Management of a High Hazard, Low Risk Environmental Issue at Dounreay, Scotland

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ABSTRACT

Dounreay hot particles (Particles) are small fragments of irradiated nuclear fuel that are present in littoral and marine environments adjacent to the Dounreay nuclear establishment in northern Scotland. The first Particle was identified by UKAEA, the site operator, and recovered from the Dounreay foreshore, in 1983 and a single Particle was recovered from the adjacent, publicly accessible Sandside Beach the following year. It was not until 1996, however, that significant numbers of Particles were identified and recovered. Since that time an extensive research and development programme (described herein) has been undertaken to identify the source of Particles, their movement and lifetimes in the marine environment and their effects on human and environmental health. Particles were released to the North Atlantic Ocean in the mid to late 1960’s and early 1970’s. There is no evidence of an on-going source of Particles from the Dounreay site. The source of Particles recovered from the Dounreay foreshore and from local beaches is the cache currently residing in marine sediments adjacent to Dounreay.

Sediment modelling studies indicate that the Dounreay Particles are generally transported sub-parallel to the coast in a north easterly direction. Studies to define contact frequencies and risks to human health suggest that the health risks associated with Particles are insignificant. There is, however, a significant perception of risk.

UKAEA hopes to define a long term Particle management programme *via* the development of a best practical environmental option (BPEO) facilitated through consultation with all stakeholders.

INTRODUCTION

The Dounreay nuclear site, located on the north coast of Scotland, was responsible for the release of an unknown quantity of approximately sand-sized fragments of irradiated nuclear fuel during the 1960's and 1970's. These Dounreay hot particles (Particles) were formally recognised on the Dounreay foreshore in November, 1983. Over 1100 individual Particles have since been found in 4 separate littoral or marine environments (Figure 1; Table 1): Sandside Beach, 1 km west of Dounreay; the Dounreay Foreshore; Dunnet Beach, approximately 25 km east of Dounreay; and in marine sediments adjacent to the Dounreay site. In addition, 86 Particles have been found on the Dounreay site itself.

Particles are detected in the environment by their gamma (mostly ^{137}Cs) activity but total activity is dominated by the beta emitters ^{90}Sr and associated ^{90}Y. They were produced during the reprocessing of fuel at Dounreay during the 1960s and 1970s. Two main types of Particles, produced from Materials Test Reactor (MTR) and Dounreay Fast Reactor (DFR) fuel, have been identified. MTR Particles, ~ 90 % of the total, were produced as a result of fault conditions during milling and cropping operations, prior to reprocessing. Milling activities stopped at Dounreay in 1973. DFR Particles were most likely produced during combustion incidents in the dissolution cycle during reprocessing. Several such incidents are known to have occurred between 1969 and 1972.

The majority of the solid waste materials produced during reprocessing operations and incidents were disposed of to the licensed disposal and storage facilities on the site. Some of the Particles, however, were inadvertently released into the site's low active drainage system and discharged, *via* a long effluent tunnel, through the liquid effluent outfall diffuser into the sea.

