The Ground Environment Management Scheme (GEMS): Technologies for Detecting and Monitoring Subsurface Leakage and Contaminant Transport, Supporting the Decommissioning of Legacy Silos at the Sellafield Site, UK – 14162

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ABSTRACT

The Sellafield site in West Cumbria (UK) is home to some of the highest hazard nuclear facilities in the Nuclear Decommissioning Authority estate. The removal of wastes from one of these facilities (Magnox Swarf Storage Silos) is required to reduce the hazard and risk. The waste removal operations will increase the likelihood of a leak to ground from the facility.

The Ground Environment Management Scheme (GEMS) is a programme of work that aims to reduce and manage the risk associated with a leak from the facility to ground. An element of this scheme is the selection and development of leak detection and ground monitoring systems. The proposed detection and monitoring systems are a combination of plant based and ground based components including more novel techniques such as time-lapsed electrical resistivity tomography, which have not previously been deployed on a UK nuclear site. One of the safety challenges to designing and installing such systems on the Sellafield site, is the ability to drill boreholes in a contaminated, heterogeneous geology. The technique of coreless sonic drilling is a candidate method to mitigate some of the installation challenges associated with drilling in areas of ground contamination. The development of the technique and a recent non-active trial has shown the capability of the technology for the installation of ground based systems around the Magnox Swarf Storage Silos.

INTRODUCTION

The Sellafield site is located on the north-west coast of England on the margins of the Lake District National Park (*Figure 1*). The surrounding land use is predominantly agricultural with a number of farms and villages. There are two major surface water features present within and adjacent to the site, the Rivers Calder and Ehen which join to the south-west of the site where they discharge into the Irish Sea.

In 1947, the site was acquired by the Government as the location for Britain's plutonium production plant. In the early 1950s, the world's first civil nuclear power generation reactors (Calder Hall) were constructed on the opposite side of the River Calder from and site development and expansion has continued since that time. With the exception of a prototype reactor built in the 1960s, this later expansion has largely been for the purpose of reprocessing spent nuclear fuel and the temporary storage of solid and liquid reprocessing wastes prior to nitrification, encapsulation and storage. The site is operated by Sellafield Ltd, under the Parent Body Organisation Nuclear Management Partners.

