REMEDIATION OF RADIUM CONTAMINATED LAND AT A FORMER ADMIRALTY RESEARCH CENTRE

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ABSTRACT

Ditton Manor Park is located adjacent to the M4 motorway some 2 km to the south east of Slough in Berkshire in the United Kingdom. The site was formerly used by the UK Admiralty for the development, manufacture and testing of compasses. These activities involved the use of radium-based luminising paints.

In March 1998 Ditton Manor Park was purchased from the UK Ministry of Defence (MoD) to become part of the corporate headquarters of a major computer software company. It comprised of a listed, moated manor house with various out buildings, which had been extended and used as workshops and laboratories. It is situated in extensive parklands to the north and south of about 68 ha.

Investigations revealed widespread, localised radioactive contamination of the ground over much of the site. The fabric of buildings was also locally contaminated with radium and mercury. The site waste tip was contaminated with radium, heavy metals and polyaromatic hydrocarbons. There was localised organic solvent contamination of ground south of one workshop, No. 4.

A remediation programme was developed to remove all significant historic contamination from the ground and fabric of buildings and leave the site suitable for redevelopment without the need for any special precautions. The current and future risks to the environment were to be eliminated. The remediation criteria were set on the basis of a quantitative risk assessment in close consultation with the prime regulator, the UK Environment Agency, and the Local Authority. The criteria were established, based upon the proposed uses of the site and with public access to all areas outside the moat. They were also compatible with sensitive multifunctional use, e g. housing.

The remedial works were undertaken by AEA Technology Nuclear Engineering (now RWE NUKEM). A novel feature was the very extensive use of the Groundhog gamma areal surveying system in the characterisation, remediation and validation of all land clearance. This links a highly sensitive, NaI scintillation radiation detector to a GPS detector for position location and a datalogger. At the onset of the works full comprehensive surveys were undertaken to further characterise contamination present. For localised and restricted access areas they were undertaken on foot, surveying the areas in 1 m wide strips. For larger areas three detectors were mounted in a line at 1 m spacing across the front of a four-wheel drive, all terrain vehicle. The outputs were computer processed and displayed as a series of colour contour maps showing the areal distribution of gamma doserate, which was then related to the contamination distribution.

These surveys set the scope for the remedial works and finalised the areas requiring excavation and backfilling. In addition, the advanced surveys identified contamination of the building structures and defined the areas requiring remediation. The remedial works involved:

- Advance Surveys
- Remediation of: ground contamination, both chemical and radiological; in non-listed buildings prior to demolition; ground after demolition of non-listed buildings; radiological (radium) contamination of listed buildings; of chemical (mercury) contamination in listed buildings and of the gardens of cottages along the estate edge
- Investigation and remediation beneath paving and hardstanding areas
- Dredging of the moat sediments and their associated remediation

Throughout the work there was extensive consultation with all key stakeholders. Regular liaison was established with the prime regulator, the Environment Agency, in order to ensure that remediation criteria, waste handling and disposal methods met with their approval.

This was the largest remediation project, which had been undertaken to date in the United Kingdom in both terms of scale and cost of a site contaminated with ^{226}Ra from luminising operations. The works were successfully completed within a period of 9 months. All identified contamination was removed to below levels of concern.

INTRODUCTION

The Ditton Park research centre comprised of a listed, large historic manor house (surrounded by a moat) with various out buildings, which had been extended and used as workshops and laboratories. The manor house is situated in extensive parkland to the north and south. The site incorporated a bowling green and cricket pitch, paddocks, a former allotment area, private dwellings and a Scout Hut. Close to its northern boundary it also included a defined waste tip, more workshops and a wooded area. The site was owned by the UK Ministry of Defence for the major part of the twentieth century. It was used for the manufacture and testing of compasses and development of navigation systems. The former of these activities involved the use of radium-based luminising paints. As a result of the activities undertaken on the site localised areas of the ground and buildings became contaminated, principally by radium and mercury.

The site is located in the Thames Valley and occupies an area of about 68 hectares. A map of the site is shown in Figure 1. The site is bounded to the south and east by public roads, to the north by private housing and to the west by farm land. To the south and west it adjoins a private commercial development with a canal, moat and fish pond along the boundary.