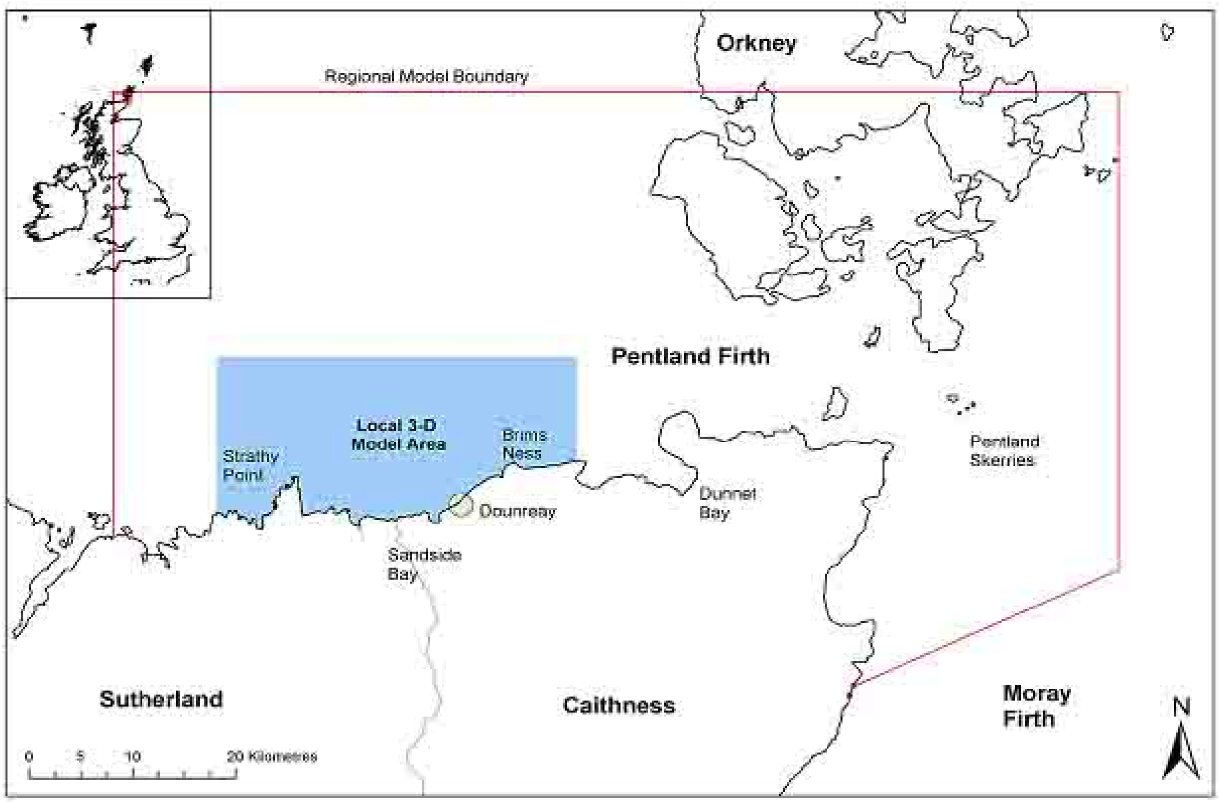

Fig. 1. Northeast Scotland showing the location of the Dounreay nuclear site, areas where Particles have been identified and the boundaries of transport models.

The diffuser is therefore recognised as the origin of the fuel fragments within the marine environment. The cessation of the operations giving rise to fuel fragments, and the installation of filters on the low active drainage system in 1984, mean that discharge of significant numbers of Particles would not have occurred after this date.

The liquid effluent diffuser chamber is located 25 m under the seabed, approximately 600 m north of the Dounreay site in a high-energy environment, subject to a variety of marine processes. Tidal currents are relatively strong, with speeds of up to 1 m/s being recorded off Dounreay, with the mean tidal range being close to 4 m (UKAEA, 1998). In addition, the area is exposed to strong winds and large waves, with a 10-year return period for waves of 9.9 m. As a consequence of these processes, the fuel fragments are relatively mobile and are subject to re-distribution within the marine environment and occasional deposition within the littoral environment, including Sandside and Dunnet beaches and the Dounreay foreshore.

UKAEA has undertaken an extensive programme of research to quantify the scale of the problem represented by the Particles and to determine potential solutions. The aim of this paper is to: summarise the findings of this research programme; discuss gaps in knowledge; and present a forward programme.

Table I. Number of Particles Found and Average Activity at Each Location.

Particle Location	Number of Particles Found*	Average Particle Activity (Bq)
Marine sediments	897	5.4 E6
Dounreay Foreshore	238	1.4 E6
Sandside Beach	55	6.3 E4
Dunnet Beach	1	8.9 E3
Dounreay site**	86	

* Figures accurate as of 10 August, 2005.

** Numbers of Particles found on-site is an estimate only, as prior to 1996 Particles were not separated from contaminated soils in which they were located (see Goss and Liddiard, 2005).

RESEARCH WORK UNDERTAKEN

The research work undertaken since 1996 has focused on a number of areas:

- potential on-going sources of Particles;
- monitoring and recovery;
- physical and chemical characterisation of recovered Particles;
- Particle transport; and
- health and risk studies.

Potential On-going Sources and Pathways to the Environment

The low active effluent system was recognised during early studies as the primary source of Particles. It was important, however, to investigate other potential on-going sources to determine if Particles continued to be released into the environment from Dounreay. Simpson (1997) reviewed all potential sources of Particles following release from reprocessing plants including:

- surface water and foul drains;
- the Dounreay Shaft intermediate level waste disposal facility;
- the old diffusion chamber;
- on-site contamination of roadways and ground adjacent to flask transport routes;
- site surface water courses (the Mill Lade);
- roofs and gutters;
- overburden, especially at the cliff edges;
- the Dounreay foreshore; and
- marine sediments.