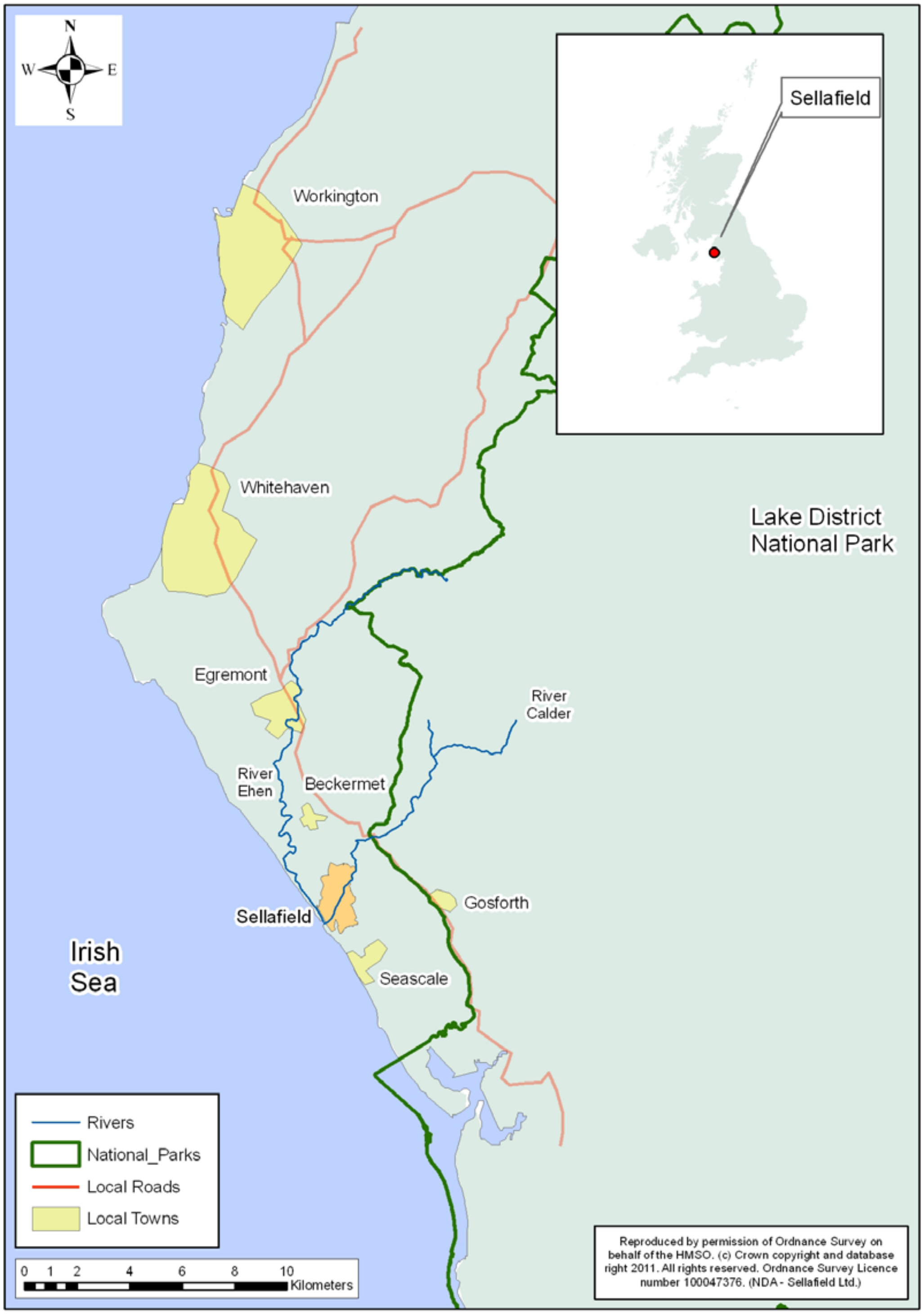


Figure 1 – Map showing the location of the Sellafield Nuclear Licensed Site in relation to the main towns and features in the West Cumbrian area (The general location in a UK context is shown in the inset)

The site is owned by the Nuclear Decommissioning Authority (NDA) on behalf of the UK government. Among other things, the NDA are responsible for [1]:

- decommissioning and cleaning up civil nuclear facilities under their ownership
- ensuring that all the waste products, both radioactive and non-radioactive, are safely managed
- implementing Government policy on the long-term management of nuclear waste

At the heart of the NDA's Strategy is the priority to cost-effectively deliver a reduction in risk and hazard across the estate. It is recognised that to deliver the reduction in risk and hazard there may need to be a near term increase in risk.

The Magnox Legacy Ponds and Silos comprise four main plants at Sellafield which were used historically to prepare fuel for reprocessing or to store waste. Radioactive materials were accumulated and remain stored in the facilities since operations ended. Over five decades these facilities have deteriorated and there is now increased urgency to reduce the risk they pose. The buildings were not originally designed with decommissioning in mind so innovative technology is being used to retrieve the radioactive material for storage in modern containment facilities [2].

The Magnox Swarf Storage Silos at Sellafield is one of the site's four Legacy Pond and Silo facilities. Sellafield Ltd are focused on safely decommissioning these buildings as part of the hazard and risk reduction programme. The facility became operational in 1964 for the underwater storage of swarf waste. The Magnox Swarf Storage Silos received Magnox fuel cladding along with a range of other items of intermediate level radioactive waste. The Magnox swarf, which is almost 100% magnesium, is stored underwater. The degradation of the swarf results in the release of gaseous hydrogen. The plant design and operations ensure that the heat and hydrogen cannot build up to exceed safe levels within the plant. The removal of the waste swarf and processing to a passively safe state is one of the highest hazard reduction activities at Sellafield [3]. It is recognized that there is a risk during the waste retrievals that the building could leak. Existing ground and groundwater contamination is known to exist in the local area [4].

