeper water. The areas selected for survey were determined from interpretation of sonargraphs of the seabed offshore and adjacent to Dounreay. The primary consideration was for open areas of sediment, which were found to be prevalent over wide areas of seabed.

The reasoning behind use of a towed detection system was two fold:

1) Deeper areas could be surveyed (economic diving limit of 30m depth using nitrox)
2) Larger areas could be surveyed quicker

The results from the towed detector surveys were difficult to interpret primarily because the detectors could not discriminate between elevated radioactivity caused by natural sources (sediment composition variations) and that caused by discrete radioactive particles containing Cs-137. Much if not all of the bands of elevated radioactivity detected by the towed system was shown later, using a small NaI detector, to be due to natural radioactivity variations.

STATIC TRIALS OF A SMALL SODIUM IODIDE DETECTOR

A 76 mm x 76 mm (3 inch x 3 inch) NaI detector and associated photomultiplier tube were housed in a 3.2 mm thick sealed 304L Stainless Steel marinising unit. A water ingress alarm was fitted internally with an audible and LED warning, so that power could be shut down immediately, minimising damage to components. The marinised detector unit was secured within a tubular frame, with tubular skids to allow easier transit between successive spectral gathering locations.

Between the 1^{st} and 16^{th} September 2003, 15 days of offshore surveys were achieved, with only one full day call-off due to weather conditions. In this period, over 1200 detector drops to the seabed and associated gamma spectra were obtained [5]. This work showed that elevated count rates from natural variations and from buried particles could be distinguished and that much of the offshore seabed was rather homogeneous in terms of gamma count rate. One buried particle was detected and some underwater experiments were carried out at this location prior to its recovery by diver. The trial demonstrated also that a drop-down detector system was very inefficient for particle searches and that further improvements were required if much greater volumes of sediment were going to be monitored for radioactive particles.

TRIALS OF A LARGE SODIUM IODIDE DETECTOR

Based on the experiences with the small, frame-mounted NaI detector, a number of improvements were introduced as follows:

- use a larger detector to improve the signal strength from particles

- design and test a tracked ROV which can work in waters of 100 metres or more and which can provide slow, controlled forward travel speed

- allow for lateral movement of large detector at the front of the ROV, to enable direction of particle contact to be determined and development of a Cs-137 trigger to confirm presence of a particle

- design the hydraulics and electronics to reproducibly position the large detector out in front and about 5 cm above the sediment

- fit low-level and high-level video cameras to monitor for forward obstacles and monitor the positioning of detector respectively

- make provision for a secure housing for an on-board Cs-137 check source to energy calibrate the detector at prescribed intervals

- add a plastic scintillator probe in a fixed geometry to monitor continuously the ambient background count rate; a new reference background would be taken if the count rate changed significantly

The large detector (4 inch x 4 inch by 16 inch NaI crystal) was housed in a waterproof stainless steel jacket and laboratory tests were carried out to investigate its detection capabilities for buried particles underwater. The laboratory tests showed that, for a 5 cm detector-sediment clearance and with the detector static and parallel to the sediment surface, Cs-137 and Co-60 point sources could be detected to useful depths of 50 cm or more under the sediment [5].

A tracked ROV was designed and built to provide a reliable and stable platform for the radiation detector system. To achieve maximum reliability various design criteria were identified in the early stages of d[illegible] rs per day continuously, the ROV was d[illegible] ponents of the system. Hydraulic power f[illegible] he three phase 415 volt supply, derived f[illegible] bilical. All possible safety features are e[illegible] uit and thermal protection, and an RCB d[illegible] rotection. The soft-starter also ensures r[illegible] the three phase motor within the power p[illegible] the whole hydraulic system is operating v[illegible] the ROV operating underwater, with the l[illegible]

Figure 2. ROV in operation underwater, detector deployed in monitoring geometry. A plastic scintillator probe is visible behind the large NaI probe

Between 11th September and 27th October 2004, weather conditions permitted 22 days or part-days of ROV surveying in the offshore environment. Over 120 particle contacts were confirmed, over a total survey area of 31,000 m^2. The survey results obtained showed very similar particle densities (number per unit area) in those locations where divers had also worked, allowing for particle retrievals. They also were consistent with the presence of an offshore particle plume which is oriented north-east of the Dounreay site effluent chamber, located 600 metres offshore in 23 metres water depth.