After extensive investigation of all potential sources, it was concluded that there was no evidence of on-going release of Particles from the Dounreay site and that the Particles in the marine environment are the only source of the Particles deposited on Sandside Beach and the Dounreay foreshore.

Monitoring and Recovery of Particles

In 1983, during routine surveying of the Dounreay foreshore, the first Particle of MTR fuel was discovered. It has since been recognised that spots of contamination of high specific activity which may indeed have been Particles had been recovered from the Foreshore since the 1970's.

During 1984 a further 26 Particles were recovered from the Dounreay foreshore and significantly, one Particle was recovered from the beach at Sandside. These finds led to a programme of shoreline monitoring at a number of local beaches from Melvich in Sutherland to Thurso (Figure 1). The strandline monitoring programme continues to this day. In 1997, a second Particle was recovered from Sandside, leading to the commissioning of a large area Groundhog™ (NaI gamma spectrometry system linked to global positioning) survey during which another Particle was discovered.

Following a direction from the Secretary of State for Scotland, the Scottish Environment Protection Agency (SEPA) introduced specific requirements to monitor Sandside and several other local beaches in a Technical Implementation Document (TID) (SEPA, 1999) which supported Dounreay's liquid effluent discharge authorisation. UKAEA subsequently commissioned a vehicle mounted Groundhog system (Figure 2) which was able to cover large areas of sandy beach while maintaining appropriate detection levels. The vehicle mounted Groundhog and subsequent Groundhog Evolution systems have since detected all Particles subsequently recovered from Sandside beach and the single Particle recovered from Dunnet beach. The mean ^{137}Cs activity of the Particles recovered at Sandside is 63% of the minimum detection level of 1 E5 Bq imposed by the TID with only 8 Particles above the detection criteria. The highest activity Particle recovered from Sandside beach is 3 E5 Bq.

The Dounreay foreshore, which contains large areas of sand and gravel beach, has been monitored using a variety of techniques including beta monitoring, and both hand held and vehicle Groundhog systems. It is worthwhile noting that the foreshore beach deposits are notably coarser grained than those of Sandside Beach. The higher average activity of Particles recovered from the foreshore (Table 1) suggests that there is a correlation between activity and Particle size (see Section 2.3)

In part to determine the source of Particles, UKAEA in 1997 undertook surveys of sediments in the sea adjacent to Dounreay. A marinised, commercially available NaI detector was used by divers who recovered 35 Particles. The Particle finds lead to the imposition of a fishing exclusion zone by the Scottish Office within a 2 km radius of the Dounreay low active effluent outfall. The Food and Environmental Protection Act (FEPA) Order remains in place.

a.

b.

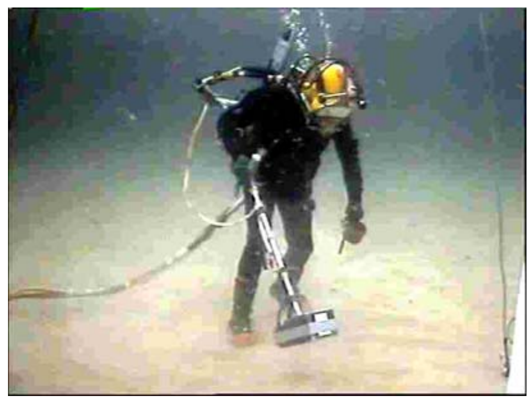

Fig. 2. Monitoring Particle location a) using the Groundhog^{TM} system at Sandside and b) divers off the coast at Dounreay.

Diver surveys (Figure 2), which have been undertaken each year since 1997, have been used to determine Particle population density and the extent of contamination in the marine environment. Maximum population densities (Crawford, 2003) are approximately 220 Particles/hectare immediately northeast of the diffuser outfall, reducing to ~ 35 Particles/hectare at a distance of 1.5 km northeast of the outfall. To the west, towards Sandside Bay, population densities fall off much more quickly to ~ 15 Particles/hectare within 100 m of the diffuser outfall.

Particle Characterisation

Recovered Particles have undergone a number of laboratory studies to determine their physical and chemical characteristics which in turn are used to define Particle lifetimes and transport mechanisms. Particles range in size from sub-mm to several mm, corresponding, for the most part, to fine to medium sand and more rarely coarse sand to fine gravel. They are generally subrounded in shape but very angular specimens (suggesting little erosion) have been recovered from the sea on rare occasions.