THE GROUND ENVIRONMENT MANAGEMENT SCHEME

The Ground Environment Management Scheme (GEMS) was established to manage the risk associated with a leak to ground from the MSSS during the waste retrievals. The Scheme has adopted a hierarchical approach to reduce the risk posed by a leak to ground (*Figure 2*). In doing so, it recognises that the risk will only be removed by the retrieval of the solid and liquid wastes from the building. Any delay in the start of the waste retrieval has the potential to further increase the likelihood of a leak as the building ages, while delays in the retrieval activities could prolong the period of any further leak, with potentially increased environmental impact.

In the adopted hierarchy the greatest benefits will be from preventing and minimising leakage, it is also recognised that this is not always practicable as the methods could present significant risks in their own right, or significantly delay waste retrievals. This therefore leads to the requirement to ensure that there is adequate leak detection and monitoring arrangements in place to allow a response to any leak from the silos.

The final element of the hierarchy is to consider the strategy for clean up of land and groundwater contamination in the vicinity of the building. This is aligned to the NDAs strategic aim to achieve restoration of sites under its ownership. As the area of contamination in the vicinity of the building only makes up a proportion of the contamination on the Sellafield site, it is important that remedial activities are considered in line with the site wide remediation strategy.

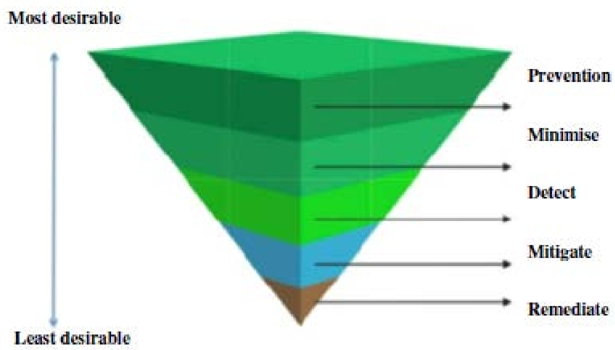


Figure 2 – GEMS Hierarchy

LEAK DETECTION & MONITORING OPTIONS

The GEMS is developing options for a multi-legged detection and monitoring system that comprises a number of components within the plant and within the ground (*Figure 3*). Each component (or leg) has its own primary function that it contributes to the overall system, as well as secondary functions allowing cross-referencing between components. Having multiple legs meets the requirement in the UK nuclear industry of defence in depth. In this case it allows the ability to cross check measurements and reduce uncertainty in decision making.

Of the main components, the in-ground gamma monitoring system and groundwater monitoring techniques are well developed on the Sellafield site. The main technology that requires development is the use of Electrical Resistivity Tomography (ERT). This technique measures the conductivity of the ground between a series of electrodes and can be used to detect changes due to leaks. The silo liquor has a high electrical conductivity, when compared to the ground and groundwater, and ERT, under trail conditions, has been proven to distinguish any change in conductivity caused by a leak to ground. The on site trial of this technology was undertaken in the vicinity of the facility and was found to exceed our initial expectations. The reader is directed to accompanying paper [5] for more information on the trial.

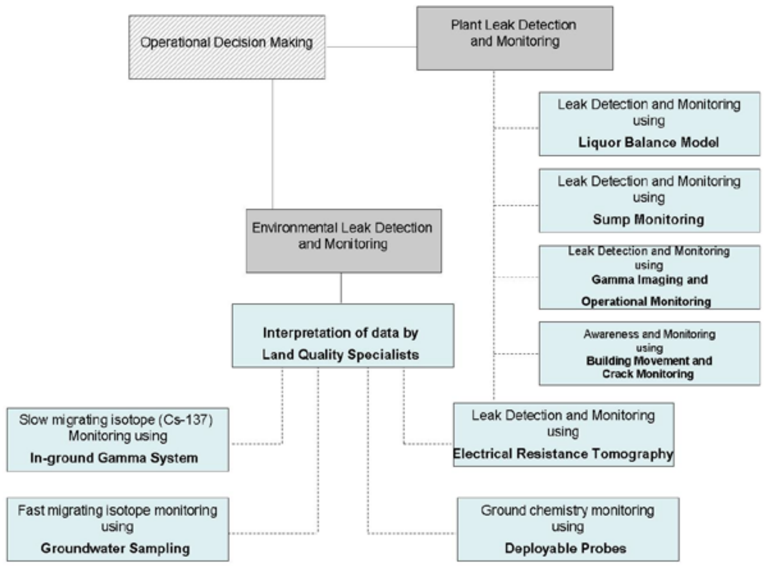


Figure 3 - Proposal system outline for the multi-legged leak detection and monitoring system

INSTALLATION CHALLENGES

A significant risk is associated with the deployment of an ERT system to monitor the ground below the Magnox Swarf Storage Silos, due to the required locations of the electrodes. Boreholes must be drilled into historically radioactively contaminated land. As such there is a risk of recovering contaminated spoil during the drilling operations. The recovery of such spoil has associated waste management and radiation exposure issues.