Further work offshore with the ROV was carried out in 2005, firstly to calibrate the particle detection efficiency of the ROV system against the efficiency of the divers and secondly to obtain experimental information to support the development of a model for in-situ determination of the Cs-137 content of buried particles, without the need for retrieval. For 2005, the detection system was upgraded with auto-stabilisation, which corrects energy drift and reduces false positives such as presence of Bi-214 resulting in Cs-137 alarms and reduces false negatives (missed Cs-137 alarms). When the ROV and divers monitored sequentially a preselected cordoned off seabed area of approximate area 2500 m^2, the results showed that the ROV is about 90% efficient in detecting buried particles when compared to divers. Those few particles which the ROV missed and which divers found were of low activity (ca 10 kBq Cs-137). A number of particles were cored during this phase. Their depths were assessed and used to test a predictive model for estimating, without retrieval, the particle depth and activity from captured gamma spectra. Results from coring during 2004 & 2005, using data from manual and static spectra, found that the model can predict reasonably accurately, within a factor of about two or better, the depth and activity of buried particles [6].

ROUTINE MAPPING SURVEYS USING THE TRACKED ROV

Particle mapping surveys were carried out in 2006 to survey areas of seabed in water depths beyond that which divers had been able to survey. Little was known about the prevalence of buried particles in these areas. Mapping work was also carried out in more distant locations both east and west of the main particle plume [7]. At the end of the 2006 surveys, approximately 150,000 m^2 were surveyed in eight targeted areas. In all of these areas, only 16 particles were detected. The particles found furthest west and furthest east were relatively small (predicted Cs-137 activity range 1.6 E+04 Bq to 2.7 E+05 Bq). Those found at the outer regions (seaward) of the main plume showed predicted activities from 1.4 E+04 Bq to 1.9 E+06 Bq. Mapping surveys further afield in Thurso Bay, in Dunnet Bay, offshore at Melvich and Strathy did not reveal any particles.

These results were consistent with the limited amount of diving work carried out in earlier years in areas more remote from Dounreay. Taking together the results from the diving programme, the mapping programme and an extensive dataset from years of monitoring of several beaches along the north coast of Scotland, a much clearer and consistent picture of the extent of the regional contamination was available – see Figure 3.