UKAEA has determined the mass of approximately 10% of recovered Particles and has established a positive correlation between Particle mass and measured activity (Figure 3). The specific gravity (SG) of MTR Particles will vary depending on the ratio of aluminium and uranium in each individual Particle. MTR fuel originally consisted of Al with up to 4 atomic % uranium and therefore had a theoretical SG of 2.7 to 3.5 (*i.e.* between the density of pure Al; and Al with 4 % uranium). Particle SG can therefore be approximated as 3.1 ± 0.4 (or 3.1 ± 13%). The theoretical range of MTR Particle SG is between the range of quartz, feldspar and calcite (SG 2.5-2.7), the most common mineral constituents of the marine sands off Dounreay (UKAEA, 2001); and the heavy minerals hornblende (SG 2.9-3.4) and magnetite (SG ≥5.1), which are common accessory minerals.

DFR Particles are composed predominantly of niobium oxides, which are likely to have a SG range of 4.7 to 7.4 (SUERC, 2004). DFR Particles, however, are noticeably porous and the bulk SG will therefore vary with the relative amount of pore space and the medium filling this space.

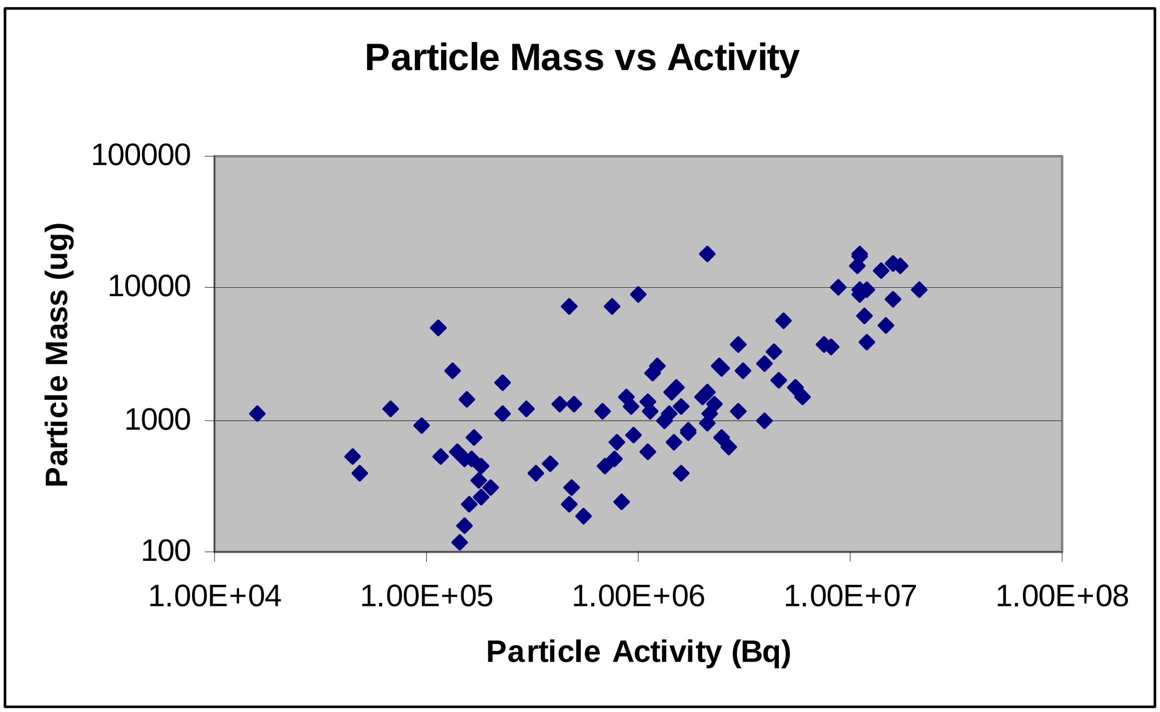

Fig. 3. Particle mass vs. ^{137}Cs activity

DFR Particles are generally much more fragile than MTR and are highly porous. External surfaces of both particle types recovered from the marine environment contain a marine precipitate which may partly protect the Particle from erosion. There is inconclusive evidence of physical fragmentation and corrosion of the interior of the Particles hence it is not possible at this stage to define Particle lifetimes in the natural environment.

Particle Transport

Particle transport in the marine environment is dependant on 3 main factors:

- the location of the Particle source;
- the physical characteristics (size, shape, specific gravity) of the Particles; and
- the magnitude and direction of wave and tidal currents.