In 2010 Sellafield Ltd engaged a specialist drilling contractor to support Sellafield Ltd in developing a drilling technique capable of achieving vertical and inclined boreholes whilst generating little or no drilling spoil (waste).

A drilling trial [6] was set up at a site approximately 6 miles to the south of the Sellafield Nuclear Licensed Site that replicated the geological conditions on the Sellafield Site. An innovative drilling method was trialed, using a Rota-sonic drilling rig to carry out 'coreless' drilling. This involved advancing a number of specially developed 'lost cones' varying in type and size from 113mm diameter to 200mm diameter. The cones were advanced through very difficult drift deposits comprising of dense sands and gravels with cobbles and very stiff boulder clay, to depths of approximately 40m below ground level. This trial was also used to test the installation methodology of the ERT string of electrodes prior to the on-site trial.

The technique was developed further during a second trial [7] at a sand and gravel quarry in Auchterarder, Scotland, UK. This trial work was undertaken to include drilling through obstructions (buried concrete blocks), monitoring vibration levels and assessing spoil (solid and liquid) volumes. The trials also developed remote handling tools to reduce contact dose during manipulation of drilling tooling by the drilling crew.

PRINCIPLES OF CORELESS DRILLING

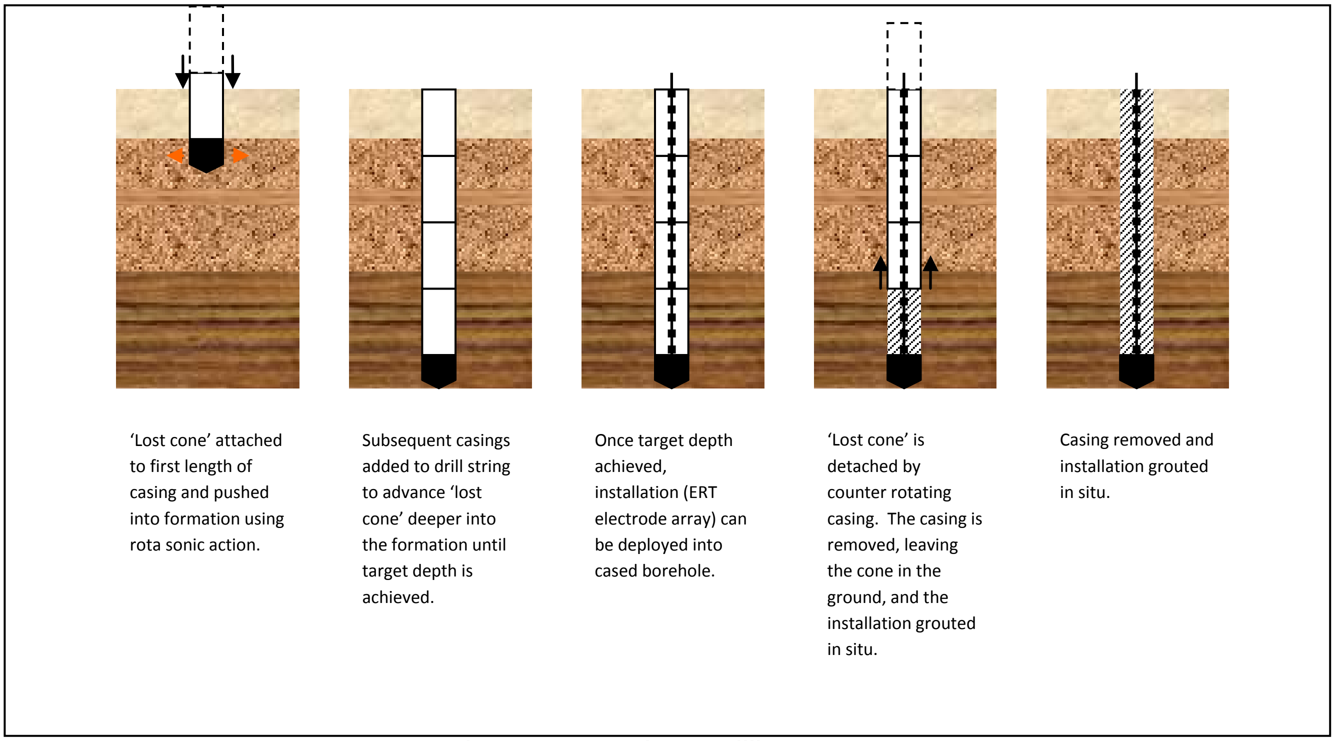


Figure 4 - Coreless Drilling Process

The principle of coreless drilling is to drive a ‘lost cone’ into the ground and attach subsequent lengths of casing, thus creating a cased borehole to the required depth. As the cone and casing are advanced through the sub surface geology the earth is displaced laterally, assisted by the high frequency vibration induced by the sonic rig.

Due to this displacement principle no waste is generated during the installation of the drill casing. Once the target depth is reached an installation can be deployed (for example an ERT electrode array) and the casing retracted (see figure 4). It is only during retraction that limited volumes of solid and liquid waste is produced, by the action of scraping the drill casing.

DRILLING TRIALS
Aims & Objectives

The drilling was undertaken using a mini Rota-Sonic drill rig, otherwise known as a 100C drill rig, which utilises Geosonics’ TRUSONIC drilling technology. The aims and objectives of the drilling trials are summarised below:

- To determine the suitability and optimise the technique of coreless drilling;
- To determine if coreless drilling technique can produce boreholes to the required depth, diameter and inclination for the correct installation of the monitoring systems;