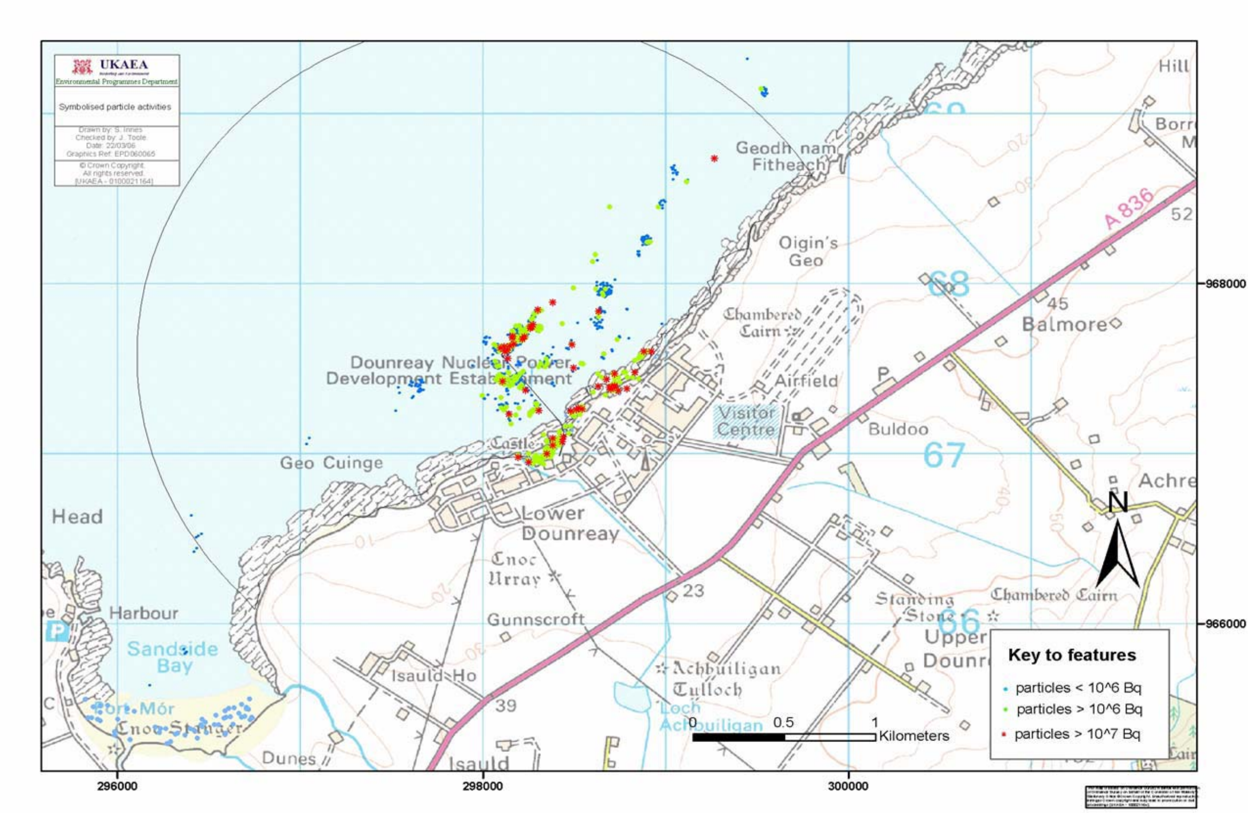

Figure 3. Distribution of radioactive particles offshore from diver survey data. Those particles posing a significant health risk (> 1.0 E+06 Bq) if contacted or ingested are coloured red and green.

Nevertheless, there were still some knowledge gaps about offshore contamination, so in consultation with DPAG, further work was carried out by the mapping ROV in summer of 2007.
There were three main objectives for the 2007 survey:

1. *Monitor pre-selected areas of seabed adjacent to Dounreay for particle contamination to determine their density (number per unit area).*

The results of the 2007 mapping surveys are summarized in Table I. The contrast in particle densities inshore of the diffuser compared to Sandside Bay and areas east of Dounreay are evident.

Table I. Particle densities and activity ranges for 3 main survey zones in 2007.

Mapping zone	Area coverage m^2	No of particles	Density per hectare	Range for predicted Cs-137 activity (kBq)
Inshore of diffuser outfall	10,800	39	36	0.92 - 26000
West of diffuser into Sandside bay	72,400	28	3.9	1.3 – 860
Suspected eastern edge of main particle plume	24,500	2	0.8	5.5 - 67

2. *Estimate detected particle's activity and depth using a predictive model.*

This was successfully carried out for all but 4 of the 69 particles detected. One of these was mobile, two small particles gave ambiguous results and another was a Co-60 particle for which a prediction algorithm is not available.

3. *Recover particles within or moving towards Sandside bay which were predicted to be ≥ 1 E+06 Bq ^{137}Cs, to prevent them arriving on Sandside beach.*

No particles were predicted to have Cs-137 above this threshold. The highest predicted activity was 8.6 E05 Bq. Using an estimate of 1.2 million m^2 for the areas of sandy sediment lying between Sandside beach and the diffuser outfall together with an average density of 3.9 particles per hectare (Table I), provides a rough estimate of 465 particles which potentially are resident between the diffuser and the beach. This figure is based on the particles detected in the 2007 survey in this zone and is not corrected for detection efficiency which will be less than 100% for low-activity particles particularly if they are not near the sediment surface. It is known from the comparison with divers [5] that the ROV does not find all particles with activity about 1 E04 Bq and will be increasingly less sensitive as particle activity decreases. The ultimate destination for these particles will probably be Sandside beach from where they may be detected by radiometric monitoring systems (the beach monitoring programme) and removed.

The overall conclusions from the diving, mapping and beach monitoring programmes is that the highest particle population densities remain concentrated close to the old diffuser, which is considered to be the most likely discharge point. It is in this main plume where almost all of the high-activity particles reside (see Figure 3 above), potentially making an offshore particle retrieval programme more bounded and more manageable than it might have been.

TRIALS OF A REMOTE PARTICLE RETRIEVAL ROV FOR OFFSHORE REMEDIATION

Fathoms Ltd deployed a remotely-operated vehicle capable of detecting and retrieving particles buried up to 50cm deep in the sediment. The ROV used for the mapping surveys was modified. The final assembly delivered a closed system, with secure particle retention and immediate visual graphical image when particle was captured. All data was logged for the record as was video footage of all operations. Particle recovery is achieved with minimal environmental impact- micro as opposed to macro disturbance.
The recovery system allows a controlled delivery of suction head to the seabed. The rise/fall assembly is manufactured from stainless steel. The modified ROV is controlled from a surface vessel where recovered particles are separated from the sediment and packaged for return to Dounreay- see Figure 4.

Figure 4. The modified ROV used for offshore cleanup trials in August and September 2008.

An earlier modified ROV was first trialled offshore of Dounreay in December 2007. While there were some technical problems encountered, five buried particles were successfully detected and four of these were captured and successfully transferred to a reception tank prior to isolation on ship and transfer to site for analysis. Following this retrieval trial, another tender exercise was conducted and Fathoms were contracted to carry out another phase in the offshore remediation programme. This phase in the clean-up of Dounreay was carried out in August and September 2008. Between the 22 August and 25th of September, 55 buried particles were successfully detected and retrieved from within the main particle plume into the reservoir on board the ROV. There were no instances where a particle was detected but failed to be retrieved. About one third of the particles were estimated to have been buried between 40 and 50 cm, showing that deep particles can be cleaned up. Over half of the particles were in the higher-activity band (> 1.0 E+06 Bq Cs-137) while the other lower-activity particles were also retrieved when found.