The North Park, South Park and the surrounding land to the north, south, east and west are overlain by Floodplain River Gravels. These deposits are underlain by the London Clay, which in turn overlies the Woolwich and Reading Beds (15-25 m thick) and the Upper Chalk. Beneath the moated area there is an outcrop of the Reading Beds with the Gravels and London Clay absent. There is up to ~1 m of made ground beneath and in the vicinity of some buildings on the site with a greater depth of made ground present in the North Park Waste Tip area.

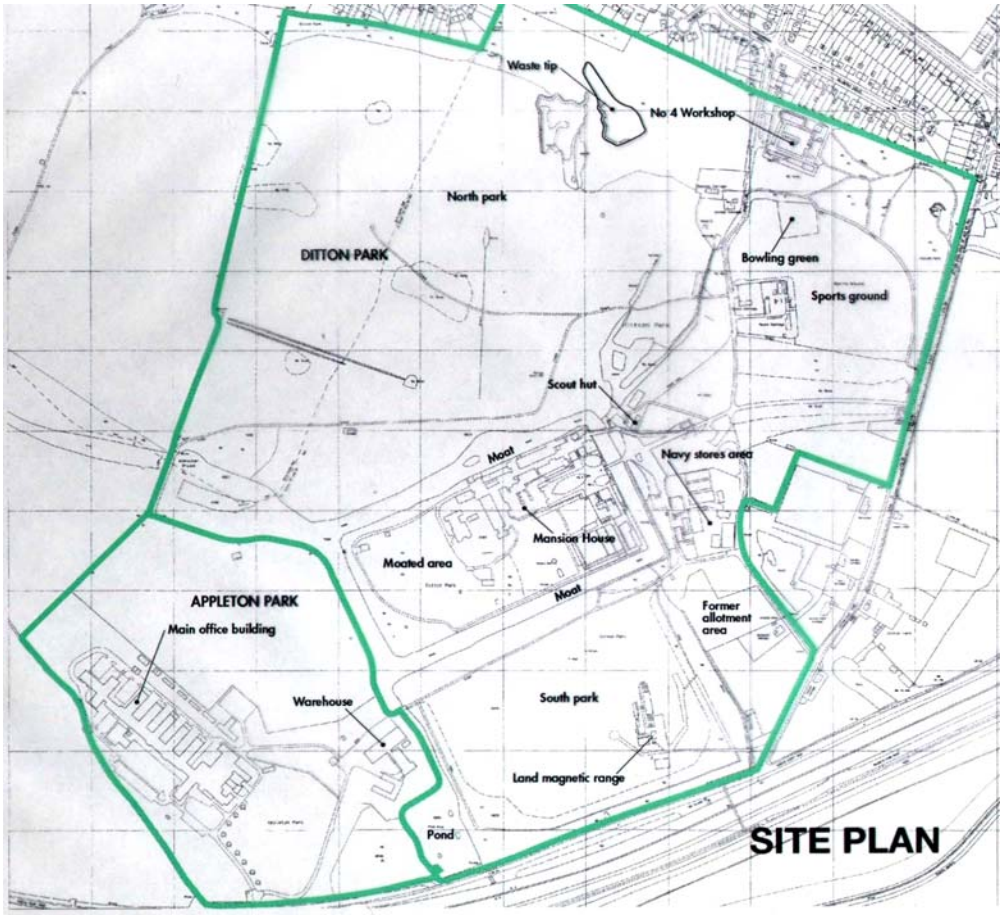

Fig. 1 Plan of the Ditton Manor Park site

The site is underlain by two aquifers. The upper shallow aquifer is the River Gravels, which is classified as a Minor Aquifer by the UK Environment Agency. The deep aquifer beneath the site is the Upper Chalk. This is classified as a major aquifer and is the principal aquifer of the region. Beneath the site the chalk aquifer is confined by the London Clay and Reading Beds, which act as an aquiclude separating the deeper aquifer from the groundwater in the gravels. In addition, various surface water bodies occur on the site. These include the moat around the Manor House and surrounding land. There is also a canal that flows from the south west corner of the site and joins the moat. A fishpond at the south western corner of the site is fed by water from the canal and moat flowing down a boundary ditch. The pond overflows via sluices and ultimately flows into the River Thames. There are other minor ponds in the North Park, which drain into the moat.