- To determine how the technique is able to deal with hard strata (boulders / concrete obstruction / dense material) beyond the normal capability of the system;
- To determine the extent of spoil (liquid & solid) produced;

- To determine the extent of cooling / lubrication liquid required;
- To determine the vibration levels at varying distances from the rig head.

Geological Conditions

It was critical that the correct site was chosen for the drilling trials to be successful. The main driving factor was finding a site which had the same or similar geological conditions to those underlying the Sellafield Nuclear Licensed Site. The area of the Sellafield Site which the Coreless Drilling method is to be deployed (MSSS) is located over a deep (40m) buried glacial channel. This channel contains quaternary deposits, comprising dense sands and gravels and boulder clay.

An initial drilling trial was undertaken at a site in the village of Drigg, approximately 6 miles to the South of Sellafield Nuclear Licensed Site. Information supplied by the British Geological Survey and historical borehole logs indicated that the site was underlain by 35m to 40m of Quaternary drift deposits comprising of sand and gravels and boulder clay.

Prior to advancing the lost cones a single borehole was completed (to a depth of 42m) using the standard rota-sonic drilling method to sample and record the geological conditions underlying the trial site (Figure 5). No groundwater was encountered in this borehole. The ground conditions encountered comprise an interbedded sequence of gravelly, sandy clay and gravelly sand. Occasional horizons of cobbles and/or boulders were encountered between depths of approximately 21m bgl and 30m bgl.

During the drilling trials of vertical and inclined boreholes, additional sampling was undertaken using the standard rota-sonic core barrel where particular horizons were significantly impacting progress of the lost cones.

A second trial was undertaken at a sand and gravel quarry in Auchterarder, Scotland. Published geological information indicated the trial site to be on a boundary between undifferentiated River Terrace Deposits of gravel, sand, silt and clay and Devensian Diamicton Till.

Again, prior to advancing the lost cones a single borehole was completed (to a depth of 12m) using the standard rota-sonic drilling method to sample and record the geological conditions underlying the trial site. The ground conditions encountered in this borehole comprised an interbedded sequence of gravely clay, sand and gravel. The exploratory borehole indicated that the site had a higher proportion of stiff to very stiff cohesive material than typically encountered at the Sellafield site.