A count rate trace obtained from the cleanup trial in 2008 – see Figure 5 –illustrates the moment when buried particles are transferred from the seabed into the receipt tank. The count rate peaks as the captured particle passes the detector. For high-activity particles (particles 1 and 3 here), the count rate after capture is higher than before capture due to the presence of the particle in the tank. In this trace, the second particle was of low-activity.

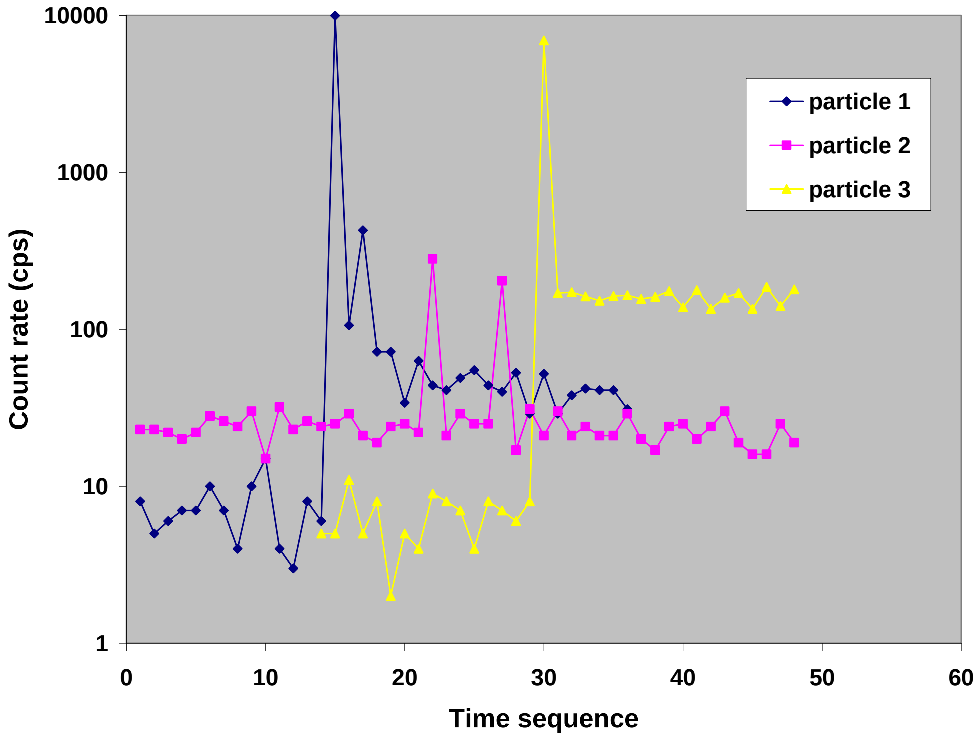

Figure 5. Profiles of count rate obtained by a detector placed near the entry port of particle receipt tank on the ROV. These three particles were retrieved at various times during surveys on 25 September 2008.

Independent experts (DPAG) estimate that there may be around 1500 fragments buried in the sediment close to the site's old discharge outlet that are a significant hazard to public health i.e. > 1.0 E+06 Bq Cs-137. The physical disintegration of these larger fragments is believed to contribute to the number of smaller, less hazardous particles found on local beaches.

The overall clean-up is targeted at an area of seabed nominally of 60 hectares. Monitoring of local beaches is continuing during the clean-up and special attention is being paid to any change in the frequency of onshore finds. Any disturbance of the seabed means a short-term increase in beach finds close to Dounreay cannot be ruled out. However video evidence suggests that the amount of physical disturbance to the seabed, both while moving the tracked ROV and while remotely retrieving the buried particles, is minimal.

The public consultation process recognised that recovery of every particle, irrespective of risk, was impractical but did find support for retrieval of those particles that pose a significant risk to health. While it is the higher hazard particles which are the focus of the clean-up, a number of smaller, less radioactive particles will also be detected and these will also be retrieved.

DSRL will continue to work closely with regulators and all interested parties during the clean-up phase to evaluate its success and adjust the programme, such as the frequency of onshore monitoring, as necessary.

During further seasons of clean-up activities, the number of particle finds and the retrieval statistics (position, depth, activity) and system performance will be reported on a weekly basis via the DSRL website.

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