POTENTIAL FOR CONTAMINATION

The extent of contamination of the ground and buildings on the site was investigated by the MoD and its contractors during the period 1993 to 1997. Further investigations were undertaken by AEA Technology in September 1997.

The following activities and materials were identified as having the potential to cause contamination of the soil, ground and surface water and listed buildings.

i) use of radium-based paints in workshops and laboratories to luminise compass dials;
ii) use of mercury in workshops and laboratories to make compass baths;
iii) use of radioactively contaminated waste materials (particularly ash and clinker) as hardcore and winter grit for pathways and roads, and as made ground;
iv) disposal of heavy metals, polyaromatic hydrocarbons, radium and asbestos materials on site at the North Park Waste Tip and to a lesser extent in other areas of the site.
v) spills and leaks of fuel tanks into ground, particularly by the Workshops.
vi) use of beryllium in a laboratory attached to Manor House.
vii) discharge of effluent at a former sewage treatment area, which was also subsequently the site of former employee allotments (heavy metals, organic compounds, and radioactivity); and
viii) contamination of the silt in the moat and associated waterways through discharging of contaminated materials into drains and into the moat.

The investigations showed that localised radiological contamination of the ground was widespread over large parts of the site and that the fabric of the buildings was also contaminated with radium and mercury. In addition, asbestos was found buried in the Waste Tip in North Park, which was also the principal location of radium contamination. Elevated concentrations of a range of heavy metals and polyaromatic hydrocarbons were found in the Waste Tip and there was a localised area of ground south of one of the Workshops with organic contamination.

The potential for ground and surface water contamination was also a major consideration. In the past a series of wells were installed on the site to monitor groundwater quality and flow directions. Sampling of these wells and surface waters confirmed that the waters had not been contaminated to date. In addition, careful removal of potentially contaminative sources would prevent them from becoming so in the future.

The owner of the adjacent commercial site, a major computer software company, had acquired the site and proposed to undertake sensitive restoration of the remaining historic buildings and the parkland to complement their adjacent headquarters. As such its use was to be very different from the past and the controls adopted by MoD were not appropriate. It was against this background that a decision was taken to remediate the whole site to a standard fit for its new use.

OBJECTIVES OF REMEDIATION WORKS

The objectives of the remediation work were to remove all significant levels of historic contamination from the ground and fabric of buildings, so that the site was safe for its proposed uses. The current and future risks to the environment were to be eliminated. The site was to be suitable for use by members of the public without the need for special precautionary measures.

DERIVATION OF CLEAN-UP TARGETS

The first stage of the remediation programme was to determine the acceptable levels of risk associated with the proposed new uses and hence the residual levels of contamination compatible with those risk levels. A risk assessment was carried out by consultants, Ove Arup, on behalf of the new owner to develop remediation levels for contaminants of concern, primarily but not exclusively ^{226}Ra and mercury, for different areas of the site. These were based upon the plan for the redevelopment. The risk assessment considered the following activities and receptor groups.

Moated Area

- Long term use of the listed buildings and grounds by security staff and training officers. Employees attending training courses and occasional visitors were judged to have much shorter residence times on site. Therefore the analysis for security staff and training officers would be protective of such exposure;
- Occasional use of the grounds by staff children attending holiday camps;
- Use of the new building and grounds by pre-school children of staff attending a crèche.

Outside the Moated Area

- Long term regular use of the site by local residents for walking and cycling;
- Use of parts of the grounds by children invited to attend holiday camps;
- Use of parts of the grounds as a cricket pitch and by the Sea Scouts.

The Remediation Levels

The remediation levels, to which soil, etc, needed to be cleaned-up to, were developed by reference to the findings of the risk assessment and through consultation with the Environment Agency and MoD. The risk assessment considered the acceptable level of individual risk of serious harm or death to be $< 1 \times 10^{-6}$ per annum. This is the level of risk, which the Health and Safety Executive (HSE) considers is acceptable to members of the public. It is also the acceptable level of risk, which the UK Government was expected to confirm for the reclamation of contaminated land. For radioactivity this risk level was judged to be equivalent to an additional annual dose of 20-30 μSv.