Figure 5 - Typical core samples recovered from exploratory borehole (left Drigg and right Auchterarder)

Lost Cone Development

During the trials the principal of coreless drilling using a 'lost cone' was developed. Several cone types were developed in various sizes (89mm to 200mm) in order to penetrate obstructions and hard strata to achieve the required target depth and borehole angle. A total of four different borehole angles were undertaken during the trials (Figure 6), including:

- Vertical
- 15º to the vertical
- 38º to the vertical
- 58º to the vertical

Figure 6 - Vertical and inclined boreholes being drilled using coreless 'lost cone' technique

In order to assess and develop the lost cones, a number of different sized cones were used during the drilling trial. Two standard versions (for all of the different diameters required) were manufactured, referred to as cross and cutting blade. Photographs of these lost cones are presented within Table I.

As the drilling trial progressed and ‘obstructions’ were encountered the lost cones were modified to try and establish the best combination for advancing through different soil types and to establish the best coupling method which allows the driller to control when the cone is lost.

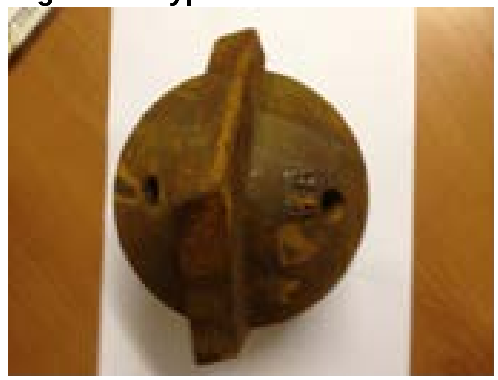
Boreholes were completed in diameters ranging from 104mm to 197mm (OD) advanced using the lost cones shown within Table II. Ground resistance increased with borehole depth and diameter, with the greatest depths achieved during drilling of the smallest diameter (104mm) boreholes. It should be noted that in order to progress boreholes to the maximum depths required, the boreholes were first drilled in narrow diameters, with the boreholes widened using larger diameter casing, before continuing drilling in a smaller diameter.

Different combinations of lost cones and casing shoes were used during the trial in order to assess which might be most suitable for use during the project works on the Sellafield site. The development started with the design, prior to the trial commencing, of the cross and cutting blade types. Other hybrid cone types were developed as the trial progressed and included:

- Cross Type
- Cutting blade welded into casing shoe with ballistic implants;
- Full face bits with ballistic implants;
- Casing shoes with ballistic implants.

The cone designs performed with varying efficacy dependent on the ground conditions in which they were being used. Where unconsolidated overburden was encountered, all cone/shoe configurations were able to progress the boreholes, albeit at differing rates. However, in over consolidated sediments or when cobbles and boulders were encountered, cones with ballistic bits and/or coring techniques were more successful in progressing the boreholes. It was noted that obstructions caused significant wear to the cutting blade cones, with cross type cones showing less wear.

TABLE I: Summary of different Lost cones / Bits Used

Cross Type Lost Cone 	**Cutting Blade Type Lost Cone** 
Drive Shoe used for both types of Cone 	**Cutting Blade Type set within full face drill bit** 
Full Face Bit and Casing Shoe 	**Cutting Blade type cone with edges / fins removed** 

Cone Locking Mechanisms

A number of locking mechanisms for holding the cones/bits in place during drilling but allowing for them to be disengaged and become sacrificial were also developed and tested during the trial (Figure 7):

- Push-lock with shim;
- Push-lock with pin;
- Twist-lock with pin.
- Welded

During the initial stages of the trial, the push-lock mechanism with shim did not allow reaming of the borehole due to the inability of the cone/shoe to rotate within the barrel. In this context reaming refers to method of advancing the borehole with a lost cone; pulling the cone back slightly during advancement to reduce pressure down the borehole and to help to clear the cutting faces of the cone.

Modification of the locking mechanism and the introduction of the push-lock with pin and twist-lock with pin systems increased the efficiency of all cones/shoes to achieve target depth as it was possible to ream the borehole.

The preferred option of twist-lock with pin allowed for both reaming of the borehole and retraction of the cone during drilling without loss. Additionally, this system enables the full retraction of the cone should this be required, whilst at the same time the cone can be sacrificial (by counter rotation) when required.