HR Wallingford (2000a, 2000b, 2001) undertook computer-based modelling of Particle transport using two types of sediment transport equations:

- an advection-diffusion model to simulate bulk sediment flux; and
- a particle tracking model to simulate paths of individual sediment grains.

The modelling suggests that Particles are dispersed in two groups. The largest group travels north-eastward, roughly parallel to the shore, with many individual Particles passing beyond the eastern boundary of the 3-dimensional model. The smaller, second group of Particles is transported westward but there is no evidence that Particles are being lost from the model via the western boundary.

The HR Wallingford model results are consistent with observed values for sediment transport parameters which were reported from a "minipod" developed by the Centre for Environment, Fisheries and Aquaculture Science which was deployed in the sea adjacent to Dounreay in 1997. Model output is also consistent with observed seabed geomorphology as identified by the British Geological Survey (Long and Holmes, 2005)

Health Risks

The overall risk to human health associated with exposure to Particles is dependant on:

- the probability of contact;
- the probability that a detrimental health effect occurs; and
- the magnitude of that health effect

The probability of contact for a number of critical groups has been assessed in several recent reports (e.g. Pellet, 2004; Smith and Bedwell, 2005;). Inhalation is not considered a possible contact route as Particles are much larger than the respirable size fraction. The probabilities of contact with the skin or *via* ingestion may be as high as 8×10^{-6} (lobster potters) to 4×10^{-7} (bait digger at Sandside Beach). Much more commonly though, contact frequencies are well below 10^{-7}.

Recent work by the UK Health Protection Agency (Harrison, *et. al*. 2005) has concluded that doses resulting from contact with even the most active of the Particles found at Sandside would be below the human health damage threshold. High activity Particles may have a more serious affect on health, but these Particles are found either on the Dounreay foreshore where access to the public is restricted or marine waters where public access in unlikely. Greenwood and Rehm, 2005 reviewed available data on both contact frequencies and health effects and concluded that lifetime mortality risks to *inter alia* bait diggers and other users of Sandside Beach range from E-12 to E-11. Given that the UK Health and Safety Executive (HSE, 2001) has suggested that a 1 in a million (10^{-6}) annual risk of death to members of the public from work-based activities is broadly acceptable, the real risks to human health associated with Dounreay Particles are vanishingly small.

KNOWLEDGE GAP AND FUTURE WORK

Given the exceedingly low risks to health and safety associated with Particles, UKAEA has terminated high risk diving surveys. There remain, however, uncertainties relating to the reliability of the computer model of Particle transport and the extent of marine contamination; specifically in deeper waters where it was not practicable to employ divers. In addition, it is very uncertain whether the presence of a Particle at Dunnet Beach was an isolated occurrence or if there is a possibility that additional Particles could arrive there. It is also unclear whether Particles will degrade in the environment through physical or chemical processes before radioactive decay advances to the extent that they stop being a hazard. Future work will aim to reduce these uncertainties. Research and development activities in the short term will therefore include:

1. definition of the extent of the Particle plume and population densities in the North Atlantic using a remotely operated vehicle (ROV) equipped with radiation detectors;
2. corrosion studies leading to definition of Particle lifetimes;
3. determination of MTR Particle SG and comparison with theoretical SG;
4. verification of the HR Wallingford model using: experimentally derived SG data; a refined conceptual model; and the results of the ROV studies;
5. development of refined monitoring methods and continued reassurance monitoring of local beaches; and
6. additional monitoring of Dunnet beach and assessment of the risk to the public.

UKAEA is currently undertaking a best practicable environmental option (BPEO) study to define the best management approach for long term management of the Particles issue. Consultation will be conducted in three phases starting in early 2006 and ending in 2007. The results of the research programme will be used to support and inform the BPEO process. In return, the BPEO is expected to define additional gaps in knowledge which may lead to additional areas of study.

CONCLUSIONS

The Dounreay hot particles represent a classic high hazard, low risk environmental problem which is both technically and politically challenging. Although a substantial amount of scientific research has been undertaken, uncertainties and gaps in scientific knowledge remain. Although UKAEA is striving to fill knowledge gaps, it is unknown whether this can be done to the satisfaction of all stakeholders.

The risks to member of the public, from the presence of Particles in the environment is exceedingly small. It is, however, not the actual risk but the perception of risk that defines the Particle issue as one of Scotland’s highest profile environmental problems. It will take a great deal of open and honest discussion and goodwill on all sides to find a lasting solution to this problem. UKAEA is attempting to find a suitable management solution through the application of the Best Practical Environmental Option methodology.

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