The minimum risk-based remediation level for the proposed activities and receptor groups on the site was set at 0.15 μSv/h (inclusive of background radiation, which at this site is approximately 0.1 μSv/h). This value is comparable with the proposed remediation value for radioactively contaminated land to be redeveloped for domestic housing considered by the Environment Agency (permitted excess dose of 0.05 μSv/h). The technical specification for remediation of the Ditton Park site incorporated all of the following remediation criteria:

	Ground within and outside the moated area	Within the gardens of private cottages within the site
Maximum permissible concentration of ^{226}Ra	0.37 Bq/g	0.10 Bq/g to 0.5 m depth and 0.37 Bq/g below 0.5 m
Maximum permissible concentration of Hg	10 mg/kg	10 mg/kg
Ambient gamma dose level	0.15 μSv/h	0.10 μSv/h

Ground within and outside the moated area:

In all areas, where buildings and paving were removed, any historic chemical contamination of the ground was identified by the Soil Quality Standards. The values used were the ICRCL and then Dutch Intervention limits except for the species identified below. Those areas exhibiting particularly elevated results for toxic elements were identified and marked in-situ. Any material above these results, which had not already been remediated due to radiological conditions, was to be excavated and removed from site.

Soil Quality Standard for material on site

Determinand	Soil Quality Standard (mg/kg)	Determinand	Soil Quality Standard (mg/kg)
General hydrocarbon contamination	No visual or olfactory evidence of contamination. TPH < 500	Chromium	380
Volatile Organic Hydrocarbons	No visual or olfactory evidence of contamination. PID measurements at background levels for site.	Copper	190
Chlorobenzenes	< 30	Nickel	210
Arsenic	55	Zinc	720
Cadmium	12	Free cyanide	20

Scope of Site Works and Methodology

The contamination remediation works were undertaken by AEA Technology between October 1998 and August 1999. At the onset of the works a series of fully comprehensive surveys were undertaken to further characterise contamination present. The ground surveys utilised the AEA Groundhog system, which links a highly sensitive, NaI scintillation radiation detector to a GPS detector for position location and a datalogger. For localised and restricted access areas the surveys were undertaken on foot, surveying the area in 1 m wide strips. For larger areas two

detectors were mounted in a line at 1 m spacings across the back of a four-wheel drive, all terrain vehicle. The outputs of these surveys were computer processed and displayed as a series of colour contour maps showing the areal distribution of gamma count rate, which was then related to the contamination distribution. An example is shown in Fig. 2.