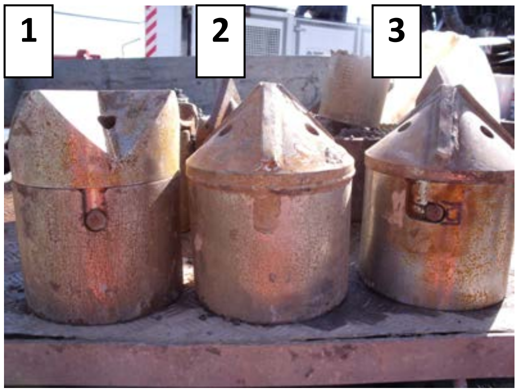


Figure 7 - Locking Mechanism Development: 1) Push-lock with shim, 2) welded onto drive shoe, 3 & 4) twist lock with pin

Advancing Through Obstructions

During the initial trials at the Drigg site, limitations were identified with the lost cone technique, relating to advancing through obstructions and/or hard strata and drilling beyond 30m depth. As such this limitation was further reduced at the second trial using a full face bit and / or standard coring.

The drilling strategy adapted to changes the method when encountering an obstruction when using coreless drilling. In order to simulate an obstruction, two concrete blocks (1m x 1m x 1m) were constructed in mass concrete (C20 equivalent) and installed side by side in an excavation, with the base approximately 3m below ground level. The excavation was then backfilled with arisings and compacted.

During the trial it was proven that the lost cone technique was unable to penetrate the buried concrete. The change in drilling methodology allowed the borehole to be advanced using a coring bit and full face bit. Once through the obstruction the lost cone could be lowered down the borehole again and used to reach the target depth.

During this phase of the trial, it was noted that the lost cone rate of progress was greatly reduced when drilling through cohesive material and/or cobble and boulder rich deposits. The full face system was found to be much more effective in such material.

Drilling Derived Waste

The method of sonic coreless drilling results in a significantly reduced volume of drilling derived waste (DDW) when compared to conventional drilling techniques. When using the lost cone technique DDW is only produced when the casing is removed from the ground. To minimise waste when the casing is extracted a stiff rubber donut scraper was placed around the casing to clean / scrape any residual soil / slurry into the drill through tank. In general a 40m borehole generated <0.1m3 of solid waste.

The volume of DDW recovered is largely dependent on the specific geology encountered in a particular borehole, with cohesive material increasing the DDW.

Generally, boreholes were drilled dry where possible, with small amounts of water added to the side of the casing. The use of a flush medium was minimised where possible, however some flush was required to progress past obstructions. Water was brought to the site in 1000l IBC's. This enabled the volume of flush water to be monitored at each borehole location. Flush water returned to the surface via the casing, was captured in an open (drill through) tank fitted around the borehole. The volume of captured flush water was taken upon completion of each borehole.

When using the full face bit to advance through the concrete obstruction ~300 litres of water per linear meter was used as lubricant and ~200 litres was captured in the drill through tank.

When using the full face bit to advance through natural ground a total volume of 980 litres was used for 6.3 linear meters (150 l/m). A major influencing factor is the time taken to advance through the ground: a slower rate of progress would equate to the consumption of more flush water. In the same borehole a total of 700 litres was captured (110 l/m). Again the progress rate has a significant influence on the volume of flush return. In addition, the permeability of the strata also influences the flush returns. In strata with high permeability it would be expected that the capture rate would be lower since flush water would be able to drain away more readily than in low permeability glacial till encountered at the (Auchterarder) trial site below 6m bgl.

Work is continuing to further develop the (full face) coreless technique to minimize and control the disposal of DDW.

Inclination Control

To ensure precise installation of monitoring systems and to reduce the risk of a strike of the building structure during drilling it will be necessary to control the inclination during the advancement of boreholes. To assess the potential for deflection whilst using the coreless drilling technique, inclination checks were undertaken at the Drigg trial on: one vertical borehole, two boreholes drilled at 15º and two boreholes drilled at 58º, by means of a Reflex Instruments 'Reflex Gyro'. Readings of the borehole angel were recorded at two meter intervals, once the drill rods / casing had been driven to the target depth

The inclination data for the (22m) vertical borehole were recorded twice, once lowering in the instrument into the hole and once lifting the instrument from the hole. The maximum recorded deviation from the vertical (90º) was 1.1 degrees, with the mean angle recorded on both the in and out runs as 89.07º.