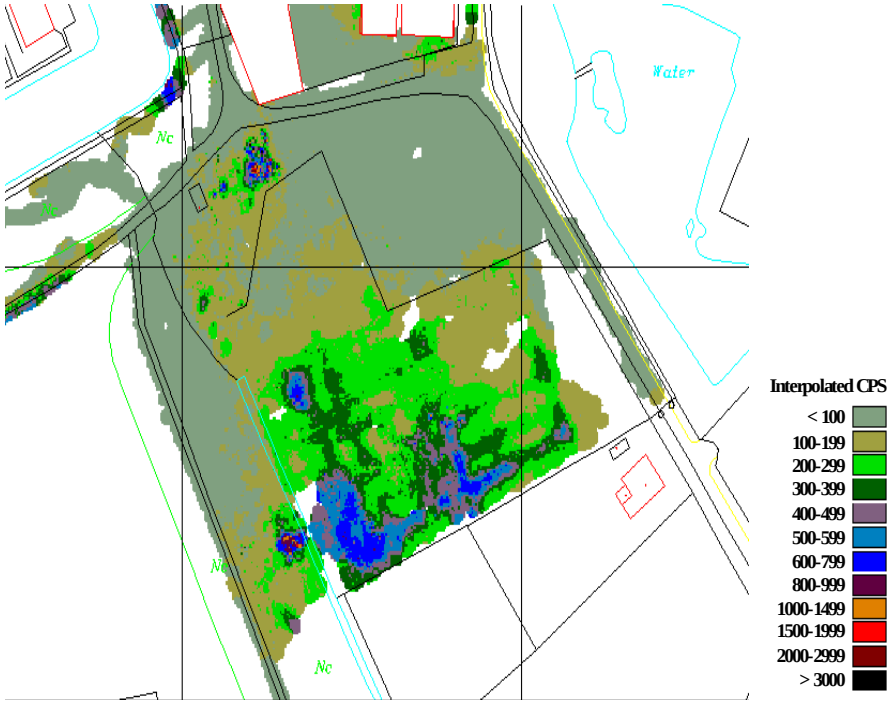

Fig. 2 Ground contamination survey of allotments area using the Groundhog system

The results of these 100% surveys set the scope for the remediation works and finalised the areas requiring excavation and backfilling. In addition, the advanced surveys identified contamination of the building structures and defined the areas requiring remediation.

The scope of the remediation works undertaken was:

- Advance Surveys
- Remediation of ground contamination, both chemical and radiological
- Remediation of non-listed buildings prior to demolition
- Remediation of ground after demolition of non-listed buildings
- Remediation of radiological (radium) contamination of listed buildings
- Remediation of chemical (mercury) contamination of listed buildings
- Investigation and remediation beneath paving and hardstanding areas
- Dredging of the moat sediments and their associated remediation
- Remediation of affected adjacent cottage gardens

The various stages of the remediation works are described below.

Further surveying work was undertaken during remediation (Verification surveys) in order to confirm the quantities or activities found and to ensure that remaining contaminated material was removed. Finally, post-remediation "Validation" surveys were undertaken after backfilling of excavations or reinstatement of works in order to confirm that contamination levels had been reduced to meet the remediation criteria. In addition, Third Party testing was undertaken to provide independent verification of the successful completion of site works.

A variety of remediation techniques were employed during the programme, depending on the nature, location and extent of the contamination present. For each of the main activities, a method statement was prepared outlining the contamination remediation method, along with health and safety information and a risk assessment. Each method statement was reviewed and approved by the client's representative prior to implementation.

THE SITE REMEDIATION WORKS

Advance Surveys

Before any remediation works a series of advance surveys were undertaken in order to further characterise contamination present. These consisted of a radiological survey to redefine and delineate areas of ground and buildings impacted by radium contamination. The surveys comprised of surface contamination monitoring, dose measurements and intrusive sampling. They covered:

- All paved and unpaved external areas, including the moat and fishpond on an average l m line spacing.
- The floors, walls, ceilings and internal features of all buildings, excluding the cottages.
- The exposed ground and drains beneath floor slabs and hard paving as soon as taken up, and the slab or paving materials originating from demolition in all areas.
- All manholes and drains across the site
- A CCTV survey of the drains within the moated area, where possible.
- A mercury vapour survey was conducted in some of the buildings, that were subsequently to be demolished, and within all of the rooms within the listed buildings that remained.
- Intrusive survey by coring/pitting below slabs/paving to be retained, including chemical and radiological analysis of the ground.

Calibration Trials

In order to apply the radiological remediation criteria, which were given as specific activities or dose rates, with the count rate readings taken on site, calibration trials were undertaken. These included:

- Setting the levels of acceptability for Groundhog, e.g. 750 cps.
- Setting the sentencing limit for the assay of LLW at the excavation face, e.g. 4 μS/h.
- Setting the sentencing for waste assay at assay tables.

Ground Remediation

The ground contamination works undertaken on site included:

- Surface radiological monitoring, excavation in horizontal layers, waste stream characterisation, testing and removal from site of soils exhibiting elevated levels of radioactivity from `hot spot' areas defined by the advance radiological surveys. Repeat surface radiological monitoring of the base and sides of remediation excavations to show compliance with the Specification.
- Radiological monitoring of the ground exposed by the breaking out of floor slabs, foundations and paving, and of the concrete arisings to confirm its suitability for removal from site. Testing and subsequent removal from the site of soil with elevated radiation levels.
- Validation surveys, which were gridded radiological surveys, in areas of the site remediated during the works previously covered by buildings, paving, hardstanding, etc, following demolition and removal.
- Excavation, testing and removal off site of any chemically contaminated materials identified during the remediation, demolition and clearance works.
- Investigation and remediation of a defined area of suspected hydrocarbon contamination in the Park
- Third Party testing of completed excavations in selected sub-areas.

Drains

An advance survey was undertaken to confirm the layout of the drains onsite and to identify any manholes, drain runs and surrounding backfill or ground, which had been contaminated by the site's former uses. The advance survey consisted of radiological monitoring within all manholes, a CCTV survey of three lengths of drains within the moated area and localised excavations at drain defects found with the CCTV. Radiological measurements were made in counts per second using Harwell Instruments 1667 $\beta\gamma$ scintillation probes or Groundhog NaI detectors. Measurements of the local background were also taken. Damage was located in two of the surveyed drains leading from contaminated manholes. This was then investigated by local excavation and subsequently removed.

Where radiation above background levels was measured in the manhole, the drain runs leading to and from the manhole were excavated to the level of the drain bedding. Rainwater gullies found to be contaminated were also removed, together with the attached drain. Contaminated electric drawpits and water valve access chambers were either removed or decontaminated. All contaminated material was disposed of off-site. Where buildings were demolished, all drains, gullies and manholes were generally removed as part of the general demolition and ground remediation works.

The base and sides of the drain trench excavations were surveyed using Groundhog detectors and gamma spectrometry samples were taken to confirm compliance with the site remediation criteria. Once verification surveying had shown that no further contamination remained above

the remediation criteria, the excavations were backfilled. A validation survey was then undertaken to demonstrate that the remediation criteria had been achieved. This consisted of surface radiation measurements in counts per second across the whole area of the ground with a Groundhog detector and a surface dose measurement with a Mini doserate meter. The validation surveys showed that the remediation criteria had been achieved.

Area of suspected organic contamination

The previous investigations carried out suggested that part of this area might be contaminated at depth with chlorinated hydrocarbons. Water samples taken from the sampling wells indicated slightly elevated results, as did soil samples from approximately 3 m depth in a trial pit.

Eleven trial pits were excavated on a 10 m grid in December 1998 to properly investigate this area. The pits were excavated to approximately 4 m depth and representative samples were taken at 0.15, 1, 2, 3, and 4 m depth. The works were carried out by a qualified and experienced chemist. A photo-ionisation detector (PID) was used to screen all the samples and the arisings from each pit.

The ground conditions encountered generally comprised a thin layer of topsoil overlying various sand and/or gravel strata. No significant in-situ readings were noted on the PID throughout the investigations. There were no visual or olfactory indications of hydrocarbon contamination (the chlorinated compounds tend to impart a distinctive odour). In total, 33 samples were submitted for chemical analysis of which 32 were tested for VOCs and 15 for other chemicals, including metals, cyanide, phenols and total hydrocarbons. The results of the VOC analysis indicated that all of the samples tested were below the detection limit (1 mg/kg) of the method used. This suggested that the area was not significantly contaminated by these determinands. It was therefore decided to limit the remedial excavation to three locations identified from the previous investigations

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Surveying during Remediation Works

The calibration trials undertaken at the beginning of the works and agreed with the relevant parties enabled in-situ detectors, such as the Groundhog probe and dose rate meters, to be used to assess the extent of contamination as the excavation proceeded.

The Groundhog probe was used initially to define the lateral extent of the excavations, often undertaken in 300 mm lifts (the maximum depth to which certainty can be applied for significant activity in soil). Excavation then proceeded using a mechanical excavator bucket with an agreed and calibrated geometry. Each bucket was monitored with a hand-held device measuring radioactive dose. The result was recorded and the material sentenced according. If appropriate, the Groundhog probe was used repeatedly as the excavation proceeded, each time redefining the extent of remedial work necessary. On completion of each area, the resulting excavation was resurveyed for approval purposes.

Handling of Waste Arisings

Waste materials such as soil, hardstanding, hardcore or building rubble arising from remediation works and excavations were sentenced to one of the following disposal routes:

- Uncontaminated rubble was sentenced as clean spoil.
- Material excavated from designated contaminated areas, reporting less than 4 μSv/h in a standard geometry bucket or remediation rubble with a measured activity greater than 0.37 Bq/g but less than 14.8 Bq/g, was sentenced to the Exempt waste stockpile under Statutory Instrument 1962, No. 2648, of The Radioactive Substances (Phosphatic Substances, Rare Earths etc.) Exemption Order.
- Material excavated from designated contaminated areas reporting greater than 4 μSv/h or rubble greater than 14.8 Bq/g was sentenced to the waste assay buildings.