The inclination data for the (45m) boreholes completed at an angle of 15º to the vertical were recorded to have a maximum variance from the instrument input angle (15º) of approximately 0.6º on the second of the wells measured.

The inclination data for the (24m) boreholes completed at an angle of 58º to the vertical were recorded to have a maximum variance from the instrument input angle (58º and 57º) of approximately 1.2º on both the in and out runs from the first of the 58º holes measured.
Vibration monitoring

Due to the sensitivity of the MSSS structure, strict vibration limits have been set when working close to the building. During the trial of coreless drilling, vibration monitoring was undertaken during drilling in order to assess the variations in vibrations caused by the different drilling equipment and the geology encountered. This was used to assess the potential impact of sonic drilling activities on structures during drilling on the Sellafield site. Monitoring was undertaken using a Vibrock V901 portable seismograph unit.

Each seismograph comprised a datalogging unit and geophone. The geophones were set up in a single linear array aligned perpendicular to the drilling rig undercarriage at 1m, 2m, 4m and 6m from the borehole. Provisional threshold limits for particle velocity of 15mm/s (early warning alarm) and 30mm/s (upper limit) were set by Sellafield Ltds Civil and Structural department. These limits were aligned with the age and condition of the building in the vicinity of the proposed future drilling sites.

The data loggers were downloaded to a laptop at the end of each day. During operations, events anticipated to cause a spike or shock in vibration levels (e.g setting drilling casing down close to the geophone or accidental knocks) were observed and recorded manually for corroboration with the data at a later date.

Generally during normal drilling operations the upper limit was not breached and the drilling crew were able to control the vibration levels to within the set threshold. Peaks in vibration >30mm/s were linked to extreme events such as a drop load next to the geophone or extraction of drill tooling catching the drill casing.

Casing Handling Tool

During normal drilling operations, steel casings are manually lifted into position on the casing string by the drilling crew using a 'bear hug' technique to grip the casing. For installation of boreholes around the MSSS there is a requirement to maintain an arm's length distance between the drilling crews torso and casings that may be affected by significant radioactive surface contamination. The drilling consultant engaged by Sellafield Ltd developed a prototype casing handling tool which, when used in conjunction with the rig mast winch, allows the casings to be handled at arm's length (Figure 8).

Figure 8 - Use of casing handling tool

The casing handling tool was generally considered by those observing to meet the requirements, but at the cost of a longer period of time taken to install or remove each casing length. The manual bear-hug and the handling tool technique were timed and this showed a casing change could be effected in ~30 seconds manually or two minutes using the handling tool. Using 1.5m length casing in a 12m borehole would require 8 casing lengths, equating to an additional 12 minutes of time during drilling and a further 12 minutes during de-rigging the borehole. This could equate to significant dose uptake in some areas around the MSSS. The benefits of using the handling tool versus the time implications must be considered in an As Low As Reasonably Practicable (ALARP) assessment. Work is will continue to develop and improve the handling tool to reduce the operating time.

CONCLUSIONS

The Ground Environment management Scheme has proposed a multi-legged leak detection and monitoring system for the Magnox Swarf Storage Silos. The proposed system combines mature technologies, such as in-ground gamma monitoring and groundwater monitoring, with more novel techniques such as Electrical Resistivity Tomography. However, to successfully install these ground based systems a number of technical challenges need to be overcome, particularly drilling in areas of ground contamination and difficult geological conditions.

The development of coreless drilling using the sonic drilling technique has been trialed with positive results. The capability of the technique to drill into a variable geology was demonstrated in a drilling trial which was used to test a number of different 'loss' cones. The use of the technique resulted in significant reductions in the volumes of both solid and liquid wastes. The levels of drilling induced vibration were kept below the upper limit.

The use of a drill casing handling tool was tested as a method to reduce contact dose with potentially contaminated drill casing. This successfully kept the drill casing at arms length during manipulation, however it was found to at the expense of the speed of drilling which was increased by 24 minutes for a 12 m borehole.

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