Material sentenced to the assay buildings was submitted for further classification. The assay process was designed to minimise the quantity of Low Level waste sentenced to Drigg. Small flat buckets containing the potential LLW were presented to an assay table. A Groundhog probe was mounted 0.5 m above the bucket. The material was sentenced as follows:

- If the Groundhog reading was < 2500 cps, the material was sent to Exempt waste stockpile.
- If it was greater than 2500 cps, the material was sent to the sorting tray.

Once on the sorting tray the material was subdivided and monitored using a variety of directional probes. Active relics, e.g. compass parts, clinker, etc, or particularly active soil were picked out and sentenced as LLW. The remaining material was returned to the assay table. Once the Groundhog reading was below 2500 cps, the material was sentenced to the Exempt waste stockpile. Otherwise it was sentenced as LLW. The Exempt waste stockpile was located within existing buildings that were subsequently to be demolished. It was classed as a controlled area for the complete period of the works. The stockpile was routinely sampled, with the samples being submitted for gamma spectroscopic and chemical analysis.

Exempt wastes were disposed of to one of two landfill locations, depending on their chemical content. These were Haul Waste (Ardley, Oxfordshire) for non-hazardous waste and Shanks and McEwan (Bedford) for Special Waste.

The following table summarises the total quantities of material in each category arising for the remediation programme. At all stages of the works every effort was made to reduce the waste arisings from the excavation and remediation processes, and to minimise the amount of material

Fig. 3 Radioactive assaying of waste

Fig. 4 Monitoring and segregation of waste exported offsite for disposal, particularly to Drigg as low level waste.

Table I Approximate total quantities of waste disposed offsite

Waste Category	Total Quantity disposed (te)
Exempt waste	43000
Special Waste (Exempt)	3000
Low-level Waste to Drigg	100

Testing of Imported Materials

The works specification gave physical, chemical and radiological criteria to be met by any material, such as topsoil and subsoil, which was imported onto site for backfilling and reinstatement of remediated areas. To comply with this such materials were tested to ensure that they met the appropriate criteria. The imported materials and tests were:

- Type 1 fill material to Highways specification
- General fill tested for chemicals, gamma spectra and some physical properties, e.g. grading
- Subsoil tested for chemical, gamma spectra and some physical properties, e.g. grading
- Topsoil tested to conform as general-purpose grade with BS 3882 (1994) and submitted for chemical testing.

Where chemical testing was undertaken, 3 samples were taken per source of material plus an extra sample for chemical testing for every 500 m^3 imported onto site. In addition, one sample for every 500 m^3 was submitted for gamma spectral analysis.

REMEDIATION OF RADIOLOGICAL CONTAMINATION IN LISTED BUILDINGS

Advanced surveys were undertaken to identify mercury and radium contamination in listed buildings. Typically this was on wooden floors and around fireplaces. In one building significant contamination was found and removed from large chimneys and under the floor, which required complex temporary access and propping arrangements to protect the building. The affected areas were decontaminated in line with refurbishment plans and constraints agreed with the relevant authorities. Validation monitoring and surveys were performed in and around all remediated buildings. Third party testing was also undertaken to confirm successful completion of the remedial works.

Remediation of chemical contamination in listed buildings

An advance survey was conducted to supplement information from earlier characterisation work. Firstly, a mercury vapour survey was undertaken in rooms shown previously to be free of mercury contamination in order to define the local background level. The latter was established to be 5 $\mu g/m^3$. Mercury vapour levels were investigated in all rooms of the listed buildings by measuring vapour levels along walls and floors. The detector used had a detection limit of 1 $\mu g/m^3$. Elevated mercury vapour levels were identified in 20 rooms. In these rooms building fabric was removed to identify the source. Elemental mercury contamination was discovered in 10 of the rooms.

Samples of building fabric were also taken for chemical analysis to determine the level of mercury and other metal salts in the wood and other materials, as the mercury wood preservatives were common in the nineteenth century and have previously been detected in historic buildings. They have the potential to interfere with the mercury vapour measurements. Mercury salt preservatives were found to be present in the wood. Tests did not find any evidence of anthrax spores in the horsehair plaster, which had been a cause of potential concern. All decontamination of impacted areas was undertaken in line with the refurbishment plans and the constraints agreed with the relevant authorities. The mercury contamination was removed until mercury vapour levels were reduced to background. The waste was placed into drums and disposed of offsite to a licensed landfill.

In each room where remediation had taken place, further validation surveys were taken to ensure that the remediation criteria had been reached. In addition, third party testing was undertaken to corroborate the findings of the AEA Technology surveys.

Remediation of non-listed buildings prior to demolition

In response to the findings of the advanced surveys, localised areas of contaminated building fabric were removed and disposed of off-site. Demolition then took place of the superstructure of all non-listed buildings with segregation of rubble and its disposal as exempt or clean spoil.

Remediation of ground after demolition of listed buildings

Areas where buildings were removed were treated in a similar fashion to other parts of the site. The areas were monitored using Groundhog. They were remediated, as described above, if levels above the remediation criteria were detected.

Investigation and remediation of ground beneath paving and roads

For these areas the procedure was to break out floor slabs and surface paving, radiologically monitor the arisings and exposed ground surface. All radiological and chemically contaminated ground was sampled, excavated, removed and disposed offsite. Advanced coring and trial pitting were carried out through hardstanding and some floor slabs in buildings that were to remain, followed by chemical and gamma spectroscopy analysis of selected samples. Any areas of contamination identified were excavated and removed from site. All hardstanding except important access roads were removed, surveyed and reinstated as either soft landscaping or backfilled with Type 1 material.

Dredging of moat sediments and associated remediation

Advance surveys were undertaken to identify and confirm hotspots within the moat and fishpond. They were then dredged and the sediments screened for radioactivity and analysed for chemical contaminants. Any sediments with contamination exceeding the site-based acceptance criteria were excavated, segregated and disposed offsite.

CONSULTATION

Throughout the work there was extensive consultation with all key stakeholders. The interests of the Ministry of Defence were represented on site by Aspinwall & Company. Regular liaison was established with the Environment Agency (EA) in order to ensure that remediation criteria, waste handling and disposal methods met with their approval. The responsible EA Inspector was involved throughout the project, making several visits to site to inspect the works. The local EA Groundwater Protection officer monitored the progress of the works and in particular the chemical contamination south of Workshop 4. The EA's Conservation Department was consulted concerning the dredging works and the transfer of fish within the moat. Other bodies consulted included the Customs and Excise on Landfill Tax Exemption. The Environmental Health Officers from the two affected local authorities were involved on dust, contamination and other potential nuisances and in representing the local residents' interests. The Conservation Officer was consulted for work associated with the listed buildings and the Tree Preservation Officer was consulted for advice on protecting and felling trees.

CONCLUSIONS

1. This was the largest remediation project, which has been undertaken to date in the United Kingdom in scale and cost of a site contaminated with ^{226}Ra from luminising operations. The remediation works were successfully completed within a period of 12 months.
2. Comprehensive investigations and remediation were carried out across the whole 68 ha site area and within buildings that remain on site.
3. The remediation criteria for the site were set on the basis of a quantitative risk assessment in close consultation with the Environment Agency and the Local Authority.
4. The remediation criteria were established based upon the proposed uses of the site and with public access to the areas outside the moat. The selected criteria were also compatible with sensitive multifunctional use, i.e. housing;
5. The remediation works have removed all identified contamination resulting from the site's former use by the MOD to below levels of concern;
6. There is no evidence of any contamination of groundwater beneath the site nor of any off-site migration of contaminants.
7. The likelihood of appreciable quantities of residual contamination above the site remediation criteria, as yet undetected is considered to be negligible, given the very comprehensive nature of the surveys undertaken, their sensitivity, coverage and the auditable records maintained. Likewise, the risk of such material being present in very localised spots is at levels above the remediation criteria is also considered to be very low.